

Environment & Changing Climate 2025

Conference Proceedings

Organized by Independent University, Bangladesh (IUB) & The COLOCAL Project

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Foreword

As global environmental challenges intensify, the urgency to align strategic climate governance with context-specific adaptation becomes increasingly evident. The Environment & Changing Climate: Global Strategies and Local Actions conference at Independent University, Bangladesh (IUB) brings together researchers, policymakers, community leaders, and innovators to explore multidisciplinary approaches to climate resilience.

Through thematic sessions, collaborative dialogue, and knowledge-sharing events, the conference aims to highlight strategies that bridge the gap between global commitments and grassroots action. By fostering partnerships, amplifying indigenous and community-based knowledge, and showcasing innovative practices, the event aims to generate actionable insights that advance environmental resilience, accelerate sustainable development, and strengthen our collective capacity to respond to the climate crisis.

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The Co-Creating Knowledge for Local Adaptation to Climate Change in Least Developed Countries (COLOCAL) Project is an initiative under the Norwegian Agency for Development Cooperation's NORHED II 2021-2026 programme.

The project was initiated by the International Centre for Climate Change and Development (ICCCAD) at the International University of Bangladesh, which leads a network on climate change and capacity building in Least Developed Countries (LDCs). They were instrumental in selecting the partners, who are part of the LDC Universities Consortium on Climate Change (LUCCC) network, based on a needs assessment and interest.

The aim of this project is to build capacity of universities in LDCs for Community-Based Adaptation (CBA) and Locally-Led Adaptation (LLA) education and research. The project is designed to contribute to the goals of LUCCC, including south-south collaboration, working with the most vulnerable to foster collaborative learning and capacity-building.

The participating LUCCC partners are University of Makerere in Uganda, Eduardo Mondlane University in Mozambique; Pokhara University in Nepal; and Independent University in Bangladesh, with the Norwegian University of Life Sciences as a north-based partner. Activities under the project include undertaking research that focuses on vulnerable communities facing diverse climate risks, adopting bottom-up approaches to knowledge co-creation. Such research-based knowledge is expected to feed into educational curricula development and capacity-building activities. The project will engage in capacity building at multiple levels through inter and intra-country co-learning involving students, university researchers and educators, community groups, local governments, and policy makers.

The expected outputs of the project include strengthened educational and research capacity, improved knowledge on CBA, including skilled CBA knowledge co-creators, and partnerships to support needs-driven, locally-based and contextually sensitive adaptation. The outputs are expected to influence policy, planning and practice around CBA through co-learning and knowledge dissemination.

Website: <https://www.luccc.org/projects/colocal>

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Paper 1

Bridging Policy and Practice: Climate Finance and the Loss & Damage Funds in Bangladesh

Nuzhat Fatima Purnota, Md Shanawez Hossain

Abstract

Climate finance has become a central mechanism in addressing the growing vulnerabilities of developing countries, particularly Least Developed Countries (LDCs) like Bangladesh, to the adverse impacts of climate change. Over the past three decades, global climate financing frameworks have evolved through landmark agreements such as the Rio Earth Summit (1992), the Kyoto Protocol (2005), and the Paris Agreement (2015), culminating in the recent establishment of the Loss and Damage Fund (LDF) at COP27 in 2023. This paper critically examines the evolution of climate change funds and their implementation in Bangladesh, with a particular focus on adaptation, mitigation, and the potential role of the newly introduced LDF in addressing climate-induced loss and damage. Using a qualitative methodology, the study relies on secondary data drawn from government policy papers, budgetary plans, donor reports, journal articles, and international agreements to map Bangladesh's climate finance landscape over the past two decades. The findings reveal significant gaps between fund allocation and actual implementation, with major portions of climate funds directed towards infrastructure and mitigation projects. At the same time, comparatively fewer resources reach the most vulnerable communities. Furthermore, weaknesses in governance, transparency, and institutional capacity hinder the effective utilisation of climate funds, often resulting in misaligned priorities and limited outcomes in building resilience. The paper argues that while Bangladesh has developed robust policy frameworks—including the Bangladesh Climate Change Strategy and Action Plan (BCCSAP), Climate Fiscal Framework (CFF), and Delta Plan 2100—the translation of these plans into effective action remains constrained by governance challenges and inadequate coordination among stakeholders. The study underscores the urgent need for inclusive and accountable financing mechanisms that prioritise marginalised and climate-affected communities, integrate gender-sensitive approaches, and promote stronger public-private partnerships for efficient fund utilisation. The LDF, if operationalised with transparency and equity, could offer Bangladesh a critical opportunity to address both economic and non-economic climate-induced losses. The paper concludes by recommending enhanced institutional capacity, participatory governance, and comprehensive monitoring and evaluation frameworks to ensure that climate funds, especially the LDF, contribute meaningfully to sustainable development and resilience-building in Bangladesh.

1. Introduction

The climate financing landscape of Bangladesh has been helping the development of the country, whether in building resilience, infrastructure, in the renewable energy sector, or other sectors like agriculture, for over 2 decades (MoF, 2023). International conventions have played a big part in recognising the need for climate financing for the least developed countries. The United Nations Framework Convention on Climate Change (UNFCCC) has been playing a crucial role in operationalising the climate financing mechanisms for developing countries, especially the ones who are the victims of climate change.

Bangladesh has been one of the critical victims to endure the impacts of climate change (Eckstein et al., 2021; Wright, 2014; Kabir, 2014), which allows its government to access the climate finance subsidies. In most cases, these funds are spent on projects catering to adaptation and mitigation measures in the most vulnerable parts of the country. The involvement of multilateral investors, including the private sector, state governments, and bilateral donors, is prominent in financing development projects in Bangladesh. In fact, according to a press release by the International Monetary Fund (IMF) in 2023, investors and donors like the Asian Development Bank (ADB), the World Bank (WB), International Finance Corporation (IFC), Multilateral Investment Guarantee Agency (MIGA), Asian Infrastructure Investment Bank (AIIB), Agence Française de Développement (AFD), the European Union and the European Investment Bank (EIB), as part of Team Europe, the Green Climate Fund (GCF), the Government of South Korea, Japan International Cooperation Agency (JICA), and the United Kingdom came up with a collaborative approach to help Bangladesh strengthen its ability to cope with its adaptation and mitigation measures due to the impacts of climate change which is named the Bangladesh Climate and Development Platform (BCDP) (International Monetary Fund, 2023).

The BCDP will assist Bangladesh in achieving its climate agenda by developing a solid stream of climate projects that are integrated with a funding strategy approved by the donors. This would also aid scalability in attracting private investment throughout the country, mainstreaming projects into development plans, and decreasing the financial strain on the state sector. During the COP24 in Katowice, Poland, in December 2018, the IPCC stressed the need for setting ambitious targets to maximise mitigation and adaptation efforts for all parties (World Health Organisation, 2018). Developed nations must aid developing countries with funds, development of technology, and capacity building to enable them to carry out necessary operations. Bangladesh has been claiming its rights to the aid, being eligible to all the criteria as mentioned by IPCC, and being a lower-middle-income climate-vulnerable country since 2015. Additional global climate financing mechanisms and funds supporting the developing countries include the Global Environment Facility (GEF) Adaptation Fund, Global Climate Change Alliance (GCCA), Least Developed Countries Fund (LDCF), Adaptation for Smallholder Agriculture Program (ASAP), Climate Investment Fund (CIF), UN-REDD Readiness Program, Green Climate Fund

(GCF), and more. Thus, though all these funding mechanisms have become a central mechanism in addressing climate change-induced vulnerabilities of developing countries, there are also debates and concerns regarding the effective utilisation of climate funds. Particularly, weakness in governance, transparency, and institutional capacity in many developing countries resulted in misaligned priorities and limited outcomes in building resilience. Thus, there are many instances where we can see climate change adaptation measures, projects, and programs resulting in unintended consequences and receiving criticisms for being ineffective or inefficient (Dewan, 2021; Chakraborty & Burgess, 2023).

1.1 Objective, Methodology, and Contribution

With this backdrop, the main objective of the paper is to look at the history of climate change funds in Bangladesh and analyse the trend of project-wise budgetary allocations to address the adverse impacts of climate change. The analysis shows the gap in fund allocation and its implementation. Additionally, it also explores the contributions of the international funds in supporting national development in climate-vulnerable areas to address climate change-induced loss and damage with the recently acknowledged Loss and Damage Fund.

This paper follows a qualitative research methodology. The data is gathered from secondary data like action plans, policy papers, journal articles, and international reports focusing on climate financing, development projects, climate change resilience plans, and loss and damage. The paper further recommends policy suggestions to better handle the loss and damage fund in order to meet the fund's goals. The data used are taken from budgetary plans over a span of twenty years and are critically analysed. The barriers of policy implementation, as well as gaps in progress, are addressed. Furthermore, the research examines how stakeholder interaction may prove to be beneficial in this context.

This study aims to understand the current climate finance landscape of Bangladesh, providing a guide for policymakers, practitioners, academicians, and field workers (such as from NGOs) to have a better understanding of how future plans should be designed and executed to ensure the utmost fund utilisation.

2. Evolution of Climate Change Funds to Loss and Damage Fund

2.1 Brief history of climate change funds

Amidst the increasing critical climate events throughout the years, Bangladesh aspired to put the Bali Road Map of COP13 (2007) into effect, meaning poverty reduction and development were among the country's primary aims (MoEF, 2009). Hence, it requested international assistance as an LDC to become more resilient to climate change, claiming that the resources available in 2008 during COP14 were insufficient to address climate change adequately. The Government of

Bangladesh (GoB) drafted the first Bangladesh Climate Change Strategy and Action Plan (BCCSAP) in 2008, which was built on the National Adaptation Plan of Action (NAPA), originally written in 2005. However, Bangladeshi policymakers acknowledged that the NAPA was an insufficient strategy that did not solve the country's climate change challenge. Thus, the government subsequently embarked on a more complete planning process, using its own financial and intellectual resources (Munjurul et al., 2012). The GoB felt the urgency of implementing the BCCSAP, adhering to its crucial climate needs, so it initiated the plan with its national funds rather than waiting for international aid to flow in. Hence, the Bangladesh Climate Change Trust Act (BCCTA) was established in 2010. Following the decisions of the GoB in the previous years, the Planning Commission's General Economics Division (GED), sponsored by UNDP and UNEP, commissioned and carried out a Climate Public Expenditure and Institutional Review (CPEIR) to analyse this spend, its policy and strategic drivers, the institutions delivering it, and identifying ways to manage it more effectively (O'Donnell et al., 2013). In the year 2014, the Climate Fiscal Framework (CFF) was published, where the CFF incorporates climate change implications into national fiscal and budgetary procedures. Its goals were to establish national ownership of climate funding, encourage government-NGO-private sector cooperation, and improve results management. The CFF provides the concepts and instruments needed for developing climate fiscal policies (CFP). It ensures that climate fundings are managed effectively, transparently and sustainably.

In 2015, Bangladesh started implementing the Sustainable Development Goals (SDGs). It ensured focusing on SDG13 (Climate Action), which gives significant importance to climate change adaptation, mitigation, and building capacity. The Nationally Determined Contributions (NDC) were also published the same year. The NDC was the climate action plan for Bangladesh, and it focused on the country's climate change adaptation and mitigation plans to increase its resilience towards climate vulnerability. In 2016, the Country Investment Plan for Environment, Forestry, and Climate Change (CIP-EFCC) was issued. CIP-EFCC linked climate funds to national development agendas. It highlighted investment needs in climate-resilient industries. The Climate Performance Audit Guidelines (CPAG) were established in 2018 with technical assistance from the Inclusive Budgeting and Financing for Climate Resilience (IBFCR) Project, which is funded by the Ministry of Finance and UNDP. It complies with the International Organisation of Supreme Audit Institutions (INTOSAI) standards. The CPAG seeks to guarantee that climate-related initiatives provide value for money while also benefiting the populations that are most vulnerable to climate change. The recommendations assist auditors in planning and carrying out climate performance audits. They contribute to determining the efficacy, efficiency, and impact of climate-related undertakings. Later that year, in September 2018, the Bangladesh Delta Plan 2100 was approved, which is a century-long visionary plan to oversee the delta of the country. It incorporates all delta-associated sector policies and plans, focusing on building resilience, safety, and prosperity in the long run. The BDP2100 pledges to utilise 2.5% of GDP on delta interventions, including new investments and the maintenance of current initiatives. The Bangladesh Country Programme for the Green Climate Fund (GCF) was released as well in

2018, defining the country's climate change goals and an agenda of projects to be implemented in partnership with the GCF. Then, in 2019, the Perspective Plan 2021-2041 was introduced. It aims to define the country's SDGs, with an emphasis on the economic, social, and environmental components to ensure long-term sustainability. Bangladesh aspires to mitigate climate risks, improve resilience, and achieve sustainable development goals by incorporating climate factors into fiscal management practices. Thus, the CFF was updated again in 2020 to reflect the current landscape of financial needs related to climate change. Additionally, the principal goal of the Eighth Five-Year Plan (8th FYP) is to begin implementing the Perspective Plan 2021-2041, which intends to move Bangladesh closer to Upper Middle-Income Country (UMIC) status by 2031. On February 13, 2023, the World Bank's budget support program issued the Green and Climate Resilient Development (GCRD) Guideline, which aligns with the core initiatives of the 8th Five-Year Plan (2021-2025), Perspective Plan 2021-2041, Nationally Determined Contributions-U, National Adaptation Plan, Delta Plan 2100 and Mujib Climate Prosperity Plan (MoF, 2024).

2.2 Evolution of climate change funds

Loss and Damage come into play when adaptation and mitigation are no longer applicable in a scenario. The concept arose for the first time in the Bali Action Plan in 2007 and is completely intertwined with disaster risk reduction (UNFCCC, 2007). In COP27, the loss and damage fund was established after a long-negotiated discussion of the demands of the LDCs for specific funds to address loss and damage as a means of compensation by the polluters. Different organisations and governments of developed countries ensured the assistance for severely impacted communities and the countries facing “unavoidable” impacts of climate change loss and damage. However, the outcome depends on ensuring proper implementation of the fund, meaning that good governance is crucial in such delicate situations where vulnerable communities are at stake at times of life-threatening disasters. It is crucial for Governments to improve resilience of the climate victims by establishing platforms in order to ensure a transparent, accountable, participatory, and integrated approach of the affected communities at all stages of fund governance (Kabir, 2014).

These initiatives over the years served the main purpose of helping Bangladesh prepare for the impacts of climate change with interdisciplinary strategic systems. From using adaptation to mitigation measures to minimise climate change effects, to implementing different financing strategies to deal with the impacts, to improving policy architectures over the years periodically with short-term, mid-term, and long-term plans.

3. What Happens with the Fund?

The developed countries agreed to provide support of about USD 100 billion per year starting from 2020 for the least developed countries to combat the effects of climate change when the

LDC parties demanded to hold them accountable during the international climate negotiations under the UNFCCC. Several multilateral banks, including ADB, World Bank, UN agencies, GCF, LDCF, etc., started channelling the aid to the LDCs. However, 80% of the fund has gone to mitigation efforts to reduce greenhouse gas (GHG) emissions, and 20% of it has gone to the poor countries to support adaptation measures, 2% of which actually makes it to the most vulnerable communities (Huq, 2020).

According to the Bangladesh Climate Public Expenditure and Institutional Review (CPEIR), BCCRF and PPCR's special donor funds add just 2% to 3% to overall climate-sensitive spending, resulting in a ramping effect. Over three financial years, 2009-11, an 11% increase in financial support from donors resulted in a 16% rise in climate-sensitive expenditure (General Economics Division Planning Commission, GoB, 2012). Donor resources often focus on climate change, but in Bangladesh, both climate resilience and climate change are handled together. Hence, it is advised that donor climate funds be targeted as general support to climate-sensitive activities within the Climate Fiscal Framework (O'Donnell et al., 2013). It can be observed that the allocations made for the projects are not being implemented properly. According to the Bangladesh's Citizen's Climate Budget Report 2020-2021, an estimated total of Tk. 3,52,800 crore within 2015-2030 is required to facilitate adaptation measures and Tk. 2,26,800 crore for mitigation measures within the year 2011-2030 in accordance with the NDC (MoF, 2020).

The following data describes the budget allocations for different ministries from the Bangladesh Climate Change Trust Fund (BCCTF) during FY 2009-2010 to FY 2019-2020:

Table 1: BCCTF projects and their budgetary allocations

Ministries/Divisions	Number of BCCTF Projects	Allocations for BCCTF projects (in crore taka)
Ministry of Water Resources	132	1,044
Local Government Division	441	1,313
Ministry of Environment, Forest and Climate Change	68	415
Ministry of Agriculture	20	136
Ministry of Disaster Management and Relief	8	126
Ministry of Education	29	77
Ministry of Defence	9	45
Other Ministries/Divisions	20	170

Table 1 shows that the Bangladesh Climate Change Trust Fund projects were allocated in different ministries and their budgets accordingly. The BCCTF was originally established to build the country's resilience towards climate change. However, the budget allocations do not reflect the same goals. There were only 8 projects allocated for the Ministry of Disaster Management and Relief, whereas 441 projects were allocated for the local government divisions. There is no clear evidence on how the funds for these local government division projects were spent. Moreover, 132 projects were assigned to the Ministry of Water Resources, but it is not clear if all these projects were for building the country's resilience towards climate change, or other separate developments. The budgetary allocations according to the BCCTF for the BCCSAP thematic areas are shown in the table below:

Table 2: Budgetary allocations according to the BCCTF for the BCCSAP thematic areas for FY 2009-2010 to FY 2019-2020

BCCSAP Thematic Areas	Number of BCCSAP Thematic Area-wise Projects	BCCSAP Thematic Area-wise Allocation (in crore taka)
Food Security, Social Protection and Health	103	358.8
Comprehensive Disaster Management	12	158.8
Infrastructure	395	2,025.95
Research and Knowledge Management	35	131.56
Mitigation and Low Carbon Development	173	608.62
Capacity Building and Institutional Strengthening	9	42.01

According to Table 02, the least number of projects were allocated to building capacity and institutional strengthening, whereas it is crucial for the country to have a strong institutional capacity first in order to tackle critical challenges like climate change. The highest allocation was targeted towards infrastructure, which is fair considering the development of cyclone shelters in cyclone-prone areas that help manage disasters more efficiently. Bangladesh is one of the few countries with a strong cyclone resilience capacity, as the country's disaster management program has created a successful Cyclone Preparedness Program (CPP) (Kazi & Urrutia, 2016). Bangladesh's target of reaching net zero by 2050 explains the 173 projects assigned to the *Mitigation and Low Carbon Development* theme.

Table 3: Division-wise allocation according to the BCCTF for FY 2009-2010 to FY 2019-2020

Divisions	Division-wise Projects from BCCTF	Division-wise allocation from BCCTF (in crores taka)
Dhaka	122	540.73
Chittagong	131	618.61
Barishal	134	587.59
Khulna	79	282.72
Rajshahi	75	197.43
Rangpur	58	168.28
Sylhet	41	138.98
Mymensingh	31	114.51
More than one Division	56	576.9

Table 03 indicates the division-wise projects from BCCTF and their allocated budgets. Dhaka and Chittagong, as major cities, had urban development projects assigned. Barishal and Khulna, as climate-impacted zones, had 134 and 79 projects allocated. Barishal had 3 more projects than Chittagong, whereas Chittagong should have had more projects allocated since it has both urban development projects and severe climate-impacted zones. On the other hand, Dhaka was assigned 122 projects where the main climate concerns were the development of urban infrastructure (e.g., drainage systems and urban planning) in order to accommodate climate migrants (Mithu, 2023).

In Table 04, the projects are based on climate change hotspots. Here, Barind and drought-prone areas had zero (0) climate-relevant projects allocated and 9 water sector projects; however, no budget was allocated for such a climate-vulnerable area. In the dry season, when the rainfall is lower than usual, agricultural output is insignificant, caused by a lack of soil moisture essential for desirable crop production (Brammer, 1987). Farmers face irrigation challenges due to reduced availability of water, resulting in a decline of agricultural yields, particularly rice, increasing the likelihood of food deficits, economic failure, and more (FAO, 2011; Jamal et al., 2023). This indicates a gap in budget allocation in climate-vulnerable areas.

According to Table 05, it can be understood that the budget increases over the years to help implement the NDC Adaptation Plans. The country's aim to be adaptable to the adverse climate change impacts is reflected in its fiscal budget plan.

Table 4: Bangladesh Delta Plan-2100 projected spending based on climate change hotspots

Climate Change Hotspots	Water sector projects for climate hotspots	Climate-relevant projects for climate hotspots	Projected total allocation for climate actions (in crore taka)
Coastal Zone	23	13	73,094
Rivers and Estuaries	7	5	48,456
Urban Areas	12	5	11,034
Barind and Drought-Prone Areas	9	0	0
Chittagong Hill Tracts	8	2	4,406
Haor and Waterland	6	4	1,814
Cross Cutting	15	5	56,335

Table 5: Budgetary allocation for Climate Change adaptation activities according to the Nationally Determined Contributions (NDC)

Fiscal Years	Allocation Against NDC Adaptation Plan (in crore taka)
2016-2017	13,274.68
2017-2018	10,508.96
2018-2019	17,875.61
2019-2020	22,831.22
2020-2021	23,192.12

In light of Table 06's adaptation and mitigation budgets, it can be seen that the budget for FY 2016-2017 was lower but increased in the following years, almost doubling in amount from 2019. Such an increase in budget can be the result of receiving donor funds (Green Climate Fund, 2017). According to (Masum et al., 2020), many mitigation projects are financed differently by their partner organisations based on each sector. For example, projects that are developed under the Technology, Innovation, and Renewable Energy sector are financed by national institutions, overseas development organisations, international financial institutions, and national and international banking channels. Similarly, Biodiversity and Afforestation projects

are supported by national institutions, overseas development organisations, international and local banks, whereas Waste Management and others are mainly supported by national institutions.

However, poor governance practices restrict the implementation of these projects (BCCTF, BCCSAP, etc.), and funds are lost in the process (Masum et al., 2020). Inconsistencies depend on the type of project being implemented (Masum et al., 2020), but a lack of transparency, accountability, and public participation leads to increased corruption. Even though there are efforts from both the donors and the recipients' end to minimise the impacts of climate change, whether in disbursement or utilisation of climate change funds and projects, the existing gaps and lack of operationalisation capacity make it challenging for both parties to understand the need for finances and the capacity to employ those resources (Hossain & Purnota, 2024).

Table 6: Budgetary allocation for Climate Change mitigation activities according to the Nationally Determined Contributions (NDC)

Fiscal Years	Allocation Against NDC Mitigation Plan (in crore taka)
2015-2016	955.85
2016-2017	835.25
2017-2018	1,143.50
2018-2019	1,252.16
2019-2020	3,454.13
2020-2021	3 4,003.37

4. Summary, Discussion, and Policy Recommendations

4.1 Summary and Discussion:

The concept of Loss and Damage itself is very complex and has contextual differences when it comes to vulnerabilities of a community. Each community experiences the impacts of climate change, including loss and damage, differently, and hence, the adaptation efforts require unique considerations and budget allocations accordingly. The usage of mapping tools like the Climate Vulnerability Index (CVI) has the potential to ensure budgetary allocations considering exposure, vulnerability and adaptive capacity as its indicators for building sound projects and programs. However, CVIs must be used in cross-ministerial vicinity instead of just Local Government Divisions (LGDs). Analysis in this paper shows that, in Bangladesh, due to a lack of inter-ministerial coordination, corruption, and a lack of adequate monitoring and evaluation, a significant gap is seen in budget allocation and its actual implementation over the years. Further, analysis also shows that the least number of projects were allocated in building capacity and

institutional strengthening, whereas it is crucial for the country to have a strong institutional capacity. There are also discrepancies in the area-wise distribution of funds, such as in some cases, more vulnerable areas were allocated fewer funds.

From the analysis of this paper, it is evident that Bangladesh, as one of the most vulnerable countries, recognises its impacts, losses, and damages and tries to prioritise its efforts in climate adaptation. However, maintenance of resources is often seen as a challenge due to a multilayered lack of capacities at different stages of implementation. And challenges are multifaceted, starting from the allocation of funds in proper projects, timely disbursement of funds, proper coordination between public and private stakeholders, and failure to incorporate vulnerable community voices in different stages of adaptation and mitigation measures. Thus, Bangladesh needs a holistic approach to reduce the gap between policy and practice in reducing climate change-related vulnerabilities by ensuring proper utilisation of climate change funds.

4.2 Policy Recommendations:

The challenges mentioned in this paper can be overcome by a series of good policy practices. Some of the crucial policies that should be considered include:

A. Inclusion of all stakeholders in the decision-making process:

Consultation of all stakeholders, which includes communities, practitioners, the private sector, and researchers, is crucial in allocating a climate budget along with the relevant ministries in order to overcome challenges that are recurring or issues that might arise during the budget drafting (Irfanullah, 2025). Marginalised communities should be considered in the decision-making process to ensure their protection in social contexts, so that the loss and damage fund can assist them in being fully accustomed to their specific needs. Similarly, a gender transformative approach (GTA) should be adopted in the Loss and Damage Fund (LDF) in order to minimise gender specific vulnerabilities (Gurung et al., 2023).

B. Promotion of Public-Private-Partnerships (PPP) for maximum fund utilisation:

Moreover, national institutions lack capacity, meaning that despite having the funds, they fail to perform efficiently. Gaps in planning, coordination, and implementation of projects, followed by corruption, hold back the full potential of development and restrict the effective utilisation of resources. Therefore, collaborating with private sectors like the public-private-partnerships (PPP) and community-based approaches can help with the proper management and utilisation of funds strategically. Additionally, engaging with the national institutions can increase capacity through their expertise and experience to better address the loss and damage caused due to climate change.

C. Community voices should be heard:

It is extremely important to have an inclusive decision-making platform where the community's perspective and needs will be prioritised and the responsive actions will be catered to their needs. A bottom-up approach must be considered during the vulnerability or risk assessment process. It should also ensure that the fund reaches the communities that suffer from recurring disasters and are significantly vulnerable to the effects of climate change. The loss and damage fund must also consider both economic and non-economic losses and damages to be addressed with equal priority.

D. Ensuring good governance for transparency and accountability throughout all levels of the governance institutions:

An improved governance system, an inclusive, transparent, and accountable financing mechanism to address loss and damage, is crucial. Public-Private Partnerships (PPP) can help ensure transparency and accountability better during project implementation. Comprehensive tracking frameworks, like Monitoring, Evaluation, Accountability, and Learning (MEAL), should be used to ensure equitable usage of the allocated resources throughout all levels of the relevant governance institutions.

E. Thorough Audits and M&E throughout the project or budget timeline:

The climate change projects must go through thorough Audits and Monitoring & Evaluation processes at different stages of their implementation timeline to ensure the utmost utilisation of their allocated resources.

F. Capacity building & knowledge sharing should be improved to understand donor-receiver requirements to enhance financing status:

The receiver country should be committed to fulfilling its commitments towards the donor regarding the effective utilisation of the funds. Failing to do so will create nothing but havoc in terms of understanding both the donor and receiver's perspectives, and a lack of trust will lead to lesser fund allocation for the country (Hossain & Purnota, 2024). Hence, capacity building and understanding the needs of both the donor and receiver are important. It will not only help Bangladesh reach its full capacity, but also help build friendly cooperation with the donor.

G. Strengthening the local government capacities to allocate and utilise climate finance for targeted projects:

One of the main challenges is strengthening the local government's capacities in order to allocate and utilise climate finance for targeted projects. The funds should not only address the losses and damages that have already occurred, but also help build resilience to minimise future loss and damage from happening, especially in the vulnerable regions like the coastal areas and the Chittagong hill tracts. Hence, prioritisation of projects is crucial in the budget

allocation phase. Hence, building the LGD's capacities in order to use frameworks, like the CVI, for identifying and implementing targeted projects is required.

5. Conclusion

Despite Bangladesh facing challenges in implementing the climate funds at an institutional level, these funds have the potential to change the course of climate risks in the country if utilised the right way. Even though the country did invest in climate-resilient development projects in different regions, improving its capacity, it still has much room for improvement and addressing climate change in a new dimension. A better governance system where corruption is eradicated, actions are transparent and accountable, with stakeholder inclusivity, can increase the potential of the country being more climate resilient. Along with the proper monitoring tools and techniques, support from international actors, and an improved policy landscape can assist in the implementation of climate change funds to take the country to new heights.

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Paper 2

What if we finish like dinosaurs? Exploring climate change through inquiry-based learning

José Gabriel Otálvaro-García

Abstract

This study explores the development of eco-critical thinking in fourth-grade students through the implementation of Inquiry-Based Learning (IBL) framed within the Cambridge educational model. Using a qualitative approach grounded in Participatory Action Research (PAR), and supported by Lesson Study (LS) and the PIER cycle (Planning, Implementation, Evaluation, and Reflection), the research analysed both classroom activities and student-created posters focused on climate change. These learning experiences revealed how students began to understand the multidimensional nature of climate change by connecting scientific concepts to social and ethical dimensions. Students demonstrated early signs of environmental citizenship by identifying human causes of environmental degradation, articulating consequences such as species extinction, and proposing mitigation strategies ranging from personal habits to community actions. The results suggest that IBL deepens content knowledge and enhances students' critical and reflective capacities. Discussion of findings highlights how students shifted from memorisation to inquiry, questioning the human-nature relationship and developing reasoned positions through classroom dialogue and visual representations. The integration of the Cambridge framework enriched these processes, encouraging learners to synthesise diverse perspectives and construct meaning from lived experiences. The emotional engagement and ethical questioning observed point to the formation of eco-rational thinking, which empowers students to act responsibly in response to environmental crises. Ultimately, this research demonstrates that when climate education is inquiry-driven, context-connected, and ethically framed, it can plant the seeds for transformative learning from an early age.

1. Introduction

The prevailing environmental crisis is a matter of utmost concern for the present generation. The deterioration of soil, water, and air has precipitated a series of consequences, including the onset of the most intense and frequent natural phenomena, biodiversity extinction, and contamination (Daigle & Vasseur, 2019; Vega C. et al., 2020). This phenomenon has been designated as the triple global crisis (TGC), a term coined by the United Nations (UN) to denote the concurrent decline of natural resources, diminished productivity, and ecosystemic degradation (Daigle & Vasseur, 2019; Rahman & Rosli, 2025; United Nations, 2024). The most significant threat confronting humanity is climate change (CC), defined as long-term shifts in global temperature patterns (PNUD, 2015; United Nations, 2023; World Bank, 2023). These alterations can be attributed to natural phenomena, such as shifts in environmental activities, or anthropogenic factors, which are the result of human activity (Calisaya Huanchi et al., 2023; Daigle & Vasseur, 2019). Thus, daily activities like transportation, electricity production and consumption, and agriculture can lead to an increase in the production of greenhouse gases (GHGs) (Askri et al., 2016; Calisaya Huanchi et al., 2023; Nordahl et al., 2020; Walling & Vaneekhaute, 2020).

Greenhouse gases (GHGs) are gases present in the Earth's atmosphere that trap heat, thereby contributing to the planet's overall warmth (Walling & Vaneekhaute, 2020). These gases can be categorised into four distinct types: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases (World Bank, 2023). The greenhouse effect (GHE) is defined as the atmospheric phenomenon that maintains an appropriate temperature for life to exist. In this order of ideas, GHGs play a critical role in the development of life. Nonetheless, the marked rise in the concentration of these gases disrupts the ecological balance, thereby leading to heightened intensity and frequency of climate phenomena, displacement, hydric stress, and other ramifications for biodiversity and human well-being (Blanco et al., 2022; Nordahl et al., 2020; Winter et al., 2022).

It is intriguing to note that even when an individual seeks to enhance the quality of life on a global scale, this endeavour often inadvertently triggers a series of events that may jeopardise the viability of ecosystems and human existence (Blanco et al., 2024; Figueroa Gómez & Russo Andrade, 2023). Simultaneously, international actors are facilitating the realisation of the Sustainable Development Goals (SDGs) by 2030 through a variety of strategies (Narong, 2025).

The SDGs constitute an urgent call to action for all nations. It acknowledges that the eradication of poverty and other forms of deprivation must be accompanied by strategies that enhance health and education, reduce inequality, and promote economic growth (McInnes, 2018; United Nations, 2024). Concurrently, these strategies must address climate change (CC) and safeguard the planet's oceans and forests. Consequently, it is imperative to implement strategies that assist both the present and future generations in mitigating the adverse effects of CC (Ortiz-Hernández, 2019; Trott et al., 2023; Winter et al., 2022).

Education, particularly in the form of climate change education (CCE), stands as a primary solution (Stevenson et al., 2017). This is a branch of environmental education (EE), which is defined as an educational approach from the perspective of a critical and political lens, focused on understanding and addressing socio-environmental challenges in particular settings. This approach fosters collective thinking and action for environmental care, while also questioning the dominant capitalist and extractive systems that have played a major role in the planet's environmental crisis (Cárdenas Támara, 2002; Leff, 2003; Muñoz-Montilla & Páramo-Bernal, 2018; Sauvé, 2004).

Furthermore, the CCE can be conceptualised as a specialised branch of EE, designed to empower individuals to comprehend and address the consequences of the climate emergency (Christodoulou & Grace, 2024). This initiative is designed to impart a comprehensive set of competencies, including knowledge, skills, attitudes, and values, that equip individuals with the necessary tools to take informed action and assume the role of agents of change, with a core commitment to sustainability (Christodoulou & Grace, 2024; Igboanugo & Naiho, 2024; Shavrovskaya et al., 2021; Venegas-Mejía et al., 2025). Indeed, the CCE bears a close relationship to the concept of education for sustainable development (ESD). The CCE serves as a foundational framework for comprehending the interplay between the SDGs and the ESD, facilitating the establishment of green alternatives for understanding and acting in the TGC (Narong, 2025; Seifert et al., 2019; Velepini, 2025).

Nevertheless, the EE curriculum, administered by the CCE, has been found to redirect the pedagogy employed in the classroom, while concomitantly encompassing the cultivation of 21st-century competencies in young learners (Akinsemolu & Onyeaka, 2025; Piazza et al., 2025; Shavrovskaya et al., 2021). The objective of the CCE is to enhance the comprehension of socio-environmental issues, with a focus on the analysis of the causes and consequences of CC at both the local and global levels (Göçoğlu et al., 2025; Mochizuki & Bryan, 2015; Rahman & Rosli, 2025). Concurrently, students are instructed on the effects of their actions with regard to GHG emissions and their effect on the CC.

Conversely, the implementation of CCE necessitates a well-defined approach. Given its recent emergence, educators have been compelled to engage in extensive research and experimentation to identify the most efficacious strategies and methodologies for addressing its intricacies (Christodoulou & Grace, 2024; Igboanugo & Naiho, 2024). Firstly, CC is a socio-environmental issue, and as such, it must be approached through an interdisciplinary and contextualised lens (Christodoulou & Grace, 2024; Mochizuki & Bryan, 2015; Thornton, 2023). In order to facilitate comprehension among students, it is essential to elucidate the manner in which this phenomenon impacts not only biodiversity but also the economy, development, and society. Secondly, the CCE cannot be taught from an individual perspective (Brumann et al., 2022; Stevenson et al., 2017; Trott et al., 2023). The fundamental reason for humanity's involvement in this TGC is that it must be cooperative and social. Through interdisciplinarity, students construct eco-rational thinking (Thornton, 2023; Winter et al., 2022).

In light of the aforementioned considerations, the Inquiry-Based Learning (IBL) paradigm constitutes an educational strategy in which students are engaged in the construction and fortification of competencies and skills applicable to life, analogous to scientists in their pursuit of knowledge (Borba et al., 2024; Brumann et al., 2022; Pedaste et al., 2015). In addition to seeking for the development of these abilities among students, IBL incorporates both low-order thinking skills (LOTS) and high-order thinking skills (HOTS) (Pedaste et al., 2015). Through these integrative approaches, students are empowered to explore and construct their own conceptualisations of phenomena through a variety of methods, including observations, hypotheses, and experiments. Furthermore, IBL places significant emphasis on the active involvement of students, encouraging them to engage in the process of scientific inquiry and to take ownership of their own learning journey (Brumann et al., 2022; Igboanugo & Naiho, 2024). A large quantity of IBL models exists; however, a common conclusion among them is the presence of a recurrent cycle in the discovery process of the student, ultimately culminating in the development of critical thinking skills (Pedaste et al., 2015).

Finally, the CCE and IBL methodologies facilitate the development of students' ecological rationality by equipping them with the capacity to comprehend the multifaceted dimensions of CC, encompassing economic, agricultural, societal, and policy aspects. These approaches enable students to discern the repercussions of CC on human and environmental development on a global scale. By transcending individualistic thought processes, these methodologies search for a paradigm shift towards collaborative endeavours and the establishment of sustainable practices within local and global communities.

The objective of this research is to start developing critical and eco-rational thinking in fourth-grade students by implementing inquiry-based learning focused on climate change.

2. Methodology

The research methodology is qualitative in nature, employing the Participatory Action Research (PAR) approach with fourth-grade students from a private educational institution in the municipality of Cota, Cundinamarca. Consequently, the Lesson Study (LS) and the PIER cycle (Planning, Implementation, Evaluation, and Reflection) were implemented.

In the context of an educational environment, PAR should be conceptualised as a pedagogical approach that fosters collaborative learning and the active engagement of students, educators, and the academic community in the pursuit of solutions to pressing issues, such as climate change (Zapata & Rondán, 2016). PAR is not merely a methodological framework; rather, it is a comprehensive approach to knowledge generation that draws upon experiential insights, embracing a transformative and participatory paradigm (Rodelo Molina et al., 2021). The value of this initiative lies in its capacity to empower educational actors to analyse their environment,

formulate informed decisions, and collaborate in pursuit of environmental sustainability (Betancur-Tarazona et al., 2022).

As demonstrated in Figure 1, LS work and the PIER cycle are foundational components of PRA, as both approaches endeavour to enhance pedagogical practice (PP). This objective is realised through the implementation of strategies in the classroom that exhibit greater flexibility and the execution of substantial modifications to educational processes. The overarching aim of these changes is to enhance the effectiveness of achieving the Learning Outcomes (LO).

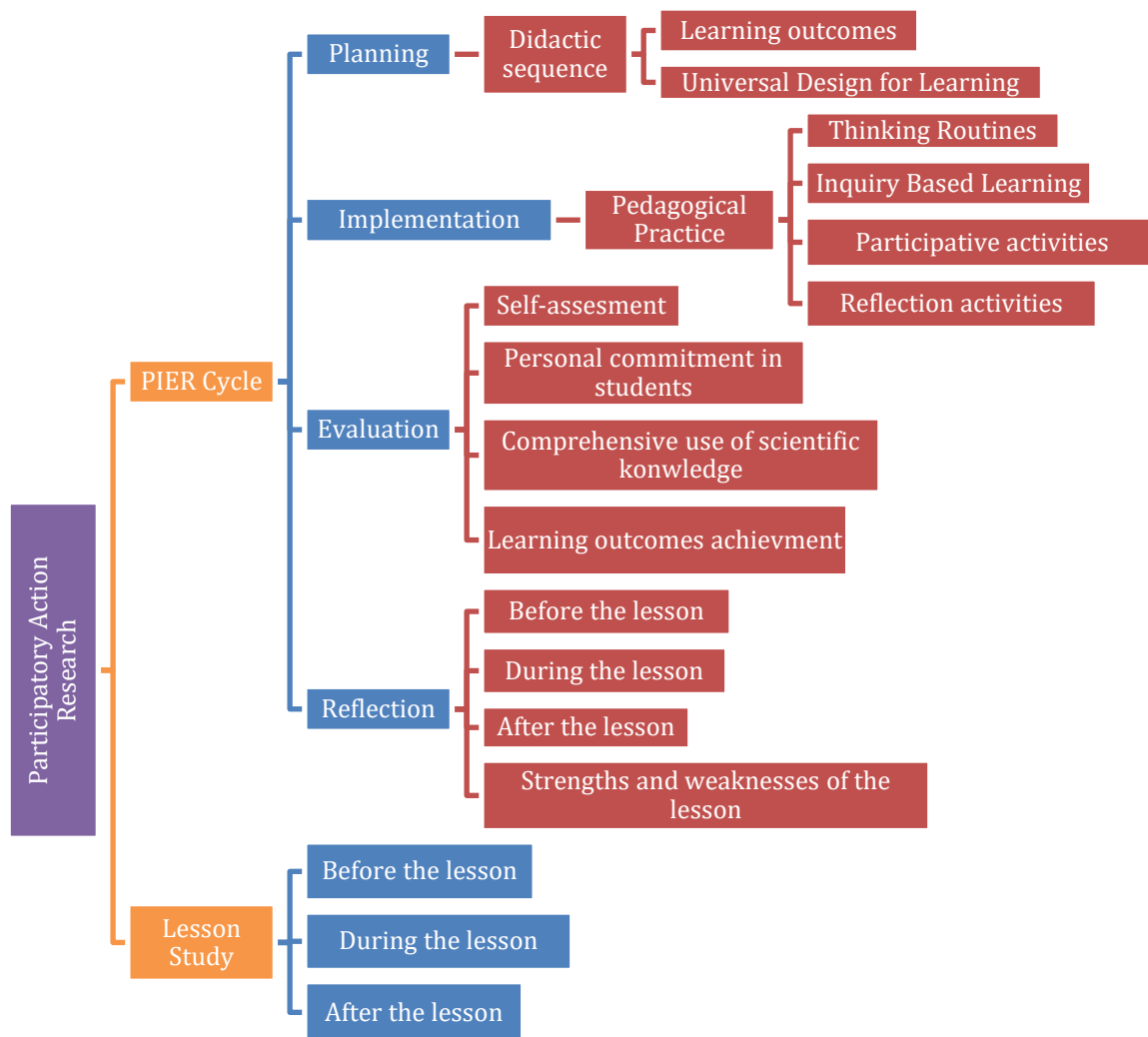


Figure 1: Relationship between Participatory Action Research, Lesson Study, and the PIER cycle for the implementation of Inquiry-Based Learning in pedagogical practice.

The Universal Design for Learning (UDL) is a model that promotes the creation of inclusive educational environments that adapt to the diverse needs of students. By encouraging continuous communication, respectful dialogue, and assertive teaching practices, UDL fosters inclusive

learning spaces built on mutual respect and tolerance. Rooted in insights from neuroscience, cognitive psychology, and technological progress, UDL supports the use of multiple means of representation, engagement, action, and expression. Its core goal is to ensure that educational opportunities are accessible to all learners, recognising diversity not as a challenge, but as a valuable element in the learning process (Herrera-Nieves et al., 2022; Menoscal Merchán & Navarrete Casco, 2023).

This is due to the fact that within the group of students, cases of inclusion in the classroom were found, which promoted the design of alternatives for the adaptation of learning environments, in order to promote the development of critical and eco-rational thinking.

In order to fulfil the stipulated objective, a series of topics were incorporated that, despite not having explicit similarities, are intrinsically related to the CC phenomenon. As shown in Figure 2, there is an interconnectivity between the topics addressed, which denotes an interdisciplinary approach in the analysis methodology.

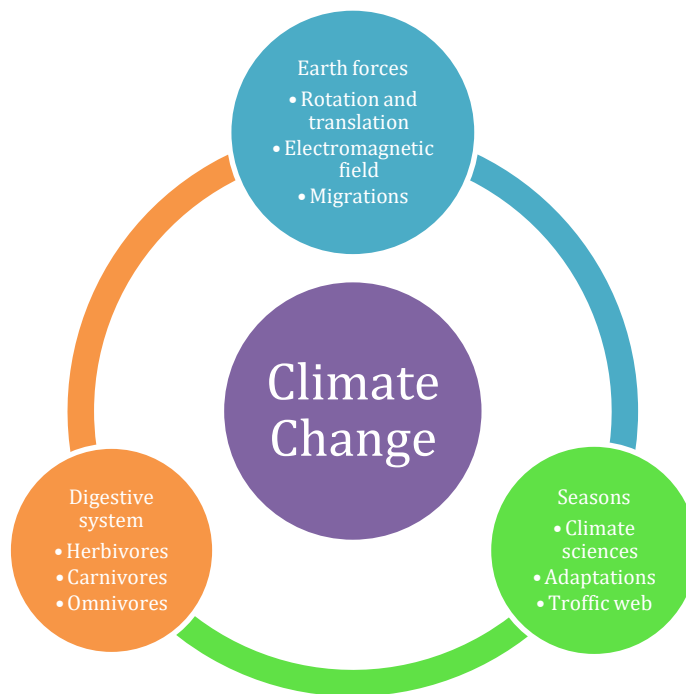


Figure 2: Interrelation between the topics addressed in the pedagogical practice and climate change.

3. Results

The analysis of the graphic and written evidence elaborated by the students reveals significant advances in the construction of scientific, communicative, and socio-environmental competencies. The productions demonstrate the appropriation of the concepts presented at the

beginning of, as well as the emerging ability to relate these concepts with personal experiences, local contexts, and global issues.

First of all, one of the most significant aspects is the understanding of the functioning of ecosystems, evidenced in Image 1, where students identify and correctly order producers, consumers at different levels, and decomposers. This type of representation does not respond to a simple memorisation of categories, but rather articulates relationships of energy dependence between organisms, supported by the use of arrows, colours, and visual hierarchies. The clarity with which this knowledge is expressed suggests the presence of systemic thinking in formation, which allows them to understand the flows and cycles within the environment.

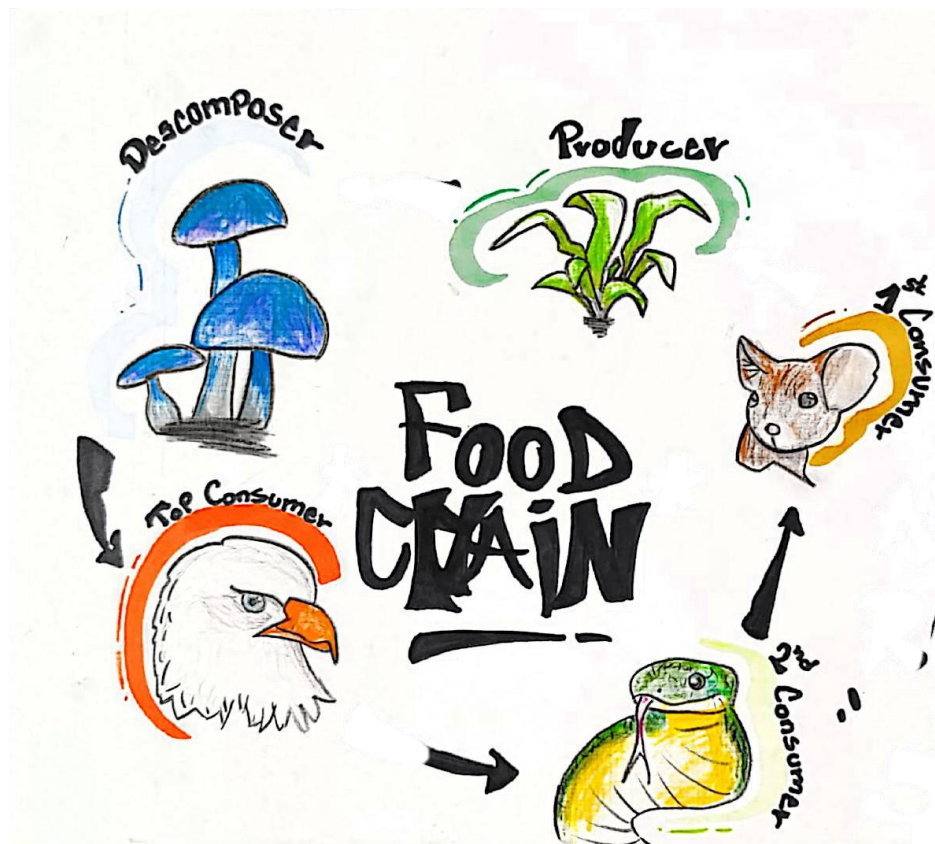


Image 1: Food chain and trophic levels.

Images 2 and 3 also show a progressive appropriation of scientific language in a second language. Thus, terms such as weather, temperature, consumer, climate change, and migration are used with coherence and purpose. The use of the second language is part of the process of disciplinary meaning construction, reinforcing both scientific literacy and bilingual competence. The alternation between English and Spanish observed in some texts reflects a communication strategy of the student, which allows the construction and expression of complex ideas despite linguistic limitations.

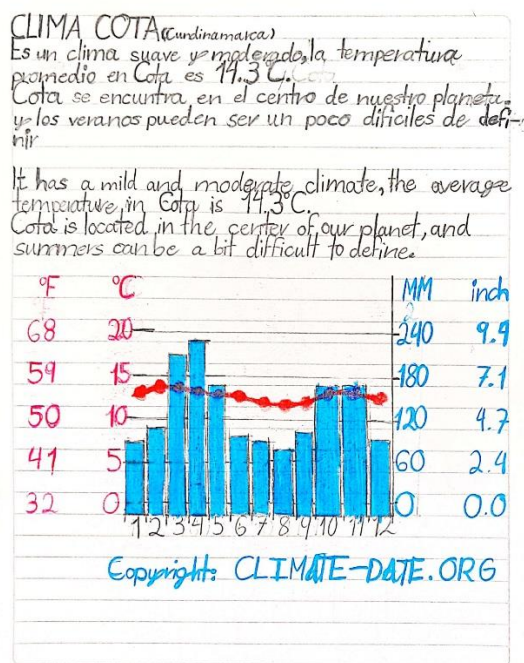


Image 2: Climate analysis of Cota.



Image 3: Differences between weather and climate.

Another key element in these productions is the use of visual language as a tool to organise, represent, and communicate knowledge (Images 2 and 3). Through diagrams, illustrations, concept maps, and bar charts, students construct abstract ideas from diverse forms of conceptual and procedural organisation, thus maintaining bridges between the symbolic and the conceptual.

Accordingly, the texts that address the habitat of animals such as otters (Image 4) and capybaras (Image 5) show a deeper level of reflection. In them, students not only describe biological or ecological characteristics, but also begin to problematize the effects of climate change on ecosystems. Consequently, statements such as “Climate change can destroy the habitat of otters” denote the construction of the critical capacity to think in terms of cause and effect, predict consequences, and recognise human action as a factor of socio-environmental impact.

On the other hand, the distinction between weather and climate is treated with conceptual clarity in several works. Students can differentiate phenomena of short duration (“cloudy morning”) from prolonged patterns (“cold climate”), and complement their descriptions with numerical data, comparisons between cities such as Bogotá, Cartagena, and Cota, as well as personal observations of thermal variations throughout the day (Images 6 and 7).

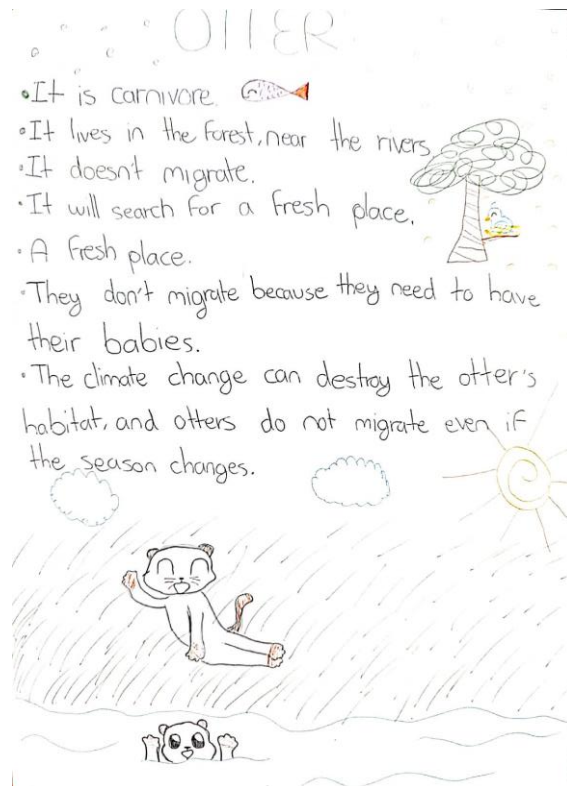


Image 4: Otter habitat and climate change.

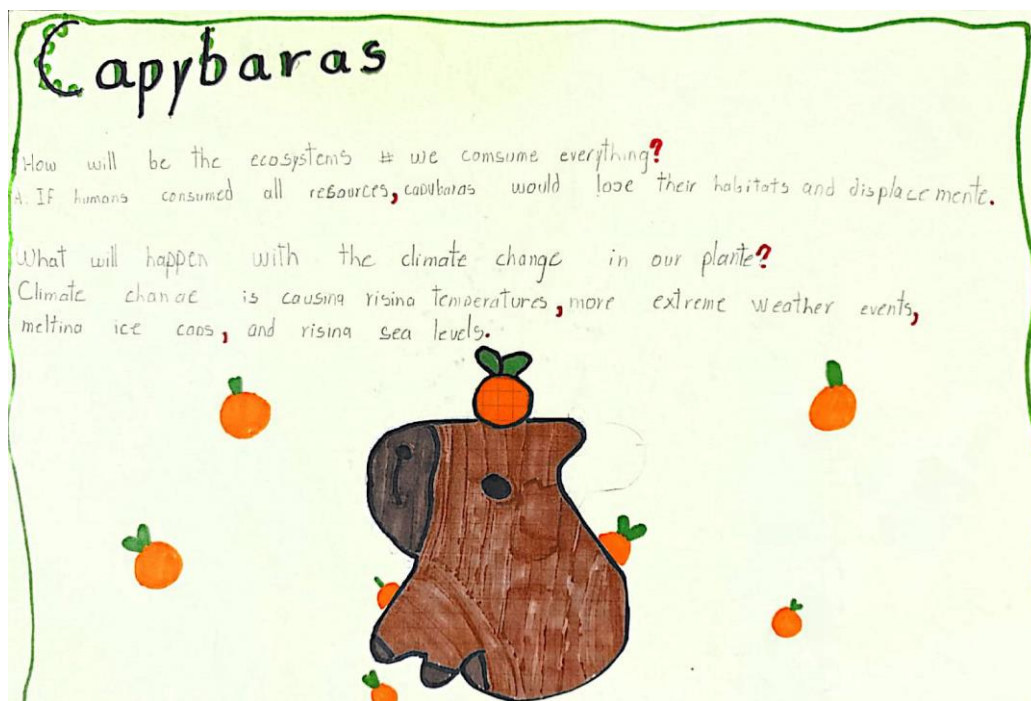


Image 5: Human impact on capybaras.

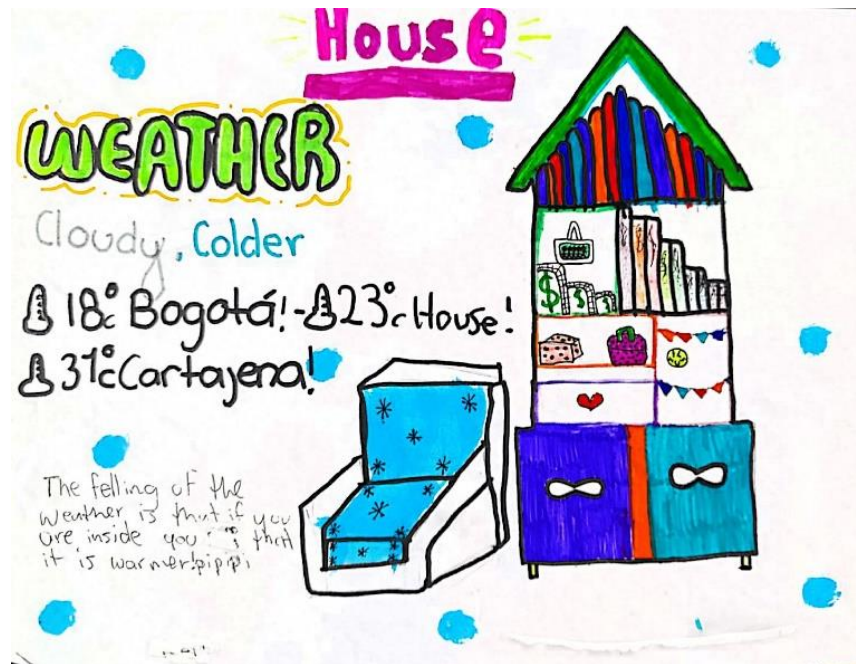


Image 6: Climate comparison between Bogotá and Cartagena.

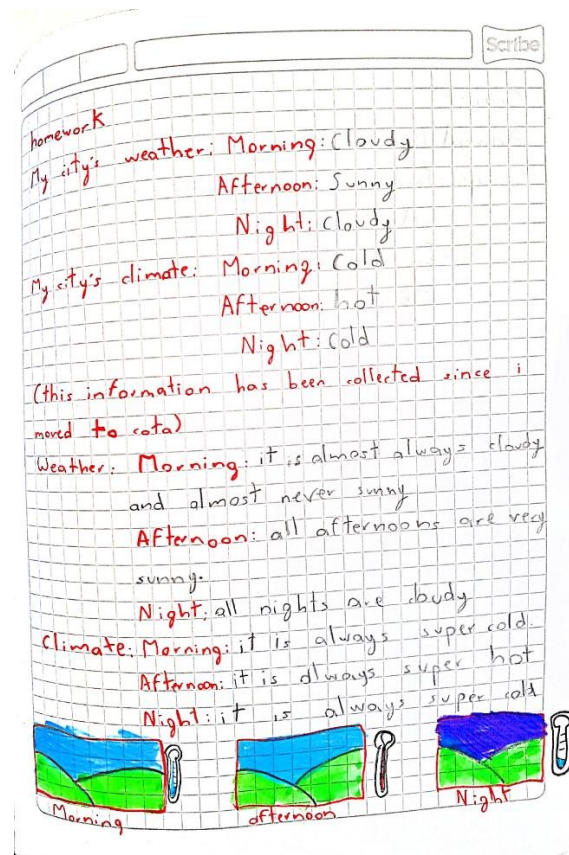


Image 7: Climate comparison between Bogotá and Cota.

In this order of ideas, the synthesis posters elaborated by the students show a progressive understanding of the concept of climate change, which is not presented in an isolated or merely defining manner, but is articulated with its causes, consequences, and possible solutions. In Image 8, the extinction of species and the melting of polar regions are highlighted.

Likewise, several posters include statements expressing concern, critical positioning or calls for action. Image 9 includes a reflection on the consequences of climate change on the extinction of species, incorporating the concepts of migration and adaptation.

A particularly powerful case is found in Image 10, where the poster is organised around a question: “What if we end up like dinosaurs? (extinct)”. This formulation interpolates the viewer from both an emotional and cognitive development, positioning the student as a reflective subject capable of drawing analogies between historical extinction processes and future threats arising from climate change. The choice of the dinosaur as a symbol of irreversible consequences projects an incipient awareness of the fragility of human life in the face of ecological imbalances and reveals an eco-socio-environmental thinking in formation.



Image 8: Before and after the Antarctica ecosystem poster.

Finally, it is especially relevant to observe how students begin to structure an eco-rational thinking. Through their productions, an initial awareness of the interrelation between human actions and environmental transformations is evident. They understand that excessive consumption of resources can affect other species, that climate change alters natural habitats, and that these alterations have both local and global consequences. This understanding, still in the process of maturing, constitutes a fundamental basis for the formation of citizens with ecological sensitivity and critical capacity in the face of contemporary socio-environmental challenges.

4. Discussion

The analysis of student-generated materials, particularly the climate change posters, illustrates how Inquiry-Based Learning (IBL) facilitates the emergence of eco-critical thinking among primary school learners. Far from being passive recipients of information, students actively engage with environmental issues, drawing connections between scientific content, ethical responsibility, and lived experience. This approach fosters a sense of agency in confronting ecological challenges (Brumann et al., 2022).

Rather than treating climate change as a static definition, students demonstrate a dynamic and contextual grasp of its causes and consequences. As described by Blanco et al. (2022), several productions reflect an awareness of human-driven environmental transformations, where industrial activities and resource exploitation are identified as central contributors to planetary change. The posters further reveal how environmental education, when embedded early in academic formation, can promote a culture of responsibility and prevention of socio-environmental risks. These elements resonate with the objectives outlined by Christodoulou & Grace (2024), which emphasises the formation of environmentally conscious and socially responsible citizens.

Through the lens of IBL, students investigate real-world socio-environmental issues—such as biodiversity loss and rising global temperatures—using a structure that supports exploration, questioning, and solution-building. This method equips learners not only with scientific knowledge but with the critical disposition needed to interpret complex systems and engage in ethical reasoning (Christodoulou & Grace, 2024; Igboanugo & Naiho, 2024). Posters often move beyond identifying problems to proposing feasible actions—such as reducing pollution or conserving natural habitats—thereby transforming understanding into purpose-driven expression.

The implementation of the Cambridge model further amplifies this process by framing learning as an experience that combines academic rigour with practical inquiry. Through the model's emphasis on global perspectives and personal reflection, students are encouraged to interpret climate-related phenomena both analytically and empathetically. Activities aligned with the Cambridge approach—such as comparative climate analysis across regions or reflective

questioning on environmental futures—enhance learners' capacity to synthesise information across disciplines and scale (Stevenson et al., 2017; Thornton, 2023).

The organisation of poster content into sections such as causes, effects, and solutions mirrors the logical sequencing promoted by Brumann et al. (2022) and Pedaste et al. (2015). Visual elements like diagrams, arrows, and conceptual maps are employed not as decorative additions, but as tools to communicate and structure complex ideas. This suggests the development of representational and metacognitive skills that support systemic thinking.

Importantly, the emotional and ethical layers of environmental engagement are present throughout the students' work. In one striking example, a student asks: "What if we finish like dinosaurs (extinct)?"—a metaphor that underscores vulnerability and prompts reflection on the long-term consequences of climate inaction. This kind of analogical reasoning, combined with an emotional appeal, signals the emergence of eco-critical awareness grounded in both cognitive and affective domains (Thornton, 2023; Winter et al., 2022).

Moreover, the inquiry-driven process allows students to recognise and reassess misconceptions, a practice encouraged in constructivist and inquiry-based science education (Brumann et al., 2022; Pedaste et al., 2015). By investigating climate phenomena through iterative questioning and evidence-gathering, learners engage in scientific thinking that mirrors authentic knowledge production. This aligns with the argument that science education must prepare students to navigate the uncertainties of the Anthropocene with critical insight (Christodoulou & Grace, 2024).

In addition, the IBL framework creates a context for students to understand the temporal and spatial scales at which environmental problems manifest. Taking into account Christodoulou & Grace (2024), through drawing, students learn to differentiate between immediate and slow-onset environmental changes, recognising that biodiversity loss, for example, does not occur as a single event but is the cumulative result of persistent human activity. This understanding deepens their ability to interpret the complexity of ecological systems and cultivates an awareness of their roles within those systems.

The evidence also indicates that IBL nurtures a sense of ownership and empowerment. As students formulate questions, gather data, and propose solutions, they shift from a position of passive learning to one of proactive inquiry. This empowerment is central to the development of environmental citizenship, where learners are not only informed but motivated to take responsible action in their communities (Christodoulou & Grace, 2024; Thornton, 2023).

Furthermore, the Cambridge model reinforces this trajectory by integrating inquiry as a core competency. Its emphasis on developing reflective learners who can apply knowledge in meaningful contexts (Brumann et al., 2022; Pedaste et al., 2015). In this way, the Cambridge framework does not simply enhance content delivery; it transforms the educational experience into one that is inquiry-rich, globally relevant, and ethically grounded.

Finally, the development of eco-critical thinking—understood as the capacity to interrogate environmental realities from scientific, ethical, and socio-political perspectives—emerges as both an outcome and a necessity. As suggested by Stevenson et al. (2017) and Winter et al. (2022), climate change education must aim beyond awareness; it must foster the kinds of thinking and learning that inspire action and support the emergence of social tipping points. The findings from this analysis suggest that when students are provided with meaningful opportunities to inquire, reflect, and connect content with real-world challenges, they are better positioned to become agents of ecological transformation.

Ultimately, the combination of Inquiry-Based Learning and the Cambridge model forms a robust foundation for climate change education at the primary level. It creates a learning environment in which students are not only equipped with knowledge but encouraged to think critically, act ethically, and envision sustainable futures. This approach lays essential groundwork for shaping the next generation of informed, empowered, and environmentally responsible citizens.

5. Conclusion

This research aimed to promote critical and eco-rational thinking in fourth-grade students through the implementation of Inquiry-Based Learning focused on climate change. Developed within the framework of the Cambridge educational model, the pedagogical experience guided students to explore environmental issues through scientific investigation, ethical reflection, and contextual relevance.

The analysis reveals that students were able to move beyond basic content knowledge and engage with climate change as a multidimensional issue. They began to articulate its causes and consequences, propose viable actions, and express emotional and ethical responses to the environmental crisis. These outcomes show early signs of environmental citizenship and eco-critical awareness, nurtured by the inquiry process and reinforced by reflective teaching practices. As a result, the integration of IBL and the Cambridge model proves to be an effective strategy for fostering a generation prepared to think and act in favour of environmental sustainability.

6. References

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Paper 3

Equitable and Resilient Flood Shelters: Addressing Access and Governance Challenges in Vulnerable Communities

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Abstract

Flood shelters are critical infrastructure for disaster preparedness in Bangladesh, but their effectiveness in boosting community resilience is hampered by structural, social, and governance issues. This study looks at how flood shelters in Chhatak upazila, Sunamganj—a location heavily impacted by the 2022 flash floods—can be reinforced to better serve communities during multi-hazard occurrences. Using geospatial accessibility analysis, home surveys (n = 384), and institutional assessments, the study identifies key gaps. According to the findings, more than half of households have to travel more than 30 minutes to access shelter, with communities in isolated haor areas being particularly hard hit. 44% of women, 67% of the elderly, and 91% of people with disabilities reported difficulty accessing shelters owing to distance, overcrowding, and a lack of inclusive design. Infrastructure assessments show that fewer than 18% of shelters have adequate safe water and sanitation facilities, while governance analysis shows that only about one-third of local officials report effective shelter management coordination mechanisms, and more than 80% of maintenance budgets rely on external funding. The findings indicate that current flood shelters are insufficient to address the demands of all community members during disasters. By improving accessibility, inclusivity, infrastructure, and local governance, shelters can be transformed into effective, equitable, and resilient community facilities that support both emergency response and ongoing community preparedness. This research offers practical recommendations for local planning and incorporation into Bangladesh's National Adaptation Plan for climate-resilient infrastructure.

1. Introduction

Bangladesh is one of the world's most flood-prone countries, with seasonal and flash floods posing ongoing dangers to people's lives, livelihoods, and infrastructure. The northeastern haor region, encompassing Chhatak Upazila in Sunamganj District, is prone to seasonal catastrophic floods that inundate settlements, hamper movement, and isolate residents. Flood shelters are an important part of disaster preparedness in the country, but their usefulness is frequently limited by spatial inaccessibility, insufficient infrastructure, and weak governance procedures (Das et al., 2020). The 2022 flash floods exposed these issues, with many households, particularly those in rural haor areas, struggling to get to shelter on time and safely (Howlader et al., 2024).

Flood shelters are intended to provide immediate protection during catastrophes while also functioning as hubs for community preparation and resilience-building efforts. However, the efficacy of these shelters is frequently hampered by structural flaws such as insufficient elevation, congestion, and a lack of accessible design for people with disabilities. Furthermore, water, sanitation, and hygiene (WASH) facilities are frequently poor, limiting shelter usability during emergencies. While these problems are well acknowledged, they are typically investigated in isolation, without considering the combined impact of social, geographical, and governance aspects on shelter efficacy (Khan, 2022; Slam, 2021; Al-Mamun et al., 2025).

Social vulnerability has a considerable impact on shelter access and utilisation. Women suffer challenges due to caregiving responsibilities and social conventions, the elderly face mobility limitations, and people with disabilities face structural barriers such as the lack of ramps or accessible facilities. These populations are disproportionately impacted by both distance and infrastructure constraints, although the relationship between social vulnerability and shelter accessibility is rarely measured in empirical studies. Understanding these trends is critical to ensuring inclusive disaster preparedness that meets the requirements of the entire community. Governance and institutional performance are also important factors influencing shelter effectiveness. Local shelters are overseen by a combination of government officials and community-based committees, but coordination mechanisms are frequently ineffective, and maintenance is primarily reliant on external funds, resulting in shaky institutional capability. Even structurally solid shelters may fail to meet community requirements during crises without efficient governance, emphasising the significance of combining institutional assessments with spatial and social considerations (Uddin, Hossain, & Dhar, 2019; Alam, 2011).

Despite rising understanding of these difficulties, there is still a study deficit in analysing flood shelters using an integrated approach that considers infrastructure, governance, accessibility, and social vulnerability at the same time. Previous research has generally concentrated on structural adequacy or spatial proximity, ignoring the multifaceted nature of shelter efficacy, especially in complex haor settings where flooding is common and multi-hazard preparedness is essential (Alam, 2011).

This study closes the gap by performing household surveys, GIS accessibility analysis, and governance assessments in Chhatak Upazila. Its goals are to (i) measure spatial and social gaps in shelter access, (ii) evaluate perceived service quality and inclusivity, and (iii) assess the combined effects of infrastructure, governance, and accessibility using a Shelter Performance Index (SPI). The findings are meant to provide practical recommendations for enhancing shelter design, management, and policy integration, thereby promoting equitable and resilient flood preparedness in Bangladesh.

2. Methodology

2.1 Study Area:

Chhatak is an upazila of Sunamganj District in the Sylhet Division of northeastern Bangladesh. The administrative center is located in Chhatak town. Geographically, it is located at 25.0417°N, 91.6750°E, with a total area of 434.76 km² and 43,727 residents. The upazila is distinguished by haor wetlands and riverine systems, especially the Surma River, making it prone to seasonal flash floods and waterlogging. Its settlements are a mix of center towns and dispersed peripheral villages, with many residents having restricted access to infrastructure and essential services during floods (Bangladesh National Portal, 2025).

According to the 2011 Bangladesh Census, the population of Chhatak Upazila was 397,642, with 28.95% being under the age of ten. The literacy rate among people aged 7 and up was 38.55%, lower than the national average of 51.8%, while the gender ratio was 1009 females for every 1000 males. Approximately 12.74% of the people lived in cities, with the rest in rural areas reliant on agriculture and fishing. The most common religious affiliation was Islam (94.76%), followed by Hinduism (5.19%), with other religions or unstated accounting for 0.05% (Bangladesh National Portal, 2025).

2.2 Data Collection & Analysis

This study used a cross-sectional survey approach to investigate flood shelter accessibility, service quality, and governance in Chhatak Upazila, Sunamganj District, northeastern Bangladesh, which was badly impacted by the 2022 flash floods. A structured questionnaire was distributed to 384 families selected through stratified random sampling to ensure representation of both central and peripheral communities. The survey collected extensive information about travel time to the nearest shelter, perceived difficulty in accessing shelters, and demographic parameters such as gender, age, and disability status. Respondents also rated shelter services on a Likert scale of 1 to 5 for accessibility, inclusivity, safety, and management coordination.

To investigate spatial accessibility, home and shelter locations were mapped using ArcGIS Network Analyst, which included local road networks and seasonal flooding limits to compute

journey times and identify places with the most access issues. Simultaneously, a governance assessment was carried out utilising structured interviews with local crisis management officials and shelter administrators, with an emphasis on coordination mechanisms, resource distribution, and maintenance procedures. The survey and institutional data were combined to investigate how infrastructure and governance affect both functional accessibility and perceived service quality in shelters.

Data analysis included both descriptive and inferential methodologies. Descriptive statistics summarised trip durations, perception scores, and accessibility issues across social groups, highlighting disparities based on gender, age, and handicap. Binary logistic regression was used to determine the effects of distance, gender, age, and disability on reported shelter access difficulties. A Shelter Performance Index (SPI) was created to combine infrastructure adequacy, governance, and accessibility, allowing shelters to be rated as poor, medium, or high performance. The interrelationships between perception elements were displayed using correlation heatmaps, which provided insight into the multidimensional character of service quality.

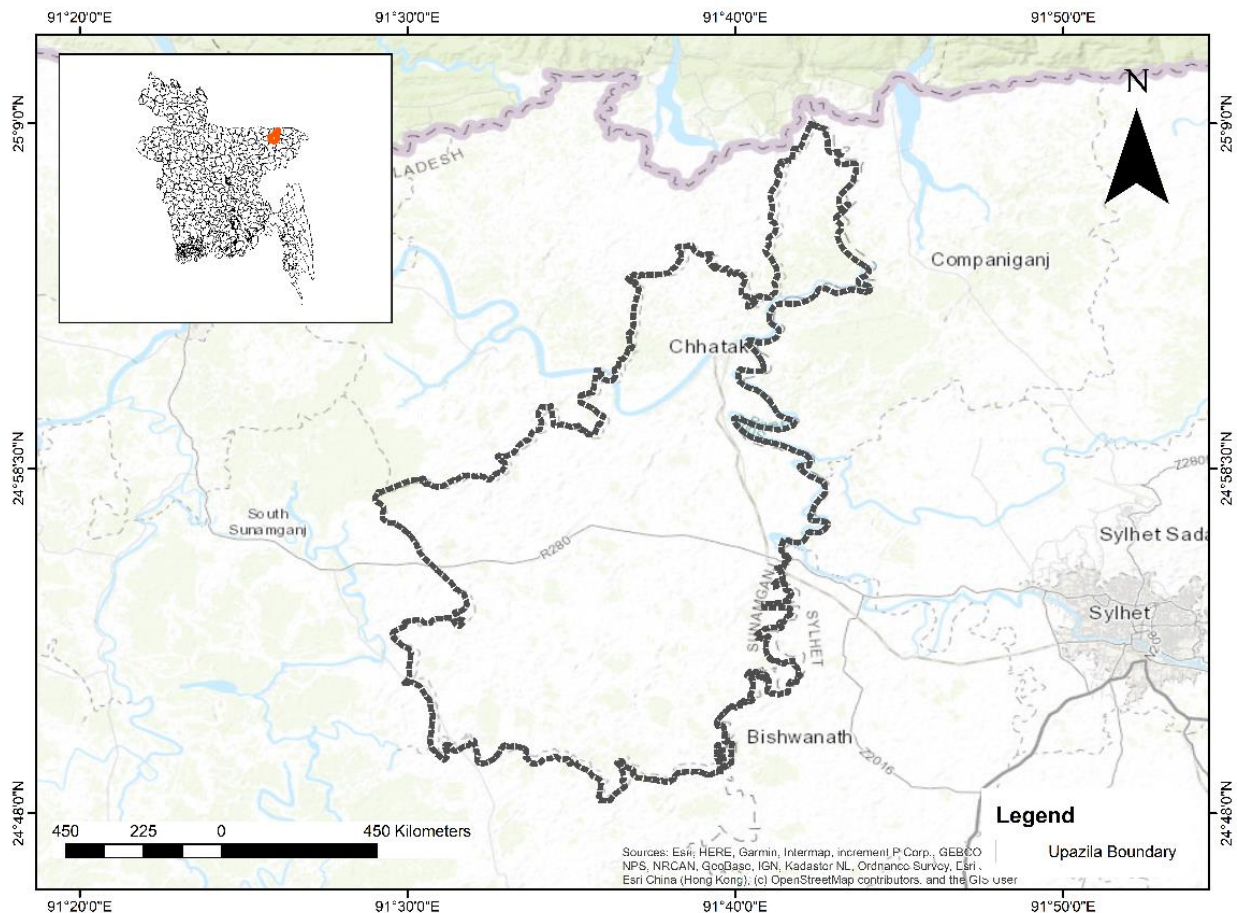


Figure 1: Study Area Map

3. Results and Interpretation

3.1 Spatial Accessibility Deficit and Territorial Inequalities

GIS-based travel-time modelling and household survey data analysis show a notable lack of spatial accessibility throughout Chhatak Upazila. Only 20.8% of the 384 families polled lived within a 15-minute travel radius of the closest flood shelter, and more than half (54.7%, $n = 210$) needed more than 30 minutes to get there (Table 1). For houses in rural haor areas, which are physically separated and frequently cut off during peak flood episodes, this discrepancy underscores a crucial gap in functional accessibility.

Shelters are concentrated in villages that are centrally located, leaving outlying settlements underserved, according to the spatial distribution of shelters. The conventional emergency travel threshold of 30 minutes is exceeded by many families in the outer unions, according to isochrone maps produced by GIS analysis. It might take a long time or be almost impossible for locals to get to a shelter during flash floods without extra transportation or evacuation arrangements in place. A structural limitation in the disaster preparedness plan is reflected in this situation, which highlights the gap between the availability of physical infrastructure and its practical utility.

Effective accessibility is probably lower than nominal measures indicate because the travel-time data also indicate that even households within a nominally acceptable range (15–30 minutes) may encounter difficulties because of bad road conditions, seasonal flooding, or a lack of safe routes. Households that rely on informal or public transportation are disproportionately impacted by this functional inaccessibility, especially in the early hours of unexpected flood disasters.

These findings suggest that, from the standpoint of resilience, shelter coverage is uneven and insufficient to satisfy the needs of every member of the community, especially in high-risk outer zones. The current approach exposes a sizable section of the population to delayed or unsuccessful evacuation in the absence of targeted evacuation help, additional micro-shelters in remote locations, or deliberate shelter reallocation. Given that homes in remote areas are more likely to contain women, the elderly, and people with disabilities—all of whom already face greater mobility barriers—these spatial disparities notably exacerbate social vulnerabilities.

Households' self-reported ability to go to a shelter during periods of high flooding was also recorded in the survey; only 67.7% of respondents said they could get to a shelter safely in time, and 32.3% said it would be difficult or impossible (Table 1). Despite the apparent existence of shelters in the larger upazila, this suggests that almost one-third of the population is actually shut out of emergency facilities.

The information shows a multifaceted accessibility issue where seasonal environmental conditions, journey duration, transportation infrastructure, and spatial distribution all combine to create a systemic danger for communities in the periphery. To address these disparities, it is necessary to update shelter placement plans, integrate them with transportation planning, and

make localised backup plans to guarantee that all households, especially the most remote ones, can access services that can save lives during floods.

Table 1: Shelter accessibility and travel time (n = 384)

Indicator	Category	Frequency (n)	Percentage (%)
Travel time to nearest shelter	≤ 15 minutes	80	20.8
	15–30 minutes	94	24.5
	> 30 minutes	210	54.7
Able to reach shelter during peak flood	Yes	260	67.7
	No	124	32.3

3.2 Socially Differentiated Access: Gendered, Aged, and Ability-Based Exclusion

A binary logistic regression was used to explicitly quantify the effects of social and spatial factors on difficulties accessing shelters, even though descriptive statistics show that women, the elderly, and those with disabilities suffer disproportionate impediments. The independent variables were gender (Female = 1), elderly (≥ 60 years = 1), handicap (Yes = 1), and distance to shelter (> 30 min = 1), while the dependent variable was difficulty reaching a shelter during floods (Yes = 1, No = 0).

All factors were statistically significant, according to the regression results (Table 2), demonstrating that groups that are socially and geographically disadvantaged are significantly more likely to experience difficulties. Compared to homes closer to a shelter, those more than 30 minutes away were 4.58 times more likely to report having trouble getting there. The probabilities were 2.27 times higher for female respondents, 3.09 times higher for older respondents, and 11.6 times higher for those with disabilities, who faced the biggest obstacle.

These results highlight how susceptibility is intersectional, with social traits and physical isolation combining to increase risk. Social characteristics like gender, age, and disability greatly restrict functional access, even when shelters are theoretically accessible. This shows that infrastructure alone is not enough to provide equal resilience. These findings also point to the necessity for focused interventions from a policy standpoint, including accessible shelter retrofits, planned community assistance for vulnerable populations, and the thoughtful placement of new shelters in underprivileged regions. The most marginalised communities will not benefit from disaster preparedness measures if these multiple vulnerabilities are not addressed.

The results of the binary logistic regression indicate that social and spatial factors have a significant impact on the difficulty of accessing shelters. The access problem was substantially more likely to affect women, older individuals, those with impairments, and households more than 30 minutes from a shelter. These characteristics accurately predict vulnerability, as demonstrated by the model's 79% classification accuracy and 48% variance explanation

(Nagelkerke $R^2 = 0.48$). To guarantee equitable catastrophe resilience, our findings quantitatively support the descriptive trends in Section 3.1 and emphasise the necessity of governance and infrastructure initiatives that specifically address socioeconomic vulnerability.

Table 2: Binary Logistic Regression Predicting Difficulty Accessing Shelters (n = 384)

Predictor	B	SE	Wald	p-value	OR (Exp(B))	95% CI for OR
Distance (>30 min)	1.52	0.30	25.7	0.000	4.58	2.65 – 7.91
Female	0.82	0.25	10.7	0.001	2.27	1.39 – 3.71
Elderly	1.13	0.34	11.0	0.001	3.09	1.61 – 5.94
Disability	2.45	0.60	16.6	0.000	11.6	3.70 – 36.7
Constant	-1.12	0.28	16.0	0.000	0.33	–

3.3 Perceived Service Quality and Governance Experience

The way that households view flood shelters reveals significant shortcomings in governance, inclusivity, and service quality. Respondents used a Likert scale with 1 representing very poor and 5 representing outstanding to score five important indicators: safety, managerial coordination, adequacy of WASH facilities, accessibility, and inclusion for women. The average scores showed general dissatisfaction with shelter services, ranging from 2.2 (WASH adequacy) to 2.6.

According to these findings, shelter shortcomings are multifaceted, resulting in decreased perceived and functional resilience due to a combination of inadequate infrastructure, inadequate governance coordination, and limited inclusivity. For example, governance studies reveal that only roughly one-third of local officials claim efficient coordination mechanisms, over 80% of maintenance budgets rely on external funding, and less than 18% of shelters fulfil minimal WASH standards. The conclusion that shelters cannot adequately serve the population during multi-hazard situations is supported by this combination of institutional and structural shortcomings.

Improving WASH and inclusive facilities, bolstering local governance, and putting in place regular maintenance financed by sustainable local resources are all necessary integrated measures to close these gaps. Improving these elements will probably boost community trust, enhance the perceived quality of services, and encourage more prompt and fair shelter use during floods.

The heatmap illustrates the intimate relationship between WASH, safety, and management, suggesting that enhancements in one area are likely to support the functionality of the shelter as a whole. Accessibility, inclusivity, and other criteria have moderate relationships, indicating that perceived quality is influenced by social and organisational aspects in addition to infrastructure. When taken as a whole, these results highlight the necessity of concurrent investments in inclusive design, governance, and infrastructure to improve the quality of shelter services.

Table 3: Household perception of shelter services (Likert 1–5, n = 384)

Indicator	Mean	Std. Deviation	Interpretation
Shelter is easy to access during floods	2.30	1.10	Low accessibility
Shelter facilities are inclusive for women	2.50	1.00	Moderate dissatisfaction
Sanitation and water supply are adequate	2.20	1.20	High dissatisfaction
Shelter management is well-coordinated	2.60	1.00	Weak governance
The shelter environment feels safe and dignified	2.40	1.10	Safety concerns

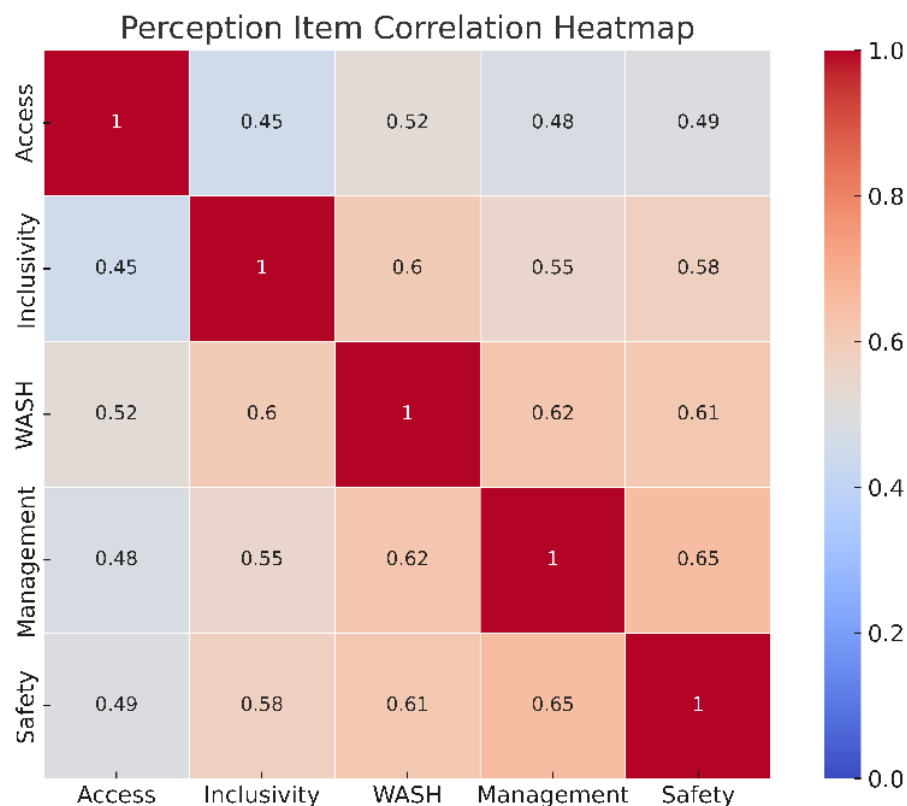


Figure 2: Heatmap of perception item correlations

3.4 Infrastructure Adequacy and Governance Experience

Chhatak Upazila's flood shelters have significant governance constraints and structural flaws that compromise their perceived and actual resilience. Only a small percentage of the available shelters met the minimal safety and accessibility requirements and offered sufficient, safe water and sanitation facilities, according to the assessment of available shelters. Overcrowding during high flood events, poor drainage, a lack of ramps for people with disabilities, and insufficient floor elevation are examples of structural problems. Shelters that serve outlying Haor communities are most affected by these shortcomings.

Poor management coordination is revealed by governance analysis. Most maintenance expenditures are dependent on outside funding, and only roughly one-third of local authorities report that coordination mechanisms are operational, resulting in weak institutional capability. These restrictions are reflected in household opinions, which show low levels of satisfaction with maintenance dependability and management coordination.

A Shelter Performance Index (SPI), which measures the performance of governance and infrastructure together, was computed as follows:

$$\text{SPI} = 0.4 \times \text{Infrastructure Score} + 0.3 \times \text{Governance Score} + 0.3 \times \text{Accessibility Score}$$

The performance of the shelters was then divided into three categories: Low (<0.4), Medium (0.4–0.7), and High (>0.7). Most shelters, according to the results, are classified as low performing, underscoring structural deficiencies in the governance and physical infrastructure areas.

Table 4: Shelter Performance Index (SPI) Classification (Proportional Representation)

SPI Category	Percentage (%)	Key Characteristics
Low (<0.4)	60–65	Poor WASH, weak governance, and long travel for surrounding households
Medium (0.4–0.7)	25–30	Partial WASH, moderate governance, moderate travel times
High (>0.7)	10	Adequate WASH, strong governance, and short travel times

4. Conclusion

This study identifies key gaps in flood shelter accessibility, infrastructure, and governance in Chhatak Upazila, revealing that existing facilities are insufficient to address the demands of all community members during multi-hazard flood occurrences. Household survey data, combined with geospatial accessibility research, found that more than half of households have to go more than 30 minutes to the nearest shelter, with women, the elderly, and people with disabilities being disproportionately affected. Structural assessments revealed that most shelters lack adequate WASH, safety, and inclusive amenities, while governance evaluations revealed that coordination mechanisms are ineffective and upkeep is primarily reliant on outside funding.

The findings emphasise the multidimensional character of shelter vulnerability, in which spatial, social, infrastructural, and governance elements interact to restrict effectiveness. The Shelter Performance Index (SPI) and logistic regression analysis objectively revealed that shelters with poor infrastructure and governance, particularly in rural places, are the least accessible and inclusive. These findings highlight the importance of coordinated interventions that address physical infrastructure, governance capability, and social fairness in order to promote community resilience.

Based on these findings, practical recommendations include improving shelter accessibility, incorporating inclusive design elements, updating WASH and safety infrastructure, and increasing local coordination and maintenance systems. By transforming shelters into well-managed, inclusive, and resilient community facilities, policymakers and practitioners may improve both emergency response and long-term preparedness. Finally, this study offers evidence-based recommendations to help inform local planning, disaster management techniques, and national climate adaptation activities in Bangladesh, thereby contributing to equitable and long-term flood resilience.

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Paper 4

Decolonising Climate Governance: Indigenous Women and Traditional Environmental Knowledge as Foundational Practice

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Abstract

A fundamental shift in the knowledge systems that underpin global climate governance is necessary to address climate change, not just technological innovation. Indigenous and local knowledge systems are fundamentally distinct from Western scientific traditions; they are rooted in relationality, land-based practices, and oral transmission, integrating empirical observation with cultural and spiritual contexts (Harding, 2015). These frameworks oppose reductionism, emphasising interdependence and contextual specificity. However, within prevailing climate policy, they remain marginalised as anecdotal or supplementary, an erasure that signifies deeper structures of epistemic injustice.

This paper builds on Vandana Shiva's ecofeminist critique of reductionist science as a patriarchal project of domination and violence (Shiva, 2010). It emphasises Indigenous women not as passive victims but as knowledge producers whose ecological expertise is essential for climate survival. Indigenous women possess comprehensive ecological knowledge that contests technocratic and extractive methodologies in addressing climate issues, ranging from water governance to biodiversity stewardship. Their epistemologies, grounded in reciprocity and relationality, embody politically sovereign alternatives that are predominantly marginalised within climate finance mechanisms and international policy frameworks.

Utilising various global case studies, the paper illustrates how the ecological practices of Indigenous women represent advanced forms of climate governance. It contends that prioritising these voices is not solely an issue of inclusion but of justice: climate governance must acknowledge Traditional Environmental Knowledge (TEK) as fundamental rather than marginal. This paper situates Indigenous women's knowledge at the forefront of global climate discourse, contributing to a broader decolonial initiative aimed at restructuring climate governance to promote equity, resilience, and ecological survival.

1. Introduction

As climate impacts intensify, decisions about what counts as valid expertise determine which responses are funded, scaled, or ignored. The politics of knowledge is therefore not peripheral to climate governance; it is constitutive of it. If climate governance continues to define expertise narrowly, it will continue to fund what breaks and ignore what works. The problem is not only technical; it is epistemic, and the sociology of scientific knowledge (SSK) makes this visible by insisting that we analyse all knowledge, scientific or otherwise, as socially situated. Its symmetry principle removes the presumption that Western science has automatic epistemic privilege; what counts as “true” or “false” must be explained by the same tools (Merton, 1979). Here, the key implication is simple: scientific authority rests on institutions, norms, and histories, not on timeless neutrality (Merton, 1979; Godfrey-Smith, 2021; Barnes & Bloor, 1982).

This reframing prepares the ground for reassessing whose knowledge structures climate action and under what standards. For climate politics and policymaking, this matters because Indigenous and rural women’s knowledge has consistently been treated as supplementary – “rich in culture, light in method.” That caricature cannot stand once we treat knowledge symmetrically; as Harding shows, many Indigenous knowledge systems combine empirical observation with moral and ecological reasoning, are transmitted orally, and are highly contextual - features that make them effective in place, not deficient (Harding, 2015).

The point is not to romanticise but to recognise parity: different standards, different evidence practices, and different forms of accountability can be coherent and rigorous (Wylie, 2022; Kuhn, 1970), and in other words, “pluralism is not relativism” (Boghossian, 2006; Wylie, 2022). The implications of parity become clearer when read alongside feminist and postcolonial critiques of development and science, which draw attention to how power shapes what is counted as valid knowledge in the first place.

2. Theoretical Framework: Epistemic Parity and Ecofeminist Grounding

To speak clearly about climate governance, we must first decide what counts as *knowledge* and who counts as a *knower*. In Vandana Shiva’s terms, this is not a technical preface but the heart of the politics at stake. “Development” and “modern science” present themselves as neutral, universal, and progressive, yet Shiva shows how both are, in fact, gendered projects that centre extraction, control, and growth while devaluing the relational work of women and nature (Shiva, 2010). Classic development metrics prize output and accumulation; they code care, sustenance, and regeneration as “unproductive” and therefore ignorable (Luxemburg, 1951; Boserup, 1970; Mies, 1986; Schlegel, 1977; Foster, 1973; Porritt, 1984). This is a form of epistemic injustice, where a system that decides ahead of time which labours count, and which lives can be

discounted. The same logic that organises development also shapes the scientific paradigms that inform climate policy, mapping the politics of value directly onto the politics of method.

A parallel move also occurs in science, particularly in the Western Scientific paradigm. The reductionist paradigm disassembles living systems into manageable parts, treats nature as a machine, and privileges abstraction over embeddedness (Merchant, 1980). Often presented as objectivity, this orientation has historically excluded women as knowers and discounted ecological reasoning grounded in place and relationship (Harding, 1986; Keller, 1985; Easlea, 1981; Anderson, 1960). Shiva's critique is not an anti-science gesture; it is an invitation to look honestly at how standards were set and who they served (Shiva, 2010).

The point is not to reject science but to disclose how its standards were historically set and whom they have served. Once we do, a different picture of expertise comes into view. Shiva names that alternative the feminine principle - not an identity category but an epistemic stance. It centres interconnection, diversity, nonviolence, and care; it affirms that knowledge is most reliable when it keeps life going (Shiva, 2010; Merchant, 1980; Harding, 1986; Keller, 1985). To give an example, if we look into the Indian/South Asian thought, *Prakriti* - *nature as a living, dynamic force* - captures this orientation: where land, water, and forests are relations, not objects (Woodroffe, 1931; Beane, 1977). Read through this lens, the daily ecological practices of Indigenous and rural women are not cultural anecdotes - they are methods, they produce predictions, allocate resources, prevent harm, and repair damage. In other words, they are procedures of governance that coordinate collective survival. Placed alongside SSK's symmetry principle, this ecofeminist reorientation reveals how "method" itself is never neutral: what is recognised as rigorous is deeply entangled with history, institutions, and the distribution of power.

3. From Inclusion to Responsibility in Climate Policy and Governance

Modern policy design has not kept pace with these insights. In contemporary practice, climate governance still tends to frame the crisis as a technical problem solvable by better data and communication, elevating centralised expertise and sidelining embedded practice (Bulkeley, 2000; Pepermans & Maesele, 2016). As Swyngedouw and Latour argue, the supposed separation of science from politics is itself political - a move that naturalises one way of knowing and obscures the conflicts and choices beneath it (Swyngedouw, 2010; Latour, 2015). The result is a persistent epistemic hierarchy: Indigenous women's knowledge is cited for legitimacy but excluded from agenda-setting, standards, and budgets (Pepermans & Maesele, 2016; Sultana, 2022). Treating knowledge as neutral obscures the ethical question of how authority over climate decisions is allocated and why certain actors continue to be recognised as "experts" while others are invited only at the margins.

A growing empirical record shows what is being missed. Across diverse contexts, women's environmental practice is systematic and adaptive: it observes, tests, refines, and sustains. In Benin, rural soil fertility strategies evolve through continuous innovation (Brouwers, 1993). In Andean agro-pastoral communities, gendered specialisation of expertise - women in animal health, men in soil management - demonstrates complementary knowledge regimes essential to resilience (Fernandez, 1992). In Zimbabwe and Sudan, women's biodiversity and food-processing knowledge - such as the use of wild plants and traditional fermentation - provides nutritional and ecological robustness (Dirar, 1991). In India, home gardens once dismissed as unscientific turn out to be biodiversity engines that use space and resources with high efficiency (Gupta, 1989). These are not footnotes; they are routine governing functions - predicting outcomes, allocating effort, conserving diversity, and reducing risk.

This framework clarifies the policy task: move from inclusion to responsibility. If parity of knowledge systems is accepted, institutions must assume responsibility to redefine standards and procedures accordingly. That begins with plural accountability: knowledge should be judged by what it sustains and whom it serves, not by whether it conforms to a single, abstract template (Harding, 2015; Wylie, 2022). In climate governance terms, that means recognising practice-specific indicators and place-specific tests - the kinds of measures that track function (for example, whether practices sustain seasonal water reliability or maintain seed diversity) rather than just throughput. When standards are recast in this way, the evaluative emphasis shifts from model fit to ecological fit: the essential question becomes whether a practice keeps hydrology, soils, seeds, and species alive across seasons of stress.

Two structural barriers must be addressed to make this real. First, the gendered visibility gap: development practice and research often privilege knowledge linked to public or commercial arenas (frequently male-coded), leaving women's contributions unrecorded, unfunded, and unsupported (Fernandez, 1992; Brouwers, 1993; Gupta, 1989). Second, the extraction problem: women's medicinal and agricultural knowledge is routinely harvested as raw data, then formalised and commodified elsewhere, with no acknowledgement or benefit-sharing - a pattern that makes Indigenous Intellectual Property Rights a matter of justice, not branding (Greaves, 1994). These barriers together produce epistemic injustice: who speaks is discounted in advance, and what works is disqualified by form (Sultana, 2022) - obliging institutions to document, resource, and protect these knowledge systems.

The policy consequence is to mistake format for rigour. Because embedded knowledge is not always presented as decontextualised metrics or peer-reviewed outputs, it is misread as anecdote. SSK's symmetry principle challenges that habit: what counts as better must be answered by who defines it, by which measures, and toward what ends (Merton, 1979; Barnes & Bloor, 1982). If the end is ecological survival with justice, then standards must reward relational effectiveness: the ability to maintain fertility, stabilise water and soils, preserve agrobiodiversity, and meet nutritional needs - precisely the outcomes documented across the women-led practices noted

above (Brouwers, 1993; Dirar, 1991; Gupta, 1989). In short, standards should reward what keeps systems alive rather than what is easiest to count.

Reframing knowledge as politically sovereign clarifies the path forward. “Sovereign” here does not mean statist; it means authoritative in practice. It is the capacity to set indicators, prioritise actions, and govern resources without waiting for external permission. That authority is already exercised, routinely, in diverse settings documented in the literature. The role of climate governance is not to bestow legitimacy upon it but to recognise and finance it. In SSK terms, this is the move from “supplement” to “foundation” (Pepermans & Maesele, 2016; Sultana, 2022). Recognising this authority is a globally relevant governance question, not a regional exception. When authority follows demonstrated capacity, practice ceases to be tolerated at the margins and becomes the benchmark against which interventions are judged.

Consider water. In the Doon Valley in India, women warned that quarrying would destroy springs and jeopardise drinking water. They were not credentialed as hydrologists, yet their situated observation proved accurate: the springs were sensitive to forest and substrate disturbance (Bandyopadhyay & Shiva, 1987). Across the Deccan and Mysore regions of India, community irrigation and rainwater harvesting were documented as more efficient than modern schemes that ignored local gradients and maintenance realities (Sengupta, 1985; Krishna Murthy, 1983; Jahan, 1981). These are not isolated curiosities. They show a pattern: women’s ecological work, grounded in reciprocity and relationship, anticipates outcomes and organises collective action to maintain water, soil, seed, and forest health (Shiva, 2010). The evidence here is at once empirical and ethical: the methods that sustain interdependence are the methods that keep systems alive.

Set against this, the technocratic model - with its faith in augmentation and control - often misreads living systems because it refuses relationship as a source of knowledge. Large dams and deep tube wells promise supply; the record that Shiva compiles is sobering; displacement, salinity, mismanagement, and even man-made drought (Patkar, 1987; INTACH, 1987; Worster, 1984; Reiger, 1980; Economic Times, 1984; Jahan, 1981) - underscoring why standards must be calibrated to ecological function and risk. If what we call “governance” repeatedly fails to predict harm and prevent loss, while embedded practice reliably does both, then the dispute is not merely about policy choices. It is about what we recognise as knowledge. Within this framing, the stance of the paper is straightforward: the objective is descriptive clarity about practice and measured accountability about policy effects. The analysis recognises governing capacity where it is enacted and avoids romanticisation by keeping evaluation tied to outcomes and standards. These criteria are legible across geographies where communities manage water, soils, seeds, and forests. What follows examines how these principles are enacted across distinct ecologies and institutions, showing when practice becomes policy - and when it is silenced.

4. Reconstructing Governance (Justice Beyond Inclusion)

If it is accepted that Indigenous and rural women's ecological knowledge governs, then the task is institutional: how should climate governance be rebuilt so that this knowledge is foundational, not supplementary? Shiva's work points to an inversion: from augmentation to regeneration, from central control to decentralised stewardship, from extractive growth to sustenance and care (Shiva, 2010; Chs. 6–7). The empirical and ethical rationale is consistent - the record of mega-projects has been uneven; similar schemes come with documented ecological and social costs, including salinity, mismanagement, displacement, and risk externalisation (Patkar, 1987; INTACH, 1987; Economic Times, 1984; Jahan, 1981). In contrast, what Shiva assembles from movements and community records shows that women-led, place-fit systems deliver water security, soil stability, and forest regeneration (Bandyopadhyay & Shiva, 1987; Sengupta, 1985; Krishna Murthy, 1983; Worster, 1984). Taken together, these records define governance outcomes that institutional designs should be able to recognise and resource.

Governance must reset its standards toward regeneration and contextual fit. Treat springs restored, reliable seasonal flow, reduced fetch distance, slope stability, canopy recovery, and seed/food diversity as primary metrics of success, moving away from counting only augmentation or throughput (Shiva, 2010; Chs. 6–7; Worster, 1984; Bandyopadhyay & Shiva, 1987; Sengupta, 1985; Krishna Murthy, 1983). Ending one-size-fits-all primacy follows from this: fit-to-watershed appraisals should precede large schemes, and megaprojects that risk undermining recharge and stability should be de-prioritised (Patkar, 1987; INTACH, 1987).

Authority and finance must align with demonstrated capacity. Rather than inviting participation without power, formal decision roles should be established for the knowledge holders who already perform rule-setting, maintenance, and allocation; budget lines, not only consultations, are required (Shiva, 2010; Right Livelihood Foundation, 1987). Funding should flow to the community rainwater systems, local irrigation, forest regeneration, and seed diversity practices documented as effective (Sengupta, 1985; Krishna Murthy, 1983; Bandyopadhyay & Shiva, 1987).

Rights are the enabling infrastructure for governance-by-practice. Without land–water–forest access, responsibilities fracture and the very practices that sustain ecologies become untenable (Shiva, 2010; Chs. 1, 6). Together, these shifts mark a redefinition of what governance measures and values. Institutional redesign is not a matter of adding consultation boxes but of revising mandates so that the practices that keep systems alive set the standards by which programmes are selected, funded, and evaluated.

Two cautions from within the record are important. Avoid essentialising: the feminine principle is an epistemic and ecological orientation, not a fixed identity (Shiva, 2010). The Chipko movement exemplifies this: village women defended forests as a way of life and governance, not as a symbol of gender alone (Right Livelihood Foundation, 1987). Avoiding essentialism must

be matched by material redesign. A system can cite Traditional Environmental Knowledge (TEK) while maintaining the old budgets and authorities; that is, tokenism. Shiva's chapters tie epistemic recognition to material shifts - in who decides, who is funded, and what indicators drive action (Shiva, 2010; Bennett, 1987; Clairmonte & Cavanagh, 1986). Only then does "recognition" translate into durable institutional change.

The evidentiary ground remains disciplined: Doon Valley (springs and quarrying), community irrigation and rainwater (Deccan and Mysore), anti-dam assessments, and Chipko's decentralised autonomy (Bandyopadhyay & Shiva, 1987; Sengupta, 1985; Krishna Murthy, 1983; Patkar, 1987; INTACH, 1987; Worster, 1984; Right Livelihood Foundation, 1987; Jahan, 1981). The argument is simple enough for a policy audience and strong enough for an academic one: treat what sustains life as expertise; design institutions accordingly. In the end, the proposed reconstruction is less a rupture than a return - to standards that respect interdependence, to authority that flows from care, and to finance that follows function. If knowledge is governance, and if women's ecological practice has long performed that role, then the task is to make official what is already true. That is what it means to put TEK at the foundation, and it is the only honest way to speak of justice in a warming world (Shiva, 2010).

5. Indigenous Women's TEK as Governance in Practice: A Cross-Continental Comparative

Across three continents and four sites, this analysis describes how Indigenous women turn embedded ecological knowledge into governing practices that safeguard water, forests, coasts, soils, and food systems - often without formal recognition or resourcing. In the Marshall Islands, women's intergenerational knowledge enters national planning through participatory adaptation pathways and nature-based projects (Greenpeace Australia Pacific, 2025; SPREP, 2025; kiwainitiative.org). In Narok County, Kenya, the Paran Women's Group mobilises 64 community groups to restore the Mau catchment with 120,500 native tree seedlings while rebuilding livelihoods and transmitting medicinal and seed knowledge (UNDP, 2025). In the Chittagong Hill Tracts (CHT), Bangladesh, women sustain water and biodiversity through micro-infrastructures and place-based observation even as policy and justice systems marginalise them (Mahboob, 2025; Shifa, 2025). And the Chipko movement in Himalayan India shows historically how women's relational practices became a politically sovereign challenge to extractive, reductionist governance (Bandyopadhyay & Shiva, 1987; Shiva, 2010; Reiger, 1980; Worster, 1984; Viswanathan, 1987).

Together, these cases clarify two things. First, TEK as practised by Indigenous women already governs; it produces monitoring, rules, infrastructures, prioritisation, and maintenance. Second, institutional design often misrecognises this governance, treating it as anecdote or culture rather

than as a valid basis for policy, funding, and authority. The details below outline practices, institutional gaps, and implications for climate governance.

Marshall Islands (Aur, Namo, Wotho): Women's roles as navigators, educators, community leaders, and political figures are documented in public narratives that connect cultural authority to climate action (Greenpeace Australia Pacific, 2025). Under a National Adaptation Plan process, the government engaged 362+ community participants (including women, youth, fishers, traditional leaders) to co-design transformational adaptation, pairing nature-based measures (mangroves, seagrass, reefs) with iterative institutional frameworks and periodic updates (SPREP, 2025). Project examples show women leading ecosystem restoration and community workshops that align ecological repair with food security (kiwainitiative.org). Read through the framework developed above; this is more than participation; it is an institutional pathway that converts lived observation into policy-relevant design and monitoring.

Paran Women's Group (Narok County, Kenya): A network of 64 Indigenous women's groups (over 1,000 women) combines native nurseries, agroforestry, beekeeping, medicinal knowledge, and clean-energy briquettes to regenerate the Mau Forest catchment and diversify livelihoods. The planting of 120,500 seedlings - prioritising Indigenous species such as *Olea africana*, *Dombeya torrida*, *Sesbania sesban*, *Teclea nobilis* - creates buffers, stabilises slopes, and rebuilds biodiversity while supporting household needs and schooling (UNDP, 2025). The group's work has been recognised internationally (including a Climate Award at COP28 and a Gender Just Climate Solutions Award), and it pairs ecological action with advocacy for gender-responsive budgeting and inclusion in decision-making (UNDP, 2025). What appears as "community planting" becomes, under the lens of governance, an ensemble of anticipatory management, rule-setting, and budget claim-making.

Chittagong Hill Tracts (Bangladesh): Women's daily hydrological intelligence - reading tree canopies and bird calls to locate springs; building bamboo check-dams, shaded wells, and rainwater systems; cultivating 55 crop varieties and 289 medicinal/edible plants - sustains water and nutrition in degraded watersheds (Mahboob, 2025). Yet exclusion from land rights, planning, and justice systems deepens risk: longer water treks, heightened exposure to violence, and silenced trauma persist, with low reporting and access to legal recourse (Shifa, 2025). Policy often treats culture as an obstacle and women as beneficiaries rather than knowledge producers (Shifa, 2025). The contrast with the Marshall Islands is telling: where consultative and iterative architectures exist, practice travels into plan; where they do not, effective practices remain underfunded and unprotected.

Chipko (Himalayan India): Women's collective defence of forests rested on empirical observation of how tree loss drove water scarcity, landslides, and crop failure, and it articulated a sustenance-based ecological polity that challenged technocratic control (Bandyopadhyay & Shiva, 1987; Shiva, 2010; Reiger, 1980; Worster, 1984; Viswanathan, 1987). Chipko shows TEK as politically sovereign - setting alternative criteria of success (groundwater, slope stability) and

compelling institutional response. It is a reminder that institutional redesign often follows, rather than precedes, public clarity about what governance is for.

6. Relational practice as governance: practical examples

Across sites, women govern through relationality - long-term attention to species, seasons, soils, springs, tides, and reef ecologies - translating observation into rules and routines. In the CHT, reading forest signs to find water, maintaining shaded wells, and building bamboo check-dams are applied hydrology: low-cost, locally maintained infrastructures that both predict and prevent harm (Mahboob, 2025). In Narok, species selection and nursery care embed practical criteria (which tree where, how to restore buffers), while medicinal and seed knowledge ensure that biodiversity remains a living asset (UNDP, 2025). In the Marshall Islands, women's lagoon knowledge and food systems inform nature-based measures (mangrove/seagrass/reef stewardship) that fit shoreline dynamics and community needs (Greenpeace Australia Pacific, 2025; SPREP, 2025; kiwainitiative.org). Chipko reframed forests as hydrological governance, not timber inventory (Bandyopadhyay & Shiva, 1987; Worster, 1984). This is governance because it monitors, allocates, maintains, and protects - and because it is accountable to outcomes communities can see and measure: spring flow, fetch distance, seedling survival, slope stability, and agrobiodiversity maintained. What technocratic plans present as "soft" values - kinship, reciprocity, care - are, in practice, reliable heuristics for managing complex ecologies under stress.

7. From practice to policy: when institutions make space

The difference between practice as survival and practice as policy is a matter of procedural authority. The Marshall Islands case shows structured consultation and iteration - a National Adaptation Plan (NAP) that integrates community observations, updates policy every decade, and pairs nature-based solutions with institutional strengthening (SPREP, 2025). Project vignettes reveal how women's groups are positioned to co-design coastal protection and food security measures (kiwainitiative.org). In Narok, international recognition and local engagement with authorities transform custodial practice into claims on budgeting and decision-making (UNDP, 2025). Chipko shows that when women's ecological knowledge becomes visible through collective action, it forces institutional recognition, reshaping rules and priorities (Bandyopadhyay & Shiva, 1987; Shiva, 2010). By contrast, the CHT shows the cost of institutional silence: plans and funds that do not document or integrate women's practices leave effective micro-infrastructure underfinanced, while justice gaps (low reporting, stigma, inaccessible systems) compound harm (Shifa, 2025). The lesson is procedural: if consultation,

documentation, budget lines, and monitoring are designed to capture lived indicators of ecological health, TEK transitions from supplement to foundation.

8. Outcomes that matter: fit-to-place indicators

Across the sites, outcomes are tracked through practice-proximate, place-fit indicators rather than abstract throughput. In the CHT, women's practices shorten fetch distances, protect springs, and buffer dry spells through rainwater systems and shaded wells (Mahboob, 2025). In Narok, Indigenous species nurseries and planting create buffer zones, stabilise slopes, and rebuild biodiversity across farms, schools, and riverbanks (UNDP, 2025). In the Marshall Islands, mangrove, seagrass, and reef stewardship are tied to food security and shoreline protection, with community observations feeding a national adaptation architecture (Greenpeace Australia Pacific, 2025; SPREP, 2025; kiwainitiative.org). In Chipko and allied documentation, forest health is linked to groundwater recharge and landslide prevention, challenging extractive framings and making a public case for women-led governance (Bandyopadhyay & Shiva, 1987; Worster, 1984; Shiva, 2010). These outcomes translate directly into adoptable metrics - spring flow stability, reduced fetch time, seedling survival and species mix, canopy recovery, agrobiodiversity counts, slope integrity - through which TEK authorises standards on its own terms.

9. Political sovereignty, not token inclusion

Framing Indigenous women's TEK as politically sovereign clarifies the task. Sovereignty here is not statehood; it is the authority to define indicators, set priorities, allocate effort, and maintain infrastructures (e.g., nurseries, check-dams, reef work) without waiting for external permission. The Paran Women's Group asserts this in practice - choosing species, tending nurseries, restoring buffers, and advocating for gender-responsive budgets (UNDP, 2025). In the Marshall Islands, women's leadership moves from cultural narrative to state-recognised planning processes (Greenpeace Australia Pacific, 2025; SPREP, 2025). Chipko shows how women's sustained action reorders what counts as rational resource policy (Bandyopadhyay & Shiva, 1987; Shiva, 2010). The CHT materials demonstrate both the existence of this authority (micro-infrastructure, biodiversity knowledge) and the costs of its non-recognition (Mahboob, 2025; Shifa, 2025).

10. Risks and safeguards: avoiding essentialism and burden-shifting

No single identity can substitute for the diversity of practices described here. A practice-specific, place-bound account avoids essentialising. Equally, financing that pays for maintenance and secures rights prevents burden-shifting - ensuring care is not converted into unfunded mandates. When standards reward regeneration and when budgets pay for the upkeep of the systems that keep communities alive, the invisible labour of care is neither romanticised nor exploited; it is recognised as expertise.

11. Policy/practice implications – as drawn from the cases cited

The cases point to a convergent institutional agenda. Material rights to land, water, forests, and coasts are the enabling conditions of governance-by-practice, and safety/justice access is integral to resilience (Shifa, 2025). Finance should follow function: invest in rainwater systems, nurseries and planting, mangrove–seagrass–reef stewardship, local monitoring, and small-scale livelihoods tied to these practices (SPREP, 2025; UNDP, 2025; kiwainitiative.org). Equally, standards must institutionalise lived indicators - spring flow, fetch distance, seedling survival and species mix, canopy recovery, agrobiodiversity counts - so projects are selected and evaluated on ecological performance in place (Mahboob, 2025; UNDP, 2025; Bandyopadhyay & Shiva, 1987). Procedural pathways like the Marshall Islands' NAP demonstrate how consultation and iteration can embed TEK in agenda-setting, with votes and budgets rather than invitations alone (SPREP, 2025). This comparative section draws solely on the journalistic, policy, project, and historical materials cited; it makes no claims beyond these sources and treats ecological performance claims as provisional pending longitudinal monitoring.

12. Conclusion: Knowledge as Governance, Justice as Design

This paper began with a simple proposition: the way we define expertise determines what climate actions are imagined, funded, and defended. Read through the symmetry principle in the sociology of scientific knowledge (Merton, 1979) and the ecofeminist critique of reductionist science (Shiva, 2010), and the stakes are clarified. What counts as “rigorous” has never been neutral; it is patterned by institutions, histories, and hierarchies that have long discounted relational practices - especially those maintained by Indigenous and rural women - as cultural colour rather than governance. The materials examined here move that boundary. They show, across contexts, that TEK is not a supplement to technocratic planning but a governing capacity that anticipates harm, maintains ecological function, and organises collective care.

The theoretical questions that opened this study can now be answered directly. First, Shiva's ecofeminism links patriarchy, science, and ecological destruction by showing how a reductionist

paradigm framed the living world as an object of control and extraction, coding care and regeneration as non-knowledge (Shiva, 2010; Merchant, 1980; Harding, 1986; Keller, 1985). The “feminine principle,” read alongside Prakriti in South Asian thought, is not identity politics but an epistemic realignment: knowledge is trustworthy when it keeps life going; land, water, and forests are relations before they are resources (Woodroffe, 1931; Beane, 1977). Brought into conversation with SSK’s symmetry, this becomes a standard-setting claim: the same analytic tools must explain success and failure across all knowledge traditions; no tradition is entitled to automatic privilege (Merton, 1979; Barnes & Bloor, 1982; Godfrey-Smith, 2021).

Second, what distinguishes Indigenous women’s ecological knowledge from dominant technocratic approaches is not a lack of method but a different one. Relationality and reciprocity are here methodological commitments: long-duration observation, obligation to place, and attention to interdependence are the means by which predictions are made, infrastructures are maintained, and harm is prevented. In this register, “policy-relevant knowledge” is evidence that reliably sustains flows, soils, seeds, slopes, reefs, and livelihoods - outcomes that communities can verify and institutions can adopt as criteria (Wylie, 2022; Brouwers, 1993; Dirar, 1991; Gupta, 1989). These are not soft values; they are fit-to-place standards for governing complex systems under stress.

Third, to frame Indigenous women’s TEK as “politically sovereign” is to treat it as authoritative in practice: the capacity to set indicators, prioritise actions, and allocate effort without waiting for external permission. Sovereignty here is not statehood; it is rule-making grounded in social legitimacy and proven effect. The cases render this visible. In the Marshall Islands, a consultative National Adaptation Plan translates lived observation into iterative state planning (SPREP, 2025; Greenpeace Australia Pacific, 2025). In Narok, the Paran women operationalise catchment governance through species choice, nurseries, and buffer creation while pressing for gender-responsive budgets (UNDP, 2025). In the CHT, women’s hydrological intelligence sustains springs and agrobiodiversity even as policy and justice systems marginalise them (Mahboob, 2025; Shifa, 2025). Chipko supplies the historical proof that such practice can compel institutional reordering and redefine rational resource policy (Bandyopadhyay & Shiva, 1987; Shiva, 2010; Worster, 1984).

The empirical and methodological questions follow: Where does TEK provide viable or superior solutions? The record is concrete: bamboo check-dams, shaded wells, rainwater systems, diverse seed and medicinal plant stewardship, coastal mangrove–seagrass–reef care, and native-species buffers that stabilise slopes and rebuild catchments. Where have finance and policy failed? In the routine misrecognition of these practices as anecdote, the absence of systematic documentation in sector plans, and the channelling of resources toward one-size infrastructure and monocultural “greening” that undermines recharge and biodiversity (Mahboob, 2025; Shifa, 2025). The risks of essentialising are real, and the paper’s design guards against them by staying practice-specific and place-bound, resisting any claim that gender alone confers ecological virtue. Equally

important is avoiding burden-shifting: recognition without rights and budgets converts care into an unfunded mandate.

The political and normative questions complete the arc. The structures of epistemic injustice identified here - visibility gaps, extraction of women's knowledge without acknowledgement or benefit-sharing, and the procedural separation of "science" from politics - are not incidental (Pepermans & Maesele, 2016; Sultana, 2022; Swyngedouw, 2010; Latour, 2015). They are design choices that can be reversed. The institutional reconstruction proposed in the body of the paper is therefore modest and decisive: reset standards toward regeneration and contextual fit; align authority and finance with demonstrated capacity; and secure land-water-forest rights so governance-by-practice can endure (Shiva, 2010; Bandyopadhyay & Shiva, 1987; Sengupta, 1985; Krishna Murthy, 1983). Consultation and iteration, as in the Marshall Islands' NAP, are not process ornaments; they are the procedural pathways through which TEK moves from practice planning to budget (SPREP, 2025). Measured this way, "recognition" is inseparable from redistribution.

None of this romanticises labour; it measures it. Spring flow stability, reduced fetch time, seedling survival and species mix, canopy recovery, agrobiodiversity counts, and slope integrity are the kinds of indicators that make relational effectiveness legible to policy (Bandyopadhyay & Shiva, 1987; UNDP, 2025; Mahboob, 2025). When such indicators steer funding and evaluation, the distance between what keeps systems alive and what earns support narrows. That is the governance shift the cases demand.

What, finally, does this contribute to a universal project of climate action? It offers a standard that treats what sustains life as expertise. Authorise those who already keep watersheds, forests, reefs, soils, and seeds alive to set the terms by which interventions are judged. The symmetry principle denies epistemic privilege; the ecofeminist critique supplies the ethic of care and interdependence; the cases show the instruments and the outcomes. The path forward is not an abstract reconciliation of "local" and "scientific" knowledge, but a redesign of institutions so that effective, place-fit practice sets the baseline for policy. In that sense, to put TEK at the foundation is not to add culture to science; it is to rebuild science-policy systems so that survival standards - relational, empirical, and just - govern what is built, funded, and protected (Merton, 1979; Shiva, 2010).

If climate governance is to be credible, it must stop treating the work that sustains life as peripheral and start treating it as the measure. This is a normative claim and a procedural one. It is also a practical route to resilience: where institutions secure rights, finance what works, and adopt lived indicators, communities and ecologies endure. Where they do not, the costs are already legible on parched hillsides, collapsing springs, and eroded coasts. The choice is not between tradition and innovation; it is between designs that ignore the terms of survival and designs that let them lead.

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Paper 5

AHP-based Multi-criteria Assessment of Drought Vulnerability in Rangpur Division, Bangladesh

Meghla Halder, Borni Guha, Shudip Paul, Dipraj Roy

Abstract

Drought vulnerability reflects the extent to which environmental, economic, and social systems suffer during prolonged dry periods. In Bangladesh, the northwestern Rangpur Division, comprising Dinajpur, Gaibandha, Kurigram, Lalmonirhat, Nilphamari, Panchagarh, Rangpur, and Thakurgaon, faces severe drought risk due to its dependence on agriculture, river-fed irrigation, and climatic variability. Although major rivers such as the Teesta, Dharla, and Brahmaputra traverse the region, seasonal water fluctuations, declining groundwater recharge, and rising evapotranspiration intensify drought impacts, threatening food security and rural livelihoods. This study applies an integrated Analytical Hierarchy Process (AHP), Geographic Information System (GIS) framework to evaluate drought vulnerability across Rangpur Division. Six critical factors -Elevation, Slope, Normalised Difference Vegetation Index (NDVI), Normalised Difference Water Index (NDWI), Normalised Difference Drought Index (NDDI), and Aspect were selected to represent topography, vegetation health, water availability, and slope orientation. Each factor was weighted using AHP, standardised, and analysed in GIS to generate thematic layers. These layers were integrated and classified into five vulnerability classes, ranging from Class 1 (very low vulnerable) to Class 5 (very highly vulnerable). Results reveal notable spatial variations. High to very high drought vulnerability covers 50.37% and very low drought vulnerability is 3.79% only in the study area, indicating an alarming trend likely to worsen in the future. Thakurgaon is the least vulnerable district, with only 10.39% of its area in the very high vulnerability category, while Kurigram is the most vulnerable at 31.23%. Areas with low vegetation, unfavourable slope, and aspect showed the greatest susceptibility. The findings underscore the urgent need for district-specific adaptation strategies, including improved irrigation infrastructure, sustainable groundwater management, crop diversification, and reforestation. By mapping drought susceptibility, this study provides actionable guidance for policymakers and development agencies to enhance agricultural resilience and rural livelihoods, supporting long-term climate adaptation in Rangpur Division.

1. Introduction

Anthropogenic climate change's widespread and rapid progression has unambiguously sparked a paradigm shift in both the intensity and frequency of harmful weather events; as a result, the widespread occurrence of torrential pluvial events, unusual river storms, and prolonged hydro-meteorological desiccation presents a significant existential threat to various socio-ecological systems throughout the entire globe (Alharbi et al., 2022; Miralles et al., 2019). Drought is one of the most significant consequences of human-induced climate change. It is defined as a long-term lack of accessible water supplies that affects large areas and lasts for a long time. This makes it a widespread natural hazard (Abdela et al., 2023; Ayugi et al., 2022; Rossi et al., 2023). Lack of rainfall is another cause contributing to the limitation of water. Such extended rainfall deficits have serious repercussions for human well-being, agricultural productivity and ecological stability in addition to upsetting the natural hydrological cycle. Drought can have grave repercussions, particularly mass migration, the loss of livelihoods and a higher threat of sickness and fatalities (Akter et al., 2025; Zinat et al., 2020).

Because of the limited precipitation, Bangladesh has dry weather for six months from November to April. In recent years, there have been more droughts in various sections of the entire country with variations in severity (Mamun et al., 2020). Two primary structural units make up the Bengal Basin, which encompasses a significant portion of Bangladesh. These units are the Precambrian Rangpur Platform and the Bengal Foredeep. The Rangpur Platform, which is in the northwestern part of the country, has a large alluvial plain made up of Pleistocene terraces that rise and fall gently toward the south and southeast. This has a big effect on how water drains and how soil develops in the area (Rashid et al., 2015). The Brahmaputra–Jamuna fluvial system, beginning from the Himalayan orogenic area and traversing India before entering Bangladesh, constitutes one of the world's largest braided river networks. The morphology is influenced by the intricate interplay of climatic variability and tectonic processes, resulting in significant periods of erosion and accretion that perpetually alter the fluvial landscape (Rahman et al., 2025).

Rangpur Division was selected as a focal study area not only because of the local population's socioeconomic dependence on riverine systems for agriculture and habitation but also due to the region's acute vulnerability to fluvial erosion and sedimentation. This selection is further substantiated by the escalating impacts of climate change and the conspicuous paucity of long-term hydro-geomorphological data concerning river dynamics. Northern Bangladesh is also at a significant danger of drought because it has a lot of people, and the rain doesn't fall evenly. Researchers from many different scientific domains, including ecology, hydrology, meteorology, geology, and agricultural sciences, are very interested in this expanding vulnerability. Researchers from various fields are progressively striving to comprehend the complex ecological, hydrological, and socio-economic ramifications of this enduring environmental issue

(Mortuza et al., 2019; Akter et al., 2025; Uddin et al., 2020; Rahman et al., 2025). Wide-ranging and catastrophic drought can exacerbate employment insecurity, restrict access to essential food supplies, and precipitate abnormal price surges, particularly among rural populations.

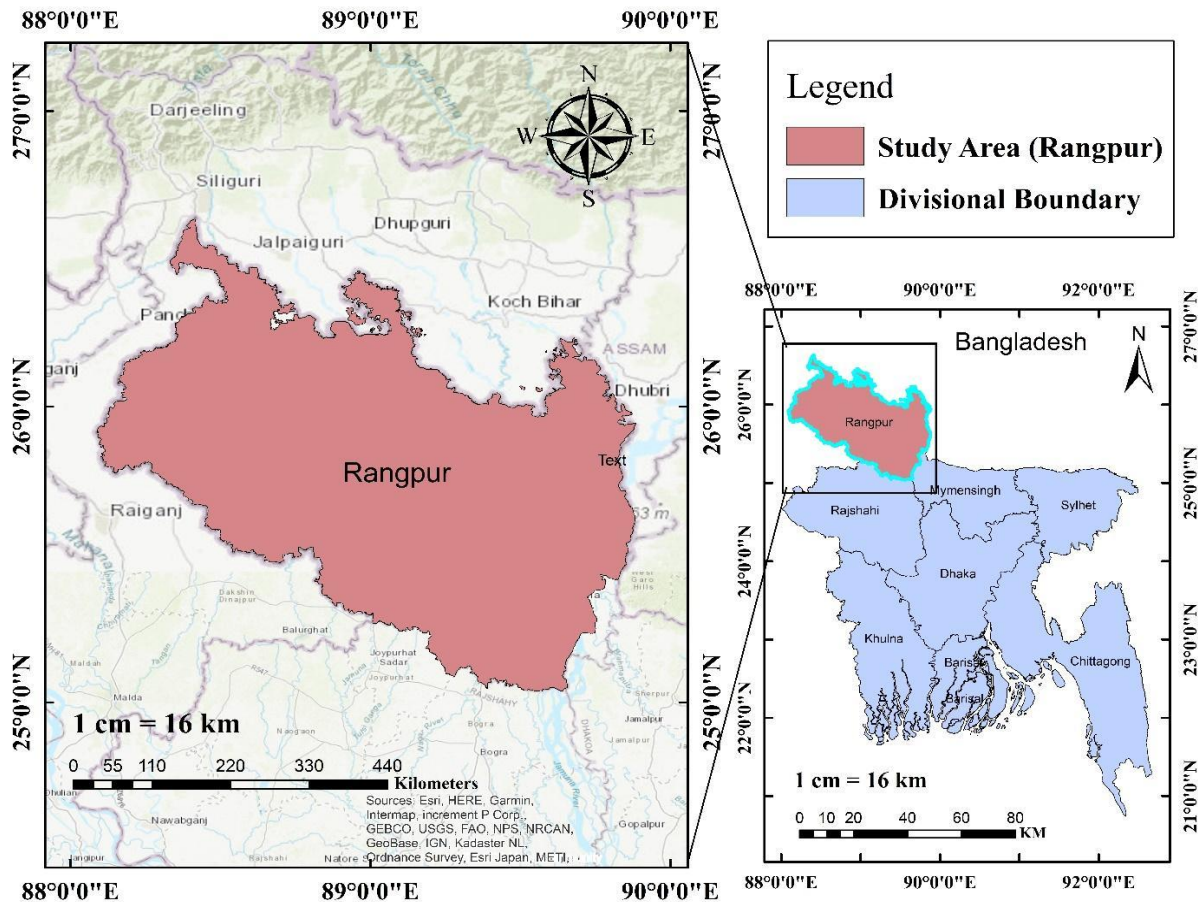
Given Bangladesh's predominantly agrarian economy, the spatial and temporal distribution of precipitation assumes critical significance as it directly governs agricultural productivity, sustains rural livelihoods, and underpins food security. The northern region of Bangladesh, known for its vast agricultural activities, plays a vital role in maintaining the country's overall economic stability. However, many of its surface water sources, such as rivers, streams, and canals, tend to shrink or even dry up completely during the dry season. This seasonal water scarcity has far-reaching consequences, as prolonged droughts severely impact the environment, disrupt social well-being, and threaten both agricultural productivity and the livelihood security of local communities (Das & Halder, 2023). Nevertheless, this ongoing aridity emphasises how critical it is to put into practice practical and long-term measures meant to lessen the various effects of drought (Akter et al., 2025; Alexandersson, 1986).

The Rangpur Division exhibits significant susceptibility owing to its reliance on rain-fed agriculture, constrained water resources, and the prevalence of periodic dry spells. The health of a significant demographic is intricately tied to agriculture; thus, extended periods of drought fundamentally impact crop production, revenue generation, and the overarching stability of food supply in this region. Geographic Information Systems (GIS) provide a powerful platform for accurately mapping regions of varying drought risk, enabling researchers to visualise and analyse the spatial heterogeneity of vulnerability. When coupled with decision-making frameworks such as the Analytic Hierarchy Process (AHP), this approach facilitates multi-criteria spatial assessment by systematically integrating diverse indicators into a weighted evaluation matrix (Hodasová et al., 2025; Saini et al., 2022). The incorporation of these methodologies not only enhances the precision and effectiveness of drought risk assessments but also promotes evidence-based decision-making by identifying the regions that need the greatest attention. As a result, vulnerability mapping becomes an essential tool for planning and prioritising risk reduction strategies, enabling policymakers to design and deliver targeted interventions and support systems that address the specific needs of each risk zone.

In the context of Bangladesh's Rangpur Division, this study aims to employ an AHP-based GIS multi-criteria approach to conduct a comprehensive evaluation of drought vulnerability to inform policymakers, local stakeholders, and planners. The anticipated outcomes include the identification of highly vulnerable areas, guidance for resource allocation, and the development of targeted drought mitigation strategies. Moreover, by linking spatial patterns of vulnerability to agricultural and water management practices, the study seeks to enhance climate resilience and ensure long-term sustainable agricultural production. Ultimately, this research establishes a robust theoretical and practical foundation for adaptive planning and evidence-based interventions, thereby mitigating the adverse environmental, social, and economic impacts of drought.

2. Study Area

The country of Bangladesh, which is situated in South Asia, is situated in the middle of the Indian subcontinent's northeastern zone. It is surrounded by India to the west, north, and east; Myanmar to the southeast; and the Bay of Bengal to the south, which together constitute a large deltaic landscape that extends from 20°34'N–26°38'N in latitude to 88°01'E–92°41'E in longitude (Ahammed et al., 2020). This research focuses on the Rangpur Division, which is located in the northwestern portion of Bangladesh. It has an area of roughly 16,154.25 km² and extends from 25°20'N to 26°37'N in terms of latitude and from 88°50'E to 89°53'E in terms of longitude (Mamun et al., 2020) (Fig.1). The division predominantly comprises fertile alluvial plains developed through sediment deposition by major river systems such as the Teesta, Brahmaputra, Dharla, Atrai, Dharia, Tangon and Mahananda (Mamun et al., 2020). It shares its northern and western boundaries with West Bengal (India), its eastern frontier with Meghalaya (India), and its southern boundary with the Rajshahi Division. Owing to its diverse physiographic characteristics, climatic variability, and agricultural dependence, Rangpur Division represents an ideal area for assessing drought vulnerability in northwestern Bangladesh.



3. Methodology

The evaluation of the risk posed by droughts may be affected by a number of different factors. Within the geographic framework of this study, 6 criterion layers were developed to assess drought vulnerability. The sources of the remote sensing indices are described in Table 1. Elevation, slope, aspect, Normalised Difference Water Index (NDWI), Normalised Difference Vegetation Index NDVI, and Normalised Difference Drought Index (NDDI) were among the 6 conditioning parameters used to determine drought in the study areas using the analytical hierarchy process (AHP). (Fig. 2) provides a comprehensive suggested methodology.

3.1. Analytical hierarchy process

The Analytic Hierarchy Process (AHP) approach was used to create a pairwise comparison matrix for the conditional variables. The Analytic Hierarchy Process (AHP) is a well-established multi-criteria decision-making (MCDM) approach that is commonly used in environmental and hazard assessments for the purpose of tackling complicated issues such as drought assessment (Sivakumar et al., 2021). In the past, a number of scholars have used paired comparison methods in order to assess the relative impact of conditioning variables in the process of flood and drought risk mapping (Vojtek & Vojteková, 2019). A comparative scale was created by Saaty in 1980, which assigns integer values ranging from 1 to 9, where 1 signifies equal relevance and 9 symbolises extreme importance (Table 2). In this research, all of the characteristics were grouped in a hierarchical structure, and their relative importance was assessed by utilising the comparative scale. A diagonal reference matrix containing 11 pairwise comparisons was developed with all diagonal elements equal to 1 (Table 3). The remaining cells in each row reflect the relative importance of other parameters in relation to one another. The normalised principal eigenvector, relative weight matrix, and pairwise comparison matrix were computed to determine the final weight of each parameter (Table 4). The normalised eigenvector was obtained by dividing each column value by the column total, and the average of each row was then calculated to derive the final weights of the thematic layers. These normalised eigenvector values represent the influence percentage of each factor on drought vulnerability.

The calculation of the Consistency Ratio (CR) was performed in order to ascertain the dependability of the pairwise comparisons. A number that is less than or equal to 0.1 signifies an appropriate degree of consistency, whilst a value that is more than 0.1 suggests that the matrix needs to be adjusted (Yahaya et al., 2010). The CR is expressed as:

$$CR = \frac{CI}{RI} \dots\dots\dots (1)$$

where CI refers to the consistency index and RI is the random consistency index.

$$CI = \frac{\beta - n}{n - 1} \dots\dots\dots (2)$$

where $\beta_{\max}$ is the maximum eigenvalue of the comparison matrix

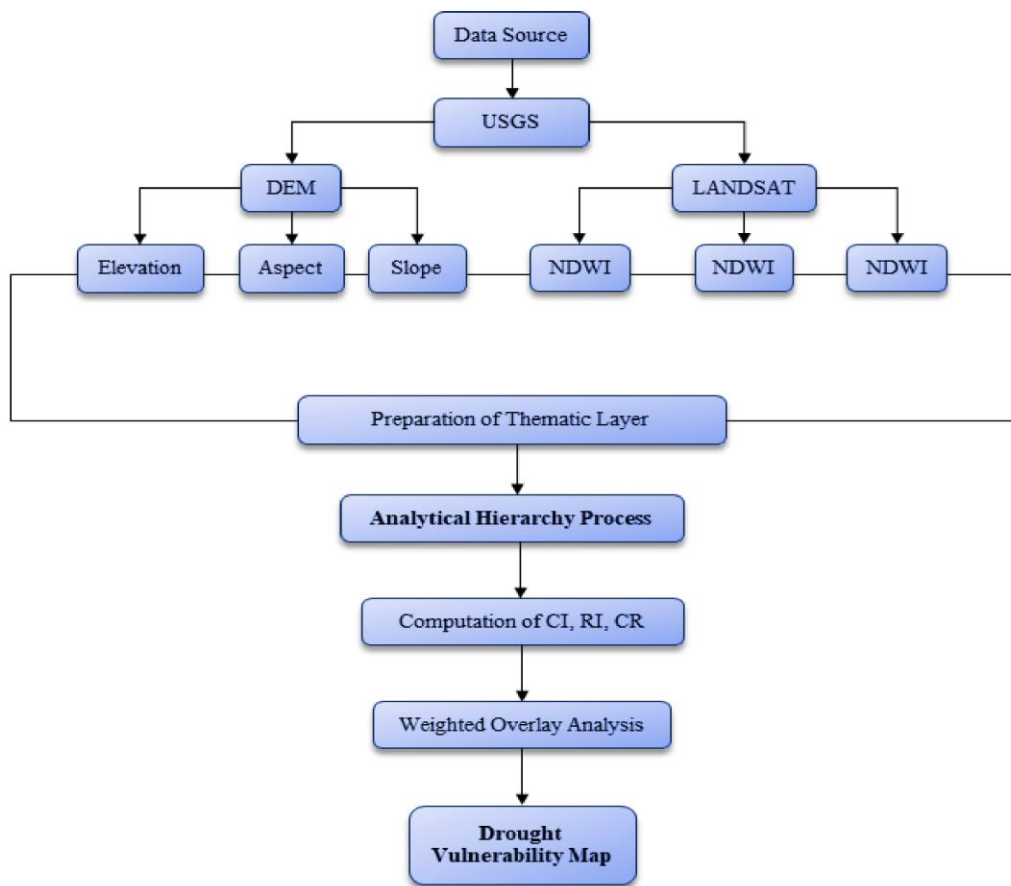


Figure 2: Adopted methodology for drought vulnerability in the Rangpur Division area.

Table 1: List of data with their specific characteristics utilised in Rangpur Division

Types of Data	Data Sources	Time Period	Intended Use
Landsat 8 Imagery Band-7 (30 m resolution)	USGS	1/11/2024 - 10/11/2024	NDVI, NDWI, NDDI
Digital Elevation Model (DEM) data (30 m resolution)	USGS	2024	Elevation, Slope and Aspect analysis

Table 2: Scale of relative importance (by Saaty, 2008)

Relative importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Table 3: The RI value taken from Saaty's scale (Saaty, 1980)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.2. Weighted Overlay Analysis

Over the course of the research, the Weighted Overlay Method (WOM) was used in order to assess and identify areas that might potentially be affected by drought. For the purpose of integrating different environmental aspects within the framework of a Geographic Information System (GIS), this technique is advantageous since it is straightforward, efficient, and effective. For the purpose of developing the drought risk zonation map, a total of eleven environmental characteristics were taken into consideration. On a scale ranging from one to five, a numerical rating was given to each element based on its relative relevance in determining drought sensitivity. Higher values imply a larger contribution to the incidence of drought. Additionally, equivalent weights and rankings were given to each individual class inside each factor map. This was done to guarantee that the geographic variability of each conditioning variable was accurately represented. After that, the weighted thematic layers were included in the Geographic Information System (GIS) via the use of the Weighted Overlay Analysis. In this analysis, each layer was multiplied by its own weight, and then the multiples were added together to get the ultimate drought vulnerability index, which is represented by:

$$D = \sum_{i=1}^n T_j \times d_i \dots \dots \dots (3)$$

where D denotes the composite drought index, T_j denotes the weights of each parameter multiplied by the drought parameters (d_i).

The resulting drought vulnerability map was classified into five distinct zones, such as very high, high, moderate, low, and very low (no drought), to depict the spatial heterogeneity of drought risk across the Rangpur Division (Table 4).

Table 4: Pairwise comparison matrix of the selected parameters for drought vulnerability

Parameters	NDVI	NDWI	NDDI	Slope	Aspect	Elevation	Weights
NDVI	1	7	5	9	9	9	0.55
NDWI	0.143	1	1	4	4	9	0.15
NDDI	0.2	1	1	4	4	9	0.16
Slope	0.111	0.25	0.25	1	2	4	0.06
Aspect	0.111	0.25	0.25	0.5	1	1	0.04
Elevation	0.111	0.111	0.111	0.25	1	1	0.03
Consistency Index (CI):0.094 and Consistency Ratio (CR) :0.076							

Table 5: Formula for calculating Remote Sensing Indices.

Indices	Formula	Sources
NDVI	$NDVI = (NIR - RED) / (NIR + RED)$	(Myneni et al., 1995)
NDWI	$NDWI = (NIR - Green) / (NIR + Green)$	(Jackson et al., 2004)
NDDI	$NDDI = (NDVI - NDWI) / (NDVI + NDWI)$	(Gu et al., 2008)

4. Result

4.1.1 Elevation

Elevation denotes the orthometric height or vertical displacement of a terrestrial point relative to a geodetic reference surface, typically mean sea level, thereby serving as a fundamental geomorphometric parameter that governs hydrological gradients, drainage dynamics, and spatial variability in surface processes (Das et al., 2025). This factor plays a critical role in shaping environmental and human systems as variations in elevation can significantly influence climatic conditions, hydrological processes, and ecological patterns. For instance, elevation affects temperature, humidity, and precipitation levels, which in turn govern vegetation growth, soil characteristics, and land-use practices. It also determines the spatial arrangement of human settlements, since communities often adapt their infrastructure and activities to suit the elevation gradient of their location. From a planning and resource management perspective, elevation is

indispensable for infrastructure development, drought risk assessment, watershed management, flood-risk assessment, and the promotion of a sustainable environmental framework. Areas of varying elevation display different potentials and limitations for agriculture, construction, and ecosystem preservation, making elevation analysis essential for targeted development strategies. In order to conduct an in-depth investigation of these differences, a computer Elevation Model (DEM) is used. A DEM is a computer depiction of the topography of the ground surface that offers extensive data on slope gradients, drainage networks, watershed borders, catchment regions, and a variety of geomorphological variables. These datasets are fundamental to environmental monitoring, natural resource management, and geospatial analysis. In this investigation, a 30-meter resolution Shuttle Radar Topography Mission (SRTM) DEM dataset, sourced from the United States Geological Survey (USGS), was utilized to assess elevation across the study area. The results show a lot of variety in terms of location: the southern area is defined by low-lying terrain, while the northern region is mostly characterized by higher altitudes. Statistical findings indicate that elevation values relative to the mean sea level range from -13 meters to 122 meters (Fig. 3).

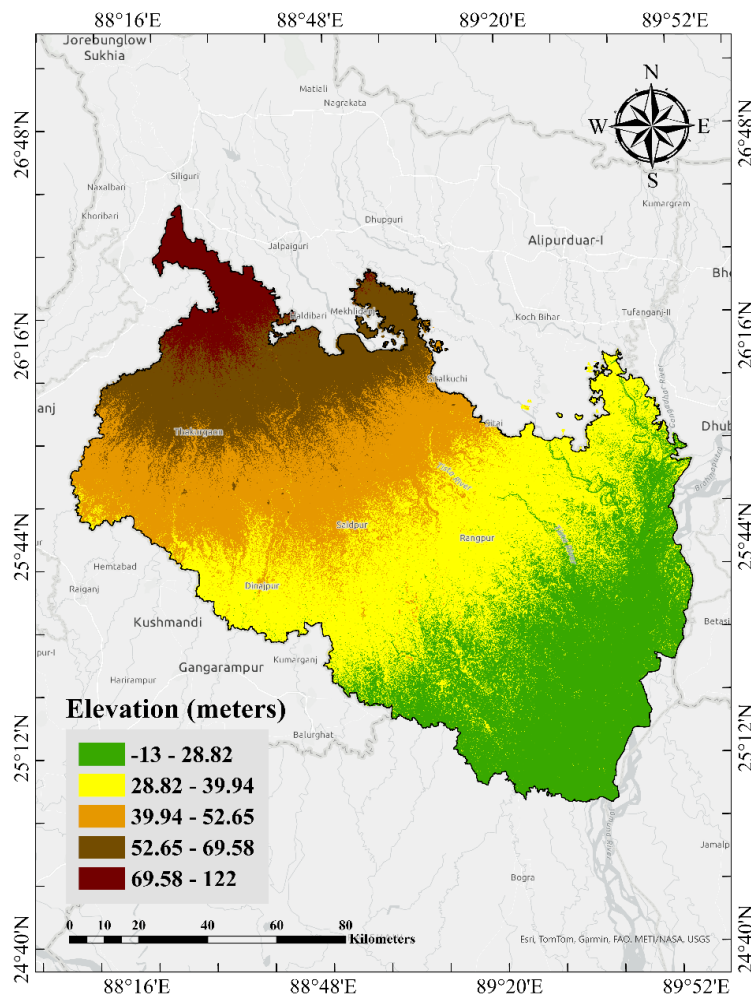


Figure 3: Spatial distribution of elevation across the Rangpur Division, Bangladesh, from DEM data.

4.1.2 Slope

Another key aspect that impacts the probability of drought is slope. It shows how rapidly elevation varies over a horizontal distance, and it may be displayed in degrees or as a percentage. Slope is a basic topographic feature that changes the way water flows, such as its speed and discharge. These changes are directly connected to the slope's gradient (Hossain & Mumu, 2024). Water infiltration is decreased, and surface runoff is increased on steeper slopes. On the contrary, the regions with higher water infiltration and less influence on surface runoff are indicated by lower slope values (Tayyab et al., 2021). In comparison to sharply inclined terrains, lower slope gradient landscapes are less susceptible to incidents of drought (Jain et al., 2015). In statistical analysis, the slope values in degrees range from 0 to 51.85, indicating a variation from nearly flat to moderately steep terrain across the study area (Fig. 4).

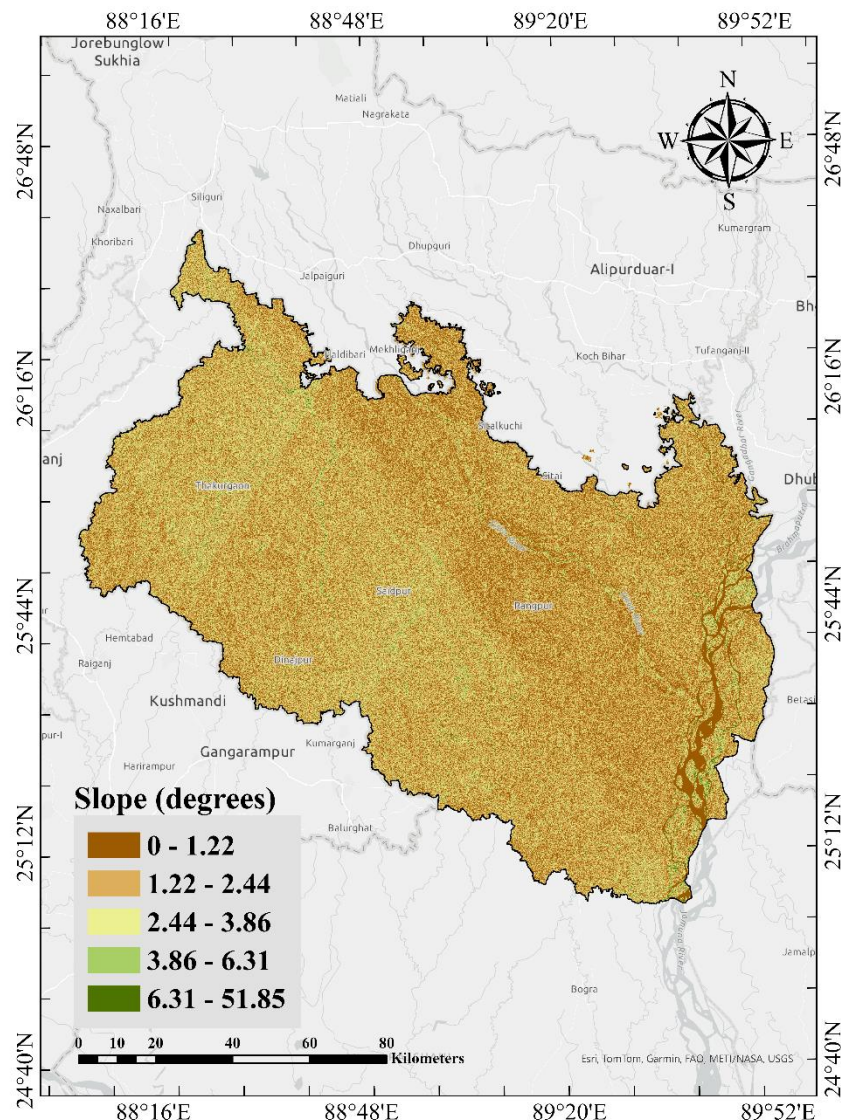


Figure 4: Spatial distribution of slope across the Rangpur Division, Bangladesh.

4.1.3 Aspect

Aspect is the direction that a slope faces on a compass, which is commonly measured in degrees from north. It is an important factor in analysing topography and the environment since it has an effect on microclimatic conditions, how plants grow, how water drains, and how much sunlight plants receive. Hydrological factors control the parameter, and the aspect map of the study area was classified into multiple categories to analyse how slope orientation affects hydrological behaviour and related landscape characteristics (Alharbi et al., 2022; Bennie et al., 2008). The influences of temperature, humidity, water penetration, surface runoff, and soil evaporation processes were taken into consideration to arrive at a particular value for each class (Alharbi et al., 2022) (Fig. 5).

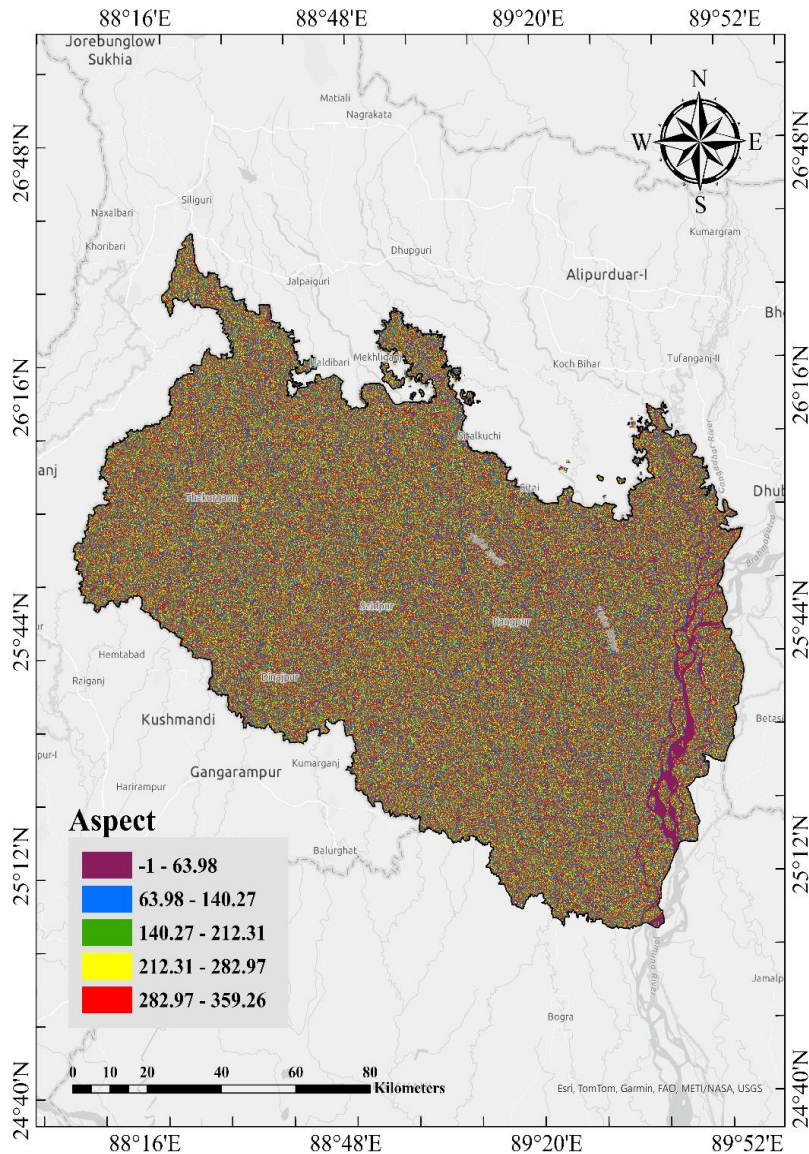


Figure 5: Spatial distribution of slope across the Rangpur Division, Bangladesh.

4.1.4 NDVI

The NDVI is determined by taking the total reflectance values of red and near-infrared (NIR) light, subtracting their respective values, and then dividing the result by the total of both sets of reflectance values (Kriegler et al., 1969). The normalized differential vegetation index (NDVI) is a useful response variable for identifying and quantifying drought disturbance in dry and semi-arid settings. Plants under stress have low values (Tucker & Choudhury, 1987) (Table 5). The range of NDVI pictures is -1 to +1 where -1 represents sparse vegetation or barren land and +1 indicates healthy and dense vegetation (Myneni et al., 1995; Tucker et al., 1986). It is very important to track vegetation growth, agricultural productivity, and maintain the ecosystem. According to the processed data, NDVI values in the Rangpur Division vary between -0.09 and 0.51, reflecting a spatial transition from barren or sparsely vegetated surfaces to areas with moderate vegetation density (Fig. 6).

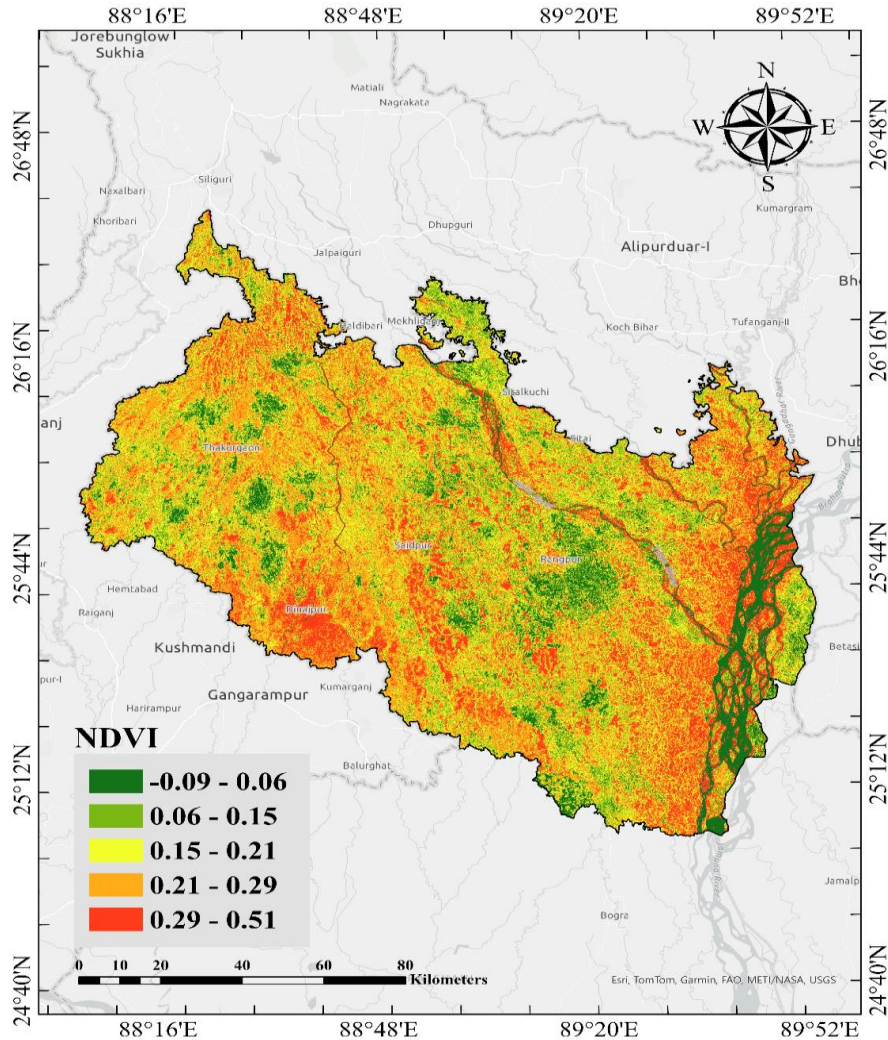


Figure 6: Spatial distribution of the Normalised Difference Vegetation Index (NDVI) across Rangpur Division, Bangladesh.

4.1.5 NDWI

The Normalized Difference Water Index (NDWI) is a modern, satellite-derived indicator that utilizes near-infrared (NIR) and shortwave infrared (SWIR) spectral bands to assess changes in vegetation canopy water content and the spongy mesophyll through the analysis of SWIR absorption (Gao, 1996; Kahkashan et al., 2016) (Table: 5). It serves as a reliable metric for detecting water stress in vegetation, making it highly valuable for drought monitoring and early warning systems (Alharbi et al., 2022; Gu et al., 2008). The NDWI typically ranges from -1 to $+1$ (McFEETERS, 1996; Wang et al., 2008). Lower values are generally associated with bare soil or built-up areas, indicating non-vegetated or low-moisture surfaces, whereas higher values correspond to water-rich vegetation or open water bodies. Following data processing, NDWI values for the Rangpur Division were found to range between -0.53 and 0.13 , reflecting spatial variability from extremely dry or non-vegetated surfaces to areas with limited surface moisture (Fig. 7).

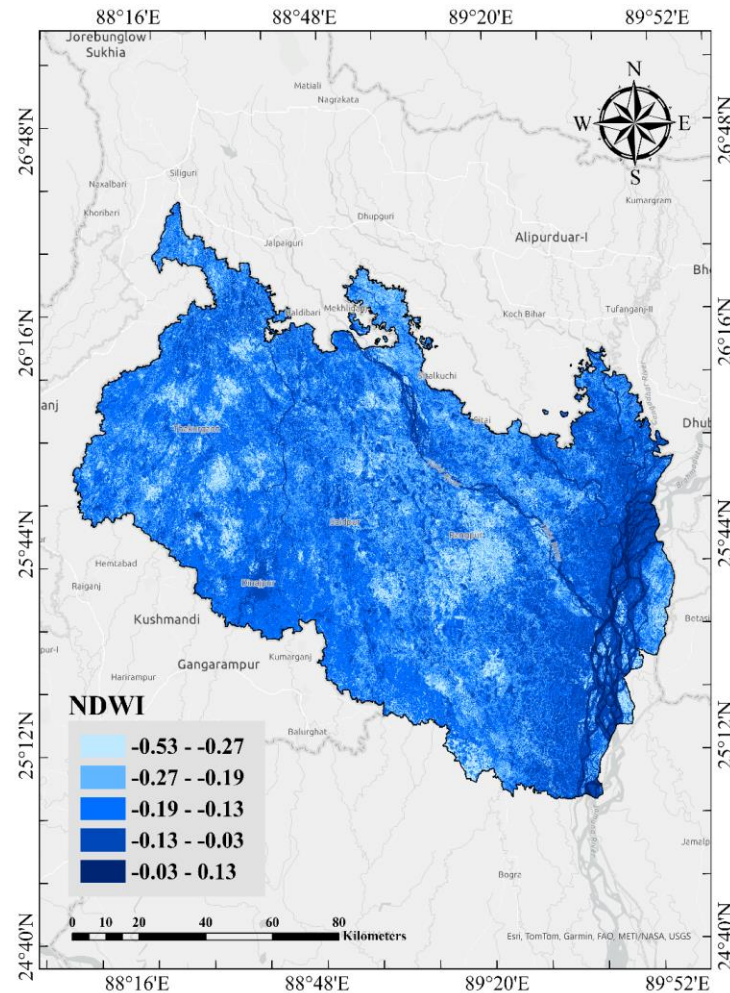


Figure 7: *Spatial distribution of the Normalised Difference Water Index (NDWI) across the Rangpur Division, Bangladesh.*

4.1.6 NDDI

The Normalised Difference Drought Index (NDDI) is a powerful and sensitive tool used to detect drought conditions by combining two important vegetation and water indicators. Initially developed by (Gu et al., 2007), the NDDI integrates the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI), providing a comprehensive picture of both vegetation health and water availability in a given area (Artikanur et al., 2022) (Table: 5). NDVI measures vegetation vigour by analysing the difference between visible red and near-infrared spectral bands, reflecting how much chlorophyll is absorbed by plants versus how much light is reflected, essentially giving insights into plant health and density (Alharbi et al., 2022). In the context of the Rangpur Division, processed data showed NDDI values ranging dramatically, from $-13,321.29$ to $13,196.85$ (Fig. 8). This wide variability highlights the significant spatial differences in drought intensity and vegetation stress throughout the region. Such large fluctuations emphasise how some zones face extreme drought conditions while others maintain relatively stable water and vegetation status. Through this index, researchers can better understand local drought patterns and help inform targeted water management and agricultural practices, boosting resilience against prolonged water shortages. Overall, the NDDI serves as an insightful environmental indicator, capable of guiding decision-makers in identifying drought-prone areas and deploying timely mitigation strategies to protect ecosystems and communities alike.

4.2 Geospatial distribution of drought vulnerability

The examination of how vulnerable the study region is to drought indicates that a large part of it, roughly 29.96% of the total land area, is at high risk (Table 6). This clearly shows that the area is quite likely to experience drought across a wide range of weather circumstances. The no-drought zone, on the other hand, only covers 3.79% of the land, largely near riverbanks (Table 6) (Fig. 9a). These areas, especially those connected to perennial rivers like the Brahmaputra, tend to remain unaffected by drought. However, rivers such as the Teesta, whose natural flow has been severely disrupted by upstream dam construction in India, face much higher drought susceptibility. Altogether moderate to very high drought vulnerability zones make up nearly three-fourths (76.92%) of the entire region, highlighting the widespread nature of the problem (Fig. 9a). Beyond the risk of drought itself, the area also faces several other challenges: increasing soil dryness, falling groundwater levels, decreasing rainfall, and disrupted river flow due to upstream water management practices. Despite being located near both the Himalayan and tropical rainfall zones, this region has become surprisingly more drought-prone than many other parts of Bangladesh. At the district level, Dinajpur ranks as the most drought-affected district, with $3,445.80 \text{ km}^2$ (83.67%) of its area classified under moderate to very high vulnerability. Rangpur follows with $2,343.42 \text{ km}^2$, or about 67.49% of its area affected (Table 7) (Fig. 9b).

Although Panchagarh is a smaller district, it is proportionally the hardest hit about 86.98% of its land falling within these high-risk categories. Other districts also show significant vulnerability: Thakurgaon (79.91%), Nilphamari (77.55%), Gaibandha (74.31%), Kurigram (73.78%), Lalmonirhat (70.16%), and Rangpur (67.49%) (Table 7) (Fig. 9b).

To combat this growing crisis, the government has implemented the Teesta Barrage Project, which supports both agriculture and domestic water needs. While the barrage helps manage excess water during the monsoon, long-term resilience will require integrating nature-based solutions (NBS) into drought management. Approaches like ecosystem-based adaptation (EBA) and blue infrastructure can strengthen the region's ability to withstand future droughts. Promoting Climate-Smart Agriculture (CSA), such as rain-fed farming, contour trenching for soil restoration, and reforestation along riverbanks, can also reduce land degradation, restore ecological balance, and support both environmental and economic sustainability across the region.

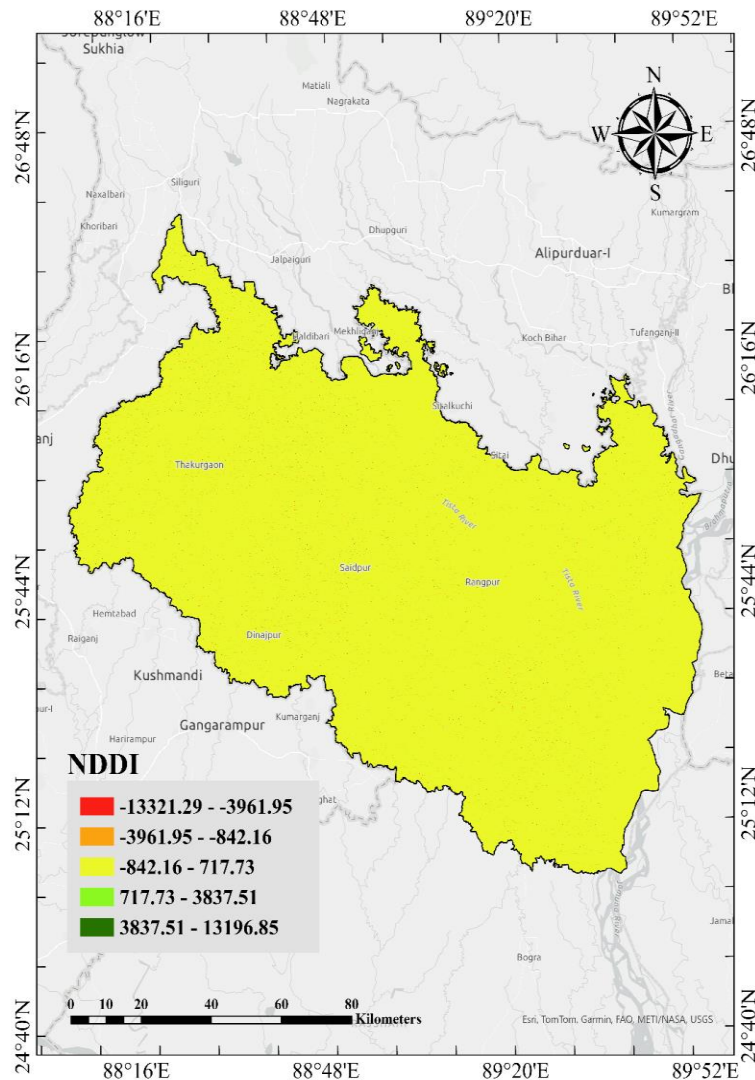


Figure 8: Spatial distribution of the Normalised Difference Drought Index (NDDI) across the Rangpur Division, Bangladesh.

Table 6: Spatial distribution of study area (in Km²)

Category	Vulnerability Area	
	Area (km ²)	%
Very Low	613.3122	3.796599
Low	3114.339	19.27875
Moderate	4288.561	26.54756
High	4839.936	29.96075
Very High	3298.106	20.41633

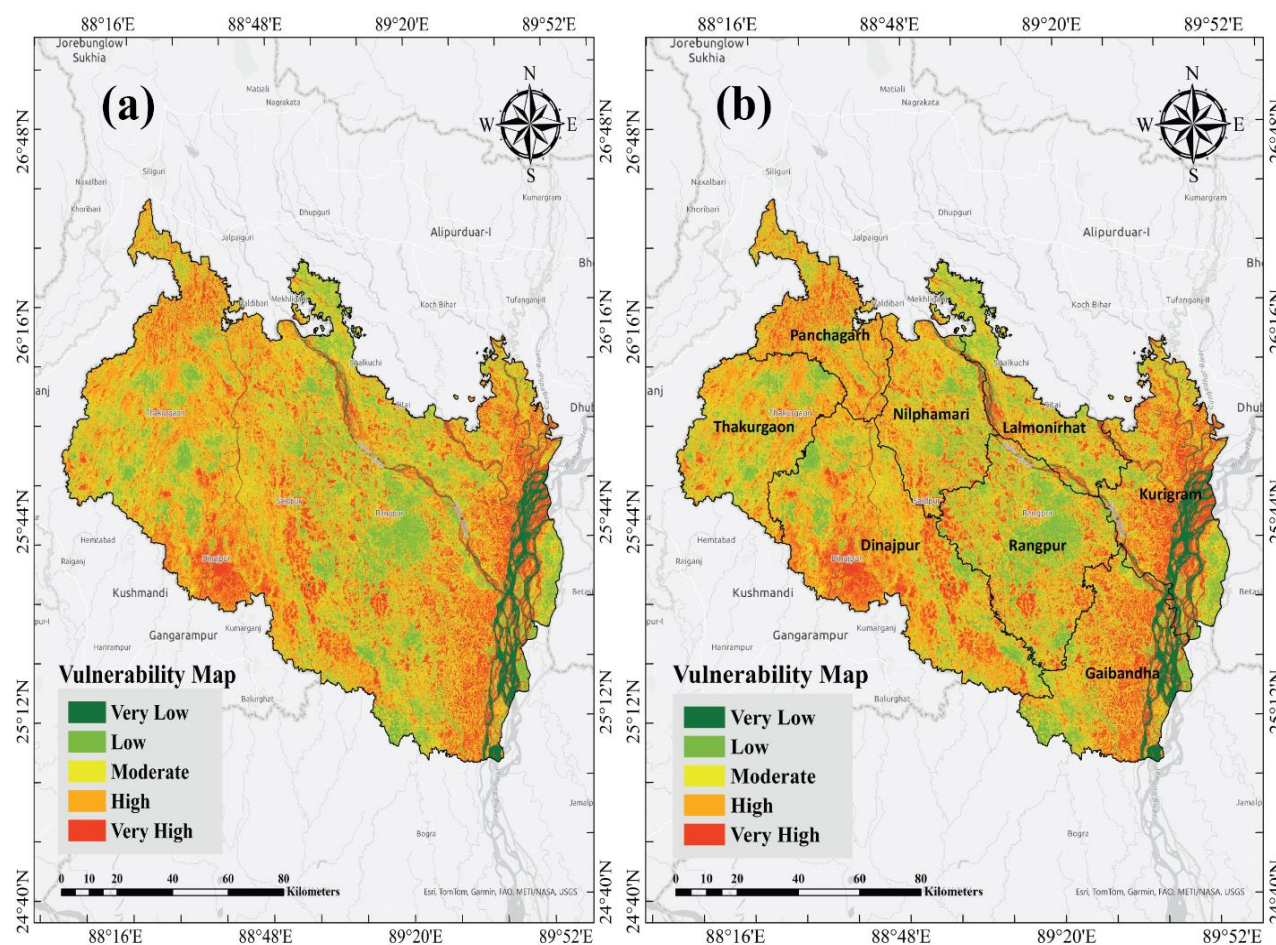


Figure. 9: *Spatial distribution of Drought vulnerability zones in the Rangpur Division: (a) Overall vulnerability map and (b) District-wise vulnerability delineation showing varying degrees of Drought susceptibility from very low to very high.*

Table 7: Spatial distribution of the study area (in km²) district-wise.

District	Category	Area (Km ²)	%	District	Category	Area (Km ²)	%
Dinajpur	Very Low	21.24	0.62	Nilphamari	Very Low	14.65	0.93
	Low	541.31	15.71		Low	340.42	21.52
	Moderate	796.57	23.12		Moderate	485.25	30.68
	High	1359.81	39.46		High	491.86	31.10
	Very High	726.89	21.09		Very High	249.61	15.78
Gaibandha	Very Low	217.58	10.09	Panchagarh	Very Low	8.38	0.62
	Low	336.55	15.60		Low	167.09	12.40
	Moderate	510.47	23.66		Moderate	356.82	26.47
	High	498.63	23.12		High	499.14	37.03
	Very High	593.93	27.53		Very High	316.38	23.47
Kurigram	Very Low	307.18	13.73	Rangpur	Very Low	16.17	0.69
	Low	279.54	12.49		Low	745.67	31.82
	Moderate	482.99	21.58		Moderate	668.01	28.51
	High	469.42	20.98		High	555.88	23.72
	Very High	698.81	31.23		Very High	357.70	15.26
Lalmonirhat	Very Low	25.61	2.06	Thakurgaon	Very Low	2.51	0.14
	Low	345.20	27.77		Low	358.56	19.95
	Moderate	433.35	34.87		Moderate	555.11	30.88
	High	270.72	21.78		High	694.47	38.64
	Very High	167.99	13.52		Very High	186.79	10.39

5. Conclusion

This study was conducted to assess drought risk in the Rangpur Division using a multi-parameter approach integrated through the Analytic Hierarchy Process (AHP). The findings indicate that approximately 77% of the study area is affected by drought, highlighting a significant level of environmental vulnerability. The primary factors contributing to this risk include low vegetation cover, moderate elevation, and steep slopes. Although the present study applied a selected set of parameters, the methodology can be extended to other regions by incorporating high-resolution datasets and social sensitivity indicators to better capture the multi-dimensional impacts of drought. Moreover, the inclusion of vulnerability analysis encompassing socio-economic and cultural dimensions is essential for a holistic risk assessment, as community susceptibility plays a vital role in shaping drought outcomes. To ensure long-term resilience, a strategic adaptation

framework is necessary to enhance the region's adaptive capacity and improve its economic sustainability. Despite the implementation of several scientific and technological interventions, drought remains a persistent challenge. Therefore, adopting nature-based solutions (NBS) such as ecosystem-based approaches (EBA) and blue infrastructure could offer a robust, climate-resilient pathway for drought risk reduction. Gaining a deep understanding of how climate change, population growth, and land-use changes are shaping ecological systems is essential for effective and sustainable drought planning. This study highlights the urgency for robust policy interventions and the need to weave nature-based solutions into the fabric of densely populated areas where the risk of hydrological disasters is greatest. By focusing on these approaches, communities can both adapt to changing conditions and actively reduce the likelihood and severity of droughts across the basin. Integrating strategies like restoring wetlands, planting trees along embankments, adopting conservation agriculture and implementing urban green infrastructure are proven ways to strengthen resilience against drought and water shortages. The research supports the creation of scientifically grounded guidelines for future artificial groundwater recharge zones, key to maintaining reliable water supplies. With this knowledge, policymakers and planners are better equipped to champion sustainable water management practices and foster long-term drought resilience for both people and ecosystems throughout the region.

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Paper 6

Pathways from East Asian Experiences of China-South Korea-Japan: Promoting Climate Awareness via Climate Literacy in Bangladesh

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Abstract

Bangladesh is internationally acknowledged as one of the most climate-sensitive nations, with frequent floods, cyclones, saltwater contamination, and heat waves. Notwithstanding such risks, a considerable disparity persists between climate knowledge and ongoing adaptation efforts for climate change. Climate literacy, which includes knowledge, skills, ethics, and civic involvement, has become a crucial tool to address this disparity. Although Bangladesh has included climate change-related subjects in national policies and curriculum, efforts are nonetheless dispersed, poorly institutionalised, and inadequately monitored and implemented. In contrast, East Asia's dominant trio, the CKJ - China, Korea, and Japan, as three of the most influential economies with robust education systems, provide enriched and insightful examples of integrating climate literacy through curriculum reform, pedagogical development, public media collaborations, and community involvement. This research aims to achieve three objectives: first, to analyse CKJ policy strategies implied for expanding the climate literacy and identify adaptable practices; second, to assess the present conditions and limitations of climate literacy initiatives in Bangladesh; and third, to propose context-specific strategies for enhancing climate awareness and action in Bangladesh. This research synthesises key pathways using a comparative policy-transfer methodology, guided by the Knowledge-to-Action (K2A) framework. The results indicate that the CKJ experiences may guide a more systematic and structured approach to establishing climate literacy in Bangladesh. Therefore, this research enhances the field of climate education and provides practical recommendations for policymakers aiming to convert knowledge into resilience-enhancing actions in at-risk environments.

1. Introduction

Bangladesh is internationally identified as one of the most climate-sensitive countries, with frequent floods, cyclones, saltwater intrusion, heatwaves, and other severe climatic events that endanger financial stability, food security, well-being, and infrastructure. In 2024, 33 million children in Bangladesh faced educational interruption owing to climatic extremes, including heatwaves and floods (UNICEF, 2025). Additionally, in the year 2024, economic losses due to increasing temperatures totalled US\$1.78 billion (Paul, 2025).

Notwithstanding these significant climate change impacts, Bangladesh demonstrates a disparity between public climate awareness and effective adaptation measures. Although most people recognise climate change, few have the climate literacy to translate knowledge into significant action. A youth survey revealed that over 50 percent of participants were unable to sufficiently articulate climate change, despite 77 percent stating it was included in educational curricula; 70 percent voiced concern regarding future impacts, although many felt reluctant to take any action (UNICEF, 2021). In a nationwide assessment, even though 93 percent of secondary students were able to identify the effects of climate change, just 3 percent of eighth graders were able to articulate a reply to a series of basic climate change questions (Rommo, 2024). The statistics indicate a significant gap in climate literacy; although knowledge is up in theory, comprehension, expertise, ethical behaviour, and civic participation are notably lacking.

In order to overcome this imbalance, climate literacy, which includes knowledge, expertise, knowledge of ethical behaviour, and community engagement, is becoming more widely acknowledged as a key component that empowers communities to take measures that increase resilience. One of the main avenues for institutionalising climate awareness on a large scale is by incorporating climate literacy into formal education institutions. Yet, Bangladesh's efforts in this field continue to be dispersed, insufficiently structured, and unsupervised.

Conversely, the triad of East Asia - China, South Korea, and Japan (CKJ), provides insightful instances of how to more efficiently create more public awareness on climate change via expanding climate literacy and sustainability learning. These nations have been making significant efforts, such as revising school curriculum, establishing pedagogical assistance programs, forging media collaborations, and fostering community-level climate initiatives. Gaining an understanding of how these countries have enhanced climate literacy will provide Bangladesh with insights for developing a locally relevant, meaningful, and effective national policy framework to boost climate literacy.

Therefore, this study investigates how Bangladesh's efforts to promote climate awareness via climate literacy expansion may benefit from the experiences of East Asian forerunners of this field, the CKJ. The primary goal is to ascertain feasible policy avenues for converting climate knowledge into tangible actions for community resilience. This study, informed by the *Knowledge-to-Action (K2A)* framework, aims to accomplish three interconnected objectives:

- To examine the CKJ policy solutions that have effectively included climate literacy into national education frameworks, public discourse, and community involvement. This includes analysing curricular revisions, pedagogic methods, and multisectoral cooperation that foster climate-aware behaviour.
- To analyse the present condition of climate literacy in Bangladesh, pinpointing institutional downsides, operational barriers, and sociocultural impediments that obstruct the diffusion of climate literacy and the changing of behaviour.
- Lastly, to provide context-specific transferable policy recommendations for Bangladesh based on evidence-based insights derived from the CKJ experiences. This involves suggesting approaches that correspond with Bangladesh's socio-economic landscape and policy framework using the K2A model.

These objectives collectively aim to connect knowledge with practice, directing policymakers towards evidence-based reforms that improve climate literacy, awareness, and adaptive ability in one of the most climate-vulnerable countries globally.

2. Literature Review

2.1. Understanding Climate Literacy: Going Beyond Just Acquiring Knowledge

The concept of climate literacy has recently been reframed as a multi-faceted framework that encompasses the understanding, mitigation, adaptation, and civic involvement of climate change (Reis & Ballinger, 2018). Ethical thinking, compassion, and collaborative action are all part of it, in addition to a scientific understanding of atmospheric dynamics. A person is considered climate-literate by the United States (US) National Oceanic and Atmospheric Administration (NOAA) if they are able to make informed decisions based on their knowledge of the Earth's climate system (NOAA, 2009). What Mochizuki and Bryan (2015) call the “mind, heart, and actions” approach has been gaining ground as a means by which climate literacy may facilitate transformational learning that unites the rational and emotional aspects of human experience. Besides, the threefold paradigm of knowledge, emotions, and conduct has grown in importance in the field of education. Support for climate policy was more strongly predicted by views of human responsibility and causality than by awareness of the facts alone. Learning that is both emotionally anchored and interactive promotes long-term improvements in behaviour (Reid, 2019). According to *Transformational Learning Theory* (Fleming, 2018), these results are in line with the idea that changes in perspective and action may be achieved via active participation and introspection. According to Bhattacharya et al. (2020), climate literacy is crucial for sustainable transitions and should be seen as more than just an educational objective. There is a rising corpus of academic opinion that says students need to be actively involved in climate change adaptation via their roles as knowledge creators, ethical agents, and community catalysts.

2.2. Education as a Climate Action Tool

The development of adaptation and mitigation strategies to withstand climate change is a critical function of education. Learning more about climate change and taking action to mitigate it are two of the primary tenets of *Sustainable Development Goal (SDG) 13.3* and the *Paris Agreement* (UNFCCC, 2016). Education, according to empirical research (Anderson, 2012), increases the perception of risk, improves environmentally conscious behaviour, and fortifies public support for climate policy. Various pedagogical methods are being used by educational institutions worldwide to include climate literacy. New Zealand's '*Education for Sustainability*' curriculum incorporates action competence and local adaptation, whereas Finland incorporates sustainability topics throughout science, geography, and civics (Sinakou et al., 2019). According to Jiménez et al. (2015), the '*Environmental Education Strategy 2017–2030*' in Costa Rica exemplifies integration via community collaborations and experiential learning. Despite the existence of policy frameworks, improvements in curriculum and teacher preparation have lagged, according to worldwide data. Scholars contend that the following features are common to effective climate schooling systems: first, congruence with national sustainability objectives; second, empowering educators via professional development networks; and lastly, curriculum consistency across subject matter and grades (Ardoín et al., 2019). Below, the study examines certain East Asian models that exhibit these characteristics, with education serving as a civic and cognitive tool for climate adaptation.

2.3. East Asian Insights: The CKJ Triad

In China, environmental ethics and socialist modernisation are intertwined via the larger '*Ecological Civilisation*' plan, which includes climate literacy programs. The National Curriculum Standards have included sustainability themes since 2003, and modifications that followed were in line with carbon neutrality goals. As a result, environmental education has been institutionalised from elementary school all the way up to college. Students who took part in environmental initiatives had more positive views about the environment and more confidence in their own abilities to make a difference, according to empirical research (Li et al., 2024). Despite this, there are still gaps between rural and urban areas, and equal results are hindered by resource constraints and uneven teacher preparation (Fu & Hashim, 2024). While China's experience shows that climate literacy can be scaled via state-led cooperation and consistent policies, it also highlights the need for contextual flexibility and local adaptation.

According to Lee (2025), the *Third Master Plan for Environmental Education (2020-2030)* advocates for carbon-neutral school models, student engagement in projects, and inquiry-based learning. According to studies conducted in South Korea, 'learning communities' and 'eco-school networks' have a beneficial effect on both student agency and educator professional development (M. Lee & Kim, 2016; S. Lee & Kim, 2017). Although Korea's dedication to aiding educators is consistent with the Education for Sustainable Development (ESD) for the

2030 Roadmap of UNESCO, there are still obstacles to overcome; for example, many educators want more organised training in climate pedagogy despite these successes.

An institutionalised structure that connects schools, communities, and local governments has emerged from Japan's environmental education, known as *kankyō kyōiku* (Glackin & Greer, 2021). The robust Education for Sustainable Development (ESD) framework in Japan has contributed to the improvement of climate literacy. This framework incorporates climate change education within the National Curriculum Standards, as stated by Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2020. Education that promotes '*thinking globally and doing locally*' via behavioural reform and environmentally friendly habits is advocated for in the Second ESD Implementation Plan (2021), which recognises climate change as a key concern. But as Glackin and Greer (2021) point out, climate change and pollution are often presented as facts in science and social studies classes without any critical thinking, student participation, or focus on taking action components. As a consequence, climate literacy has become more focused on abstract concepts and abstract ideas rather than on practical applications and citizen participation in decision-making. Although Japan's ESD regulations have a solid institutional groundwork, the key to attaining significant sustainability learning results is to promote climate education that is both transformational and community-linked.

2.4. Climate Literacy in the Global South: The Case of Bangladesh

Floods, cyclones, and heatwaves strike Bangladesh often, affecting both lives and education. The country is ranked among the most climate-vulnerable countries. But there is still a lack of severe conceptual and behavioural climate literacy, even though it is well known. Higher levels of engagement and resilience are produced by community-based, immersive, and locally-focused learning methods, according to the literature (Hossain et al., 2025). Still, these programs are not part of the national policy framework; they are more of pilot projects run by NGOs. To turn climate knowledge into long-term civic action in Bangladesh, a comprehensive strategy is necessary, modelling it after the organised institutionalisation in CKJ.

Climate education is getting a lot of attention, but there is still a lack of study on how to institutionalise climate literacy in low- and middle-income countries like Bangladesh. On the other hand, China, South Korea, and Japan provide a special case study on the relevant policy frameworks because they have integrated climate literacy into their national education systems through well-thought-out policymaking, revised curricula, and the professionalisation of educators, all while sustaining fast economic development and technological advancement. The policy frameworks and pedagogical innovations from East Asian models might be adapted to Bangladesh's unique institutional context; however, there have been few such comparative studies of these models. The study's originality, therefore, lies in its goal of filling this research gap by comparing the policy frameworks utilised for successfully implementing climate literacy in CKJ and assessing the workable policies that Bangladesh could implement based on the CKJ triad's experience.

3. Research Framework (K2A-Informed)

An actionable and scalable climate-literacy policy framework for Bangladesh has been developed by this study using an adapted K2A framework, which draws on comparative data from CKJ. Policy data gathered via document analysis and thorough threefold policy analysis, as detailed in the study's methodology section, formed the basis for the construction of this research framework. The three interconnected phases of this K2A framework: *Research, Translation, and Institutionalisation*, form a structured and logical model that helps in the generation, interpretation, and incorporation of comparative ideas and local evidence into long-term policy and practice.

- 1. Research Phase:** This phase utilises three more sub-components: discovery, efficiency, and effectiveness. This provides context-specific evidence on CKJ techniques and the baseline level of climate literacy in Bangladesh.
- 2. Translation Phase:** This phase emphasises transforming research results into practical policy instruments and facilitating their adoption via strategic distribution and stakeholder involvement.
- 3. Institutionalisation Phase:** This phase aims to integrate the practice of climate action by institutionalising climate literacy into Bangladesh's education policy, teacher development, and monitoring mechanisms to guarantee long-term sustainability.

Table 1: Knowledge-to-Action Framework (K2A) (created by the authors based on the original framework of the Centres for Disease Control and Prevention, 2014)

Phase	Component	Purpose
<i>Research Phase</i>	Discovery	A systematic mapping of existing policies in CKJ, resulting in a comparative evidence map relevant to Bangladesh.
	Efficacy	Identifies transferable policies from CKJ tailored to the educational context and resource circumstances of Bangladesh.
	Effectiveness	Pilot interventions to be implemented in certain schools to evaluate adoption and immediate results. Results contribute to iterative assessment using indicators for knowledge, skills, attitudes, and civic participation.

<i>Translation Phase</i>	Knowledge to Products	Research findings are transformed into practical outputs, including a curriculum learning-outcome matrix, instructional guides, experiential kits, a monitoring and evaluation framework, and policy briefs.
	Dissemination for Engagement	Key stakeholders, such as the Ministry of Education (MoE), National Curriculum and Textbook Board (NCTB), teacher training institutions, non-governmental organisations, and development partners, are to be involved via policy discussions, seminars, webinars, and media outreach to enhance tools and foster ownership.
	Decision to Adopt	Feasibility briefings assist decision-makers in scaling the policy initiatives.
<i>Institutionalisation Phase</i>	Practice	Initial endeavours concentrate on creating and initiating the pilot projects of the policies, while recording beneficial practices and local modifications.
	Institutionalisation	In conjunction with the MoE and the Ministry of Environment, Forest and Climate Change (MoEFCC), this phase formalises the finalised policies and integrates them into the national education system.

4. Research Method

A rigorous document analysis is conducted to gather evidence for CKJ and Bangladesh policies. Then, three complementary policy-analysis approaches, *Traditional*, *Mainstream*, and *Interpretive*, have been adopted from Browne et al. (2018). Each is operationalised with particular approaches and analytical procedures to answer the research objectives of the study. The study can capture the dynamics of technical feasibility, political stakeholders, and the framing that influences acceptability by using numerous orientations.

4.1. Document Analysis

Using document analysis, this research delves into the evolution of climate literacy policies and strategies in Bangladesh and the CKJ. The method places an emphasis on constructing meaning and interpreting it in context. It provides the empirical foundation for knowledge development, translation, and institutionalisation, making it important to the K2A framework. Using NVivo

and inductive theme analysis, the documents were analysed and coded. The coding revealed common themes related to multisectoral initiatives, capacity development, pedagogy, community capacity building, and curriculum adjustments.

4.2. Policy Analysis

To complement the document analysis, this study applies three interrelated policy-analysis approaches to capture the technical, institutional, and discursive dimensions of climate literacy policymaking in Bangladesh. Together, these approaches ensure analytical depth, linking evidence generation with the core of the K2A research framework.

A. Traditional Analysis Approach: Problems and Feasibility

The traditional policy mapping approach identifies the policy initiatives implemented in the CKJ that are relevant to problems of the study, such as curricular integration, teacher professional development cascades, and green school incentive programs. Each alternative policy initiative has been carefully evaluated using a problem-solution analysis, resource estimation, cost-effectiveness analysis, and a risk and implementation assessment, which ultimately highlighted operational obstacles or feasibility for each chosen policy from the CKJ's adopted policies. This technique effectively identified the most technically viable and culturally appropriate, cost-effective policy choices for incorporating climate literacy into Bangladesh's education institutions.

B. Mainstream Analysis: Actors and Networks

This approach facilitated thorough stakeholder mapping, which identified key institutions, including pertinent ministries, directorates, NGOs, CSOs, INGOs, teacher unions, and donors, while examining their responsibilities, interests, and authority. The network analysis subsequently facilitated the identification of important actors in the field and their impact paths.

C. Interpretive Analysis Approach: Framing and Adaptable Discourse

The interpretive policy analysis approach helped to identify the omissions and silences, indicating which facets of the issue remain unexamined and if any of the existing initiatives are being resistant rather than promotive. It outlines conflicting narratives, such as economic expenditure vs developmental capacities or theoretical focus vs practical skills, to pinpoint easily adaptable discursive mechanisms for strategic reframing. This method investigates the framing of climate education across policy, media, and institutional discourse, and how these narratives influence reform results while bypassing resistive framings. This is essential for successful translation and institutionalisation.

Table 2: Data Material Types and Sources for the Document Analysis (created by the authors based on the analysis)

Date Material Type	Data Source
<i>Policy Materials</i>	National environmental and education policy documents, education and climate directives, relevant government policy projects reports, national curriculum frameworks, and related sector plans of all four countries.
<i>Institutional Materials</i>	Teacher-training manuals, curriculum modules, school program reports, and NGO, INGO, OECD & WB pilot evaluations report on the countries.
<i>Discursive Materials</i>	Media coverage, parliamentary statements, and press releases shape the public narrative of climate literacy in each country.

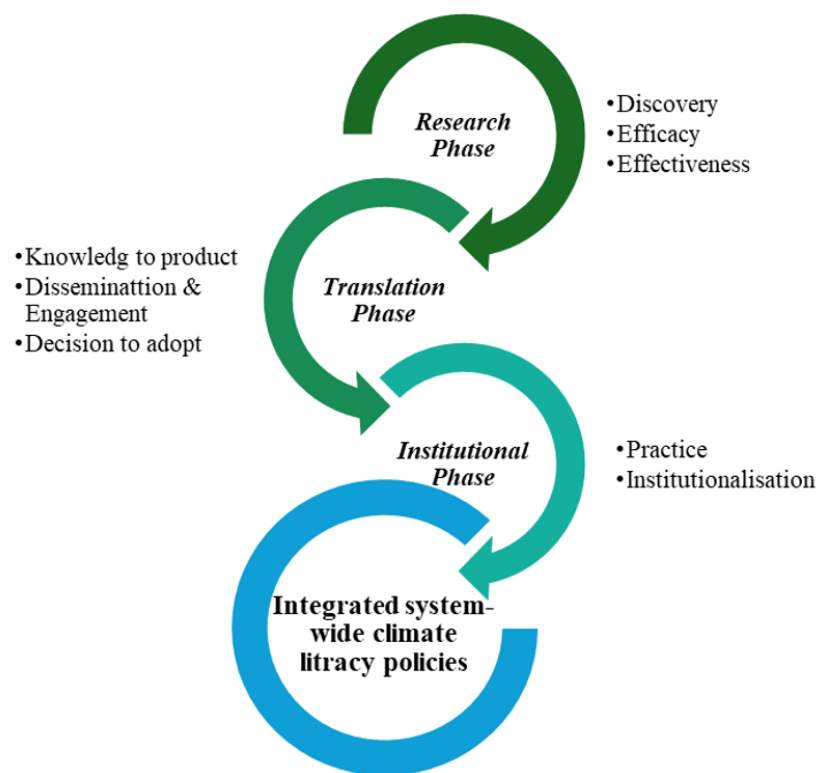


Figure 1: Knowledge-to-Action (K2A) Framework to Build Up Integrated System-Side Climate Literacy Policies (created by the authors based on the original framework of the Centres for Disease Control and Prevention, 2014)

5. Results

5.1. Comparative Insights from CKJ: Policy and Strategy Findings

China
<i>Environmental Education Implementation Guideline (2003)</i>
The guideline mandates the incorporation of environmental education in elementary and secondary schools, urging institutions to impart not only information but also attitudes and behaviours conducive to sustainability. This created a foundational, systemic framework for climate and environmental teaching in educational institutions.
<i>Curriculum and Textbook Reform (2020)</i>
The Geography Curriculum Standard for Compulsory Education and the Biology Curriculum Standard have been revised (2017/2020) to include ideas such as ‘ <i>human-land cooperation</i> ,’ sustainable development, and ecological civilisation. Geography textbooks include interaction between humans and the environment and environmental conservation, while biology courses highlight reverence for nature and conservation.
<i>Higher Education Carbon-Neutral Science & Technology Action Plan (2021)</i>
It is a strategic initiative aimed at engaging universities in the advancement of research, innovation, and education about carbon-reduction technologies, while integrating carbon-neutral research into campus research and development and curriculum. This enhances climate knowledge among STEM students and researchers.
<i>Ecological Civilisation Education Action Plan (2021)</i>
It is a collaborative initiative between the Ministry of Ecology and Environment (MEE) and the MoE in China, which incorporates ecological civilisation education into the national curriculum. It requires educational programs for schools, kindergartens, and colleges that foster understanding of ecological principles, environmental legislation, and sustainable lifestyles, engaging families, communities, and governmental entities. The ecological civilisation action plan encompasses public and community-oriented education, volunteer initiatives, and environmental awareness campaigns to include all societal sectors.
<i>‘Green & Low-Carbon’ National Education System Plan (2022)</i>

It is a MoE policy that incorporates green and low-carbon principles across kindergarten, basic, vocational, and higher education, requires teacher training on ecological civilisation and carbon objectives, and advocates for the implementation of green curriculum and activities at the school level by 2025.

Multilateral & NGO Partnerships

China engages in multilateral and NGO partnerships, including pilot projects with UNESCO, UNU, and civil society networks. These collaborations involve hosting UNESCO/UN initiatives, such as ESD and carbon-neutrality pilot projects. Local NGOs and youth networks implement campus low-carbon pilot sites and student climate action programs, offering resources, teacher training, and community engagement models to effectively translate policy into classroom practice.

South Korea

Environmental Education Promotion Act (2008)

This Act requires the advancement of environmental education, including topics related to climate change, as a component of the overarching objective of sustainable development at both national and local levels. It establishes a legal foundation for integrating climate-related topics into educational curricula and teacher training programs. It facilitates access to environmental education for communities and fosters cooperation between educational institutions and local authorities. The Act facilitated the creation of a policy framework that integrates ‘eco-citizen’ competences, especially those related to climate change, into the educational plan.

Multi-Stakeholder/NGO Partnership: “Climate Scouts” Youth Programme (2019)

A private-corporate cooperation including *Aramco Korea* and the *NGO Coalition for Our Common Future* that educates university mentors to educate primary kids on climate change knowledge, behaviour, and comprehension. It shows the role of non-governmental entities in enhancing climate literacy via youth mentorship, intergenerational knowledge transmission, and the promotion of attitudinal transformation beyond mere information acquisition.

3rd Master Plan of Environmental Education (2020)

The South Korean government pledged to provide substantial funding for climate change education and communication under this strategy. It encompasses targeted initiatives: creating and distributing climate change educational resources aligned with the curriculum and facilitating climate-related activities for university students. The strategy integrates school culture and learning settings, such as eco-friendly schools and waste reduction initiatives, with climate literacy objectives.

Revised National Curriculum of Korea (2022)

The 2022 curriculum change for the ‘*Environment*’ topic (middle and high school) encompasses areas including Environmental Systems, Climate Crisis and Climate Action, Sustainability, and Civic Engagement. The instructional method employs a connect-explore-engage framework, integrating knowledge, attitude, and action components.

Regional/Local Policy Taskforce (2025)

The Ulsan office established a specialised task force to oversee climate and environmental education, provide instructional materials for local schools, and collaborate with community partners, such as local centres for climate crisis response.

Digital & Greening Education Project: “GOGO School Teachers’ Association - ‘Connecting the Dots: Data-Driven Carbon Literacy’

The project helped children use digital technologies to monitor power consumption, analyse trends, and cultivate behavioural and carbon literacy insights among over 200 children and 700 families. This effort utilises technology to enhance climate literacy by assisting students in connecting facts, everyday behaviours, and understanding of carbon emissions.

Japan

Basic Environment Plan & Basic Environmental Law

This law of Japan has specific provisions for environmental education and learning, both in formal and informal settings, promoting public engagement and enhanced educational resources.

Eco-School Programme

Since 1997, many Japanese ministries have partnered in the *Eco-School Programme*. The objective is to enhance the environmental sustainability of new and refurbished school buildings, incorporate environmental conservation into school operations, promote energy efficiency, and engage students in environmental design and conduct.

Capacity Building & Teacher Support

Japan's national policy, facilitated by the Ministry of Environment and MEXT, endorses environmental education through teacher training, the registration of environmental education specialists, interagency collaboration, and the distribution of outreach materials, thereby supporting both formal curricula and community educational initiatives.

Implementation Plan for Education for Sustainable Development (ESD)

This strategy, developed by the Liaison Conference on ESD (comprising 11 ministries/agencies), expressly aims to enhance the knowledge of children, students, and educators about environmental conservation and climate change issues. It underscores that the Japanese government would endeavour to include climate change in education via UNESCO schools and other educational institutions, while also connecting schools with their communities.

Research & Curriculum Development for Climate Literacy

Under the umbrella term of '*climate-literate person*,' a set of educational modules was created as part of a Japanese national research project called '*Curriculum development for climate literacy and international comparison of public perception on climate change*' (Grant-in-Aid for Scientific Research, 2013-2016). A study conducted in Japan's classrooms indicated that students exhibited improved strategic thinking and future-oriented decision-making about climate policy when presented with climate-action simulations at various educational levels.

5.2. Bangladesh's Climate Literacy Policy Landscape: Gaps and Constraints

- A. ***Broken Institutional Framework:*** Education Policy 2010, National Curriculum Framework 2022, and Bangladesh's Climate Change Strategy and Action Plan (BCCSAP) all show that climate education is acknowledged at the policy level, although there is minimal institutional interaction across ministries. Rather than working together, Education and Environment function independently. Development partners (such as UNICEF, BRAC, and UNESCO) have a significant role in implementation, leading to initiatives that are pilot-driven rather

than systematic. Within the Mainstream approach, actor mapping reveals that the NCTB and the MoE have the official authority, but there is a lack of cooperation with the local education offices. According to the document analysis, two persistent obstacles are the high rate of bureaucratic turnover and the small number of inter-ministerial committees.

- B. ***Curriculum and Pedagogical Issues:*** There was a consistent discrepancy between the goals of the curriculum and how it was implemented in the classroom, according to the traditional orientation policy study. Despite environmental themes being included in the 2022 curriculum, there is a dearth of pedagogical resources, practical training, and classroom time for teachers to use them. Instead of seeing climate literacy as an area of applied competence, it is more often seen as supplemental material. Document analysis further shows that research from teacher preparation programs and other pilot initiatives shows that just under 20 percent of educators have had training specifically on climate change. Many textbooks fail to include local adaptation techniques or civic duty, instead focusing on factual information such as definitions, causes, and consequences. Rather than being presented as an opportunity for transformational or participatory learning, interpretative discourse analysis revealed that climate education is mostly positioned as a '*disaster-awareness*' concern. Because of its limited scope, it cannot be effectively used in regular classrooms or citizenship programs.
- C. ***Student Knowledge and Behavioural Outcomes:*** While students do have a good general knowledge of climate change, their conceptual grasp is shallow, and they lack the behavioural agency to make meaningful changes, according to a thematic orientation of policy assessment reports and student questionnaires. Even while more than 80 percent of pupils in the studied schools understood the term '*climate change*,' only around 15 percent could relate it to local efforts to either adapt to or mitigate the effects of the phenomenon. Even while students were very worried about the effects of climate change (hot waves, floods), reports say that only 12 percent of students participated in any environmental events organised by their school. Female students exhibit more pro-environmental sentiments and empathy than their male counterparts, which may be related to their sense of communal duty in times of crisis. The ability to manage resources, adjust to local conditions, and actively participate in policymaking were all areas where both sexes were deficient in practical literacy.
- D. ***Capacity of Teachers and Institutions:*** As a major obstacle, educators' preparedness surfaced. A lot of teachers see climate change and related subjects as secondary or technical. Climate literacy courses are only offered by a small number of schools that prepare teachers. National frameworks for Continuous Professional Development (CPD) seldom include NGO-led workshops; instead, they tend to be one-off events. Many schools may not have the necessary green infrastructure, exhibit materials, or community relationships in place. Union Parishads and Upazila Disaster Committees, two local government entities, and schools did not work together very well, according to the report. Two essential components of successful

climate literacy, experiential learning and community participation, are hindered by this distance.

6. Policy-Transfer and Adaptable Pathways

The translation and institutionalisation phase signifies the final phase of this study, converting comparative evidence-based data from CKJ into implementable and context-sensitive policy frameworks for Bangladesh. This stage, based on the K2A paradigm, connects research results with institutional transformation by presenting a systematic approach for policy transfer, adaptation, and localisation tailored to Bangladesh's education and governance institutions.

6.1. Translating Evidence into Adaptable Policy Instruments

The six most feasible and applicable policy lessons from CKJ to close the institutional and pedagogical gaps in climate education in Bangladesh are as follows:

- A. *China's Ecological Civilisation Education Action Plan (2021)*:** This strategy exemplifies a comprehensive governmental paradigm in which the ministries of education and environment together execute climate education initiatives. In Bangladesh, this may be implemented by the MoE and the MoEFCC.
- B. *South Korea's Environmental Education Promotion Act (2008) and Third Master Plan (2020)*:** These policy frameworks formalise climate education via explicit requirements, financial support, and educator development. Bangladesh needs to implement a *Climate Literacy and Education Act*, mandating climate education as a legal obligation, accompanied by yearly national and subnational budget allocations for teacher training, curricular resources, and oversight.
- C. *Japan's Eco-School and Education for Sustainable Development Implementation Framework (1997-2021)*:** Japan's amalgamation of education, local administration, and community involvement offers a reproducible framework for Bangladesh's own green school-community partnership program. This program will enable local schools to partner with Union Parishads and Upazila Disaster Committees to implement practical adaptation projects, such as rainwater harvesting or garbage segregation, integrating classroom education with tangible climate solutions.
- D. *China's Plan for Green and Low-Carbon Education System (2022)*:** This approach integrates low-carbon principles across all educational tiers. Bangladesh may implement such a *Low-Carbon Campus Initiative*, including student-led initiatives focused on renewable energy, carbon assessments, and school-affiliated environmental groups. This would foster behavioural literacy and data-driven environmental accountability from a young age.
- E. *South Korea's "Climate Scouts" Youth Initiative (2019)*:** The Korean concept of youth mentoring and intergenerational learning may be adapted into Bangladesh's national youth

volunteer network formally by the government, linking students, universities, and community mentors. Executed via a partnership between the Department of Youth Development and the MoE, it would promote peer-led education, social innovation, and community participation in adaptation.

F. *Japan's Teacher Accreditation and Capacity-Building Scheme for ESD:* Bangladesh could implement a *Climate Education Certification Track* in teacher training institutes, inspired by Japan's Teacher Accreditation and Capacity-Building Scheme for ESD. Incorporating the CPD framework would guarantee uniform teaching excellence and institutional viability.

6.2. Pathways for Institutionalisation in Bangladesh

Three interconnected paths are proposed to transit from pilot efforts to systemic implementation:

- A. *Integrated Policy Framework:*** Establish a *National Climate Literacy Council* to oversee curriculum development, evaluation, and inter-ministerial cooperation. Incorporate climate literacy indicators into the Education Sector Plan to monitor progress.
- B. *Teacher and Institutional Enhancement:*** Integrate climate-based pedagogy into all teacher education curricula; establish an online climate resource repository overseen by NCTB; and promote climate innovation awards for educational institutions.
- C. *Community-Government Collaborations:*** Enhance vertical connections across educational institutions, municipal authorities, and NGOs via collaborative climate-action initiatives, bolstered by minor grants and public-private partnerships.

6.3. Contextual Customisation

Considering Bangladesh's budgetary and administrative limitations, implementation should use a gradual, decentralised, and flexible approach. Pilot initiatives in climate-sensitive coastal and floodplain regions may inform national scaling. Partnerships with NGOs and INGOs like BRAC, WB, UNDP, UNESCO, and UNICEF will facilitate local engagement, while digital technologies will enhance outreach to distant schools. The suggested six-policy model consolidates CKJ's institutional, legal, and community-driven frameworks into a cohesive system for Bangladesh. By legally requiring climate literacy, professionalising instructors, and incorporating local action, Bangladesh may unify disparate programs into a cohesive national climate literacy framework, thereby promoting resilience and sustainable development objectives.

7. Conclusion

This research has shown that fostering climate literacy is not just an educational objective but a strategic avenue for climate resilience and sustainable development in Bangladesh. The

comparative examination of CKJ demonstrated that successful climate literacy arises from cohesive institutional frameworks, robust legislative requirements, empowered educators, and community-oriented learning environments. Conversely, Bangladesh's disjointed institutional framework, inadequate pedagogical assistance, and reliance on project-based implementation impede systemic advancement. This study utilised the K2A framework to convert insights from CKJ into six flexible policy pathways, which encompass the formation of a National Climate Literacy Council, the enactment of a Climate Literacy and Education Act, and the incorporation of eco-school models, low-carbon campus initiatives, youth networks, and teacher certification systems. Collectively, these metrics provide a pragmatic framework for converting climate knowledge into actionable, contextually relevant teaching. The suggested policy transfer model emphasises the need for inter-ministerial cooperation, teacher professionalisation, and community-driven engagement to embed climate literacy inside Bangladesh's educational framework. By incorporating these methods into current frameworks instead of establishing rival systems, Bangladesh may transition from disjointed initiatives to a cohesive, nationally coordinated system. This study ultimately reconsiders climate education as a fundamental component of adaptive government, integrating knowledge, ethics, and civic duty. If effectively implemented, the routes outlined above may assist Bangladesh in developing a generation of knowledgeable, empowered, and resilient individuals capable of spearheading community-focused climate action in one of the world's most susceptible situations.

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Paper 7

Climate impacts on rural cultivation incomes in coastal Bangladesh: A Ricardian case study

Jeffrey Chow, Guang Yang

Abstract

Heavy reliance on cultivation renders the Bangladesh coastal zone highly vulnerable to climate change. These impacts include not only changes in temperature and precipitation regimes, but also greater flooding, tropical storm surges, and salinity intrusion. This study utilises a Ricardian approach to econometrically discern the impacts of climate change-related phenomena on net revenues of coastal agriculture and aquaculture. The lack of insight regarding adaptation strategies has been a frequent criticism of Ricardian analyses. Hence, this study follows a similar cross-sectional methodology to examine the differential effects of climate change-related phenomena on rural livelihood diversity. This study utilises data from the Household Income Expenditure Survey from 2000, 2005, and 2010. The study analyses regress cultivation income on climate variables while also testing the impacts of soil, flood risk, other geophysical variables, and household socioeconomic characteristics. In economically precarious areas such as coastal Bangladesh, households may experience either profits or losses for any given activity within a particular year. Thus, this study utilises alternate formulations of the Simpson's Livelihood Diversity Index (LDI) that include either gross revenues for all rural livelihood activities or net incomes from only profit-generating activities. Alternate LDI formulations are regressed onto the climate and other explanatory variables described above. Both agriculture and aquaculture profits are sensitive to climate conditions and to damage from excessive riverine flooding and storm surge inundation. High salinity and poor drainage are detrimental to farms, but aquaculture ponds are more resilient to salinity and benefit from poor drainage. Temperature and precipitation normals affect rural livelihood diversity even more so than cultivation incomes. Conclusions. Several climate normals significantly affect livelihood diversity but not cultivation profits, suggesting that conventional Ricardian analysis focused on land rents obscures adaptation by cultivators. Thus, climate change will impact rural cultivation decisions beyond the effects on profits alone.

1. Introduction

Socioeconomic, geographical, and climatic characteristics make Bangladesh one of the countries that are most sensitive to the damaging impacts of climate change (Huq et al., 2019). The country's underdevelopment, heavy reliance on agriculture, and exposure to extreme weather events make it particularly vulnerable. Due to sea-level rise and greater frequency of strong tropical storms, the coastal zone of Bangladesh is especially prone to inundation, salinity intrusion, storm surges, and rapid geomorphological changes (Chow et al., 2019). These climate impacts potentially threaten household livelihoods, infrastructure, and economic productivity in the coastal zone. This study uses the Ricardian approach to investigate the impact of climate change factors, some endemic to coastal areas, on agricultural and aquaculture productivity in the coastal zone of Bangladesh. In addition to climate normals for temperature and precipitation, this study investigates the impacts of salinity and inundation factors on both agriculture and aquaculture productivity.

2. Methodology

2.1. The Ricardian method

The Ricardian method uses cross-sectional data to econometrically analyze the determinants of agricultural productivity, embodied in the resultant farm net revenues (Mendelsohn et al., 1994). The farmer chooses crops or livestock and inputs for each unit of land to maximize net revenues, an optimization problem describable as:

$$\text{Max } \pi = \sum_i P_i Q_i(\mathbf{X}, \mathbf{C}, \mathbf{G}, \mathbf{S}, \mathbf{Z}) - \sum \mathbf{P}_x \mathbf{X} \quad (1)$$

where P_i is the market price of crop i , $Q_i(\dots)$ is a production function of crop i ; $\mathbf{X}$ is a vector of purchased inputs (other than land) such as seed, fertilizer and labor; $\mathbf{C}$ is a vector of climate variables; $\mathbf{G}$ is a vector of soil, flood risk, and other geophysical variables; $\mathbf{S}$ is a vector of characteristics that reduce exposure to inundation damage due to storm surge such as overland distances to coasts and rivers; $\mathbf{Z}$ is a vector of other control variables such as socioeconomic and demographic characteristics, and farm size; and $\mathbf{P}_x$ is a vector of input prices. .

Assuming the farmer chooses the crop or livestock and endogenous inputs $\mathbf{X}$ to maximize net revenues, the solution to Equation 1 suggests a reduced form model of net revenues as a function of just the exogenous variables:

$$\pi^* = f(P_i, \mathbf{P}_x, \mathbf{C}, \mathbf{G}, \mathbf{S}, \mathbf{Z}) \quad (2)$$

This study estimates the following log-linear econometric model, where for every farm j :

$$\ln \pi_j = \beta_0 + \beta_1 C_j + \beta_2 C_j^2 + \beta_3 G_j + \beta_4 Z_j + \beta_5 S_j + \varepsilon_j \quad (3)$$

β_0 is a scalar intercept term, β_1 to β_5 are horizontal vectors of parameters estimated by ordinary least squares regression, and ε_j is an error term. The productivity response to precipitation and temperature is nonlinear, so linear and quadratic terms for these two climate variables are typically used in Ricardian studies. Because farmers face similar agricultural input and output prices across the coastal areas evaluated in this study, insufficient variation prevents the measurement of their impact, and they are dropped from the model. Inundation risk and salinity characteristics in the vector $\mathbf{G}$ are derived from geophysical models of coastal Bangladesh. The vector $\mathbf{S}$ includes geophysical factors which reduce storm surge vulnerability—the distance from rivers and the distance from the coastline—which are generated using a geographic information system (GIS) in this study.

2.2. Data sources

This study looks at the households in the coastal divisions of Khulna, Barisal, and Chittagong, as well as several districts in the southern parts of Rajshahi and Dhaka divisions. Specifically, this study encompasses 37 districts considered coastal by the Institute of Water Modelling (IWM), a think tank established by the Government of Bangladesh (Figure 1). Districts are generally considered coastal if they are south of or directly adjacent to the Padma River. IWM is the source of the GIS shapefile identifying the geolocation of these districts, as well as the digital elevation model (DEM) used in this analysis.

The economic and socio-demographic data used to estimate the econometric model come from the Household Income and Expenditure Survey of Bangladesh, which follows a standard stratified random sampling procedure (Bangladesh Bureau of Statistics 2000, 2007, 2011). Net revenues for crops and aquaculture are calculated from reported revenues and production expenditures. The survey also includes cropland acreage, but the areas devoted to aquaculture are unknown. The HIES does not distinguish the type of aquaculture. This survey provides detailed data on assets, socioeconomic and demographic characteristics, production, and prices. This study utilizes household survey data from the 2000, 2005, and 2010 cropping seasons, considering each year in separate econometric analyses as well as in combined analyses.

Temperature and precipitation data are obtained from WorldClim (Hijmans et al. 2005), and include monthly climate normals (50-year averages) for each 30 arc-second grid in Bangladesh for 1950-2000. Monthly data is aggregated by season. Winter is December, January, and February, spring is March, April, and May, summer is June, July, and August, and fall is September, October, and November.

Coastal soil salinity data, produced in 2009, come from CEGIS and the Soil Resources Development Institute (SRDI). Other soil and ecological data come from the Bangladesh Agricultural Research Council (BARC, 2015). In the form of GIS shapefiles covering the entire country, these datasets include soil drainage, mineral composition, moisture, and texture. BARC also provides several ecological datasets that pertain to coastal inundation, such as agricultural

constraints, major flood types, and inundation zonation. An additional indicator of storm surge inundation risk—the maximum flood depth derived from cyclone events between 1960 and 2007—is drawn from an IWM study (Ahmad, 2009).

Households' locations are identified to the *mouza* (i.e., sub-county) by the HIES. Household economic and socio-demographic data are matched with climate, soil, ecological, and other geophysical data at the *mouza* level according to a GIS shapefile provided by the Arranayk Bangladesh Tropical Forest Conservation Foundation.

2.3. GIS and econometric model and variables

This study undertakes separate econometric analyses for agriculture for each study year of 2000, 2005, and 2010. Aquaculture profits are analyzed for the year 2010, but not for 2000 and 2005, due to an insufficient number of surveyed households performing aquaculture in the earlier surveys. However, this study also includes comprehensive econometric analyses, separately for agriculture and aquaculture, combining data from all three survey years and incorporating year fixed effects as independent variables. The dependent variable is either the natural log of agricultural profits per hectare or the natural log of aquaculture profits. Since the natural logs are undefined for negative values, households operating at a loss for a given year are dropped from the analyses. Removing these data points, 97 farming households and 19 aquaculture households, does not substantially change the makeup of the sample according to the independent variables utilized in this study. Summary statistics and descriptions for all dependent and independent variables are listed in Tables 1a to 1c.

Other socioeconomic and demographic variables from HIES, examined as potential explanatory variables, include the number of rooms and floor space in the family home, household size, the number of income earners, electrification, mobile phone ownership, classification as rural, literacy of the household head, presence of a male household head, incidence of chronic illness of the household head, age of the household head, and the total value of the household's assets. The household asset value includes the home, livestock, agricultural equipment, other real estate properties, and other assets such as stocks and jewelry. The natural log of total household asset value is used as a potential explanatory variable. Since the HIES does not include the same data across all three years, certain variables are tested in some analyses but not others. For example, the 2000 HIES does not include information on mobile phones. Also, only the 2010 HIES includes information on home floor space and on household-reported climate shocks, such as irregular precipitation, floods, and landslides/erosion. Hence, these variables are investigated only in the 2010 analyses.

All other climate, soil, and geophysical variables are matched to the household by *mouza*. The area-weighted means of scalar variables, such as temperature, precipitation, and distances, are calculated for each *mouza*. For categorical variables, including all soil and inundation variables, the mode is assigned to each *mouza*. Additionally, soils predominantly with a pH greater than

7.3 are considered alkaline. Since observations are necessarily correlated due to households within a particular *mouza* having identical values for these variables, errors in the econometric models are clustered by *mouza*. This study also reports employing standard errors to compensate for heteroscedasticity.

Several soil and geophysical characteristics are incorporated into the model in the form of mutually exclusive categories due to their original presentation by their respective sources. These include soil salinity, soil drainage, soil texture, soil minerals, soil moisture, main constraint on agricultural production, main flood type, inundation zonation, and storm surge inundation depth. Categories for each of these characteristics are transformed into indicator dummy variables for the econometric analyses. Path distances to the nearest river and distance to the coastline are calculated with the ArcGIS Path Distance tool, with the DEM utilized as the surface raster. Otherwise, the default settings are employed.

Due to the large number of potential explanatory variables, this study takes a two-step approach to generate a final set of econometric model specifications. In the first step, sets of variables (either categorical sets or thematic sets, e.g., socioeconomic and demographic variables, described in Tables 1a to 1d) are individually tested in models that include the full suite of climate variables. The second step produces a comprehensive model that retains the full suite of climate variables, as well as the geophysical, socioeconomic, and demographic variables with statistically significant coefficients.

3. Results

3.1. Econometric results: agriculture

Table 2 reports results from the econometric analyses for agriculture in 2000 for the model with the full suite of climate variables and all statistically significant geophysical, demographic, and socioeconomic variables. There is no evidence that coastal agricultural profits per hectare in 2000 are sensitive to temperature and precipitation normals, with no coefficients significant at the $p=0.05$ level for any of the climate variables. However, agricultural profits are sensitive to soil salinity, but the effects are nonlinear, with significantly negative coefficients for indicators of only moderately saline and strongly saline soils. Agricultural profits also vary significantly with distances from rivers, with farms further from rivers receiving greater net revenues. Among the demographic variables, household size is the only significant regressor and is positively correlated with higher profits. Cultivated land area is negatively correlated with agricultural profits per hectare, which would be expected since the two variables are endogenous. The negative correlation does suggest, however, that there are no economies of scale prevalent in coastal agriculture in Bangladesh. None of the variables related to inundation are significant for the year 2000 analyses, once the significant soil, geographic, demographic and socioeconomic variables are included in the model.

Table 3 displays results from the econometric analyses for agriculture in 2005. There is moderate evidence that coastal agriculture profits per hectare in 2005 are impacted by fall precipitation normals, increasing in a concave manner with additional rainfall. No other temperature or precipitation variable is significant for the 2005 analyses. The results also suggest that salinity negatively impacts agricultural profits. As in the 2000 analyses, the effect appears to be nonlinear. However, in 2005, farms with slightly saline soils had higher agricultural profits, and farms with strongly saline soils had lower agricultural profits. Soil drainage also appears to have non-linear impacts. Farms with soils classified as moderately well drained and poor to very poor drainage also have significantly lower profits. On the other hand, farms with clay soils have significantly greater profits. Among the socioeconomic and demographic variables, having a male household head is significantly correlated with higher agricultural profits. Total land cultivated is negatively correlated with profits per hectare, again suggesting that economies of scale generally do not apply to coastal agriculture.

Among the variables related to inundation, areas that suffer from severe river flooding, moderate tidal surge, or are within the risk area for 3m or more of storm surge inundation also yield significantly lower agricultural profits.

Unlike the results from 2000 and 2005, the econometric analyses for agriculture in 2010 strongly suggest that agricultural profits vary significantly with climate normals (Table 4). The results indicate that agricultural profits are sensitive to spring and summer temperature normals, increasing concavely with higher spring temperature and decreasing convexly with higher summer temperature. Agricultural profits also decrease convexly with greater spring precipitation. Profits increase concavely with fall precipitation, but the evidence is not as strong. Again, agricultural profits seem to have a nonlinear relationship with salinity, as moderately saline soils are associated with higher profits while very strongly saline soils are associated with lower profits. Imperfect to very poor drainage also corresponds to significantly lower profits. Clay and silty soils correspond to higher profits. Among the socioeconomic and demographic variables, rural farms have higher profits, but farms whose household heads have suffered chronic illness within the last year have lower profits. Households with literate household heads also have significantly lower farm profits. In 2010, the total household asset value was also significantly positively correlated with agricultural profits. Again, a negative correlation between agricultural profits and cultivated land area confirms the absence of economies of scale in coastal agriculture.

The 2010 analyses also strongly suggest that farms in areas vulnerable to severe flash flooding or in very lowland areas have significantly greater profits. Notably, areas within 150km of the landfall for cyclones Sidr or Aila did not yield significantly different agricultural revenues in 2010. However, households that reported actually suffering from floods and landslides or erosion in 2010 also experienced significantly lower agricultural profits.

Table 5 reports results from the comprehensive analyses for agriculture using all three years of HIES data. Using 2000 as the base year, the coefficients for year fixed effects are significant for both 2005 and 2010, suggesting that agricultural profits were on average approximately 30% greater in 2005 and 80% greater in 2010. These comprehensive analyses also strongly indicate that agricultural profits are sensitive to summer and winter temperature normals, decreasing convexly with higher temperatures. The comprehensive analyses also indicate that agricultural profits are sensitive to spring and fall precipitation normals, decreasing convexly with greater spring precipitation and increasing concavely with greater fall precipitation.

The results for soil characteristics in the comprehensive analyses are somewhat similar to the individual year results, but without the nonlinear outcomes. Farms on strongly saline soils and poorly to very poorly drained soils have significantly lower profits, while clay soils yield significantly greater profits. Among the socioeconomic variables, the comprehensive analyses indicate that households with more members or more assets also have higher farm profits. Negative coefficients associated with total land cultivated further confirm that coastal farms do not experience economies of scale.

The comprehensive analyses strongly suggest that areas with severe river flooding, areas with moderate tidal surge, or medium-lowland areas are significantly associated with poorer agricultural outcomes. In contrast, areas classified as lowland or very lowland have farms with significantly greater farm profits.

3.2. Econometric results: aquaculture

Table 6 displays results from the econometric analyses for aquaculture in 2010 for several model specifications. Aquaculture profits appear to be highly sensitive to climate normals, increasing concavely with higher winter temperatures, and decreasing convexly with higher summer and fall temperatures. Aquaculture profits decrease convexly with greater spring precipitation and increase concavely with greater summer precipitation. Among the soil variables, aquaculture profits are higher for areas with strongly to very strongly saline soils and for areas with poor drainage. Aquaculture profits also increase significantly with distance from rivers. Among the socioeconomic and demographic variables, aquaculture profits are positively correlated with the number of income earners and with electrification. No inundation variables are significant, except for the indicator for lowland areas, which have higher profits.

Table 7 presents select results from the comprehensive analyses for aquaculture using all three years of HIES data. Using 2000 as the base year, the coefficients for year fixed effects are significant for both 2005 and 2010, suggesting that agricultural profits were on average approximately 100% greater in 2005, as well as 90% greater in 2010. The comprehensive results

strongly suggest that aquaculture profits are sensitive to spring precipitation normals only, decreasing convexly with greater rainfall. These results also indicate that aquaculture profits have a nonlinear relationship with salinity, since slightly saline areas have lower profits, but moderately saline areas have higher profits than non-saline and strongly saline areas. Aquaculture profits also increase significantly with greater distance from rivers. Among the socioeconomic and demographic variables, only the number of rooms varies significantly with aquaculture profits, the households with more rooms having greater profits. Among the inundation variables, areas at risk of 1m or 3m of storm surge inundation also have significantly lower profits.

4. DISCUSSION

4.1 Climate effects

The econometric results provide strong evidence confirming that agricultural production is sensitive to seasonal climate. The effect of summer temperature and spring precipitation normals is most robustly supported by the data. Summer temperature and spring precipitation are significantly inversely correlated with agricultural profits in both the comprehensive analyses and the year 2010 analyses. Fall precipitation is significantly positively correlated with agricultural profits in the comprehensive analyses and the year 2005 analyses. Other climate effects on agriculture are moderately supported by the results. Spring temperatures are significantly positively correlated with farm profits, but only in the 2010 analyses. On the other hand, higher winter temperatures are associated with lower farm profits, but only in the comprehensive analyses. The results across years are not outright contradictory, with the differences in statistical significance likely due to omitted confounding variables that are not constant over time.

These results are consistent with the empirical literature concerning the impact of temperature on agricultural yields in Bangladesh. Time series regression modelling of aman rice production reveals that average growing season maximum and minimum temperatures are negatively correlated with yield (Sarker et al., 2012; Chowdhury and Khan, 2015). Hence, higher summer temperatures likely reduce agricultural profits by negatively impacting aman rice yields. On the other hand, time series analyses suggest that higher maximum growing season temperatures are correlated with greater aus rice yields (Sarker et al., 2012). Thus, higher spring temperatures may increase agricultural profits by enhancing aus rice productivity. Temperature has countervailing impacts on boro rice, with higher minimum temperatures enhancing yields while higher maximum temperatures reducing yields (Sarker et al., 2012; Sarker et al., 2014; Chowdhury and Khan, 2015). However, wheat varieties cultivated in Bangladesh are prone to heat stress as well as diseases, which increase in virulence with temperature (Hossain and

Teixeira da Silva, 2013). Therefore, a hotter winter climate may depress agricultural profits through its impact on wheat and possibly boro rice.

Similar time series regression modeling reveals that growing season rainfall is positively correlated with both aman and aus rice yields (Sarker, 2012; Chowdhury and Kahn 2015). However, when controlling for climatic subregions, rainfall is negatively correlated with aus rice yield, but not with aman or boro rice (Sarker et al., 2013, 2014). The negative correlation between spring precipitation and farm profits reported above is likely due to the detrimental effects of additional rainfall on aus rice yields. Excessive spring rainfall may also interfere with the sowing of aman rice during the spring, prior to its growing season (Banerjee, 2010). In contrast, fall rainfall provides irrigational input for dry-season crops (Banerjee 2010), allowing farms that experience greater fall precipitation to generate higher profits.

The empirical literature regarding the climate effects on aquaculture ponds in Bangladesh is less extensive. The results of this study show that spring precipitation is negatively correlated with aquaculture profits in both the 2010 and the comprehensive analyses, providing strong evidence that greater spring precipitation reduces aquaculture profits. Heavy rainfall reduces working days, and may decrease water salinity during postlarvae stocking periods and increase vulnerability to disease (Ahmed and Diana, 2015). The 2010 analyses also suggest that aquaculture profits are positively correlated with summer precipitation and winter temperature, but negatively correlated with summer and fall temperatures, though these inferences are less robustly supported. Shrimp producers report that higher temperatures increase shrimp mortality and disease (Ahmed and Diana, 2015), which may be the reason higher summer and fall temperatures result in lower profits. Additionally, low winter temperatures reduce the phytoplankton upon which cultured species feed (Affan et al., 2005), diminishing productivity in ponds that are operated year-round. Hence, higher winter temperatures would increase productivity and profits from these ponds.

4.2. Soil conditions

The agricultural analyses strongly indicate that salinity, texture, and drainage are the soil conditions that have a differential impact on farm profits in coastal Bangladesh. Farms located in the highest soil salinity class in this study demonstrate significantly lower profits in 2000, 2005, and 2010, as well as in the comprehensive analyses. Salinity is most pronounced in the coastal zone during the winter months, when the lack of rainfall causes soils to desiccate and draw saline or brackish water to the surface via capillary action. Coastal soil salinity is also exacerbated by high spring tides, which inundate coastal areas, tidal flooding during the summer rainy season, as well as cyclonic storm surges (Karim et al., 1999; Haque, 2006). Dasgupta et al. (2014) find that soil salinity exceeding 4 ds/m both reduces boro rice yields and depresses rice prices through a product quality effect, while having no impact on land and labour used for production.

In contrast, relatively high salinity seems to have a positive relationship with aquaculture profits. Shrimp culture is dominated by euryhaline species that can thrive in a wide range of salinity (Ahmed and Diana, 2015). Aquaculture operations that rely on tidal flows to bring saline or brackish water into ponds may have a positive feedback relationship with soil salinity. Prolonged trapping of saline tidal water within aquaculture ponds and discharge of effluents exacerbate soil salinity by increasing seepage of saline water into nearby paddy plots (Ali, 2006; Chowdhury et al., 2011).

Relatively poor drainage, where water is removed by gravitational flow so slowly that moisture remains at the surface or at a shallow depth for significant periods during the growing season, also significantly depresses agricultural profits in the 2005, 2010, and comprehensive analyses. Poor drainage likely reduces farm profits by prolonging floods, which reduces crop yields (Banerjee, 2010). In contrast, the 2010 analyses find that poor drainage significantly raises aquaculture profits, possibly because poorly drained soils facilitate water retention in ponds.

Soil texture also has an impact on agricultural profits, but not on aquaculture profits. The 2005, 2010, and comprehensive analyses suggest that clay soils yield greater farm net revenues. According to the 2010 results, farms with silty soils also have significantly higher profits. Both are fine-grain soils that allow for complex soil structure. Soils with greater clay content have a large specific surface that retains nutrients against leaching and helps buffer against extreme pH changes (Newman, 1984). Silts are nutrient-rich soils deposited by annual riverine flooding activity (Paul, 1984).

4.3. Inundation risk

Aside from storm surge floods, Bangladesh experiences three other main types of floods (Mirza, 2002). Flash floods are characterised by a sharp rise in water level and high-water velocity, following exceptionally heavy rains occurring over neighbouring hills. Riverine floods occur from the spilling of major rivers and their tributaries, with distributaries rising and falling over the course of several weeks. Rain floods are due to high-intensity local rainfall during the monsoon. Annual monsoon flooding typically begins in May, rises with the onset of summer monsoon rainfall, and peaks in August. Floodwaters gradually subside through the post-monsoon fall and dry winter, reaching their nadir in the late spring. Crop damage during a monsoon is positively correlated with the flood volume generated by river discharge. Flooding causes annual losses of rice crop, and severe flood years cause higher losses (Paul and Rasid, 1993).

While the effects of flash floods, storm surge floods, and excessive monsoon floods on agricultural outcomes are generally negative, riverine flooding can have countervailing impacts on agricultural productivity. Severe or prolonged flooding can reduce crop yields, whereas moderate flooding increases productivity by replenishing groundwater and supplying irrigational and nutrient input, particularly in drier areas. Hence, lowland areas that receive these inputs over

the long term have significantly greater farm profits, as demonstrated in the 2010 and the comprehensive analyses. However, farms located further from rivers also have significantly greater profits in the 2000 analyses, since households closer to rivers experience higher inundation and more damage (Brouwer et al., 2007). Farms that suffer from acute episodes of erosion and flooding also report significantly lower profits in 2010. The comprehensive analyses and 2005 analyses confirm that areas that are vulnerable to severe river flooding and moderate tidal surge yield lower farm profits. The 2005 analyses also confirm that areas prone to 3m or more of tidal surge also have lower profits. The 2010 analyses also find that areas at risk of severe flash flooding have higher profits, but these results may be spurious.

Aquaculture operations are typically in low-lying flats to allow tidal flows to bring water, wild larvae, and other seed stock into ponds (Ahmed and Diana, 2015). In extensive shrimp operations, tidal flows facilitate water volume exchange, which occurs at a rate of up to 10% of pond volume per day (Wahab et al., 2003), with intensive shrimp cultures requiring even higher exchange rates (Paul and Vogl, 2011). Accordingly, the 2010 analyses show that lowland aquaculture ponds yield greater profits. Shrimp producers in southwest Bangladesh report that coastal flooding physically damages aquaculture ponds, which allows shrimp to escape and predatory wild fish to infiltrate into the ponds. Flooding also inundates the households of producers, making participation in aquaculture more difficult (Ahmed and Diana, 2015). Pond overflow during floods also results in loss of stock (Handisyde et al., 2006). Hence, the comprehensive analyses demonstrate that aquaculture operations have lower profits in areas at risk of 1m and 3m of storm surge inundation risk, with the greater inundation associated with greater damage.

5. Conclusions

This study provides empirical evidence that agriculture and aquaculture net revenues from the coastal zone in Bangladesh are sensitive to climate, soil, inundation, and socioeconomic and demographic characteristics of the operations and the households that run them. There is strong evidence that higher summer temperatures are detrimental to farm profits by exacerbating heat stress on crops, but greater fall precipitation is beneficial to farmers by increasing irrigation input for dry winter crops. Higher spring temperatures are also found to be beneficial, and higher winter temperatures and greater spring precipitation are found to be detrimental to farmers. However, these results are less well supported by the analyses. Aquaculture operations yield lower profits with higher summer temperatures, higher fall temperatures, and greater spring precipitation, with the last result most robustly supported by the data. Greater spring precipitation may lower productivity by limiting working days and reducing pond salinity beyond the tolerance range of postlarvae. Aquaculture operations benefit from higher winter temperatures and greater summer rainfall, but these results are not as strongly supported.

Farms are also sensitive to soil conditions, with higher salinity and poor drainage associated with lower profits. In contrast, aquaculture benefits from moderate salinity and poor drainage, and is tolerant of high salinity. Both agriculture and aquaculture benefit from being situated in lowlands, where farms receive nutrient inputs from annual flooding and ponds receive water and postlarvae inputs from tidal flows. Both also benefit from being situated further from rivers, where they can avoid catastrophic flood damage. The results indicate that acute erosion and flooding events impact farm productivity more than ponds. However, both agriculture and aquaculture operations receive lower profits where they are vulnerable to storm surge inundation. Due to this study's use of climate normals rather than contemporaneous weather data, as well as soil and inundation indicators that reflect long-term conditions, these results suggest that the impacts of these environmental variables are robust to households' adaptation strategies as currently practiced in coastal Bangladesh.

Land use patterns generally reflect farmers' long-term adaptive practices to mitigate risk from traditional flooding regimes (Banerjee, 2010). Nevertheless, the coastal zone in Bangladesh is uniquely vulnerable to the potential impacts of climate change from sea level rise and increased tropical storm activity. Aquaculture operations may prove more resilient to salinity intrusion than agriculture, but both are vulnerable to losses due to increases in temperature and precipitation during the main growing seasons, as well as increased risk of coastal inundation.

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7. Appendix

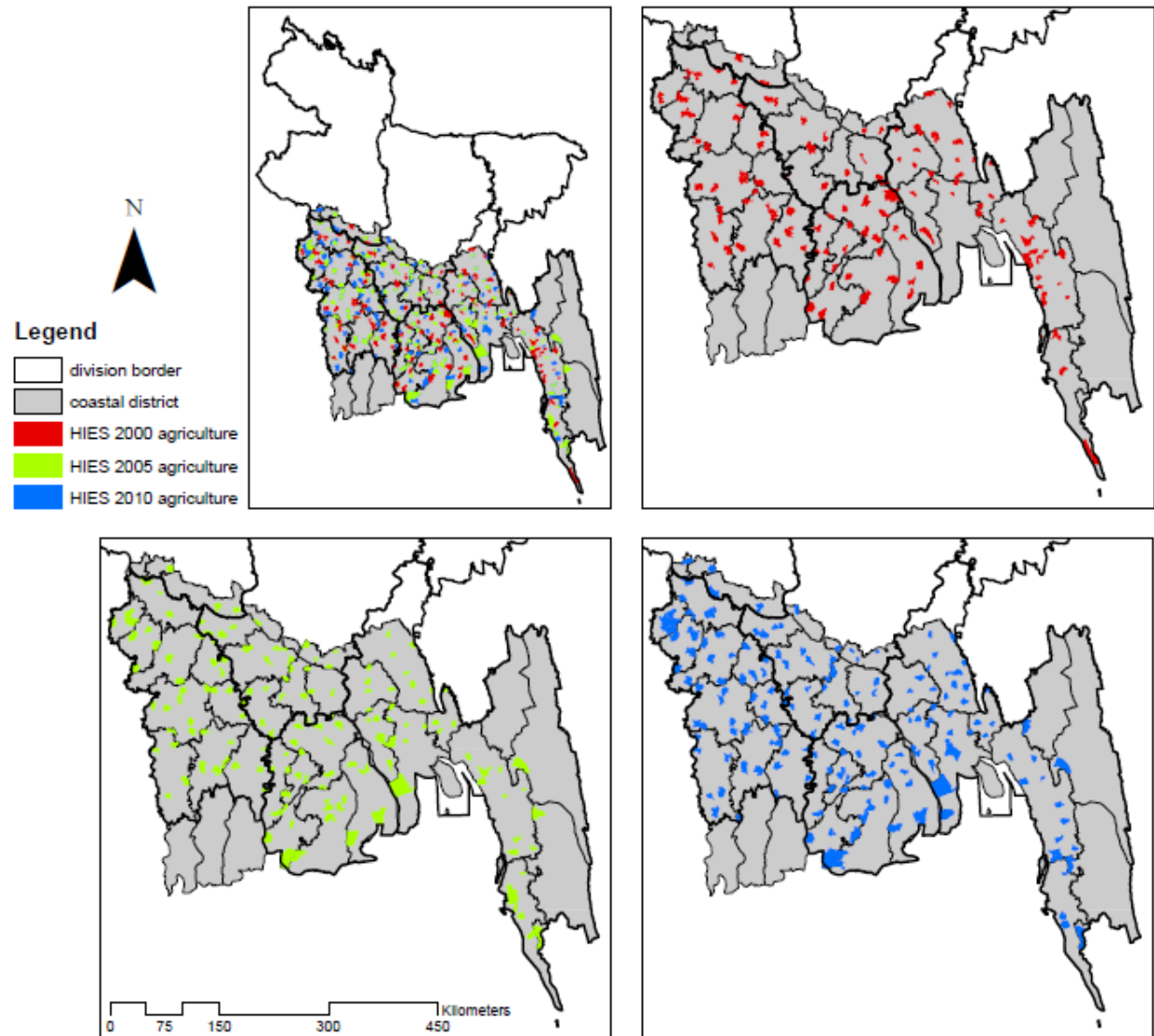


Figure 1. Maps showing coastal districts of Bangladesh and unions (i.e., counties) where HIES cultivation data is available.

Table 1a. Summary statistics of dependent variables, climate variables, and soil variables

	Variable	Agriculture households				Aquaculture households			
		2000	2005	2010	All	2000	2005	2010	All
	Sample size (no. of households)	975	1239	1553	3767	67	51	122	240
	Sample size (no. of households w/ positive profits)	954	1219	1497	3670	60	44	117	221
	no. of mouzas (positive profits)	106	136	166	327	21	21	35	70
	mean net crop revenue per hectare (1000Tk/ha)	33.0 (33.0)	47.6 (48.6)	88.2 (102.2)	60.3 (76.8)	NA	NA	NA	NA
	mean net aquaculture revenue (1000Tk)	NA	NA	NA	NA	21.8 (38.1)	53.5 (77.2)	37.2 (62.9)	36.3 (61.3)
climate normals (1950-2000)	mean spring temperature (°C)	29.0 (0.6)	28.9 (0.6)	29.0 (0.6)	29.0 (0.6)	29.3 (0.4)	29.3 (0.3)	29.2 (0.4)	29.2 (0.4)
	mean summer temperature (°C)	28.4 (0.4)	28.4 (0.4)	28.4 (0.5)	28.4 (0.4)	28.6 (0.2)	28.6 (0.2)	28.5 (0.3)	28.6 (0.2)
	mean fall temperature (°C)	23.8 (0.3)	23.8 (0.3)	23.8 (0.3)	23.8 (0.3)	23.7 (0.3)	23.9 (0.2)	23.9 (0.2)	23.8 (0.2)
	mean winter temperature (°C)	20.3 (0.5)	20.2 (0.5)	20.2 (0.5)	20.2 (0.5)	20.0 (0.4)	20.2 (0.3)	20.2 (0.3)	20.2 (0.3)
	mean spring precipitation (cm/month)	12.0 (2.7)	12.0 (2.5)	11.5 (2.7)	11.8 (2.7)	10.3 (2.3)	10.3 (1.8)	10.5 (2.0)	10.4 (2.0)
	mean summer precipitation (cm/month)	40.9 (10.5)	41.0 (12.6)	40.8 (13.3)	40.9 (12.4)	34.3 (5.5)	35.9 (5.4)	36.9 (7.4)	36.0 (6.6)
	mean fall precipitation (cm/month)	15.8 (2.0)	15.8 (2.4)	15.8 (2.6)	15.8 (2.4)	14.4 (1.2)	14.7 (1.3)	14.8 (1.6)	14.7 (1.5)
soil salinity	mean winter precipitation (cm/month)	1.2 (0.2)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)
	% non-saline (0 to 2dS/m)	84.7	88.84	84.03	85.79	70	38.63	28.18	41.63
	% slightly saline (2.1 to 4 dS/m)	6.29	3.61	5.54	5.1	6.67	13.64	1.74	5.43
	% moderately saline (4.1 to 8 dS/m)	0.94	1.15	0.27	0.74	6.67	0	0	1.81
	% strongly saline (8.1 to 16 dS/m)	6.81	6.32	9.02	7.55	3.33	43.18	48.72	35.29
soil drainage	% very strongly saline (over 16 dS/m)	1.26	0.08	1.14	0.82	13.33	4.55	18.8	14.48
	% very well drained	1.05	7.71	8.22	6.19	0	2.27	0.85	0.9
	% moderately well drained	0.94	1.48	1.87	1.5	0	0	0	0
	% imperfectly drained	23.27	15.83	21.04	19.89	43.33	11.36	9.4	19
	% poorly drained	9.75	15.59	10.89	12.15	1.67	15.91	25.64	17.19
soil texture	% very poorly drained	64.99	59.39	57.98	60.27	55	70.45	64.1	62.9
	% clay	17.19	25.92	24.11	22.92	13.33	15.91	17.95	16.29
	% sandy	1.05	3.69	2.87	2.67	0	2.27	0	0.45
	% silty	64.05	45.2	51.44	52.64	85	65.91	65.81	71.04
	% loamy	0	2.21	2.27	1.66	0	0	0	0
soil minerals	% other mixed	17.71	22.97	19.31	20.11	1.67	15.91	16.24	12.22
	mica-smectite suite	61.22	69.48	72.01	68.37	86.67	95.45	88.03	89.14
	mica-vermiculite-kaolinite suite	0.73	0	0	0.19	0	0	0	0
	mica-vermiculite suite	26.73	15.42	14.16	17.85	11.67	2.27	10.26	9.05
	kaolinite-mica suite	1.05	9.76	10.09	7.63	0	0	0.85	0.9
soil moisture	mica-kaolinite-vermiculite suite	10.27	5.33	3.74	5.97	1.67	2.27	0.85	0.9
	>400mm	19.5	11.24	13.43	14.28	10	0	12.82	9.5
	300-400mm	3.25	3.45	2.2	2.89	1.67	2.27	0	0.9
	200-300mm	50.42	38.06	39.48	41.85	45	59.09	44.44	47.51
	100-200mm	26.83	46.92	44.49	40.71	43.33	38.64	42.74	42.08
	<100mm	0	0.33	0.4	0.27	0	0	0	0
	% with alkaline soils	33.12	38.06	37.94	36.73	18.33	65.9	35.9	37.1

Table 1b. Summary statistics of socioeconomic and demographic variables

	Variable	Agriculture households				Aquaculture households			
		2000	2005	2010	All	2000	2005	2010	All
socioeconomic and demographic variables	mean no. of rooms	2.6 (1.4)	2.9 (1.4)	2.7 (1.3)	2.7 (1.4)	2.5 (1.5)	2.9 (1.7)	2.5 (1.5)	2.7 (1.5)
	mean home size (sq m)	NA	NA	38.1 (25.9)	NA	NA	NA	40.5 (25.0)	NA
	mean no. of household members	6.0 (2.4)	5.5 (2.2)	4.9 (1.8)	5.4 (2.2)	6.6 (3.5)	6.0 (2.7)	5.0 (1.9)	5.7 (2.7)
	no. of income earners	1.6 (0.9)	1.6 (0.9)	1.5 (0.8)	1.6 (0.9)	2.0 (1.1)	1.8 (1.0)	1.7 (0.9)	1.8 (1.0)
	% with electricity	19.71	32.98	43.29	33.73	18.3 (39.0)	40.9 (49.7)	55.56	42.53
	% with mobile phone	NA	5.74	64.86	NA	NA	11.36	68.38	NA
	% rural	96.65	94.18	99.33	96.92	96.67	90.91	96.58	95.48
	% with literate household head	46.02	43.51	45.09	44.81	66.67	70.45	70.09	69.23
	% with male household head	97.17	96.55	92.65	95.12	96.67	100	95.87	96.38
	% with household head with chronic disease	30.29	21.35	25.65	25.42	31.67	22.73	24.79	26.24
	mean age of household head	47.4 (13.4)	48.2 (13.5)	48.2 (13.5)	48.0 (13.5)	45.5 (12.0)	49.0 (11.6)	47.94	47.5 (12.5)
	mean total asset value (1000Tk)	84.2 (115.5)	116.4 (162.1)	330.5 (401.3)	195.4 (300.9)	101.2 (105.0)	137.7 (155.0)	348.7 (310.4)	239.5 (268.5)
	mean cultivated area (ha)	0.93 (2.2)	0.61 (0.8)	0.59 (0.7)	0.68 (1.30)	NA	NA	NA	NA

Table 1c. Summary statistics of geophysical variables related to inundation and storm surge

	Variable	Agriculture households				Aquaculture households			
		2000	2005	2010	All	2000	2005	2010	All
	mean path distance to ocean (km)	105.2 (68.7)	112.4 (70.4)	117.2 (75.2)	112.5 (72.1)	128.0 (47.1)	112.8 (48.8)	100.7 (36.5)	110.5 (43.5)
	mean path distance to nearest river (km)	2.3 (2.8)	2.0 (2.2)	2.3 (2.9)	2.2 (2.7)	2.0 (2.4)	1.1 (1.1)	1.5 (2.5)	1.5 (2.3)
	elevation (m)	9.1 (6.7)	13.2 (19.5)	14.1 (21.5)	12.5 (18.2)	6.8 (3.1)	7.5 (8.9)	5.2 (5.6)	6.1 (5.9)
main constrai nt	% deeply inundated area	10.38	7.63	8.75	8.81	11.67	4.55	32.48	21.27
	% flash flood area	8.7	4.84	3.61	5.34	1.67	0	0.85	0.9
	% hill erosion area	1.05	8.78	9.75	7.17	0	2.27	0.85	0.9
	% river erosion area	0	2.05	2.81	1.83	0	0	28.21	21.27
	% tidal surge area	7.97	8.94	9.75	9.02	15	11.36	37.61	55.66
main flood type	not flood prone	17.82	22.48	26.99	23.11	15	11.36	35.04	24.89
	% severe river flooding	0	1.31	1.87	1.2	0	0	0	0
	% moderate river flooding	18.45	28.63	22.44	23.46	6.67	13.64	5.13	7.24
	% low river flooding	34.17	24.86	27.72	28.45	50	18.18	14.53	24.89
	% severe flash flooding	0	0.98	0.33	0.46	0	0	0	0
	% moderate flash flooding	8.91	2.63	2.4	4.17	1.67	0	0.85	0.9
	% severe tidal surge	7.76	8.94	8.82	8.58	15	11.36	23.08	18.55
	% moderate tidal surge	12.89	10.17	9.42	10.57	11.67	45.45	21.37	23.53
inundati on zone	% highland	22.12	26.83	32	27.71	25	20.45	7.69	14.93
	% medium highland 1	7.44	6.73	7.41	7.19	10	9.09	3.42	6.33
	% medium highland 2	42.45	39.13	37.94	39.51	43.33	36.36	49.57	45.25
	% medium lowland	24.32	18.54	17.77	19.73	20	31.82	38.46	32.13
	% lowland	3.67	6.64	4.14	4.85	1.67	0	0.85	0.9
	% very lowland	0	0.9	0.73	0.6	0	0	0	0
storm surge depth	% 1m storm surge inundation depth	13.42	12.39	12.69	12.78	0	15.91	17.95	12.67
	% 3m storm surge inundation depth	15.09	11.9	12.16	12.83	3.33	0	2.56	2.26
	% 6m storm surge inundation depth	2.1	0.9	1.6	1.5	1.67	0	0.85	0.9
	% experienced irregular rains in 2010	NA	NA	8.62	NA	NA	NA	0.85	NA
	% experienced landslide/erosion in 2010	NA	NA	0.2	NA	NA	NA	0	NA
	% experienced flood in 2010	NA	NA	1.8	NA	NA	NA	8.55	NA

Table 2. Econometric results for year 2000 agriculture data. The dependent variable is the natural log of agricultural profit per hectare. *=p<0.1. **=p<0.05. ***=p<0.01.

R ²	0.3368
constant	965.22 (717.44)
spring temperature	35.00 (25.79)
spring temperature ²	-0.59 (0.44)
summer temperature	-55.33 (41.48)
summer temperature ²	0.96 (0.73)
fall temperature	-41.62 (63.20)
fall temperature ²	0.85 (1.34)
winter temperature	-16.83 (20.71)
winter temperature ²	0.43 (0.51)
spring precipitation	-0.85 (0.53)
spring precipitation ²	0.037 (0.23)
summer precipitation	0.025 (0.061)
summer precipitation ²	-0.000095 (0.00063)
fall precipitation	0.64 (0.56)
fall precipitation ²	-0.024 (0.018)
winter precipitation	-7.29 (5.90)
winter precipitation ²	3.35 (2.32)
moderately saline	-1.49 (0.33)***
very strongly saline	-0.72 (0.23)***
distance to nearest river (km)	0.057 (0.018)***
no. of household members	0.049 (0.012)***
cultivated land (ha)	-0.19 (0.020)***

Table 3. Econometric results for year 2005 agriculture data. The dependent variable is the natural log of agricultural profit per hectare. *= $p<0.1$. **= $p<0.05$. ***= $p<0.01$.

R ²	0.2491
constant	-229.03 (517.67)
spring temperature	7.49 (17.22)
spring temperature ²	-0.12 (0.30)
summer temperature	0.50 (15.80)
summer temperature ²	-0.019 (0.28)
fall temperature	27.89 (54.60)
fall temperature ²	-0.59 (1.15)
winter temperature	-21.40 (19.10)
winter temperature ²	0.52 (0.47)
spring precipitation	-0.66 (0.44)
spring precipitation ²	0.030 (0.18)*
summer precipitation	0.013 (0.056)
summer precipitation ²	0.00047 (0.00050)
fall precipitation	1.55 (0.72)**
fall precipitation ²	-0.051 (0.022)**
winter precipitation	-0.81 (4.80)
winter precipitation ²	0.35 (2.06)
moderately saline	1.55 (0.62)**
very strongly saline	-1.35 (0.18)***
moderately well drained	-1.11 (0.45)**
poor & very poorly drained	-0.30 (0.14)**
clay soil	0.37 (0.095)***
male household head	0.36 (0.11)***
cultivated land (ha)	-0.16 (0.038)***
severe river flooding	-0.95 (0.15)***
moderate tidal surge	-0.54 (0.17)***
3m or more of storm surge	-0.51 (0.20)**

Table 4. Econometric results for year 2010 agriculture data. The dependent variable is the natural log of agricultural profit per hectare. *= $p < 0.1$. **= $p < 0.05$. ***= $p < 0.01$.

	1
R ²	0.2173
constant	420.84 (371.68)
spring temperature	44.77 (13.39)***
spring temperature ²	-0.77 (0.23)***
summer temperature	-35.02 (13.50)**
summer temperature ²	0.62 (0.24)**
fall temperature	-39.83 (43.30)
fall temperature ²	0.83 (0.91)
winter temperature	-7.82 (17.48)
winter temperature ²	0.18 (0.43)
spring precipitation	-1.39 (0.34)***
spring precipitation ²	0.062 (0.015)***
summer precipitation	-0.013 (0.046)
summer precipitation ²	0.00054 (0.00031)*
fall precipitation	0.91 (0.50)*
fall precipitation ²	-0.033 (0.016)**
winter precipitation	-0.26 (4.30)
winter precipitation ²	0.55 (1.72)
moderately saline	0.37 (0.12)***
very strongly saline	-1.05 (0.29)***
imperfectly to very poorly drained	-0.56 (0.21)***
clay soils	0.25 (0.097)**
silty soils	0.22 (0.085)**
rural	0.81 (0.22)***
literate household head	-0.099 (0.046)**
household head with chronic disease	-0.10 (0.049)**
ln(total asset value (Tk.))	0.16 (0.033)***
cultivated land (ha)	-0.20 (0.037)***
severe flash flooding	0.54 (0.18)***
very lowland	0.30 (0.12)**
acute flood in 2010	-0.60 (0.23)**
acute landslide/erosion in 2010	-1.28 (0.25)***

Table 5. Econometric results for agriculture data from all years. The dependent variable is the natural log of agricultural profit per hectare. *= $p < 0.1$. **= $p < 0.05$. ***= $p < 0.01$.

	1
R ²	0.3239
constant	-85.18 (301.31)
2005	0.30 (0.067)***
2010	0.80 (0.070)***
spring temperature	17.52 (10.28)*
spring temperature ²	-0.30 (0.18)*
summer temperature	-24.67 (8.62)***
summer temperature ²	0.43 (0.15)***
fall temperature	44.87 (34.85)
fall temperature ²	-0.96 (0.73)
winter temperature	-33.86 (12.70)***
winter temperature ²	0.83 (0.31)**
spring precipitation	-0.95 (0.23)***
spring precipitation ²	0.043 (0.0099)***
summer precipitation	0.0019 (0.029)
summer precipitation ²	0.00056 (0.00025)**
fall precipitation	1.46 (0.33)***
fall precipitation ²	-0.050 (0.010)***
winter precipitation	-2.65 (2.71)
winter precipitation ²	1.54 (1.14)
very strongly saline	-0.90 (0.24)***
poorly and very poorly drained	0.22 (0.075)***
clay soils	0.18 (0.066)***
no. of household members	0.024 (0.0076)***
ln (total asset value (Tk.))	0.089 (0.021)***
cultivated land (ha)	-0.20 (0.019)***
severe river flooding	-0.46 (0.22)**
moderate tidal surge	-0.24 (0.099)**
lowland and very lowland	0.23 (0.087)**

Table 6. Econometric results for year 2010 aquaculture data. The dependent variable is the natural log of aquacultural profit. *= $p < 0.1$. **= $p < 0.05$. ***= $p < 0.01$.

R ²	0.4833
constant	16385.03 (2685.55)***
spring temperature	-10.96 (76.42)
spring temperature ²	0.16 (1.33)
summer temperature	-483.92 (113.05)***
summer temperature ²	8.35 (1.99)***
fall temperature	-1018.72 (352.30)***
fall temperature ²	21.32 (7.38)***
winter temperature	295.73 (114.06)**
winter temperature ²	-7.36 (2.30)**
spring precipitation	-3.51 (0.81)***
spring precipitation ²	0.14 (0.034)***
summer precipitation	0.92 (0.32)**
summer precipitation ²	-0.013 (0.0029)***
fall precipitation	-1.80 (2.58)
fall precipitation ²	0.041 (0.085)
winter precipitation	64.37 (43.74)
winter precipitation ²	-25.04 (17.43)
strongly saline	0.85 (0.22)***
very strongly saline	0.79 (0.34)**
poorly drained	0.98 (0.18)***
distance to nearest river (km)	0.12 (0.020)***
no. of earners in household	0.24 (0.085)***
electricity	0.50 (0.16)***
lowland	1.54 (0.24)***

Table 7. Econometric results for aquaculture data from all years. The dependent variable is the natural log of aquacultural profit. *= $p < 0.1$. **= $p < 0.05$. ***= $p < 0.01$.

	1
R ²	0.388
constant	3387.33 (1733.43)*
2005	0.99 (0.26)***
2010	0.89 (0.21)***
spring temperature	38.80 (39.51)
spring temperature ²	-0.65 (0.68)
summer temperature	-179.07 (108.84)
summer temperature ²	3.06 (1.91)
fall temperature	-117.51 (120.34)
fall temperature ²	2.63 (2.52)
winter temperature	1.00 (53.37)
winter temperature ²	-0.13 (1.30)
spring precipitation	-1.95 (0.72)***
spring precipitation ²	0.089 (0.031)***
summer precipitation	0.042 (0.26)
summer precipitation ²	-0.0055 (0.0028)*
fall precipitation	-0.13 (1.56)
fall precipitation ²	0.045 (0.053)
winter precipitation	18.19 (20.21)
winter precipitation ²	-8.18 (8.34)
slightly saline	-0.47 (0.23)**
moderately saline	1.42 (0.28)***
distance to nearest river (km)	0.073 (0.027)***
no. of rooms	0.22 (0.051)***
1m of storm surge	-0.88 (0.36)**
3m of storm surge	-1.16 (0.46)**

Paper 8

Forest structure and carbon stock potential of planted mangrove in Nijhum Dwip, Noakhali, Bangladesh

Mazharul Islam Alvi, A.F.M Arifur Rahman

Abstract

Mangrove ecosystems are globally recognised for their exceptional carbon sequestration and ecological services, yet planted mangrove forests remain underrepresented in blue carbon assessments, particularly in newly accreted estuarine landscapes. This study presents the first baseline evaluation of forest structure and carbon stock potential in planted mangroves of Nijhum Dwip, a dynamic estuarine island in mid-coastal Bangladesh. Using stratified random sampling, data were collected from 16 plots across four stations, covering three dominant species: *Sonneratia apetala*, *Excoecaria agallocha*, and *Avicennia officinalis*. Forest structure, species composition, and diversity indices were assessed alongside biomass and carbon stocks, derived from allometric equations and soil organic carbon analysis.

Results identified *S. apetala* as the dominant species (IVI = 207.54), with low species diversity (Shannon–Wiener index $H' = 0.68$), indicating early successional monocultures. The mean aboveground and belowground biomass were 343.36 ± 20.73 and 130.18 ± 7.08 Mg ha⁻¹, respectively, yielding a total ecosystem carbon stock of 208.18 ± 11.57 Mg C ha⁻¹. Soil carbon was a major contributor (130.84–152.92 Mg C ha⁻¹), reflecting strong sequestration potential. Two-way ANOVA showed significant variations ($p < 0.05$) in biomass and carbon among species and stations.

These findings show that planted mangroves, despite limited diversity, have substantial carbon storage and structural capacity, reinforcing their role in national carbon inventories and coastal climate adaptation. This baseline study highlights the importance of long-term monitoring and adaptive management to enhance ecological function and carbon sequestration of restored mangroves in vulnerable coastal zones.

1. Introduction

Mangrove forests are unique halophytic ecosystems that are typically found along the tropical and subtropical coastlines, thriving in intertidal zones such as estuaries, lagoons, and tidal flats (Alongi, 2009; Duke, 2011; Md Isa & Suratman, 2021). These ecosystems provide crucial ecological services, including coastal protection from erosion and storms, conservation of biodiversity by providing habitats for numerous species, and significant carbon sequestration capabilities that contribute to climate regulation (Uddin et al., 2013; Harishma et al., 2020). Although they represent only about 0.364% of global forest cover (FAO, 2020), mangroves are classified among the most carbon-dense ecosystems on the planet, having the capacity to sequester three to five times more carbon than their terrestrial forest, with an average carbon storage of 956 Mg C ha⁻¹ in both biomass and soils (Alongi, 2014; Ouyang & Lee, 2020).

In spite of their critical ecological importance, mangroves have faced significant degradation with over 1.04 million hectares lost in the past three decades due to anthropogenic activities like agricultural expansion, aquaculture practices, and various forms of coastal development (Hamilton & Friess, 2018; Bhowmik et al., 2022). This alarming degradation not only threatens the integrity of these ecosystems but also disproportionately contributes to greenhouse gas (GHG) emissions. Mangrove loss contributes an estimated 10% of CO₂ emissions from tropical deforestation, despite covering just 0.7% of tropical forest area (Donato et al., 2011; Siikamäki et al., 2012).

In response to these pressing challenges, numerous countries have adopted nature-based solutions such as mangrove afforestation and restoration to mitigate climate change and rehabilitate coastal environments (Osti et al., 2009; Uddin et al., 2022). Bangladesh, which is particularly vulnerable to climate-induced disasters due to its geographical position as a low-lying deltaic region, initiated its coastal afforestation initiatives as early as the 1960s, leading to the successful establishment of approximately 280 km² of mangrove forests that serve the dual purpose of protecting shorelines from erosion and enhancing the resilience of coastal ecosystems (Mahmood, 2015; Mahmood et al., 2020).

Nijhum Dwip; a dynamic estuarine island located in the mid-coastal region, Noakhali, Bangladesh, is one such afforested area, where mangrove plantations have been developed to reduce erosion, improve habitat quality, and support local livelihoods (Hossain et al., 2016; Nirshorgo, 2020). Nevertheless, it is important to note that the structural characteristics and potential carbon stock of these artificially established mangroves have not been thoroughly explored, particularly when compared to the well-studied natural forests such as the Sundarbans, which is renowned for its biodiversity and carbon storage capacity (Ahmed et al., 2023).

A comprehensive understanding of the dynamics associated with carbon stock in planted mangroves is of paramount importance, especially in the context of countries like Bangladesh that are in the process of integrating forest carbon accounting into their Nationally Determined

Contributions (NDCs) in accordance with the stipulations of the Paris Agreement (Rahman et al., 2021).

Given the existing research gaps in this field, the present study aims to investigate the structural characteristics of the forest and the carbon stock potential of the planted mangroves located in Nijhum Dwip Island. By systematically quantifying both aboveground biomass (AGB) and belowground biomass (BGB), as well as assessing soil organic carbon (SOC), this research aims to provide foundational data that will support blue carbon initiatives and inform ecosystem-based climate adaptation strategies in the context of Bangladesh's ongoing environmental challenges.

2. Materials and Methods

2.1 Study Area

This study was conducted in the afforested mangrove forest of Nijhum Dwip, which is a low-lying estuarine island located between 22°05'–22°09'N and 91°01'–91°05'E, the southern part of the Hatiya upazila, Noakhali district of Bangladesh (Figure 1). The island forms a dynamic deltaic landscape characterised by accretional processes, tropical monsoon climate, and an average elevation of approximately 2.4 meters above sea level (Kabir et al., 2023).

The fieldwork was carried out in October 2024 at the end of the rainy season. Surveys were conducted at four stations, each comprising four sampling plots, resulting in a total of 16 plots. Station selection was primarily based on random selection along the mangrove forest of Nijhum Dwip Island.

2.2 Data Collection

A total of 16 sampling plots, each 10 × 10 m in size, were laid out using a non-destructive quadrat technique to examine species structure and composition. The distance between plots varied from 5 to 10 m, depending on the forest's physical characteristics. All mature mangrove trees with a diameter of at least 5 cm were identified in each plot based on the guidelines provided by Giesen *et al.* (2006), and their diameter at breast height (DBH) was measured in situ. The DBH of the mangrove species were measured at 130cm above the ground (Abino *et al.*, 2014). For soil organic carbon estimation, three soil samples were collected from each plot at depth intervals of 0–10 cm, 11–20 cm, and 21–30 cm. A stainless-steel soil corer, 1 meter in height with a 5 cm diameter mouth opening, was used to extract the soil core near the center of each plot (Kauffman & Donato, 2012).

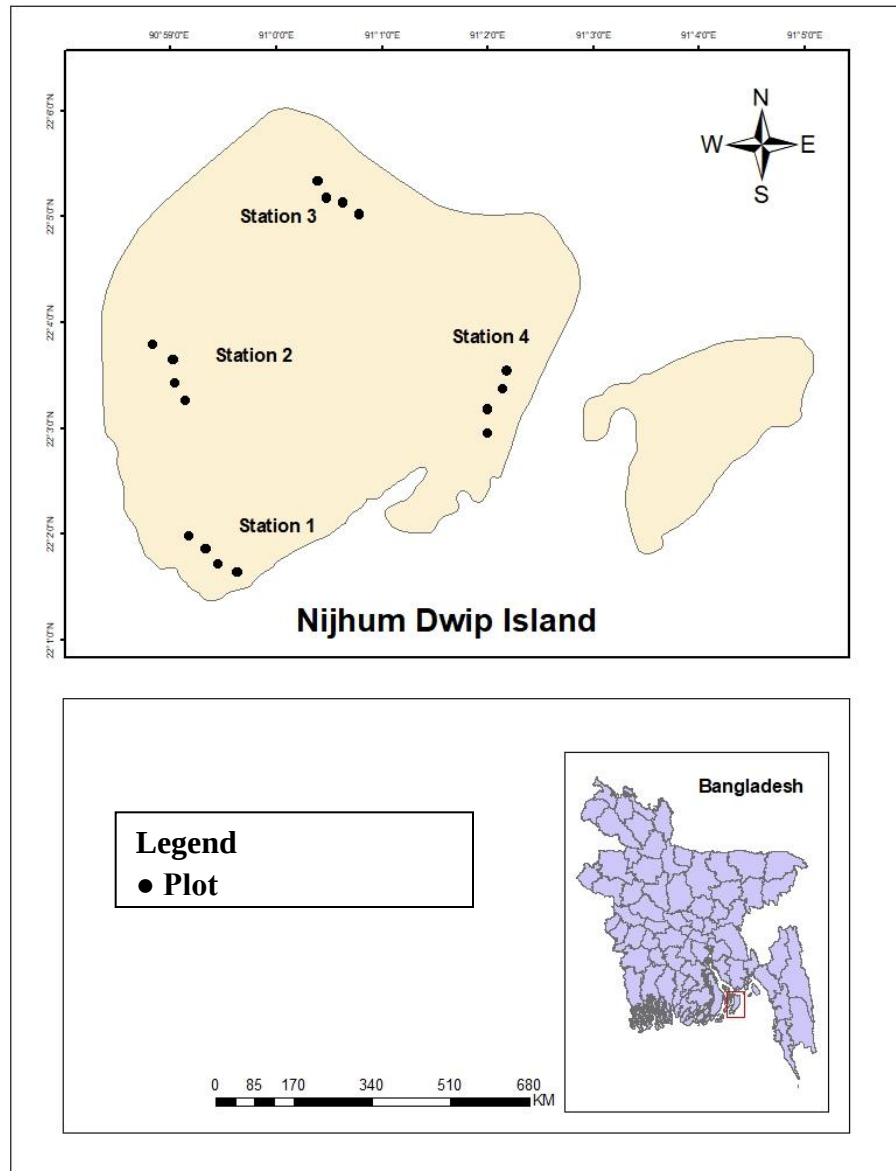


Figure 1: Location map of the study area in Nijhum Dwip Island, Noakhali, Bangladesh.

2.3 Forest Structure and Diversity Assessment

All collected data were analysed to define the structural factors (i.e., relative density, relative frequency, and relative dominance) and compositions of mangroves (i.e., density, basal area, and height) according to Cintron and Novelli (1984).

The structural significance of each species within the community was assessed using the Importance Value Index (IVI), calculated as the sum of relative density (RD), relative frequency (RF), and relative dominance (Rdom), where:

$$\text{Relative density (\%)} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100$$

$$\text{Relative frequency (\%)} = \frac{\text{Frequency of a species}}{\text{Total frequency of all species}} \times 100$$

$$\text{Relative dominance (\%)} = \frac{\text{Dominance of a species}}{\text{Total dominance of all species}} \times 100$$

$$\text{IVI} = \text{Relative Density} + \text{Relative Dominance} + \text{Relative Frequency}$$

Shannon-Wiener's diversity index (Shannon & Weaver, 1963) was applied to quantify species diversity within the mangrove habitat, where H' represents the diversity index. P_i denotes the proportion of individuals belonging to the i^{th} species, and $\ln$ is the natural logarithm.

$$H' = - \sum P_i \ln P_i$$

2.4 Biomass and Carbon Stock Estimation

We estimated the standing above-ground biomass (AGB) and below-ground root biomass (BGB) from DBH measurements using both general allometric equations. For the identified mangrove species, general allometric equations developed for the Indo-West Pacific region were applied: $AGB = (0.251 \times \rho \times D^{2.46})$ and $BGB = (0.199 \times \rho^{0.899} \times D^{2.22})$ (Komiyama et al., 2005), where ρ is the wood density (g cm^{-3}) and D is the diameter at breast height (cm). The resulting biomass values were then multiplied by 0.47 and 0.39 to estimate above-ground carbon (AGC) and below-ground root carbon (BGC), respectively (Kauffman and Donato, 2012).

2.5 Soil Organic Carbon (SOC) Estimation

Collected soil samples were transported to the Regional Laboratory of Soil Resources Development Institute (SRDI), Noakhali, for the determination of soil bulk density and organic carbon concentration. Bulk density was determined by oven-drying the core samples at 105°C for 24 hours and calculating using the formula:

$$\text{Bulk Density (g/cm}^3\text{)} = \frac{\text{Dry Soil Weight}}{\text{Core Volume}}$$

Soil organic carbon (SOC) was quantified using the Walkley-Black wet oxidation method, following the procedure described by Nelson and Sommers (1982). Soil carbon stock (Mg C ha^{-1}) was then calculated using the following formula:

$$\text{SOC stock} = \text{SOC (\%)} \times \text{Bulk Density (g/cm}^3\text{)} \times \text{Soil Depth (cm)} \times 0.1$$

3. Results

3.1 Stand Structure and Tree Composition

A total of three planted mangrove species belonging to three distinct families were identified in the study area of Nijhum Dwip Island, Noakhali, Bangladesh (Table 1). The identified species included *S. apetala*, *E. agallocha*, and *A. officinalis*. Among them, *S. apetala* was the most dominant species. The Importance Value Index (IVI) reflected this pattern of dominance, with *S. apetala* exhibiting the highest IVI (207.54), indicating its overwhelming ecological dominance in the planted forest. *E. agallocha* showed moderate dominance with an IVI of 70.75, while *A. officinalis* had the lowest IVI (21.71), suggesting limited establishment success in the plantation (Table 2).

Species diversity was relatively low, with a Shannon-Wiener diversity index (H') value of 0.68 (Table 2). This reflects the planted and species-biased nature of the mangrove forest, where *S. apetala* was preferentially established.

Table 1. Overview of observed mature tree species in the study area of Nijhum Dwip Island.

Sl No.	Local name	Species	Family
1	Kala Baen	<i>Avicennia officinalis</i>	Acanthaceae
2	Gewa	<i>Excoecaria agallocha</i>	Euphorbiaceae
3	Keora	<i>Sonneratia apetala</i>	Lythraceae

Table 2. Analysis of importance value index (IVI) and Shannon's diversity index of the mangrove forest of Nijhum Dwip Island, Noakhali, Bangladesh.

Species	No. of trees	RF (%)	Rdom (%)	RD (%)	IVI	H'
<i>A. officinalis</i>	3	12.50	5.84	3.37	21.71	0.11
<i>E. agallocha</i>	21	25	22.15	23.6	70.75	0.34
<i>S. apetala</i>	65	62.50	72.01	73.03	207.54	0.23
Total	89	100	100	100	300	0.68

The DBH of the recorded trees ranged from 17.2 cm to 37.2 cm, with mean values varying across stations and plots. The highest average DBH was recorded at Station 3, particularly in Plot 1, where *S. apetala* showed a mean DBH of 30.79 ± 5.51 cm. In contrast, the lowest DBH was observed in Station 2, Plot 2, where *S. apetala* showed a mean of 19.83 ± 2.04 cm (Table 3).

Table 3. Species composition and DBH of the mangrove forest of Nijhum Dwip Island, Noakhali, Bangladesh.

STATION	PLOT	Species	Trees	DBH			
				Mean	Min.	Max.	SD
S1	P1	Ea	6	24.73	20.7	29.6	2.96
	P2	Ea	5	22.80	21.0	26.4	2.10
	P3	Ea	6	21.37	17.5	24.2	2.53
	P4	Ea	4	25.40	24.2	27.1	1.44
S2	P1	Sa, Ao	8	25.05	18.8	37.2	6.29
	P2	Sa	3	19.83	17.5	21.3	2.04
	P3	Sa	6	26.73	20.7	33.1	4.18
	P4	Sa, Ao	8	23.16	17.2	28.3	3.83
S3	P1	Sa	7	30.79	20.4	37.2	5.51
	P2	Sa	6	28.12	24.2	32.5	2.95
	P3	Sa	7	29.71	24.2	34.1	3.65
	P4	Sa	6	26.27	22.9	32.2	3.52
S4	P1	Sa	5	27.20	19.9	31.8	4.70
	P2	Sa	3	25.40	21.7	32.5	6.15
	P3	Sa	4	26.83	22.3	29.6	3.18
	P4	Sa	5	25.04	21.8	28.6	2.76

(Note: Ao = *Avicennia officinalis*, Ea = *Excoecaria agallocha*, Sa = *Sonneratia apetala*)

Station-wise, Station 3 exhibited the largest tree sizes overall, while Station 1 presented comparatively lower variation in DBH among *E. agallocha* individuals. The standard deviation (SD) values further highlighted this variation, with Station 2 showing the widest DBH range, particularly in plots containing both *S. apetala* and *A. officinalis*.

3.2 Biomass and Carbon Stock of Planted Mangrove Forests

The mean values of DBH, AGB, AGC, BGB, and BGC of the planted mangrove stands in Nijhum Dwip are summarised in Table 4. The average biomass of mangrove stands in this study was 473.54 ± 27.81 Mg B ha⁻¹, with 343.36 ± 20.73 Mg B ha⁻¹ contributed by aboveground biomass (AGB) and 130.18 ± 7.08 Mg B ha⁻¹ by belowground biomass (BGB). This value reflects a substantial increase compared to other mangrove plantations in Bangladesh and Southeast Asia, indicating high productivity and carbon sequestration potential of the mangroves in the estuarine environment of Nijhum Dwip. The total biomass was equivalent to 208.18 ± 11.57 Mg C ha⁻¹, of which 159.40 ± 9.74 Mg C ha⁻¹ was stored in aboveground parts (AGC) and 48.78 ± 2.63 Mg C ha⁻¹ in belowground roots (BGC) (Table 4).

Table 4. The mean of DBH, AGB, AGC, BGB, and BGC of mangrove stands in Nijhum Dwip Island, Noakhali, Bangladesh. Two-way ANOVA showed statistically significant differences ($p < 0.05$) in DBH, AGB, AGC, BGB, and BGC of mangrove stands among different species.

(Note: The ‘Total’ represents the weighted average across all species)

Species	DBH	AGB (Mg B ha ⁻¹)	AGC (Mg C ha ⁻¹)	BGB (Mg B ha ⁻¹)	BGC (Mg C ha ⁻¹)
<i>A. officinalis</i>	18.77 ± 0.79	209.05 ± 20.85	98.26 ± 9.80	86.07 ± 7.79	33.57 ± 3.04
<i>E. agallocha</i>	23.44 ± 0.60	253.02 ± 15.90	118.92 ± 7.48	102.12 ± 5.79	39.83 ± 2.26
<i>S. apetala</i>	26.83 ± 0.57	466.02 ± 24.08	219.03 ± 11.32	176.36 ± 8.23	68.78 ± 3.21
Total	-	343.36 ± 20.73	159.40 ± 9.74	130.18 ± 7.08	48.78 ± 2.63

A significant variation ($p < 0.05$) in biomass and carbon stock parameters (AGB, AGC, BGB, and BGC) was detected across species and stations as revealed by the two-way ANOVA. Among the studied species, *S. apetala* exhibited significantly higher biomass and carbon values (466.02 ± 24.08 Mg B ha⁻¹ for AGB and 219.03 ± 11.32 Mg C ha⁻¹ for AGC) compared to *E. agallocha* and *A. officinalis*. Although *S. apetala* did not have the highest number of individuals, its superior performance is attributed to its larger DBH and greater wood density, which enhanced its allometric biomass accumulation.

E. agallocha displayed moderate biomass values (253.02 ± 15.90 Mg B ha⁻¹) and *A. officinalis* had the lowest (209.05 ± 20.85 Mg B ha⁻¹), aligning with their respective average DBH and species-specific wood density parameters. These findings are statistically supported by Tukey’s HSD test ($p < 0.05$), confirming that species identity significantly influenced both biomass and carbon stock variations in the mangrove stands.

3.3 Soil Carbon Stock

The soil carbon stock (SCS) exhibited spatial variability across the four studied stations in Nijhum Dwip (Figure 2). Station 2 recorded the highest mean soil carbon stock with 152.92 ± 9.73 Mg C ha⁻¹, followed closely by Station 3 with 149.18 ± 11.30 Mg C ha⁻¹. Station 4 exhibited a moderate soil carbon stock of 132.90 ± 2.92 Mg C ha⁻¹, while the lowest value was found at Station 1 (130.84 ± 8.54 Mg C ha⁻¹). Despite these variations, the soil carbon stocks across all stations remained relatively high, underscoring the role of planted mangrove systems in long-term soil carbon sequestration.

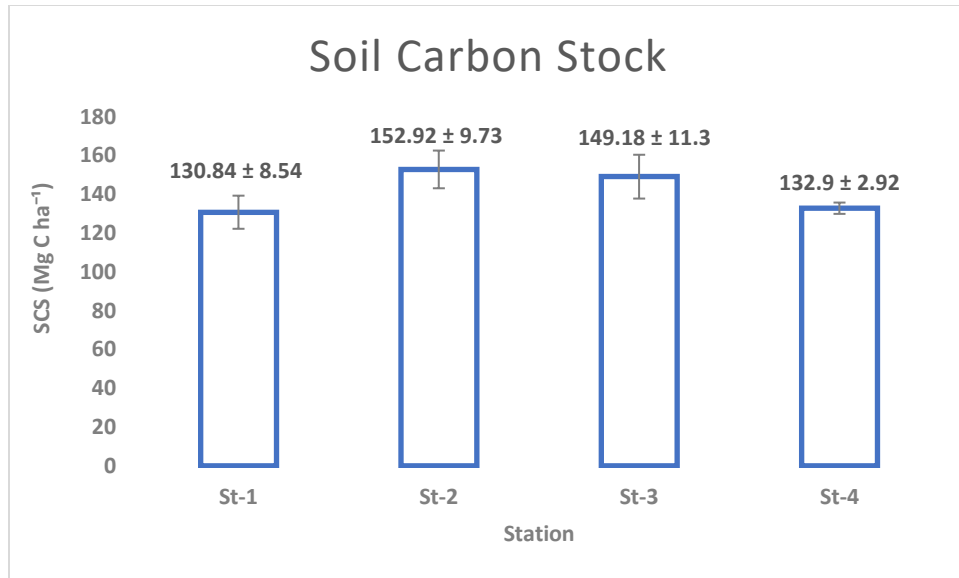


Figure 2: Mean soil carbon stock (Mg C ha⁻¹) across four sampling stations.

4. Discussion

This study provides new empirical evidence on the forest structure, biomass, and carbon stock potential of planted mangrove stands in Nijhum Dwip, a recently accreted estuarine island in coastal Bangladesh. The findings highlight the capacity of young mangrove plantations to accumulate substantial biomass and carbon, underscoring their significance as emerging blue carbon ecosystems and effective buffers against coastal hazards.

The dominance of *Sonneratia apetala* across all sampled plots, reflected by its high Importance Value Index (IVI = 207.54), demonstrates its ecological success and adaptability to the hydrodynamic and saline conditions of mid-coastal Bangladesh. Similar dominance of *S. apetala* has been reported in other afforestation sites in the region (Ahmed et al., 2022; Uddin et al., 2022) and in comparable environments of India and Indonesia (Harishma et al., 2020; Asadi et al., 2018). The low Shannon diversity index ($H' = 0.68$) mirrors the structural simplicity typical of young monocultural plantations. However, such patterns are transitional; planted stands often experience progressive species enrichment as sediment stabilisation and propagule dispersal facilitate natural recruitment (Iftekhar & Takama, 2007). This trajectory suggests that the Nijhum Dwip plantation could gradually evolve toward greater ecological complexity over time.

The estimated total biomass (473.54 ± 27.81 Mg ha⁻¹) and corresponding carbon stock (208.18 ± 11.57 Mg C ha⁻¹) indicate a considerable accumulation potential for a young mangrove system. These values fall within or above the reported ranges for similar plantations in South and Southeast Asia. For instance, Ahmed et al. (2022) reported 49.1 Mg C ha⁻¹ in a 15-year-old plantation in coastal Bangladesh, while Harishma et al. (2020) observed 195–280 Mg C ha⁻¹ in

natural stands in southwest India. The higher carbon stock in Nijhum Dwip likely reflects favourable site conditions such as nutrient-rich sediments, moderate tidal inundation, and high tree density, which collectively promote rapid growth and organic matter deposition.

Marked differences in biomass and carbon stock among species and sampling stations highlight the influence of both species-specific traits and environmental heterogeneity. The superior performance of *S. apetala*, characterised by its larger DBH and higher wood density (0.85 g cm^{-3}), is consistent with global observations that such traits are critical determinants of carbon allocation in mangrove forests (Komiyama et al., 2005; Alongi, 2014). The significant spatial variability detected across stations further supports the idea that carbon storage capacity is closely linked to local hydrology, sediment characteristics, and tidal gradients (Ouyang & Lee, 2020; Uddin et al., 2023).

Soil organic carbon (SOC) stocks, ranging from 130.84 to $152.92 \text{ Mg C ha}^{-1}$, represented a major portion of the total ecosystem carbon pool. These values are comparable to or slightly lower than those recorded in mature natural mangroves, yet they confirm that even young plantations contribute substantially to long-term carbon sequestration. Similar trends have been documented in deltaic mangroves across the Indo-Pacific region (Donato et al., 2011; Atwood et al., 2017; Stankovic et al., 2023). The relatively higher SOC observed at stations with moderate tidal exposure (Stations 2 and 3) likely reflects increased organic matter inputs from litterfall and root turnover under anoxic conditions that slow decomposition. Such spatial variation parallels findings from the Sundarbans, where freshwater-dominated zones store more soil carbon than highly saline areas (Rahman et al., 2015; Ahmed et al., 2023).

Collectively, these results demonstrate that planted mangrove stands, despite their young age and limited species diversity, can achieve ecosystem carbon stocks comparable to those of older natural forests under favourable environmental conditions. This finding reinforces the ecological and policy relevance of coastal afforestation initiatives in Bangladesh. Given that *S. apetala* shows exceptional carbon accumulation potential, it remains an appropriate pioneer species for rapid biomass production and shoreline stabilisation. However, enhancing long-term resilience and biodiversity will require diversifying plantations with complementary species such as *Avicennia marina* or *Bruguiera gymnorhiza*. Mixed-species stands are more likely to support a wider range of ecosystem functions, improve nutrient cycling, and strengthen resistance to environmental stressors.

The high carbon storage potential observed in Nijhum Dwip provides strong justification for integrating planted mangroves into national blue carbon frameworks and climate financing mechanisms such as REDD+. Recognising these plantations as functional carbon sinks could enhance Bangladesh's Nationally Determined Contributions (NDCs) under the Paris Agreement while supporting community-based restoration programs. The enrichment of soil carbon further highlights the suitability of sediment-rich estuarine sites for blue carbon enhancement, offering synergistic benefits for climate mitigation, biodiversity, and coastal defence.

Nevertheless, several methodological and ecological limitations should be acknowledged. The soil sampling depth (0–30 cm) likely underestimates total carbon storage, as mangrove soils typically retain significant carbon below one meter. Biomass estimates were derived from general allometric models, which may not fully capture the species-specific growth forms of *S. apetala* and *E. agallocha*. Additionally, seasonal and hydrological variations were not measured, limiting the interpretation of temporal trends. Future research should therefore extend soil sampling to greater depths, develop regionally calibrated allometric equations, and incorporate long-term monitoring to capture carbon accumulation trajectories and successional changes in planted mangroves.

In summary, the planted mangrove forests of Nijhum Dwip exhibit substantial potential as effective blue carbon ecosystems. Their rapid biomass accumulation, high soil carbon storage, and adaptive growth under estuarine conditions underscore their importance for coastal resilience and climate mitigation. By promoting species diversification and adopting standardised carbon monitoring, Bangladesh can enhance the ecological performance and policy relevance of its coastal afforestation programs. These findings provide a strong scientific foundation for scaling up mangrove-based nature-based solutions and advancing the role of planted mangroves in achieving national and global climate targets.

5. Conclusion

This study demonstrates that planted mangroves in Nijhum Dwip possess considerable potential for biomass accumulation and carbon sequestration, even within a relatively young plantation stage. The findings revealed that *S. apetala*-dominated stands stored substantial amounts of carbon in both above- and belowground components, highlighting the capacity of afforested mangroves to act as effective blue carbon ecosystems. The structural attributes and carbon stocks varied noticeably among stations, reflecting the influence of spatial and environmental gradients on carbon accumulation.

These results signify the ecological and climatic importance of young mangrove plantations in enhancing coastal resilience and mitigating greenhouse gas emissions. The observed carbon stocks were comparable to, and in some cases higher than, other young plantations reported across the Indo-Pacific region, underscoring the global relevance of Bangladesh's coastal afforestation initiatives. Therefore, incorporating planted mangroves like those in Nijhum Dwip into national greenhouse gas inventories and blue carbon frameworks could provide valuable contributions toward achieving the country's climate mitigation targets.

Future research should emphasise long-term monitoring of biomass dynamics, deeper soil carbon quantification, and the inclusion of mixed-species plantations to improve ecological stability and overall carbon storage potential.

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Paper 9

Sustainable Ecotourism as a Pathway to Biodiversity Conservation and Community Resilience in Tanguar Haor, Bangladesh

Nahin Naznin, AKM Mazharul Islam

Abstract

While wetland ecosystems play a significant role in biodiversity conservation and climate resilience, many remain under severe pressure from uncontrolled tourism and resource extraction. Tanguar Haor is a Ramsar-designated wetland in north-eastern Bangladesh, which represents both the opportunities and challenges of balancing biodiversity conservation with socio-economic development. While earlier research has mostly emphasised economic opportunities, there is a gap in understanding how the local communities themselves envision sustainable tourism. This study explores how sustainable ecotourism can act as a climate-resilient strategy supporting both biodiversity conservation and community well-being. Employing the qualitative research approach with purposive sampling from Tanguar Haor in Sunamganj district, data were collected through 13 in-depth interviews, 6 key informant interviews, and 5 life histories with fishermen, boatmen, local leaders, conservation experts, and youth activists. Data were analysed through thematic analysis. The key findings highlight that though tourism has created new sources of income and alternative livelihoods, it has also led to water pollution, habitat destruction, noise pollution, and biodiversity decline on the other. A recurring concern was the exclusion of local people from decision-making and the unequal distribution of tourism benefits. Study participants highly preferred low-impact and nature-based activities such as bird watching, homestays, and traditional boat trips that safeguard biodiversity while empowering communities. They strongly mentioned the need for Community-Based Tourism (CBT) to ensure their participation in tourism management, benefit distribution, and conservation practices. Participants also stated three areas of support as essential: eco-friendly infrastructure, including waste management and sanitation facilities; collaboration between local communities and administrators; and training for youth and entrepreneurs to strengthen local capacity. The study shows the interconnection between biodiversity conservation, socio-economic development, and participatory governance, demonstrating that sustainable tourism encompasses not only environmental protection but also the welfare of local communities and their involvement in decision-making processes.

1. Introduction

Wetland ecosystems represent some of the most productive habitats on Earth, hosting rich biological diversity as well as delivering crucial ecosystem services. However, in most developing nations, these areas are under significant threat from uncontrolled tourism activities, resource exploitation, as well as unplanned development. In Bangladesh, Tanguar Haor stands as a critical wetland ecosystem that symbolises both the opportunities and challenges of balancing conservation with community livelihoods. As a Ramsar-designated site and Ecologically Critical Area (ECA), Tanguar Haor supports approximately 60,000 people across 88 villages who depend on fishing, agriculture, and wetland resources for their subsistence (IUCN Bangladesh, 2015). However, growing tourism activities, combined with uncontrolled waste dumping as well as infrastructural development, have started to pose threats to the ecological integrity of the area.

According to The World Conservation Union (1996), ecotourism refers to environmentally responsible travel to relatively undisturbed natural areas that promotes conservation, minimises visitor impact, and benefits local populations. Similarly, Pengiran Bagul (2009) defines it as “responsible travel to natural areas, which conserves the environment and sustains the well-being of local people.” Ecotourism has therefore become a vital component of sustainable development in developing countries, combining environmental protection with economic opportunity (Ko & Stewart, 2002). The World Tourism Organisation (UNWTO, 2017) identifies ecotourism as one of the fastest-growing parts of global tourism. It makes up more than 6% of global GDP and is estimated to develop seven times faster than the rest of the sector. This worldwide trend shows that people are starting to see ecotourism as a way to both help the economy grow and protect biodiversity.

For Bangladesh, ecotourism has the potential to reduce poverty and encourage conservation at the same time. The Bangladesh Haor and Wetland Development Board (BHWDB, 2012) introduced a comprehensive Master Plan to protect wetland ecosystems and enhance local livelihoods. In this light, Tanguar Haor has become known as a place where tourism could help with conservation goals and create jobs that last. Still, the fastest and unregulated growth of tourism has produced severe environmental degradation, including water pollution, sound pollution, and habitat destruction (IUCN Bangladesh, 2015). These ecological concerns coexist with socio-economic challenges such as the inequitable distribution of tourism benefits and limited participation of local communities in decision-making.

Therefore, the issue lies not just in the growth of tourism but also in its sustainability, or how it can function without compromising the natural environment that supports it. Although more people are becoming aware of ecotourism's potential, few empirical studies in Bangladesh have explored the perceptions of local communities regarding sustainable tourism practices. The limited inclusion of community voices and context-specific management approaches has resulted in fragmented policies and ineffective conservation outcomes. Hence, there is an urgent need to explore how local stakeholders perceive ecotourism that is environmentally sound and socially

equitable. This study explores the relationship between sustainable ecotourism and biodiversity conservation in Tanguar Haor, emphasising the lived experiences and perceptions of local communities.

1.1 Research Questions

What are the present ecological and socio-economic impacts of tourism activities in Tanguar Haor?

How can sustainable ecotourism practices influence the enhancement of biodiversity conservation and the development of local communities, and why?

1.2 Research Objectives

A. Primary Objective

To explore the impacts of tourism activities on biodiversity conservation and how sustainable ecotourism practices can balance biodiversity conservation with the development of local communities.

B. Specific Objectives

- I. To explore the current environmental and socio-economic impacts of tourism activities in Tanguar Haor;
- II. To identify sustainable tourism practices that support biodiversity conservation and promote socio-economic development of the local communities;
- III. To know the role of local communities and administrators in tourism management;

2. Literature Review

Sustainable ecotourism has emerged as a crucial approach for balancing socioeconomic development and biodiversity conservation, especially in developing countries where natural resources are closely linked to community livelihoods. Researchers have universally noted that unplanned tourism growth can bring short-term economic gains, but in the long run, it leads to environmental degradation and social inequality (Blangy & Mehta, 2006; Nazir, 2022). In the context of Bangladesh's wetland ecosystems, sustainable ecotourism presents both opportunities and challenges: it can create employment and raise awareness about conservation, but without proper management, it can harm fragile ecosystems.

2.1 Ecotourism and Local Economic Development

Ecotourism is a form of tourism that reduces negative consequences on the environment and culture, in addition to benefiting local species and vegetation (Blangy & Mehta, 2006). By employing sustainable ecotourism, tourists employ sustainable forms of travel to preserve the natural environment and the residents, and it also creates long-term employment opportunities for the local inhabitants (Nazir, 2022). One of the most tangible, non-environmental advantages of ecotourism is the employment opportunities available to the individuals living near the host areas (Snyman, 2017). For this reason, the United Nations Environment Programme (UNEP) declared that ecotourism initiatives provide worldwide employment opportunities and enhance socio-economic prosperity (Stemet al., 2003; Anup, 2017).

Ecotourism in Ratargul swamp forest has provided a new source of income for residents. People who used to depend on fishing or farming for their living can now work as boatmen during the monsoon, carrying tourists. Some of them also established their shops in tourist areas, which has improved their income level considerably (Jahan & Akhter, 2018).

Local people's benefits must be considered in terms of employment opportunities, business alternatives, education, infrastructure, and superstructure development (Uddin et al., 2021). Although conservation and protection of natural property are important economic factors, financing remains difficult to obtain, particularly in developing countries (Balmford and Whitten, 2003). Universally, the tourism industry, particularly ecotourism, has emerged as one of the most impressive economic sectors (Xu & He, 2022).

2.2 Biodiversity Conservation Through Ecotourism

Ecotourism includes proper management of efficient trips and the conservation of nature with the aim of a perfect balance between the needs of tourism and the environment (Zahedi, 2006). The tourism industry's primary intention is to motivate locals to take part in related activities and highlight the preservation of the natural ecosystem by teaching tourists how to appreciate and preserve the culture they are visiting (Goodwin, 2016; Schuhmann et al., 2019; Dushani et al., 2021). Some studies highlight that tourists are ready to pay more than the set fees for enhanced biodiversity and environmental quality, revealing that ecotourism can serve as a source of funding for the sustainable management of wetland ecosystems (Durán-Román et al., 2021). Well-organised ecotourism, which combines long-term biodiversity conservation with local economic and social development, may benefit both protected areas and inhabitants of nearby areas (Russo & Borg, 2002). Each day, over 140 species are lost from the world's biodiversity. Biosphere reserves must be established in several tropical countries—the "hot spots" of biodiversity—to conserve what remains. Ecotourism is a suitable use of these reserves since it seeks to protect rather than destroy natural resources. Ecotourism also generates foreign exchange that helps to support the maintenance of these reserves (Bashar, 2018). Ecotourism is viewed by conservation organisations and governments as a strategy of preserving and developing rural areas.

2.3 Impact of Ecotourism on Biodiversity

Sustainable tourism can be applied to achieve goals including environmental preservation, enhancing tourist benefits, encouraging return trips, and earning financial benefits. Through ecotourism, the analysis carried out in the studies based on environmental indicators helps to improve and maintain the quality of the wetland ecosystem through nature-based tourism development (Balmford & Whitten, 2003). A study conducted in Ratargul Swamp Forest emphasises that Ratargul ecotourism can be defined as community-based ecotourism, as it provides an income opportunity for locals while simultaneously preserving natural beauty. The development of ecotourism in Ratargul swamp forest changed local people's profession, and it transformed their production system and expanded opportunities for employment as local people are involved in the tourism industry, their profession is also shifting. Many of them now work as boatmen beside farming and fishing; as a result, the economy is shifting from agricultural to business-based (Jahan & Akter, 2018).

2.4 Challenges in Biodiversity Conservation

While the tourism sector has significant socio-economic benefits, it is also causing negative environmental impacts such as ecological destruction, noise pollution, and inadequate waste management. Tourism-related infrastructure and its operations, leisure boating, and the passenger cruise industry may cause damage to ecosystems and natural habitats. Aquatic vegetation can be harmed by pleasure boats and vessels for cruises when they run around, either by cutting it with their propellers or in other ways. Additionally, construction infrastructure associated with tourism, like roads, marinas, and airports, has destroyed wetlands (Andereck et al., 2005).

Tourism creates a detrimental effect when the number of visitors exceeds the capacity of the ecosystem to cope with this use within bearable quantities of change. Conventional tourism without proper regulation can harm natural areas around the world. It can cause huge pressure on a region, leading to erosion of soil, higher pollutants, emissions into the sea, vegetation loss, a greater impact on endangered species, and increased vulnerability to wildfires (Rabbany et al., 2013).

Currently, deforestation, forest exploitation, pollution from industry and agriculture, drainage and flood prevention developments, changing land use, and excessive use of natural resources are all affecting biodiversity. Furthermore, because humans occupy nearly all of the planet's land, other species' habitats are severely hampered. Ecosystems around the world are in danger of being destroyed at a rate that has never been seen before. Climate change and loss of biodiversity have consequently become of utmost concern in the current worldwide framework (Rahman, 2015).

2.5 Ecotourism and Socio-Ecological Resilience

Ecotourism sustainability highly depends on tourists' steady arrival at the area without causing harm to natural resources. The advantages of the locals must be taken into account in terms of employment creation, business opportunities, education, infrastructure, and superstructure development. Bangladesh's potential for ecotourism depends on political stability, hopeful administration, community participation, and strong campaigns at both local and international levels. Ecotourism is said to be a more sustainable and enjoyable way to increase revenue compared to different sources of revenue generation (Bashar, 2018). For instance, Uddin (2021) explored fishery-based ecotourism in Bangladesh and found that integrating tourism with education and business significantly improved resilience among coastal communities. Another study revealed that ecotourists' willingness to pay for conservation projects in Ramsar wetlands and well-managed tourism can enhance public involvement, which is an important component of long-term resilience (Jamnia et al., 2023).

2.6 Governance and Policy Framework

Managing natural and environmental resources will be more effective if the decision-making process considers the preferences and opinions of the stakeholders (Silvano and Valbo-Jørgensen, 2008). However, the rapid growth of ecotourism raised concerns about its environmental and social consequences, emphasising the need for sustainable management strategies (Eshun & Tagoe-Darko, 2015). According to a nature-based decision-making framework, sustainable ecotourism is designed to protect the environment, maximise tourist utility, encourage repeat visits, and achieve financial benefits (Jamnia et al. 2023). To improve the efficacy of management decisions and promote co-management, community-based, and collaborative management for more effective wetland ecosystem management activities and fewer conflicts, stakeholders like ecosystem visitors, beneficiaries, and residential communities could combine their practical knowledge with scientific findings (Bostan et al., 2020). A case study conducted in Nepal based on the environmentally friendly tourism perspective of wildlife conservation areas implies that tourism can play an important role in biodiversity conservation, but this will require careful planning, efficient administration, and close collaboration between stakeholders and the conservation sector (Acharya, 2023).

2.7 Research Gap

Ecotourism is worldwide famous as an approach for biodiversity conservation and socioeconomic development, but its application has been overlooked in the context of wetland ecosystems, particularly in the Tanguar Haor. Previous literature has emphasised the economic benefits of ecotourism, such as high income and livelihood diversification (Nazir, 2022; Jahan & Akhtar, 2018), but there has been a lack of in-depth exploration into the long-term environmental and social benefits of such sustainable projects. Because of this, there remains a significant

research gap regarding the sustainability of ecotourism and its long-term positive impact on the ecosystems and local communities of the haor region.

However, the reality is that existing frameworks often lack the necessary specialised adaptations or context-specific strategies required for unique ecosystems such as wetlands. Another major challenge is that ecological and socio-economic measurements are not used together to keep track of ecotourism outcomes. While some studies, such as Du Plessis (2010), address tourist perceptions and environmental impacts, there is insufficient emphasis on holistic, adaptive management strategies that balance biodiversity conservation with community development.

This study aims to address the existing research gap by exploring the relationship between ecotourism and socio-economic sustainability in the context of Tanguar Haor. This research is to look closely at the impacts of tourism on the environment and the economy in Tanguar Haor and to find out how a sustainable ecotourism approach might help protect biodiversity while also helping the development of local communities.

3. Research Methodology

3.1 Study Design

This study employed a qualitative research approach for a deeper understanding of the interconnection between biodiversity conservation and sustainable ecotourism practices and seeks to explore how the distinct ecosystem of the Tanguar Haor wetland influences sustainable tourism practices in that area. Qualitative research focused on deeply exploring, understanding, and interpreting social phenomena in their natural setting (Creswell, 2000; DENZIN & LINCOLN, 1995). The choice to use a qualitative approach was intentional to capture the enriching experience of stakeholders such as local communities, administrators of Haor management, conservation practitioners, and, most importantly, the perspectives of tourists. The researcher utilised three qualitative data collection techniques: in-depth interviews (IDI), key informant interviews (KII), and life history interviews.

3.2 Study Area

This study was conducted in Tanguar Haor, located in the northeastern part of Bangladesh, within the Sunamganj district, close to the Indian border in Meghalaya hill region, covering an area of 9,727 hectares. It supports nearly 60,000 people in 88 villages and acts as a sanctuary for a variety of flora and fauna. The Government of Bangladesh in 1999 declared Tanguar Haor as an Ecologically Critical Area (ECA) due to its national significance and the threats of natural resource depletion. In 2000, Tanguar Haor became the country's second Ramsar site—a wetland of international importance (IUCN Bangladesh, 2015). This Haor is known for its rich biodiversity, including 140 species of freshwater fish, migratory birds, and various kinds of

aquatic flora and fauna. This study area provides a significant context for understanding how initiatives of conservation and ecotourism can coexist for the betterment of both the environment and local residents.

3.3 Sampling

In this study, the researcher adopted a purposive sampling strategy to ensure the study's specific criteria. In qualitative research, purposive sampling is one of the most widely used non-probability sampling strategies (Patton 2015). A purposive sampling strategy was adopted to ensure that participants were information-rich and directly involved in or impacted by tourism in Tanguar Haor. A total of 24 individuals were selected across three categories: local residents, tourism stakeholders, and administrative or NGO personnel. The selection ensured gender diversity, age range, and variation in occupational background. The following criteria were maintained for selecting participants:

- A. Direct engagement with Tanguar Haor
- B. Government officials and local stakeholders
- C. Temporal perspective
- D. Tourist perspective

3.4 Sample Size

The sample size of the study was determined by the principle of data saturation. When enough relevant data had been collected, and it became evident that more interviews would generate the same or similar answers, the researcher stopped taking interviews (Faulkner et al., 2017).

A total of 24 people were involved, distributed across different stakeholder groups.

Table 1: Number of study participants

Data Collection Techniques	Participants (n= 24)
IDI	13
KII	6
Life History Narratives	5

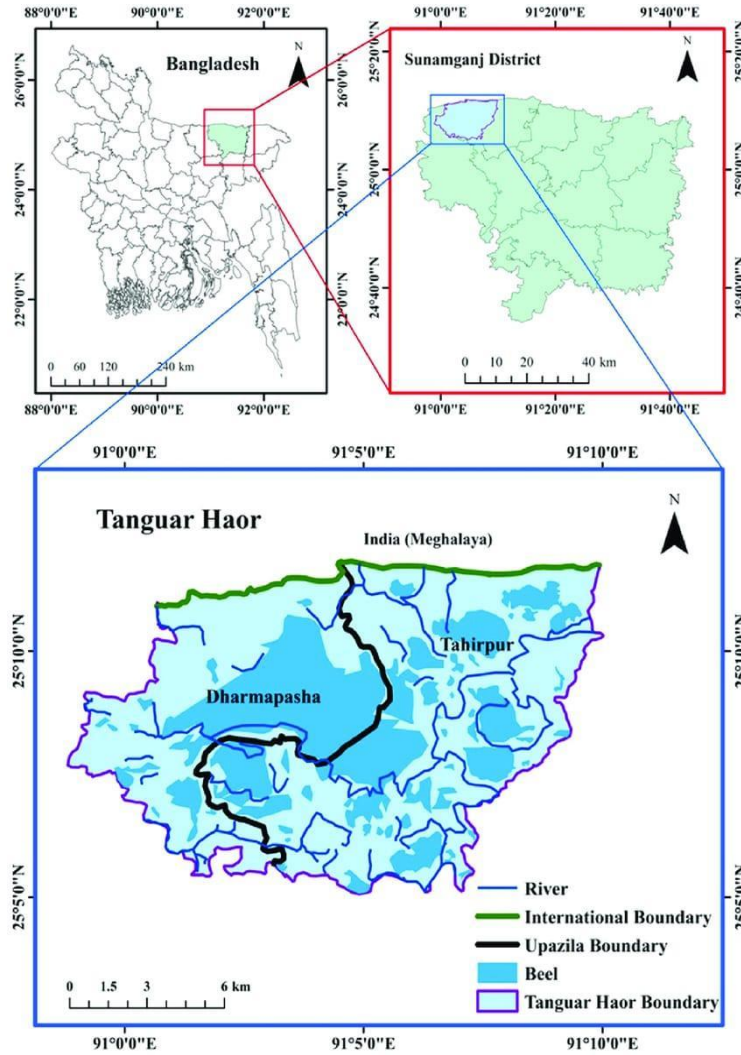


Figure 1: Depicts the geographic location of the study area (Source: IUCN; edited by author)

3.5 Data sources

In this study, data were obtained from a combination of primary and secondary data sources.

- A. **Primary Sources**—The data were collected through semi-structured interviews, life history narratives, and field observations.
- B. **Secondary Sources**—Secondary data were gathered from journals, research articles, policy documents, reports of various government and NGO organisations, newspapers, and digital resources that were relevant to the study.

3.6 Data Collection Techniques and Procedures

The researcher carried out individual in-depth interviews (IDI), key informant interviews (KII), and life history narratives as separate elements of the study to ensure extensive insights about

biodiversity conservation and sustainable ecotourism in Tanguar Haor. Three types of interviews were conducted in Bangla, the native language of both the researcher and participants. A semi-structured interview guideline was designed to collect data that would help track the research focus. This guideline helped in dealing with key concerns related to the research objectives. The researcher established rapport with the participants before conducting interviews to enrich data collection. Each interview lasted between 30-45 minutes. During the interviews, detailed field notes were taken, and the interviews were digitally recorded and transcribed verbatim for data analysis.

3.6.1 In-Depth Interviews (IDIs)

A total of 13 in-depth interviews were conducted with community members, including fishermen, boat operators, and small business owners, whose livelihoods directly depend on the Tanguar Haor, along with tourists who visited this beautiful and unique ecosystem; their perceptions were taken. These interviews explored their personal experiences, perceptions about ecotourism, and threats related to biodiversity conservation.

3.6.2 Key Informant Interviews (KIIs)

Six key informant interviews were conducted with local administrators, conservation specialists, and tourism operators to gain a comprehensive understanding of institutional and strategic perspectives on coordination between conservation and community development.

3.6.3 Life History Narratives

Life history research is a qualitative research method that explores people's individual experiences to gain an in-depth understanding of their life patterns from their point of view. Anthropologist Franz Boas utilised this method to collect detailed accounts of lived experiences, personal narratives, memories, and reflections of individuals or groups over their entire life span. This method was used to gather life histories from older community members with a long-standing connection to Tanguar Haor. A total of five life history interviews were conducted with elderly residents from the Tanguar Haor region. This method explored generational knowledge of environmental changes, historical relationships with wetlands, and transformations in the way of living as a result of conservation and tourism efforts.

3.6.4 Observation

In the context of this study, observation focused on the interplay of tourism activities, the engagement of local residents, and the impacts of human behaviours on the ecology of Tanguar Haor. In this study, observations were combined with other data collection methods to triangulate the findings.

3.7 Data Analysis

Interview data were transcribed verbatim and then translated into English. Data were analysed using thematic analysis, a well-developed qualitative research method for identifying, organising, and interpreting data into a series of patterns or themes (Braun & Clarke, 2006). The first step involved reviewing all gathered data, including transcripts from interviews and field observation notes. The data were then systematically coded to identify relevant segments or components of the raw data that could be assessed meaningfully regarding the phenomenon. After the initial coding and collation, codes were grouped into broader themes, capturing the important patterns in the data. The set of candidate themes was refined and reviewed to ensure the accuracy of the data. After that, each theme was clearly defined and given a descriptive name that reflects its significance. The final step involved a set of fully worked-out themes, analysis, and write-up of the report (Braun & Clarke, 2006).

3.8 Ethical Issues

The study was conducted based on the informed consent of the participants. The researcher followed the code of ethics designed by the American Anthropological Association (AAA) in 2012. Before conducting the study, ethical approval was obtained from Shahjalal University of Science and Technology. The purpose of the study was clearly communicated to the participants. To avoid any kind of harassment, pseudonyms were used, and interviews were stopped immediately if the environment became uncomfortable for them. Participants were informed that they were not obligated to answer any questions with which they were uncomfortable. Moreover, field notes, recordings, samples, or other primary data and identities of participants were kept in password-protected storage to ensure confidentiality and anonymity throughout the process.

4. Findings

The research findings presented in this chapter are organised according to the three primary objectives stated in the study. This study primarily analysed how tourism impacts the environmental and socio-economic conditions of the Tanguar Haor, what types of sustainable practices currently exist, and how local people and government agencies manage ecotourism. The findings are presented from quotations and verbatim obtained from in-depth interviews, key informant interviews, and life history narratives gathered from local community members, government officials, tourists, and field observations.

4.1 Environmental Impact of Tourism in Tanguar Haor

The research findings reveal that tourism activities are changing the environment, especially in terms of biodiversity, water quality, and wildlife habitat disruption in Tanguar Haor wetland. These impacts, driven by the increasing influx of visitors to the Haor, raise significant concerns

among local residents, environmentalists, and conservationists. Both the livelihoods of the local inhabitants who rely on these resources and the integrity of the environment are impacted by the shifting natural balance of the wetland ecosystem.

4.1.1 Water Quality Degradation

One of the most reported issues is the decline in water quality, mainly resulting from the tourist-generated waste. The Haor is renowned for its abundant biodiversity and pure freshwater resources, but it has been increasingly affected by pollution due to the rise in tourist activities. The amount of waste generated by tourists, such as plastic bottles, food wrappers, and other non-biodegradable materials, has put additional pressure on the region's waste management infrastructure.

A boatman stated:

“The water in our haor used to be very clean and clear; we could see the fish swimming. But now, due to the presence of a lot of plastic in the water, its quality has significantly deteriorated.”

The study participants, such as local environmental experts and conservationists, have identified that the decline in the number of fish and a general degradation of aquatic ecosystem health are directly correlated with increasing pollution levels.

4.1.2 Loss of Biodiversity

Another significant environmental result of tourism in Tanguar Haor is the gradual decline of biodiversity. More than 140 different species of sweet freshwater fish, several bird species, and a variety of plant species can be found in Tanguar Haor. However, increasing human activity in the area has been linked to disturbances in wildlife habitats and the degradation of natural resources.

These habitats have been severely disturbed by the widespread use of motorised, luxurious boats as a means of tourist transportation. Fish and bird species have suffered as a result of the noise produced by engine-powered boats and their movement through sensitive areas.

As one local fisherman of the Tanguar Haor watchtower area explained:

“The presence of excessive tourists has adverse effects on birds, especially during migration. They do not stay for as long as before. Tourists' uncontrolled movement and noise disturb their sanctuary regions, making it harder for them to survive there.”

In addition to direct physical disturbances, the presence of tourists is significantly contributing to the degradation of important wildlife habitats. Over time, littering and noise pollution have negatively impacted the ecosystem of Tanguar Haor Wetland. While some visitors are aware of the need to preserve the area's natural beauty, others are causing habitat destruction, which further complicates the effort of conserving biodiversity.

A local from a village nearby Niladri Lake expressed serious concerns about the effects of sound pollution caused by unregulated tourism. He stated:

“Tourists often roam around the haor on numerous boats playing loud music through sound systems. This not only disturbs the wildlife inhabiting the wetland but also affects our environment and the behaviour of our children. Moreover, the excessive noise makes it difficult for us to sleep at night.”

4.2 Socio-economic Impacts of Tourism in Tanguar Haor

The study findings highlighted that as a result of unregulated tourism, the local communities in Tanguar Haor are experiencing significant and complex socio-economic effects. Although locals are getting benefits from the presence of tourists, but who depend on the resources of haor for their livelihoods are also facing difficulties.

4.2.1 Economic Opportunities and Employment

In the Tanguar haor, creation of new employment opportunities is one of the most obvious and rapid socio-economic advantages of tourism. Many locals are currently depending on tourism as a source of income, particularly those who work in the service, hospitality, and transportation sectors. Many local residents who used to fish and farm for a living are now working in the tourism industry. A local boatman described how tourism has changed his livelihood:

“Tourism in Tangua has changed my life a lot. When tourism was not very famous here, I used to fish for a living. But now, I earn well by taking tourists around the haor in my small boat. I also rent out life jackets to them, which increases my income. This change has given me the opportunity to support my family much more comfortably than before.”

Similarly, the business of grocery stores and tea stalls around the tourist area has grown. A senior local vendor shared how much economic benefit his business has received from tourism:

"All the shops here thrive because of the tourists. Many people did not have homes before they opened shops in this area, but now they have built houses with the income from the shops. We can earn more now, and my son helps me at my shop."

In the context of Tahirpur, the tourism industry in Tanguar Haor has stimulated the emergence of several important supportive services, particularly in food supply, boat transportation, and hospitality related to boats. Due to the limited number of good permanent guesthouses or hotels in the area, most tourists prefer to stay in more expensive boats, which provide both accommodation and entertainment. This shift has proven to be significantly profitable for local businesses.

4.2.2 Changes in Traditional Livelihoods

The traditional livelihoods of the local population, particularly in agriculture and fishing, have been drastically altered by tourism, even though it has also produced economic opportunities. Local farmers and fishermen have expressed concerns that tourism-related development has disrupted their traditional way of life. Fishing was the main source of income for many families around the Tanguar Haor, has become increasingly difficult as tourism activities interfere with important fishing areas. For this reason, many are leaving fishing and engaging in other occupations. A fisherman mentioned:

"Tanguar Haor used to be full of fish; many species of fish could be found, and we could catch enough fish. Now, due to the presence of many boats and tourists, the water is getting polluted, the environment of the haor is changing, the fish are decreasing, and we are suffering."

This transition from traditional livelihoods to a tourism-based economy has created both opportunities and challenges. Some community people have adapted to the tourism economy, while others feel marginalised due to reduced access to their land and natural resources.

4.2.3 Cultural Shifts and Social Disruptions

Due to rising rates of tourism, changes are being observed in the local culture and social dynamics of Tanguar Haor. Although there is some positive cultural exchange between local residents and tourists, concerns have arisen about the possibility of losing traditional customs and

their own practices. Some local inhabitants feel that the rapid growth of tourism has led to the introduction of urban culture, lifestyles, and behaviours, and they believe that this is changing the social and cultural structure of the community.

A local community leader who lives beside the Tanguar Haor watchtower expressed:

“The young generation is more interested in serving tourists than in their studies. They are starting to earn money by singing for tourists or taking them on boat rides to various places, which has led many parents in the area to believe that their children are drifting away from their traditions or heritage at a young age.”

The socio-economic impacts of tourism in Tanguar Haor are both positive and negative. While tourism has created vital economic opportunities, it has also posed challenges such as inequality and loss of traditional livelihoods. The rapid growth of the tourism industry is changing the social and economic dynamics of that area, and the benefits have not been equally distributed across the community.

4.3 Community Preference for Sustainable Tourism

A significant number of participants in the in-depth interviews and key informant interviews identified certain tourism activities that they believe have a lesser impact on the environment while providing substantial socio-economic benefits to local communities. These activities have been specifically labelled as 'haor-friendly,' meaning they inflict less harm on the biodiversity of Tanguar Haor. The most frequently mentioned activities include bird watching, traditional boat trips, and seasonal tours of the haor.

There are two advantages to such nature-based tourism activities, according to local residents: they contribute to the preservation of wetland habitats and provide jobs in the area. For example, bird-watching activities help protect vulnerable areas by getting tourists to look at wildlife without bothering it. Another popular activity is traditional boat cruises, which let guests appreciate the beauty of the haor while keeping their carbon footprint low.

One tourist, speaking during an in-depth interview, shared the following sentiment:

"If tourists explore the Haor with a local guide to show them around and teach them about the area, it's good for the Haor and creates jobs for locals."

The participants mentioned the need for an environmentally friendly infrastructure that not only serves tourists but also mitigates the negative impacts of tourism on the environment.

The necessity of eco-lodges made from natural materials has been repeatedly emphasised, as these types of accommodations will blend with the natural environment and promote the sustainable use of resources. In addition, participants have demanded public waste bins, clean water stations, and improved sanitation facilities in tourist areas.

The president of the Tahirpur Tourism Association stated:

“If tourists follow the administration's guidelines regarding tourism and a structured waste management system is effectively implemented, pollution in the Haor will decrease; consequently, it will also protect the environment of the Haor and provide a better experience for tourists.”

4.4 Community-Based Tourism (CBT) as a Path Forward

A significant and recurring theme that has emerged among various stakeholders participating in the research is the establishment of community-led tourism initiatives. Participants have clearly stated that tourism management and decision-making processes will be more enhanced and sustainable with the direct involvement of the local community.

A local youth commented on this issue:

"If we participate in the decision-making process of tourism, we will be able to ensure the proper use of tourism. As a result, it will benefit the people of our community and also protect the environment."

Research findings indicate that the most popular model that has emerged is the Community-Based Tourism (CBT) model, in which local people actively participate in tourism management and contribute to the decision-making process to ensure their area's development. Through this model, the financial benefits of tourism can be equitably distributed among the locals, and conservation initiatives can also be implemented.

One NGO employee who works in CNRS stated:

“If a community tourism board is established, the people will become aware of the decision-making process, and they will be more accountable for protecting and managing their resources.”

4.5 Governance and Participation

4.5.1 Limited Involvement of Local Communities in Decision-Making

A major finding of the research was that the role of the local community in the management of tourism in Tanguar Haor is currently limited. Although tourism directly affects their livelihood, many local residents feel excluded because of their lack of involvement in the decision-making process.

A local community elder shared her experience:

“Big businessmen and administration control the management of tourism in this area. We live here—our livelihood and our life depend on this haor, but we are not included in any stage of the decision-making process.”

This type of experience reflects not only personal disappointments but also a structural limitation in tourism management. Without involving the local community in tourism planning and management, implementing sustainable tourism will be difficult.

Another local farmer highlighted:

“Tourism is increasing in the haor, leading to benefits for some, but there is nothing for ordinary people like us. Decision-making processes exclude us, and the burden of tourism losses disproportionately falls on us.”

4.5.2 Existing Governance Challenges

Another important finding in this research is the complexity of the governance structure in the current tourism management of Tanguar Haor. Although there is active participation of local

administration, environmental conservation organisations, private entrepreneurs, and local residents in the region's tourism activities, these initiatives often remain fragmented and disconnected as a result of the absence of integrated and coordinated management.

A local government official mentioned:

"Many organisations work here, but they do not work together. There is a tourism office, NGOs working on the environment, and communities, but there is no structure that brings everyone onto a single platform. As a result, tourism management often becomes chaotic, and conservation issues get sidelined."

Furthermore, the research findings emphasised that there is no specific system for monitoring and evaluation in most tourism management or environmental conservation initiatives. As a result, it becomes difficult to measure the effectiveness, impact, or accountability of the related policies. Such administrative weaknesses and structural inconsistencies are considered a major barrier to the sustainable implementation of ecotourism.

4.5.3 Collaboration Between Local Communities and Administrators

The research findings indicate the potential for improved collaboration between local communities and administrators, although there is a lack of participation from local communities and governance structures. Many local residents and administrative officials have expressed interest in actively involving the local community in ecotourism management.

The UNO officer of Tahipur Upazila noted:

"For ecotourism to be sustainable, the local community must be at the centre of the process. They need to be trained and empowered so that they can participate in the decision-making process also. When the community is involved, they become the true safeguard of their environment."

This statement clearly indicates the need to include the knowledge and traditional practices of local communities in tourism management. By ensuring their inclusion, administrative officials will be able to make these initiatives more relevant and aligned with local realities. A university student from the haor area highlighted:

"If we can meet in one place with local authorities, share our opinions, and participate in planning, then we will be able to work together to ensure that tourism is beneficial for all."

The research findings show that there is a significant gap in the participation of local communities in the management of tourism in the Tanguar Haor, but there is a potential for improvement. The local people are interested in playing a role in the management of tourism, but stronger governance structures and collaboration are needed for their participation.

5. Discussion

For this research, the researchers employed a qualitative research approach. This chapter discusses the key findings of research entitled "Sustainable Ecotourism as a Pathway to Biodiversity Conservation and Community Resilience in Tanguar Haor, Bangladesh," It focuses on the environmental impacts of tourism, sustainable practices, and governance roles within tourism management. The research findings are interpreted within the framework of current literature about sustainable livelihoods, community-based tourism, and participatory governance. This chapter analyses the similarities and differences between previous research and the current studies and shows how the findings of this research align with or differ from existing knowledge. Additionally, it highlights the practical importance of this research in enhancing the involvement of local communities in policymaking, management strategies, and similar ecosystems in Bangladesh, including the Tanguar Haor.

The key question of this research was, "What are the current environmental and socio-economic impacts of tourism activities in Tanguar Haor, and how can the practice of sustainable ecotourism contribute to biodiversity conservation and the welfare of local communities?" Findings from this study indicate a complex relationship where tourism, biodiversity conservation, and regional socio-economic realities are deeply interconnected. It is clear that the best approach to get reasonable outcomes is to use sustainable tourism practices and participatory governance structures.

5.1 Ecological and Socio-Economic Impacts

The study revealed that tourism in Tanguar Haor has led to significant ecological degradation, notably declining water quality and loss of biodiversity due to pollution, noise disturbance, and habitat disruption. These findings are concordant with existing literature, which indicates that mismanagement causes environmental risks due to tourism pressure on wetlands (Andereck et al., 2005; Rabbany et al., 2013). Other Ramsar-listed wetlands have also shown similar impacts (Menbere, 2018; Hussein & Mohamed, 2007). However, a unique feature of our research is the

direct experiences and perspectives of local people, which enrich the discussion on community-centred conservation.

Nevertheless, the socio-economic impact of tourism was multifaceted. Tourism has generated significant economic opportunities by bringing diversity to employment, which is consistent with the research of Nazir (2022) and Jahan & Akhter (2018). However, the transition from traditional livelihoods to a tourism-dependent economy has led to social inequality and cultural change, which aligns with the pattern of uneven development caused by global ecotourism (Balmford & Whitten, 2003; Xu & He, 2022). This insight enriches the literature with the idea that sustainable ecotourism is not only limited to creating economic opportunities, but it is also essential to pay attention to the preservation of traditional livelihoods and culture.

5.2 Sustainable Ecotourism Practices

Participants of this research prioritised low-impact and nature-based tourism activities such as bird watching, traditional boat trips, and eco-friendly accommodations. This preference is similar to globally recognised sustainable ecotourism standards (Zahedi, 2006; Durán-Román et al., 2021). Support for environmentally friendly infrastructure, such as waste management systems, ecology, and the use of renewable energy, also corresponds with globally recommended practices for eco-infrastructure (Goodwin, 2016; Bashar, 2018). Specifically, the emphasis on community-based tourism (CBT) models has been significantly reflected in the research, highlighting local empowerment (Russo & Borg, 2002; Dushani et al., 2021). Nonetheless, a distinctive aspect of our research is the identification of the genuine obstacles and prospects for the adoption of sustainable practices, including the infrastructural deficiencies and the fragmentation of governance. This has established a practical foundation to close the gap between the policy framework and its actual implementation (Uddin et al., 2021). Participants also noted that eco-friendly infrastructure, such as waste management systems, reusable toilets, and built ecolodges using natural materials, is at the centre of their expectations.

5.3 Roles of Local Communities and Administrators

A significant element of the research was the limited involvement of local populations in tourism management, highlighting a gap between the theoretical framework of participatory governance and its practical application (Robbins, 2019; Forsyth, 2004). This limitation aligns with insights from political ecology, suggesting that exclusionary governance systems often perpetuate social inequalities and undermine sustainable resource management (Ghosh & Ghosh, 2019). It has become clear from the direct accounts of participants in the study that institutional reform is essential to ensure genuine public participation, which has given new relevance to the literature on participatory governance.

This research provides several practical guidelines for policymakers and implementers. It highlights the importance of including sustainable tourism as part of a broader biodiversity conservation framework and calls for the structural participation of people in tourism governance. The practical implications of the research include reforms in participatory governance structures and the development of infrastructure to support eco-friendly tourism practices and the implementation of empowering activities for local communities (Jamnia et al., 2023; Acharya, 2023).

6. Conclusion and Recommendations

The wetland resources of Tanguar Haor have great potential for ecotourism development and biodiversity conservation. The quality of life of the haor region is closely linked to biodiversity, and the conservation of this biodiversity is important for improving the ecological balance and creating a viable habitat for humans. The distinct flora of the Tanguar Haor region helps protect wildlife and protect the soil from erosion. Therefore, maintaining ecological balance is very important for the overall welfare of the haor region. However, unregulated tourism, excessive resource extraction, and environmental degradation pose threats to both biodiversity and the local livelihoods of the community. To address these threats and preserve biodiversity, sustainable ecotourism practices are required in Tanguar Haor while also supporting the socio-economic well-being of the local communities. One of such mechanisms for the long-term biodiversity of wetlands is the integration of wetland resources with ecotourism and their development as an alternative source of income for local communities.

Based on the research findings, some recommendations have been proposed to enhance sustainable ecotourism practices and biodiversity conservation in Tanguar Haor. These recommendations highlight the urgent need for integrated management, community involvement, and environmentally responsible tourism practices.

6.1 Strengthening Governance and Institutional Coordination

Effective governance is extremely crucial for achieving sustainable ecotourism in Tanguar Haor. Research has shown that the lack of coordination among local administration, non-governmental organisations (NGOs), and tourism entrepreneurs acts as a major obstacle

Therefore:

- A. A multistakeholder tourism management committee should be formed to ensure coordination among local government, conservation agencies, and community representatives.
- B. The Department of Environment (DoE) and upazila administration will jointly supervise tourism activities through regular assessments and ensure the implementation of environmental guidelines.

- C. Tanguar Haor Ecotourism Management Plan (THEMP) is needed, which will provide clear guidelines for sustainable tourism development and biodiversity conservation.

6.2 Promoting Community-Based Tourism (CBT)

The research findings strongly emphasise the importance of local participation in tourism governance. To ensure equitable benefit distribution and environmental stewardship:

- A. Local communities should be given formal roles in decision-making through community tourism boards or cooperatives.
- B. Capacity-building programs, including training on ecotourism management, hospitality, and environmental conservation, should be provided to local residents, especially youth and women.
- C. Income generated from tourism should be reinvested in local development projects, such as waste management, educational development, and the construction of environmentally friendly infrastructure.

6.3 Governance and Policy Reform

- A. Integrated Management Plan: To coordinate tourism and conservation efforts, a single management authority comprising local community representatives, NGOs, and government agencies should be formed.
- B. Participatory Decision-Making: The local councils and community forums must be involved in tourism planning and implementation of policies. This will ensure that decisions attained cater for the needs of the local populations and the environmental agenda.
- C. Monitoring and Accountability: A participatory monitoring mechanism should be established such that locals provide information related to tourist activity behaviour, pollution status, and alterations in biodiversity. This will provide constant surveillance and accountability in the tourism activity.

By integrating sustainability in all aspects of tourism, from planning and infrastructure to governance and education, Tanguar Haor can be an in-life example of people-nature harmonious existence. The experiences drawn from this study can inform policymakers and practitioners aiming at balancing conservation with development in order to leave the future generation with a resilient and prosperous wetland ecosystem.

7. References

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Paper 10

Climate-Induced Migration and Equity: Protecting Vulnerable Populations Across Borders

Thomas Sheku Marah

Abstract

Climate change functions as an expanding force that moves people, but mainly targets those living in low- and middle-income nations. Although equity receives increasing attention in climate governance, the response to displacement remains disjointed, which restricts protection and necessary services for marginalised groups. This study employed a qualitative comparative analysis, which examined case studies from Bangladesh, Fiji, Kenya, and Germany. Research material came from government migration reports, along with NGO case studies and international organisation publications spanning from 2015 through 2024. Thematic coding was conducted under distributive, procedural, and recognition justice frameworks, while cross-source triangulation ensured credibility. Research findings show organisations express commitment to equity through words, yet demonstrate variable implementation of these principles in their operations. The housing, education, and healthcare distribution patterns in Bangladesh and Kenya show ongoing inequalities that persist across these sectors. Fiji establishes more comprehensive participation mechanisms for relocation planning but encounters financial and livelihood limitations in its implementation. Basic service access exists under German law, yet the government fails to identify climate displacement as a separate category. Structural inequalities grow worse when cross-border coordination remains weak because vulnerable populations receive the most negative effects. To embed equity into climate migration governance, multi-level coordination must occur along with predictable financing and active participation of affected communities. The implementation of stronger distributive, procedural, and recognition justice across governance levels enables migration responses to develop into sustainable adaptation strategies instead of crisis management.

1. Introduction

Global warming has become one of the crises of the twenty-first century that is no longer confined to the context of environmental discourse and instead is transforming the world's social, political, and economic landscape. One of its immediate effects is increased human mobility. Unpredictable events, including cyclones, floods, and landslides, as well as predictable ones, including the rise in sea levels, desertification, and the disappearance of glaciers, are compelling many people to abandon their homes and seek refuge elsewhere to find their lives and means of living (IPCC, 2022). It is estimated by the International Organisation for Migration (IOM) that tens of millions of people have already been displaced each year by climate effects, and now more than 200 million individuals may be displaced by 2050 (IOM, 2023; Rigaud et al., 2018; Clement et al., 2021).

This crisis of migration brings the deep inequities of the world into focus. The lowest- and middle-income countries, though the least significant contributors to climate change, are affected by the displacement the most. Such groups do not always have access to basic services like housing, medical care, and education, which means that they are marginalised twice due to climate effects and poor governance systems. Projected in the Intergovernmental Panel on Climate Change (IPCC)'s 2023 Synthesis Report and current United Nations Framework Convention on Climate Change (UNFCCC) talks, equity-based responses are seen as the only solution to avoid climate-induced displacement as a humanitarian emergency that creates vulnerability instead of facilitating adaptation (IPCC, 2023; UNFCCC, 2023).

Equity offers a very important normative perspective by which to assess climate migration governance. Distributive justice is one that demands equitable distribution of resources and opportunities, procedural justice is one that stresses inclusivity and participation, and recognition justice is one that requires the acknowledgement of the rights, identities, and needs of marginalised groups (Fraser, 2009; Guedes et al., 2024). Otherwise, relocation or resettlement programs may contribute to the problem of inequality (Chakraborty, 2021; Zickgraf, 2021). Equity, when practised meaningfully, can turn migration into an active adaptation plan, making it more resilient and contributing to sustainable development (IOM, 2023; Walker et al., 2024).

This paper analyses equity considerations of climate-induced migration by comparing and contrasting four different cases: Bangladesh, Fiji, Kenya, and Germany. These nations were chosen so as to represent a variety of climate risks and governance environments. The South Asian example of Bangladesh demonstrates a mass displacement caused by cyclones and floods. The Small Island Developing State (SIDS) of Fiji has led the way in the use of planned relocation as an adaptation measure. Mobility is evident in Kenya in Sub-Saharan Africa, where drought and scarcity of resources pose unique equity hurdles. As a host nation of the Global North, Germany sheds light on the issues of recognition and the sharing of responsibilities in the high-income settings. These cases, when considered collectively, give a balanced outlook on the

way equity is applied, perceived, and interpreted under various socio-economic and political circumstances.

Three research questions guide the study:

- A. How well have new policies and initiatives increased equitable access to housing, education, and healthcare for climate-displaced people?
- B. What institutional or policy gaps still limit the achievement of just climate migration governance?
- C. What are the particular steps that can be taken by policymakers to ensure protection, inclusion, and climate justice beyond national boundaries?

The study aims to further contribute to the empirical and normative literature on climate migration and justice by answering these questions. It evaluates where equity has been promoted, where more is still needed, and what doable avenues, including multi-level coordination and community-based monitoring, can be used to achieve climate adaptation that is more equitable and sustainable.

2. Literature Review

2.1 Climate-Induced Migration: Complex Drivers and Patterns

The process of climate-induced migration exists as a complex system that emerges from the combination of environmental pressures, socioeconomic weaknesses, and governance frameworks. The academic debate about climate change as a direct migration factor has evolved to focus on how climatic threats combine with poverty levels, unstable governance, and demographic changes to produce different migration results (Black et al., 2011; McLeman, 2019). Slow-onset climatic changes, such as sea-level increase and the melting of glaciers, typically degrade local economies over time, leading to planned migration movements. But sudden disasters, including cyclones and floods, result in immediate population displacement without sufficient preparation time (IPCC, 2022; Nawrotzki & DeWaard, 2018).

Current projections indicate that 216 million people will become internal climate migrants throughout Sub-Saharan Africa, South Asia, and Latin America by 2050 if there is no decisive climate and development intervention (Rigaud et al., 2018; Clement et al., 2021). Transboundary migration shows a difficult measurement pattern, yet it will increase because environmental degradation connects with international labour markets and regional political dynamics (IOM, 2023). Research indicates that migration functions as an adaptive strategy to broaden household income potential, minimize risk exposure, and develop resilience capabilities (Adger et al., 2020; Boas et al., 2019).

2.2 Equity and Climate Justice in Migration Studies

The connection between climate and mobility heavily depends on equity principles. Climate justice concepts show that people with minimal greenhouse gas emissions face maximum climate risks with insufficient tools for adaptation (Shue, 2019; Walker et al., 2024). This imbalance creates urgent moral and political dilemmas about who should pay for the necessary adaptation measures and how communities affected by displacement should receive international support.

Equity consists of three primary components, which include distributive justice for resource and opportunity fairness, procedural justice for decision process inclusion, and recognition justice for marginalized group needs, rights, and identities (Fraser, 2009; Guedes et al., 2024). The concepts within migration studies require nondiscrimination and equal access to essential services, as well as participatory planning for relocation or resettlement processes (Bettini & Gioli, 2016; Brousseau, 2024).

The evidence demonstrates that equity frequently remains unaddressed during practical implementations. The implementation of planned relocations proves effective in minimizing physical hazard exposure, but these processes do not secure land ownership rights, proper housing, or job prospects, thus generating "secondary risks" against displaced people (Zickgraf, 2021; Chakraborty, 2021). The adaptation process creates additional challenges for women, children, and indigenous communities because they receive no decision-making rights while facing higher adaptation costs (Cissé et al., 2022; Adger et al., 2020).

2.3 Governance Challenges: National, Regional, and Global

The management of climate-induced migration faces major challenges because it exists in different, fragmented systems. Migration exists as a component in National Adaptation Plans (NAPs) of multiple countries, but the implementation of these plans shows significant disparities and insufficient financial support (UNFCCC, 2023; IOM, 2023). The Kampala Convention in Africa, together with the Cartagena Declaration on Refugees in Latin America, establishes regional safeguards which protect some climate-displaced people, but their protection remains insufficient for individuals who move across national boundaries (Scott et al., 2022). The Global Compact for Migration (2018) integrates environmental migration components and the Warsaw International Mechanism under the UNFCCC addresses displacement due to "loss and damage" but lacks enforceable legal requirements to protect cross-border migration (McAdam, 2020; IDMC, 2024).

Scholars maintain that governance gaps develop because state sovereignty conflicts with the requirements of humanitarian assistance. States that receive migrants fear they will lose control of migration patterns, but sending states do not have enough funds to establish long-term solutions within their borders (Boas et al., 2019; Klepp & Herbeck, 2016). Multilevel coordination requires linking local initiatives with regional cooperation and international legal norms to achieve both coherent and equitable responses (Walker et al., 2024).

2.4 Empirical Evidence: Housing, Education, and Healthcare

Research studies that evaluate specific effects on displaced populations show service delivery as an essential equity dimension. Displaced families need stable housing and land rights for their security, but most resettlement programs offer only temporary accommodations, which fail to provide legal protection from eviction or social exclusion (Ferris, 2020; Thomas & Benjamin, 2022). Education access shows uneven distribution because targeted programs in Bangladesh and Fiji succeeded in raising school enrollment rates among displaced children, but language barriers, cost barriers, and distance barriers continue to exist (UNICEF, 2022; Hossain, 2019). Healthcare services represent the weakest point since displaced people regularly face exclusion from national insurance programs while experiencing challenges in obtaining continuous medical care (WHO, 2021; IDMC, 2024).

The existing literature shows a contradiction because migration, along with relocation, serves as an adaptive measure, yet unfair implementation creates additional vulnerabilities. Researchers advocate for monitoring frameworks that focus on equity, together with community-based participation and enhanced regional cooperation to prevent climate migration from sustaining systemic injustice (Guedes et al., 2024; Brousseau, 2024).

3. Methodology

The research uses a qualitative multi-case study methodology to explore how equity factors influence responses to climate migration. A qualitative methodology suits this study because it allows researchers to examine both institutional frameworks and policy commitments, as well as the experiences of the displaced population in migration governance systems. The study follows an exploratory approach to develop theoretical knowledge alongside practical insights, instead of creating predictive models.

The study combines two connected research levels through its comparative approach. The research examines government and international body perceptions regarding equity in climate migration frameworks through their distribution systems and procedures for population inclusion and cultural identity recognition. The research evaluates displaced community members' access to vital services, including housing, healthcare, and education, while assessing if these service outcomes align with equity-focused policy frameworks.

The research selected cases with a wide range of variations to capture multiple contexts where climate-induced migration takes place. Bangladesh was selected because it faces severe threats from sea-level rise and cyclones while experiencing major population displacement, both domestically and internationally. Fiji functions as an example of an SIDS because it

implemented planned relocation through its national adaptation framework. Kenya demonstrates Sub-Saharan African conditions, where drought and pastoralist displacement generate specific equity and resource allocation dilemmas. Germany participated as a Global North host nation to analyse both responsibility-sharing mechanisms and migrant integration approaches in affluent states. The selected cases demonstrate the struggles and benefits that emerge when global equity principles face implementation challenges in different governance and economic systems.

The research utilised various secondary sources, which included peer-reviewed academic publications and government policy documents, as well as international frameworks such as the UNFCCC and the Global Compact for Migration, and reports from organisations including the IOM, the United Nations High Commissioner for Refugees (UNHCR), and the World Bank. The study gained valuable insights from NGO case studies together with qualitative evidence from existing research, which provided important perspectives from affected communities. The use of multiple sources for data collection allowed triangulation, which strengthened both the credibility and robustness of the findings.

The study framework consists of three dimensions that define climate justice: distributive, procedural, and recognition. The assessment of distributive justice examines the way resources and opportunities are allocated to displaced populations, whereas procedural justice evaluates decision-making participation levels, and inclusion and recognition justice evaluates policy frameworks for acknowledging cultural identities and vulnerabilities among marginalised groups. The thematic coding process followed the dimensions, which were based on qualitative content analysis. NVivo software enabled the researchers to systematically organise data, which helped them detect recurring themes and cross-case patterns, and contextual divergences.

Research of this nature requires the identification of specific limitations, which should be recognised. The dependence on secondary data limits researchers from capturing immediate lived experiences, and migration governance changes render some policy documents obsolete. The study findings cannot be statistically generalised, yet they can be analytically transferred to similar contexts. The combination of multiple sources with equity theory and empirical case analysis establishes a solid basis for credibility and rigour despite these constraints. The analytical framework guiding this study is presented in Figure 1.

4. Case Study Analysis

The equity dimensions of climate-induced migration manifest differently across national and regional contexts, reflecting variations in exposure to climate hazards, governance capacity, and socioeconomic structures. By examining Bangladesh, Fiji, Kenya, and Germany, the analysis highlights both the common challenges of protecting vulnerable populations and the distinctive strategies adopted in response.

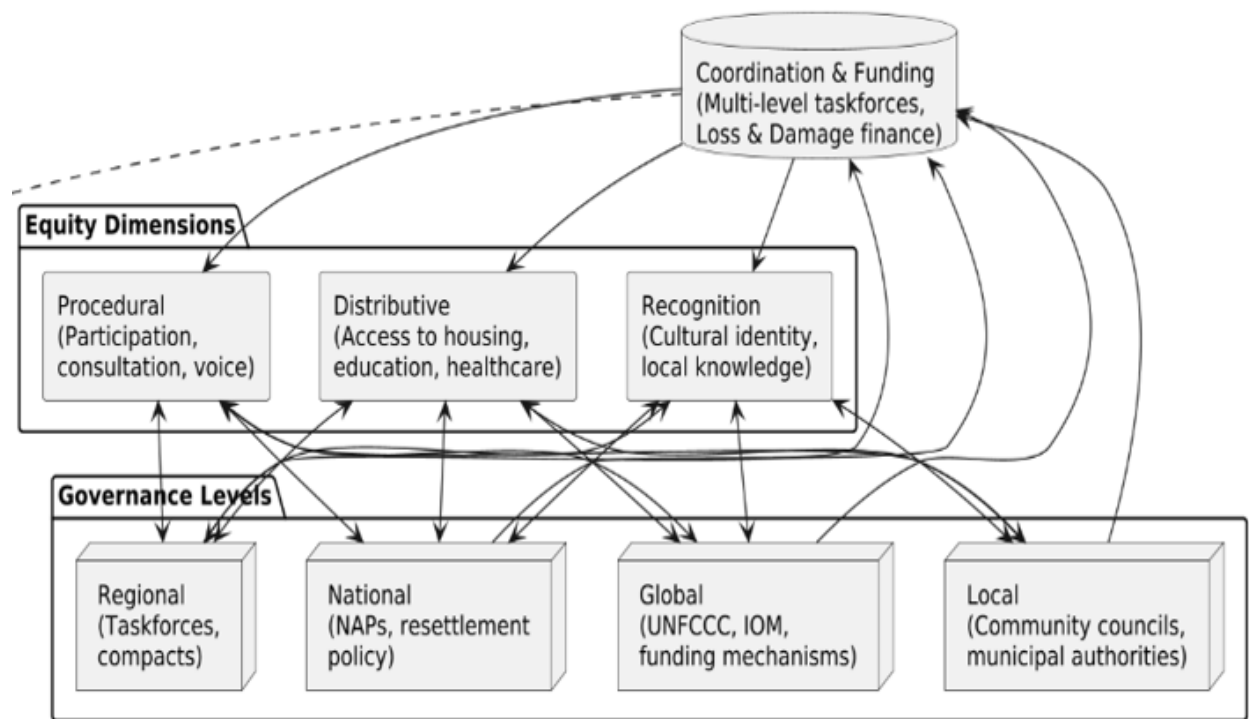


Figure 1: Conceptual framework linking equity dimensions (distributive, procedural, recognition) with governance levels (local, national, regional, global) in climate migration governance.
(Author's Own Illustration)

Climate change has created an ongoing reality of displacement for people in Bangladesh because of their geographic location and economic vulnerability. The combination of rising sea levels with frequent cyclones has compelled millions to relocate from coastal zones into urban areas while facing extreme vulnerability. The National Adaptation Plan, together with the Delta Plan 2100, acknowledges displacement as a crucial issue, but their execution has not achieved consistent results. The distribution of housing and healthcare services to displaced populations demonstrates inadequate equity because many individuals end up residing in informal settlements without basic service access. Community relocation programs in Khulna and Satkhira districts have demonstrated limited success by increasing school enrollment and healthcare access, but these initiatives remain scattered and inadequate to address the scale of displacement (Hossain, 2020; Islam & Shamsudduha, 2022).

The national response of Fiji to climate-induced migration focuses on planned relocation, which operates as the main strategy for adaptation. The Fijian government has established Relocation Guidelines, which include principles that promote equity and maintain cultural values alongside community participation. The actual implementation of relocation programs faces multiple obstacles because of restricted funding and problems regarding suitable land distribution for displaced communities. The relocation process generates equity problems because affected

communities lose their means of income, while women and Indigenous peoples lack sufficient representation during decision-making procedures. The institutionalisation of equity by Fiji through its relocation efforts serves as a valuable example for SIDS (McNamara & Farbotko, 2019; Yeo et al., 2023).

Equity challenges in climate-induced migration within Kenya stem from drought conditions and limited resources across arid and semi-arid regions. Migration because of drought and resource limitations has mainly impacted pastoralist communities, who lose their ability to find water and grazing land. The Climate Change Act of 2016, together with the National Climate Change Response Strategy, recognises displacement, but they provide insufficient guidance for establishing equitable responses to migration. Displaced families face diminished healthcare and educational services when they resettle in distant areas. The failure to coordinate national government with county government operations creates greater inequalities, which become evident through unaddressed resource conflicts that expose distributive justice system faults. Non-governmental organisations deliver water infrastructure and assistance to pastoralist women, yet these initiatives stay limited to specific areas, which do not match the extent of displacement (Opiyo et al., 2021; Kansiime & Nkonya, 2022).

Climate migration patterns create equity problems for Germany because it functions as a host nation having substantial resource capacity. The majority of people migrating to Germany do so because of political and economic reasons, yet climate-related factors increasingly affect asylum seekers during their displacement. The German administration lacks official recognition of climate migration as a legal status, but it integrates displaced populations through existing integration programs. The law provides guarantees for housing along with education and healthcare services, yet reality shows persistent inequalities that mainly affect undocumented migrants, together with asylum seekers, during administrative delays. EU member states face difficulties regarding the distribution of responsibilities, which makes Germany's position more complex because wealthier nations must address regional justice questions. Germany has implemented procedural equality by involving migrants in specific participatory groups, yet its policy framework lacks acknowledgement for climate-related vulnerabilities (Boas et al., 2019; Ober & Sakdapolrak, 2020). These comparative patterns across the four cases are illustrated in Figure 2.

The analysis of these cases demonstrates ongoing difficulties in applying equity principles to actual practice. The case of Bangladesh shows how disjointed pilot projects fail without national strategies, while Fiji demonstrates both the opportunities and challenges of integrating equity into planned relocation efforts. The intersection of resource shortage and ineffective governance makes marginalised communities especially vulnerable, according to Kenya's situation, while Germany reveals how host countries fail to treat climate migration as a unique equity matter. The research indicates that although different environments produce different results, the fundamental problem continues to be that equity receives theoretical support but receives insufficient implementation in real-world scenarios.

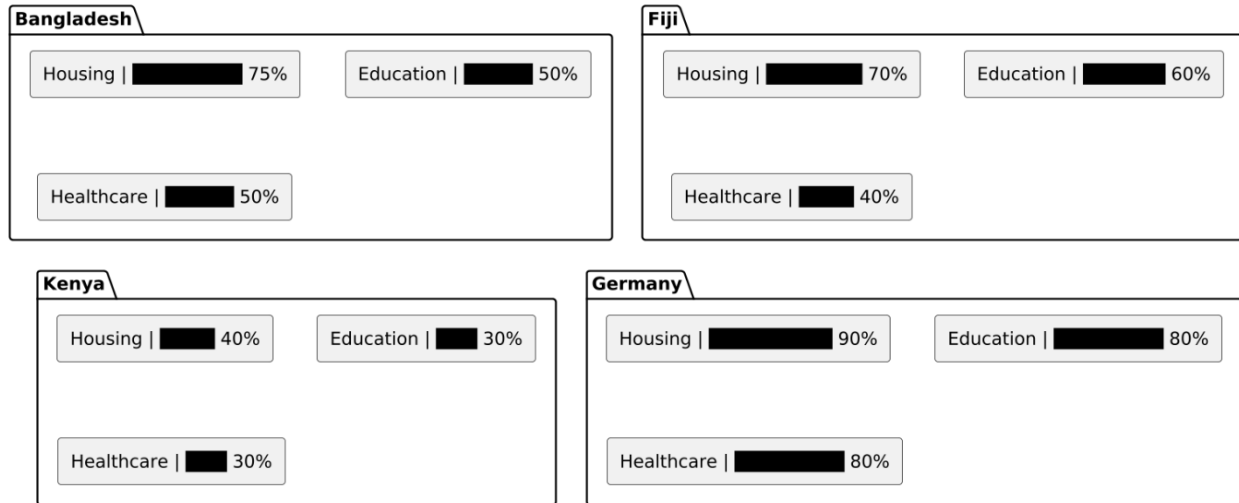


Figure 2. Comparative equity outcomes in housing, education, and healthcare for climate-displaced populations across Bangladesh, Fiji, Kenya, and Germany.
(Author's Own Illustration)

5. Discussion

The analysis of climate-induced migration governance between Bangladesh, Fiji, Kenya, and Germany shows how different approaches to equity exist in various contexts. Different contexts exist between these nations, yet their approaches toward equity show similar patterns that reveal current approach strengths and weaknesses.

The study shows that organisations consistently fail to bridge the gap between their equity statements and practical implementation. The evaluation of the four case studies shows that equity received acknowledgement in official documents and government discussions, yet practical implementation consistently lacked sufficient action. National planning instruments in Bangladesh incorporated equity principles, but the implementation faced obstacles due to resource limitations and inadequate capacity. The relocation guidelines of Fiji incorporated equity principles, but the process of obtaining funding and engaging communities demonstrated how difficult it was to maintain these commitments. The implementation of Kenya's climate initiatives struggled because of insufficient government collaboration between agencies and inadequate mechanisms for fair resource distribution, yet German integration policies, which offered extensive legal coverage, neglected to acknowledge climate-induced vulnerabilities. The implementation deficit identified by Schlosberg (2013) represents the gap between environmental justice theory and its real-world application.

The main theme centres on how equity varies across different dimensions of justice. Distributive justice remains the most contested, as displaced populations frequently face inequitable access to housing, healthcare, and education. Displaced groups in Bangladesh and Kenya experienced poor distributive mechanisms that pushed them into informal or poorly resourced areas, which perpetuated their vulnerability. The implementation of procedural justice in Fiji showed some advancement, but achieving genuine participation from women and Indigenous communities remained challenging. The distributive justice framework in Germany operated better, yet the country failed to recognise climate-related displacement through official legal or acknowledgement in policy-making. The evidence indicates that equity functions as a complex system of multiple dimensions, in which different nations emphasise or disregard specific components.

The research reveals how worldwide climate migration governance systems contain built-in structural inequalities. Wealthy nations, including Germany, maintain ample resources, yet they avoid both official recognition and formal responsibility for climate-driven migration. Vulnerable states, including Bangladesh and Fiji, bear the greatest responsibility while their resources remain limited. The global climate governance system demonstrates a clear North-South equity divide, which forms a key point of dispute between UNFCCC negotiations and the Global Compact for Migration (Betts, 2021; Biermann & Boas, 2022). The fragmented governance system creates obstacles to equity because displaced people face complex legal and institutional frameworks without international coordination, which was evident in all four studied cases.

The temporal aspect of equity stands as an important additional insight in the discussion. Climate migration develops throughout lengthy periods, yet governmental responses typically focus on present-day emergencies rather than long-term solutions. The absence of enduring plans in Bangladesh and Kenya led to emergency relief programs that delivered temporary assistance, which failed to resolve systemic inequalities. Fiji's relocation programs demonstrated better future planning, yet their sustainability through time proved challenging. The well-resourced German government encountered problems when trying to match short-term asylum requirements with long-term integration strategies. Barnett and McMichael (2018) identify that climate migration equity needs a "forward-looking justice framework," which both predicts upcoming displacement events and establishes institutional safeguards before emergencies occur.

Community agency plays an essential role when developing fair outcomes, according to the analysis. The evidence shows that displaced people function more effectively as active agents in relocation projects because Bangladesh and Fiji demonstrated through their community relocation programs and participatory planning that agency increases both legitimacy and effectiveness. Policies improve their outcomes through procedural and recognition justice because they align with local requirements and cultural traditions, and social identities. Top-down governance approaches that fail to consider the actual experiences of vulnerable groups risk failure, according to the observed neglect of such dimensions in Kenya and Germany.

The discussion shows that true equity in climate-induced migration continues to be an idea rather than a reality. National and international frameworks recognise its importance, but governance fragmentation and resource disparities, along with political reluctance, maintain barriers to achieving it. Equity needs to become a foundational element that integrates into all policy rhetoric and institutional frameworks and procedural systems that control migration at local, national, and global scales.

6. Policy Recommendations

The research demonstrates that current efforts to promote fairness in climate displacement solutions fail to fully address the needs of affected populations. The growing use of justice principles in policy frameworks remains theoretical because they fail to produce meaningful benefits for displaced people. Multiple recommendations should be implemented through coordinated actions across all levels of governance, starting from local communities up to national regions and worldwide.

National governments need to make equity the fundamental principle that guides migration and adaptation strategy development. The implementation of equity indicators requires national governments to move past empty statements about justice and establish measurable benchmarks in their NAPs, resettlement guidelines, and integration frameworks. Governments need to practice distributive justice through resource distribution that favours vulnerable groups in housing, healthcare, and education access, and procedural justice through genuine involvement of displaced people in planning activities. The implementation of recognition justice needs to become operational through programs that protect cultural identities and integrate Indigenous knowledge into relocation and adaptation activities. The relocation frameworks implemented by Fiji demonstrate important methods for institutionalising equity, which other nations should adopt and develop further.

The implementation of cross-border and regional coordination mechanisms stands as a vital requirement. Migration patterns move across different countries, but governance systems for migration remain separate and based within national territories. A system of regional task forces that follows the model of the African Union's Kampala Convention and Latin American regional compacts would improve both coordination and burden-sharing. The bodies need to integrate governmental representatives together with civil society members and displaced population representatives so that state-centred priorities do not eliminate equity considerations. The current European Union discussions about migration responsibility-sharing demonstrate both the obstacles and potential solutions for creating fair regional response systems.

Climate-induced migration requires global governance systems to adapt their frameworks for better explicit responses. The UNFCCC and the Global Compact for Migration lack any binding legal structure that protects the rights of people displaced by climate change. The Task Force on Displacement under the Warsaw International Mechanism has advanced displacement initiatives, but stronger institutional backing remains necessary. The Loss and Damage Fund, along with other global financing mechanisms, must integrate equity principles so that funds reach vulnerable populations in low-income states, which lack protection capabilities for displaced communities. The financial support system requires predictability and transparency while remaining accessible to community-level actors to prevent the bureaucratic obstacles that have hindered climate finance until now.

The community needs new methods to boost both agency and accountability mechanisms at the local level. The establishment of monitoring systems at the community level enables displaced populations to evaluate service delivery while simultaneously identifying gaps that require government and international actor accountability. The involvement of local people in decision-making processes creates both legitimacy and effectiveness because policies that represent actual conditions of displaced groups achieve better results. The relocation pilot projects in Bangladesh show that school planning and healthcare delivery become more effective when communities participate actively, which results in better access and improved outcomes.

The academic community, together with policy researchers, needs to expand its knowledge base about fairness in climate migration through continuous research efforts. Researchers need to collect detailed information about displaced populations while conducting multiple studies that follow people over time and compare successful practices between different regions. Researchers need better partnerships with communities and policymakers to close the gap between theoretical knowledge and real-world application so equity can become a practical standard instead of an unreachable ideal.

In sum, the advancement of equity in climate-induced migration demands coordination at multiple levels, together with the institutionalisation of justice principles in national strategies and a strong dedication to community agency. The absence of these measures will maintain the existing vulnerabilities and deepen inequalities, which will undermine both climate adaptation legitimacy and global climate justice commitments.

7. Conclusion

Human mobility due to climate change receives growing recognition as a factor, but governance systems for climate-induced migration show fragmented and inequitable patterns. The comparative study of Bangladesh, Fiji, Kenya, and Germany reveals that although equity serves as a common principle, its implementation remains inconsistent and incomplete. People who are displaced find themselves facing barriers to housing access and educational opportunities, as

well as healthcare services and decision-making participation, which proves the ongoing gap between theoretical commitments and actual results.

The study reveals three essential findings. The understanding of equity requires recognition of three dimensions, which include distributive and procedural justice as well as recognition justice. Different nations focus on certain dimensions of equity while ignoring others, which produces inconsistent protection for at-risk populations. The lack of equity is present in both low-resource states and high-resource countries because these nations struggle to share responsibility and recognise displaced populations. The lack of proper coordination mechanisms between regions and countries maintains systemic inequalities because displaced populations must handle multiple uncoordinated national systems.

The solution to these problems demands a complete transformation of migration governance systems for achieving equity. National strategies need to include justice principles as established standards, regional frameworks require better burden-sharing mechanisms, and global institutions must increase their legal and financial commitments. The empowerment of communities stands as an essential factor because their agency makes adaptation measures both legitimate and effective.

Climate justice stands inseparable from the need to shield people who leave their homes due to environmental transformations. Adaptation needs equity as an essential foundation, which ensures both justice and sustainability. The global community becomes capable of promoting justice together with resilience and dignity across international borders through the institutionalisation of equity at every governance level, starting from local communities up to international frameworks.

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Paper 11

Spatiotemporal Dynamics of Forest Cover Change and Carbon Stock in Rema-Kalenga Wildlife Sanctuary, Bangladesh: A Remote Sensing and InVEST Model Approach

Asadullah Ibn Masood

Abstract

Between 2000 and 2024, Rema–Kalenga Wildlife Sanctuary’s forest cover contracted sharply while tea cultivation expanded dramatically. Forest area fell from roughly 8309 hectares to about 4750 hectares (a net loss of 3559 ha, –42.8%). In contrast, tea gardens grew from only ~583 ha to ~5047 ha (+4464 ha, +765%) in the same period. The Normalised Difference Vegetation Index (NDVI) exhibited a mixed trend: mean NDVI climbed from ~0.198 (2000) to a peak of ~0.311 in 2009 and then fell to ~0.238 by 2020 before partially rebounding to ~0.269 by 2024. These greenness fluctuations did not track forest loss directly, reflecting the influence of other green cover (e.g., tea) and seasonal factors. Total ecosystem carbon stock (aboveground and soil pools) likewise fluctuated in step with forest dynamics. Carbon rose slightly from $\sim 1.688 \times 10^6$ t (2000) to $\sim 1.710 \times 10^6$ t by 2004, then declined sharply to a minimum of $\sim 1.372 \times 10^6$ t by 2014 (–12.8% net loss from 2000 to 2024). Carbon rebounded with forest regrowth to $\sim 1.683 \times 10^6$ t by 2020 before declining again ($\sim 1.473 \times 10^6$ t by 2024). Under a Business-As-Usual (BAU) scenario, projections show forest shrinking to ~3278 ha by 2050 and ~3076 ha by 2075 (with tea expanding to ~6315 ha), driving carbon down to $\sim 1.311 \times 10^6$ t by 2075. In contrast, a conservation-oriented (sustainability) scenario retains substantially more forest (~3845 ha in 2050, ~3789 ha in 2075) and carbon ($\sim 1.418 \times 10^6$ t in 2050, $\sim 1.413 \times 10^6$ t in 2075). Thus, active protection could slow projected losses by over 15–20% of forest area by 2075. These results indicate that tea plantation expansion is the main driver of deforestation in RKWS, with significant implications for future greenness and carbon storage.

1. Introduction

Bangladesh is a small South Asian country (about 147,570 km²) with one of the highest population densities in the world. Housing roughly 175 million people, Bangladesh's density exceeds 1,350 persons per km² (Worldometer, 2025). This extreme human pressure coincides with a very limited forest estate – only about 13% of the land was forested in recent assessments (Global Forest Watch, 2023). By comparison, global forest cover is roughly 31% (Global Forest Resources Assessment 2020, 2020) (and expert groups advocate an ideal $\geq 25\%$ forest cover for ecological stability). Numerous studies warn that Bangladesh's forests face extreme anthropogenic pressure, driven by its large population and rural dependence on wood (Muhammed et al., 2008). Indeed, deforestation and degradation have accelerated in recent decades. For example, one long-term Landsat analysis found an average loss of approximately 0.46% of Bangladesh's forest per year from 1930-2015 (peaking at $\sim 0.75\%$ per year in 2006–2014) (Reddy et al., 2016). Such losses are often linked to fuelwood extraction, illegal timber cutting, infrastructure, and agricultural expansion (especially in accessible areas) (Chowdhury et al., 2014). Bangladesh's largest forest, the Sundarbans mangrove, alone lost 18.81 km² of cover between 2000 and 2021, with projections showing continued loss by 2031 (Faruque et al., 2022). In short, Bangladesh's current forest area is well below international targets, and deforestation is a key factor exacerbating the country's climate vulnerability (M. S. A. Khan & Rahman, 2021; Ahammad et al., 2019).

These threats are compounded by insufficient monitoring and governance. Illegal logging and land conversion often go undetected, and enforcement is weak in many areas. Studies note that the lack of timely data on forest conditions hinders management, an issue especially severe in Bangladesh (Sumiya et al., 2024). In situ forest surveys are costly and slow, so satellite-based monitoring is needed to provide regular, objective data on forest health across the country (Kennedy et al., 2009). Without such monitoring, destructive activities like unauthorised clearing for agriculture or settlements proceed with little check (Huntington et al., 2017).

The northeastern Sylhet Division of Bangladesh contains virtually all of the country's remaining tropical hill forests. Unlike the flat plains, Sylhet's hilly landscape supports dense subtropical evergreen forests that harbour rich biodiversity. Several small protected areas in Sylhet, such as Lawachara and Satchari National Parks and the Rema-Kalenga Wildlife Sanctuary, act as critical refuges for this ecosystem. Protected areas in Bangladesh remain minimal (about 18 national parks and 20 wildlife sanctuaries, covering only $\sim 4.3\%$ of the land) (Mukul et al., 2008; Muhammed, Koike, & Haque, 2008). In Sylhet, these parks conserve the last fragments of Indo-Burma biodiversity. For instance, the Rema-Kalenga Wildlife Sanctuary (Habiganj district) spans roughly 1,795 hectares of mixed evergreen forest (Nishorgo, 2013). (See figure below.) It was created in 1982 to protect a high-biodiversity forest near the Indian border. Rema-Kalenga is home to many rare species (e.g., Bengal slow loris, various macaques, and the critically

endangered white-rumped vulture) (Nishorgo, 2013). Its preservation is seen as vital for greater Sylhet's ecological balance.

Greater Sylhet's protected forests help maintain Bangladesh's overall forest ecosystems by sequestering carbon, regulating water flows, and preserving wildlife corridors. For example, forest ecosystems in this region accumulate substantial carbon; recent field measurements estimate Rema-Kalenga's aboveground carbon stock at about 210 tonnes C per hectare (M. N. I. Khan et al., 2024). This is on par with the values reported from other protected forests in Bangladesh (233 tC/ha) (Majumder et al., 2018). Thus, Rema-Kalenga and similar sanctuaries not only harbour biodiversity but also serve as important carbon reservoirs, mitigating climate change. Given Bangladesh's rapid land-use change, there is an urgent need to monitor how Land Use and Land Cover (LULC) changes affect such forest carbon stocks and what future scenarios may hold.

2. Literature Review

2.1 Remote Sensing for Forest Monitoring

Remote sensing has emerged as an indispensable tool for mapping land cover and monitoring forest health. Satellite imagery (e.g., Landsat, MODIS, Sentinel, SPOT) and aerial data allow analysts to survey large or inaccessible forest areas repeatedly over time (Ishtiaque et al., 2020). Modern forest assessments routinely use Normalised Difference Vegetation Index (NDVI) and related spectral indices to quantify canopy greenness and detect changes. NDVI is computed from red and near-infrared satellite bands to indicate vegetation vigour; drops in NDVI signal deforestation or degradation. For instance, NDVI time series have been used to identify Sundarbans mangrove loss and to project further decline (Faruque et al., 2022). A review of Bangladeshi forest studies confirms that NDVI (alone or in composite indices) is “extensively used” for monitoring forests and degradation (Sumiya et al., 2024).

Remote sensing methods (unsupervised and supervised classification, machine learning) have been widely applied to detect land-cover change. In Bangladesh, many studies have used Landsat imagery for forest cover maps due to its long archive and free availability (Ishtiaque et al., 2020). A few analysts have also employed higher-resolution sensors or time series (MODIS, Sentinel, etc.) to track forest dynamics (Hernández-Clemente et al., 2019). These approaches allow quantification of deforestation rates, fragmentation, and habitat conversion over decades. For example, image classification combined with NDVI analysis has revealed significant forest-to-agriculture conversion patterns in both the Sundarbans and the hill forests (Ishtiaque et al., 2020).

Bangladesh-specific reviews note that while remote sensing has been extensively used for LULC mapping and change detection, these efforts have mostly focused on cover extent (especially

mangroves) rather than comprehensive forest health assessments (Ishtiaque et al., 2016). Only a few studies explicitly evaluate tree health or biomass changes. Moreover, most remote-sensing (RS) studies target the Sundarbans, with hill forests (like Sylhet) remaining relatively understudied (Redowan et al., 2020). The literature emphasizes that integrating NDVI-based mapping with other field data is crucial for forest monitoring, yet such integration is currently limited in Bangladesh (Ahammad et al., 2019). In short, remote sensing is recognized as essential for forest monitoring, but Bangladesh needs more multi-index and multi-temporal studies in its upland forests.

2.2 LULC Change and Vegetation Indices

LULC analysis via remote sensing quantifies how forest, agriculture, and other land classes shift over time. Studies apply NDVI and other indices (e.g., EVI, SAVI) to classify images into forest, water, urban, etc. Accuracy is typically validated against ground data (Dampha, 2021). Recent work in Bangladesh followed this approach: Ahmad et al. (2024) classified Sundarbans into “forest” vs. non-forest using NDVI thresholds and found that the Sundarbans’ thick, dense mangrove forest area decreased from 65% in 1970 to 59% in 2020. They then applied a cellular-automata (CA-ANN) model to project simulations for 2030-2050, which shows that mangrove coverage is likely to decline from 63.5% to 56.7%, predicting a continued loss of 628 km² if no remedial action is taken. Such studies demonstrate the power of combining NDVI-based classification with change modeling.

In upland Bangladesh, several LULC studies have mapped forest cover changes as well. For example, Hossain and Numata (2021) analyzed Landsat images for Rema-Kalenga Sanctuary, showing that the forest area grew during a 1994–2005 plantation drive but then shrank (2005–2018) as agricultural plots expanded under new land-zoning policies. Their results highlight that forest-agriculture trade-offs drive LULC. Other local studies (e.g., in Rangamati and Sal forests) similarly find that NDVI-based change detection can pinpoint hotspots of deforestation and afforestation. Overall, multi-temporal LULC mapping using NDVI has become a cornerstone method for identifying past trends and training predictive models in Bangladesh’s forest regions.

2.3 Carbon Stock and Sequestration in Bangladesh

Forests store carbon in biomass (above- and below-ground) and soils, suggesting that quantifying these stocks is essential for climate policy. In Bangladesh, this is doubly important due to the Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+) and carbon-credit frameworks. However, peer-reviewed carbon assessments remain limited. Majumder et al. (2018) reviewed Bangladesh’s forest carbon research and found that most studies focus narrowly on allometric equations for biomass, with data drawn largely from the Sundarbans and the Chittagong Hills. Strikingly, they noted no published surveys of carbon stocks in the protected areas of Sylhet Division—a glaring gap given these areas contain much of the country’s remaining primary forest.

Where measurements do exist, Bangladesh's upland forests hold substantial carbon. For instance, A. Khan et al. (2025) measured aboveground biomass in Rema-Kalenga (RKWS) and Khadimnagar National Park (KNP). They reported RKWS stocks of ≈ 165.9 tC/ha (aboveground) versus 109.95 tC/ha at KNP. Both values are within the global range for tropical moist forests (often 100–200 tC/ha) (Köhl et al., 2015). The authors also cite official figures (BFD) of ~ 195.8 tC/ha for Bangladesh protected forests in general (Majumder et al., 2018). Thus, Rema-Kalenga's carbon density is comparable to other high-quality forests. These results underscore that preserving and restoring Sylhet's forests can significantly affect national carbon budgets.

Most carbon studies in Bangladesh have been small-scale (e.g., plot inventories) rather than landscape-level. There is no long-term forest carbon monitoring program. This lack is problematic; without knowing baseline stocks and trends, Bangladesh cannot verify emissions reductions from forest protection. Recent policy analyses emphasise that accurate carbon accounting (for community forestry, REDD+, etc.) requires improved baseline data (Majumder et al., 2018). In summary, while some biomass measurements exist (mainly in mangroves and certain reserves), Bangladesh has relatively sparse data on historical land-cover carbon stocks, especially for non-mangrove forests.

2.4 Ecosystem Services and Carbon Sequestration

Forest carbon is a key ecosystem service. By sequestering CO₂, these ecosystems mitigate climate change while providing co-benefits (biodiversity, water regulation). This is explicitly recognised in Bangladesh's climate strategy (e.g., REDD+ readiness). Analysts have calculated that Bangladesh's forestry sector could make significant emission reductions if forests are conserved or restored. Booth (2012) noted that deforestation directly worsens flooding and salinity impacts, implying climate feedback. Therefore, both understanding present carbon stocks and projecting future sequestration are crucial national priorities.

2.5 Predictive Land-Use and Carbon Modelling

Understanding historical change is valuable, but predicting future scenarios is equally important for planning. Modelling future LULC and carbon under different assumptions helps policymakers visualise outcomes of current actions or policies. Across the world, land system models (FLUS, CLUE, CA-Markov, etc.) are routinely coupled with carbon calculators to project future carbon storage. For example, a recent study in China's Chang-Zhu-Tan region used a Future Land Use Simulation and Integrated Valuation of Ecosystem Services and Tradeoffs (FLUS-InVEST) framework to simulate LULC change under three scenarios (natural, ecological-priority, and urban-priority). They found that by 2035, the "urban development" scenario lost 150.93×10^6 tC, while the strict ecological scenario lost only 24.26×10^6 tC (Sun & Liu, 2024). This "what-if" approach clearly showed the carbon cost of uncontrolled urbanisation. The key insight is that model-driven scenarios can reveal how policy choices or demographic trends might affect future forest cover and carbon stock (Zheng et al., 2019).

In Bangladesh, similar predictive modelling has been rare. A notable exception is the Sundarbans study mentioned earlier (Ahammad et al., 2019), which used a CA-ANN to predict 2031 mangrove cover. Apart from mangroves, no published studies have explicitly used scenario models for Bangladesh's hill forests. This represents a research gap: without scenario analysis, planners lack a vision of potential futures (e.g., continued deforestation vs. active conservation). Given the country's rapid development and land pressure, it is important to project, for example, how expansion of agriculture or transport infrastructure in Sylhet might impact forests and carbon stocks a decade from now.

2.6 The InVEST Model for Carbon Assessment

One of the most popular tools for spatially explicit carbon accounting is the InVEST model suite, developed by Stanford's Natural Capital Project. Its carbon module is designed to estimate total carbon storage across a landscape given a land-cover map. InVEST requires a classified LULC map and carbon density values for each land-cover type (aboveground biomass, belowground biomass, soil carbon, and dead organic matter) as inputs. The model then sums carbon pools to calculate total carbon stock in each pixel and across the whole area (Imran & Din, 2021). Importantly, InVEST is spatially explicit; it produces mapped outputs (e.g., tonnes of carbon per hectare, or total carbon in each region) and can also project sequestration differences between scenarios if LULC maps for each scenario are provided (Nelson et al., 2009).

In practice, InVEST has been applied globally to assess forest carbon. For example, studies have used InVEST to value carbon in Indian protected areas and Latin American forests, often for REDD+ planning. It can produce either biophysical (tons C) or economic outputs (via carbon pricing) (Seppelt et al., 2013). In Chang-Zhu-Tan, for example, InVEST quantified how carbon storage changed under each future scenario (Sun & Liu, 2024). In Bangladesh's context, applying InVEST would allow researchers to convert a classified LULC map of Rema-Kalenga (and surroundings) into a detailed carbon stock map. The model could then be run on maps for past, present, and future scenarios to estimate how carbon stocks have changed and might change. Such modelling is useful for quantifying ecosystem service outcomes (carbon sequestration) under deforestation or reforestation scenarios (Tadese et al., 2023).

However, no peer-reviewed studies have yet applied InVEST to Bangladesh's hill forests. The existing carbon and LULC research suggests an obvious opportunity. With robust LULC data (from remote sensing) and carbon density inputs (from field measurements or literature), InVEST could fill current gaps. It would provide a reproducible framework for sustainable planning: for instance, estimating how plantation efforts or community forestry might increase Rema-Kalenga's carbon stock, or how unregulated clearing might deplete it.

2.7 Research Gaps and Rationale for the Study

In summary, the literature indicates several key points relevant to this paper. Bangladesh's forests are under intense pressure. High population density (1350/km²) and limited forest cover (13% of land) combine with weak enforcement to drive deforestation (Global Forest Watch, 2023).

The forests in the greater Sylhet area are crucial but understudied. Protected areas (e.g., Rema-Kalenga) hold rich biodiversity and high carbon (e.g., 165.9 t C/ha at Rema-Kalenga) (A. Khan et al., 2025), yet most RS/forest-health research has focused on the Sundarbans (Sumiya et al., 2024). Remote sensing (NDVI, LULC mapping) is key to monitoring. Although satellite indices have been used to map Bangladesh's forests (Faruque et al., 2022), studies specifically assessing forest health and change in hill forests are scarce.

Carbon stock data is sparse. Carbon pools in Bangladesh's forests have been estimated via allometric biomass models (Majumder et al., 2018), but broad-scale assessments (especially historical) are lacking. For example, no systematic carbon mapping has been done for Rema-Kalenga or similar sanctuaries.

Future scenarios have not been modelled. Few studies project future LULC or carbon in Bangladesh's forests, except one on the Sundarbans (Ahammad et al., 2019). Hence, planners lack a vision of the long-term consequences of current trends.

Given these gaps, this paper will combine remote sensing analysis of historical LULC with carbon stock modelling (using InVEST) for Rema-Kalenga WS. Firstly, past forest cover changes are mapped (using Landsat, NDVI, and classification), and historical carbon stocks are quantified. Then, future land-use scenarios are developed (e.g., BAU vs. sustainability approach) and InVEST is used to estimate the associated carbon stock under each scenario. This approach follows the suggestion of the literature that quantitative scenario modeling is needed to visualize environmental outcomes (Tadese et al., 2023).

Overall, the literature underscores the importance of satellite-based LULC/NDVI analysis and carbon accounting for Bangladesh's forest conservation (SDG 15). By focusing on the Rema-Kalenga Sanctuary, a representative and critical greater Sylhet forest fragment, this work will address the noted gaps. It will provide a detailed case study of land-cover dynamics and carbon storage, informing how Bangladesh's remnant hill forests contribute to ecology and climate. The principal research question is: "How have past land-cover changes in Rema-Kalenga WS affected its carbon stock, and what do future land-use scenarios imply for its carbon sequestration?"

This question extends prior suggestions by explicitly linking LULC trends to ecosystem service (carbon) outcomes through spatial modelling.

3. Methodology

3.1 Study Area

The area of interest chosen for this study is the Rema-Kalenga Wildlife Sanctuary (RKWS) and its adjacent impact zone. The sanctuary is located in the Chunarughat Upazila (sub-district) of Habiganj District in the Sylhet Division of Bangladesh (Nishorgo, 2013). The study area is located between 353085 m E and 364785 m E, and 2665125 m N and 2683275 m N. All coordinates are based on the World Geodetic System 1984 (WGS84) datum and are presented in the Universal Transverse Mercator (UTM) Zone 46N projected coordinate system (EPSG:32646) (Fig. 2). RKWS is a protected area and a wildlife sanctuary that lies within the Sylhet Forest Division.

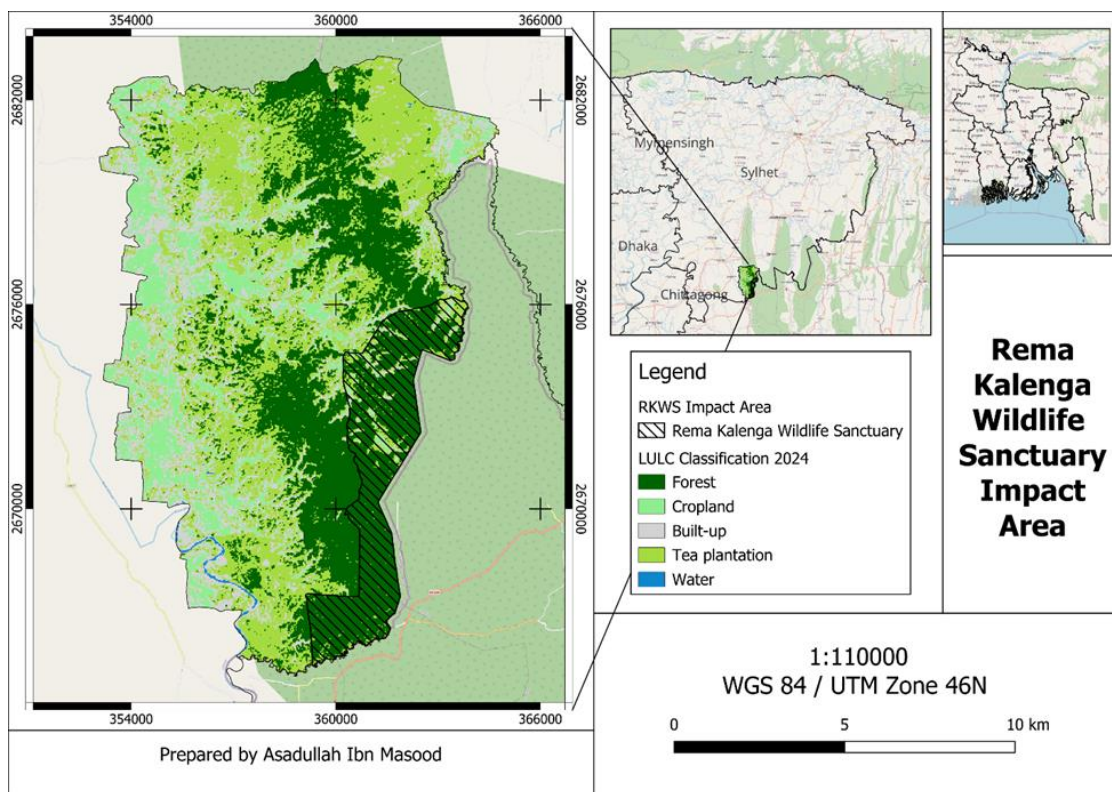


Figure 1: Rema Kalenga Wildlife Sanctuary impact area

The forest is home to over 600 species of plants, many of which are nationally red-listed, along with over 200 bird and mammal species (Nishorgo, 2013). This thriving ecosystem and biodiversity harbour ideal conditions for storing a great deal of carbon through above- and below-ground processes. The aforementioned impact zone surrounding the RKWS boundary was clipped through georeferencing a map from the United States Agency for International Development (USAID)-funded Climate Resilient Ecosystems and Livelihoods (CREL) project (Rahman & Miah, 2017). The area is bordered by reserve forest along its northwestern boundary,

tea plantations on its southwestern boundary, and the Indian state of Tripura along its southern and eastern boundaries (Mohammed et al., 2023).

3.2 Data Acquisition

All of the satellite imagery data shown in Table 1 was taken from the USGS Earth Explorer website, which is readily accessible by anyone through opening an account on the site with the required information. Only open-source and freely available data and software were used for the entirety of this research so that the methods can be replicated.

Table 1: Satellite data sources for GIS-based analysis

Landsat Name	Sensor	Sat. Path aerial	Sat. Row	Spatial Resolution	Image Captured Date
5	MSS/TM	136	43	30	12 January 2000
5	MSS/TM	136	43	30	22 November 2004
5	MSS/TM	136	43	30	20 November 2009
8	OLI/TIRS	136	43	30	20 December 2014
8	OLI/TIRS	136	43	30	19 January 2020
9	OLI-2/TIRS-2	136	43	30	23 December 2024

To administer a multitemporal assessment of the area of interest, a 5-year interval between each of the satellite image collections was implemented. The images were searched for using multiple criteria such as the preferred time of year and the acceptable cloud cover limit, which was set at less than 10%. The time of year was estimated to be in the drier season with minimal cloud coverage for the Sylhet region, so between November and January (Di Nunno et al., 2022).

3.3 GIS-Based Analysis

This study's primary component uses open-source GIS software (QGIS 3.40.6-Bratislava) for processing all the remotely sensed imagery. The same software was used to assess the LULC of the area of interest as well as for developing the future projection scenarios. The images were preprocessed and prepared for different analyses by clipping according to the shapefile made from the georeferenced map mentioned previously.

4. NDVI Calculation

NDVI is a remote sensing metric that compares the amount of near-infrared (NIR) light reflected by plants to estimate vegetation health. The index value can range from -1 to +1 and can be calculated using the raster calculator feature in QGIS as:

$NDVI = (NIR - Red) / (NIR + Red)$, where NIR stands for the reflectance in the near-infrared spectrum and Red stands for the reflectance in the visible red spectrum (Huang et al., 2020).

Upon calculating the NDVI for each of the years, a map (Figure 3) showcasing the NDVI change over time was generated using the single-band pseudo colour symbology to make the change more visible.

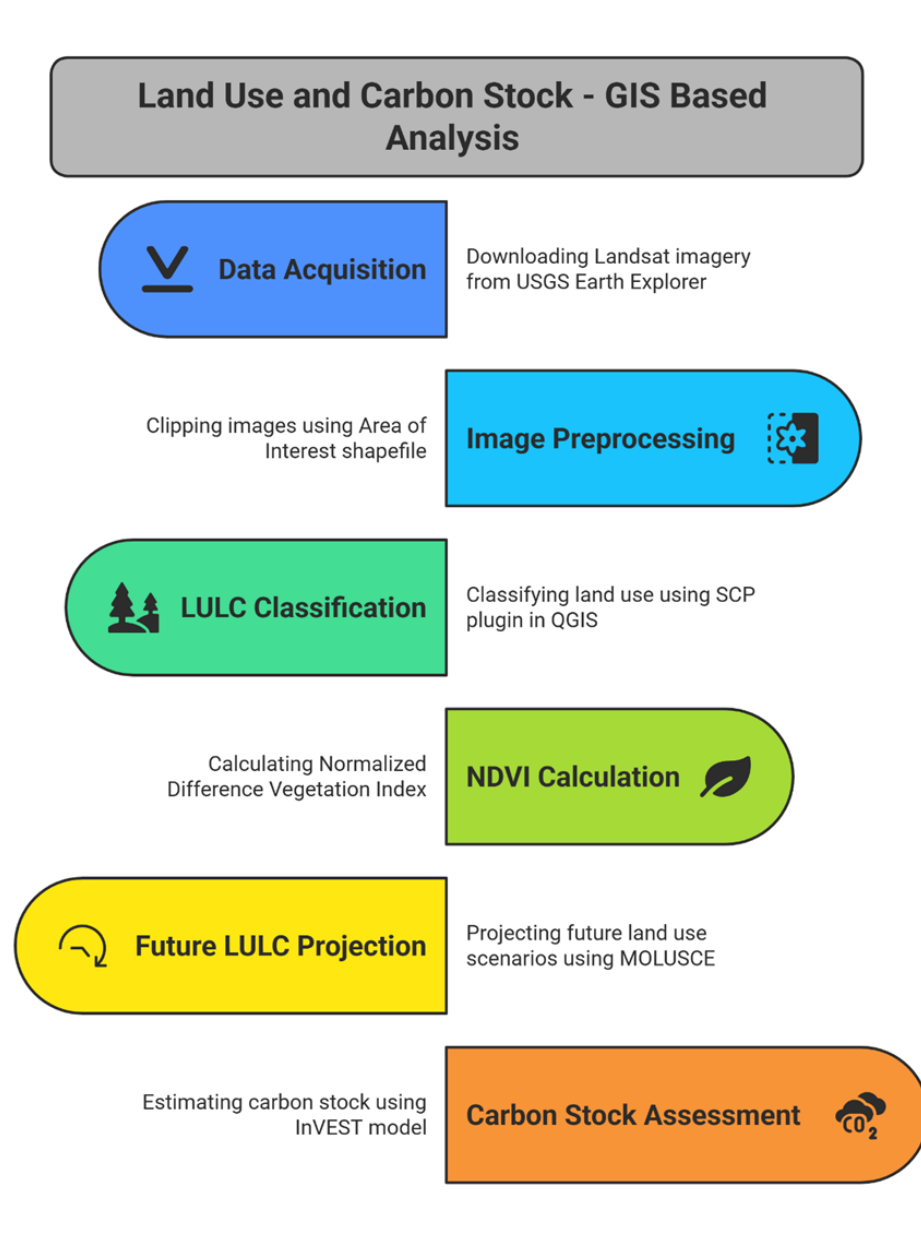


Figure 2: A schematic model for GIS-based analysis (Author's Illustration)

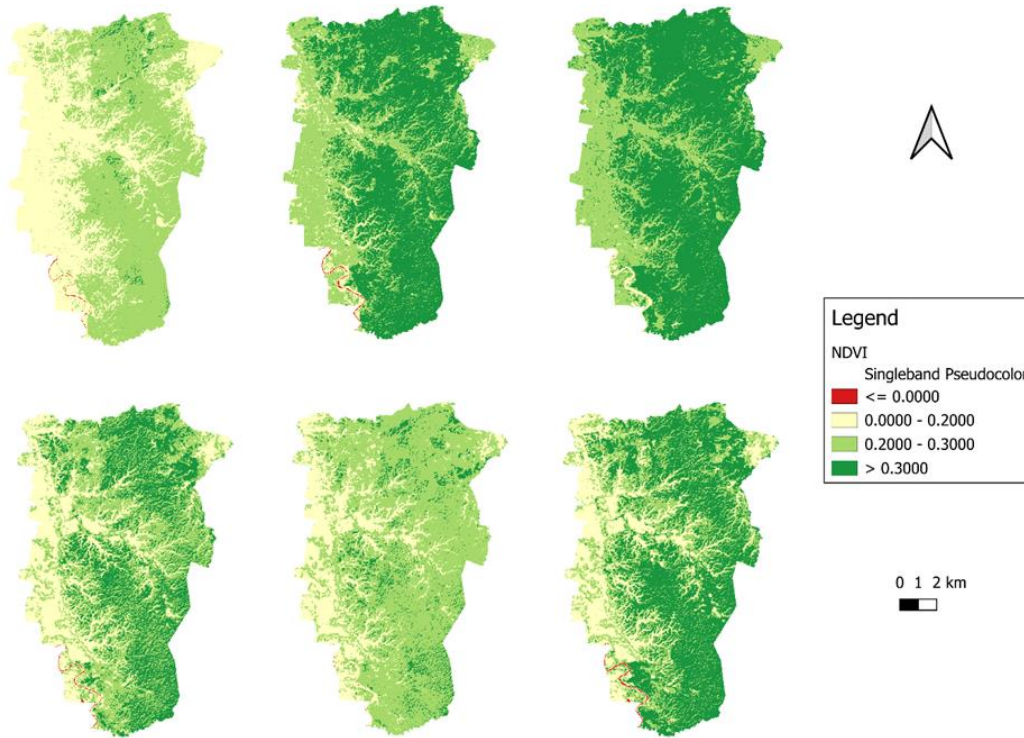


Figure 3: NDVI maps for the year 2000 - 2024

5. LULC Classification

LULC change estimation over the years was one of the primary objectives of this study, as it is crucial for determining the different land use types existing in the area and assigning the carbon pool value accordingly. By observing the satellite images thoroughly, the area was divided into five main categories of land: forest, cropland, water, built-up, and tea plantations. For the classification, supervised classification was chosen for this study due to its robustness and replicability. Using a supervised classification approach, example locations of each category were selected as training data. A classification algorithm then assigned every pixel in the images to one of the land cover categories based on its spectral characteristics. An accuracy assessment was also conducted for the latest year using Google Satellite Maps as the reference map, due to its much higher resolution compared to that of Landsat, which is only 30 m.

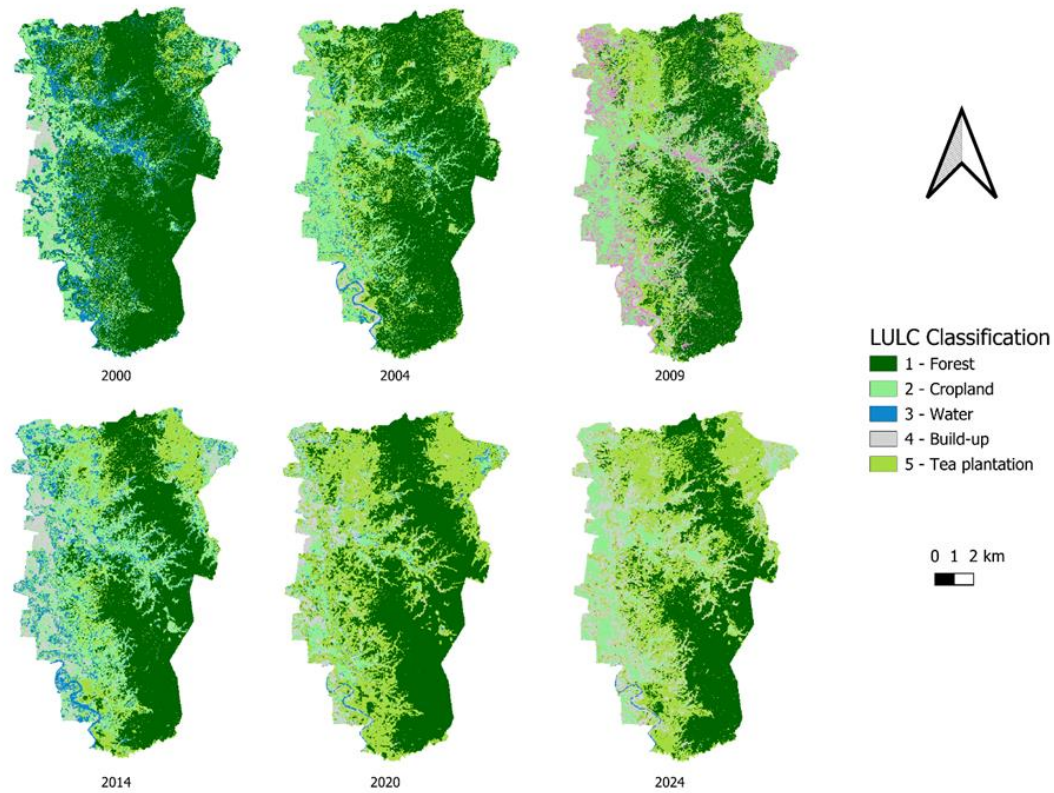


Figure 4: LULC Classification Maps

5.1 Future Projection

To explore how the landscape might change, a land-change modelling technique was applied to project LULC under future scenarios. Based on the observed changes from 2000 to 2024, two scenarios were created for later years (e.g., 2050 and 2075). In one scenario (BAU), current trends continue without new conservation actions. In the other scenario (sustainability-focused), the protected status of RKWS is assumed to have a stronger effect, limiting changes within the sanctuary. The model incorporated various spatial factors (such as proximity to roads, settlements, elevation, and slope) as drivers of change. For each scenario, it then iteratively simulated land cover transitions, producing projected LULC maps for each target year. These projected maps illustrate possible futures rather than precise predictions.

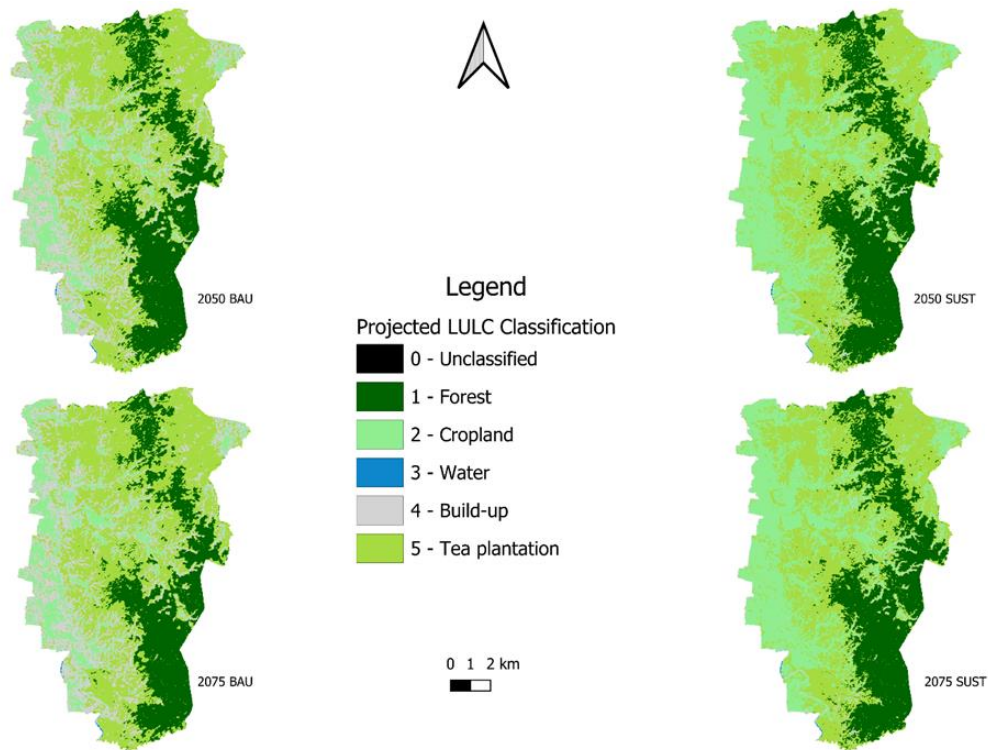


Figure 5: Projected LULC maps for different scenarios

Finally, carbon storage associated with each land cover map was estimated using the InVEST carbon model (Khan et al., 2024). Each land cover category was assigned carbon density values (for aboveground biomass, roots, soil organic carbon, and dead organic matter) based on published values for similar forest ecosystems (Kalita et al., 2016). Next, the classified LULC maps and these carbon values were input into InVEST to calculate total carbon stock in the study area for each year and scenario. This approach enabled an assessment of how carbon storage in RKWS changed over time under each scenario. In this way, the magnitude of carbon stored under the different land-use scenarios could be compared as an approximate view of the carbon implications of land cover change.

Table 2: Carbon pool for different land use classes

<i>Code</i>	<i>LULC Name</i>	<i>C above</i>	<i>C below</i>	<i>C soil</i>	<i>C dead</i>
1	Forest	110	22	40	5
2	Cropland	2	0.5	40	1
3	Water	0	0	10	0
4	Built-up	5	1	20	1
5	Tea Plantation	45	10	40	2

6. Results

Between 2000 and 2024, the land cover of Rema-Kalenga Wildlife Sanctuary (RKWS) changed dramatically. Forest area declined sharply while tea plantations expanded. For example, Figure 5 shows that forest cover fell from about 8308.5 ha in 2000 to 4749.5 ha in 2024, a net loss of 3559 ha (−42.8%). In contrast, the tea plantation area grew from 583.1 ha to 5047.1 ha (+4464 ha, +765.2%) over the same period. Most of the forest decline occurred early (2000–2009) and again in the last four years. Between 2000–2004, the sanctuary lost ~895 ha of forest (−10.8%) and lost another ~1789 ha by 2009 (−24.1%), even as the tea area grew by 1945 ha. A smaller forest loss occurred 2009–2014 (−5.0%), while the tea area dipped (−720 ha). Forest rebounded modestly by 2020 (+757 ha, +14.2%), then fell again by 2024 (−1351 ha, −22.1%), whereas tea expanded strongly from 2014–2020 (+3285 ha) before a slight decline. Thus, overall, tea expansion largely occurred at the expense of the forest.

Table 3: Change in Land Use / Land Cover Classes (ha) over the years

<i>Year</i>	<i>Forest</i>	<i>Cropland</i>	<i>Water</i>	<i>Built-up</i>	<i>Tea Plantation</i>
2000	8308.53	3062.79	1635.3	426.15	583.11
2004	7413.57	3157.38	538.74	378.54	2527.65
2009	5624.91	3356.01	1849.41	372.69	2812.86
2014	5342.4	4134.24	1328.49	1116.9	2093.85
2020	6100.02	1122.93	321.93	1092.24	5378.76
2024	4749.48	1780.02	39.96	2399.31	5047.11

Other classes also changed. Cropland fluctuated: it rose from ~3063 ha (2000) to ~4134 ha (2014), then sharply fell to 1123 ha by 2020. Built-up area roughly quintupled, from 426 ha to 2399 ha (2000–2024). Water bodies plummeted (from 1635 ha in 2000 to only 39.96 ha in 2024). These trends (Figure 5) indicate intense land-use transformation: forests and water were converted largely into tea estates, cropland, and settlements.

The NDVI showed a mixed pattern (Figure 6). Mean NDVI rose from ~0.198 in 2000 to a peak of ~0.311 in 2009. It then declined to ~0.238 by 2020 before rising again to ~0.269 by 2024. In percentage terms, NDVI increased ~57% from 2000 to 2009, then fell ~23% by 2020, then recovered ~13% by 2024. These fluctuations do not mirror the steady forest loss (42.8% decline). The highest NDVI (2009) coincided with low forest cover, while some periods of forest recovery (2014–2020) saw NDVI drop. Chart 2 emphasizes that NDVI did not steadily decline with forest area, suggesting other vegetation (e.g., tea gardens) or factors influenced greenness.

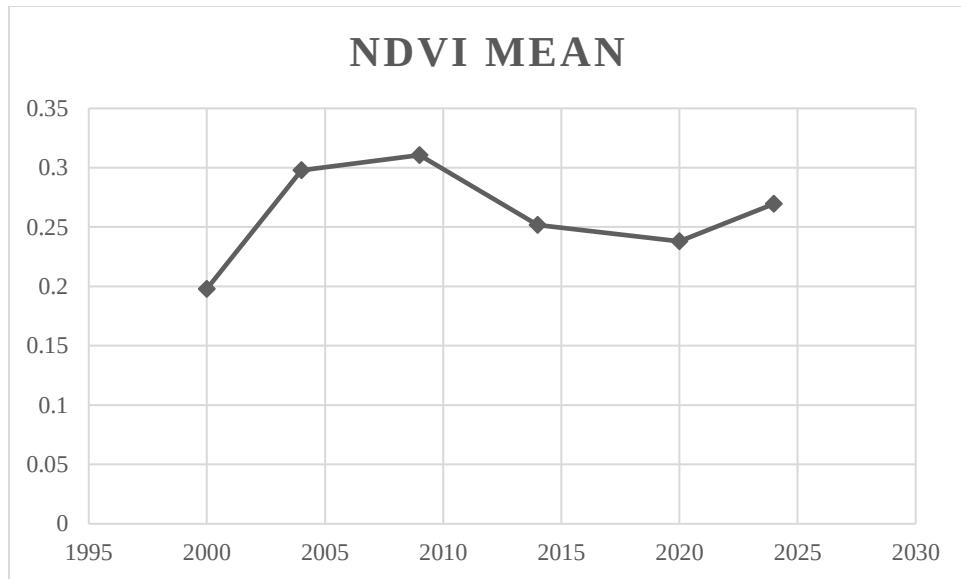


Figure 6: Change in NDVI mean over the years

Total carbon stock (all pools) similarly oscillated (Figure 8). Starting at $\sim 1.688 \times 10^6$ t in 2000, carbon stock rose slightly to $\sim 1.710 \times 10^6$ t by 2004 (+1.3%) even though forest had declined. Then it fell steeply by 2009 to $\sim 1.443 \times 10^6$ t (–15.6%) and to a low of $\sim 1.372 \times 10^6$ t by 2014 (–4.9%). This minimum corresponded to the smallest forest extent. The carbon stock then rebounded to $\sim 1.683 \times 10^6$ t by 2020 (+22.7% from 2014), reflecting the partial forest recovery in 2020. By 2024, it dropped again to $\sim 1.473 \times 10^6$ t (–12.5% from 2020). Thus, carbon stock peaked in 2004 and 2020 ($\sim 1.70 \times 10^6$ t) and bottomed in 2014. Overall (2000–2024) carbon fell $\sim 215,422$ t (–12.8%). The patterns in Figure 8 largely track forest area, with carbon declines during forest loss and increases when forest regrew, though the gains/losses are damped somewhat by the compensating expansion of tea plantations.

Table 4: Total carbon stock over the years from InVEST

Year	Total Carbon Stock (t)
2000	1688261.9
2004	1710337.95
2009	1442999.66
2014	1371988.89
2020	1683000.5
2024	1472839.47

Finally, future scenarios show divergent trajectories (Figure 10). Under the BAU scenario, forest area shrinks to ~3278 ha by 2050 and ~3076 ha by 2075 (Charts 1 & 3). Tea plantations under BAU would expand to ~6084 ha by 2050 and ~6315 ha by 2075. The corresponding carbon stock declines to $\sim 1.326 \times 10^6$ t (2050) and $\sim 1.311 \times 10^6$ t (2075) (Chart 3). In contrast, the sustainability scenario retains more forest: ~3845 ha (2050) and ~3789 ha (2075), limiting tea expansion (5606 ha by 2050, 5659 ha by 2075). Total carbon under sustainability remains higher ($\sim 1.418 \times 10^6$ t in 2050 and $\sim 1.413 \times 10^6$ t in 2075). These projections (Figure 8 & Figure 9) highlight that aggressive protection can significantly slow forest loss and carbon decline (by >15–20% of forest area compared to BAU by 2075).

Table 5: Projected Change (ha) in Land Use / Land Cover Classes

<i>Year</i>	<i>Forest</i>	<i>Cropland</i>	<i>Water</i>	<i>Built-up</i>	<i>Tea Plantation</i>
<i>2050_BAU</i>	3278.34	1788.75	9.18	2855.97	6083.64
<i>2050_SUST</i>	3845.16	4260.96	8.46	295.47	5605.83
<i>2075_BAU</i>	3075.84	1788.84	9.18	2827.35	6314.67
<i>2075_SUST</i>	3788.64	4270.41	8.46	288.9	5659.47

Table 6: Projected Total Carbon Stock (t)

<i>Year</i>	<i>Total Carbon Stock (t)</i>
<i>2050_BAU</i>	1325392.88
<i>2050_SUST</i>	1417772.88
<i>2075_BAU</i>	1311191.46
<i>2075_SUST</i>	1413205.6

7. Discussion

The results indicate a strong trend of forest encroachment and conversion, with tea plantations the chief driver in RKWS. Forest was once dominant (>80% of RKWS) but is rapidly yielding to human land uses. The marked expansion of tea plantations, from just ~7% of the area in 2000 to over 50% by 2024 (Figure 6), appears to correlate inversely with forest decline. This is consistent with other analyses: Hossain and Numata (2021) found that commercial agriculture (notably tea gardens) was a direct driver of deforestation in Rema-Kalenga (Hossain & Numata, 2021). Tea estates adjacent to the sanctuary have long exerted pressure: management reports note that tea estate labourers “exert enormous biotic pressure on the nearby forests” and even engage in illicit logging in the reserve (Nishorgo, 2013).

In short, RKWS forests are being encroached upon for agricultural land, with tea being a prime example of an intensive land use supplanting natural woodland.

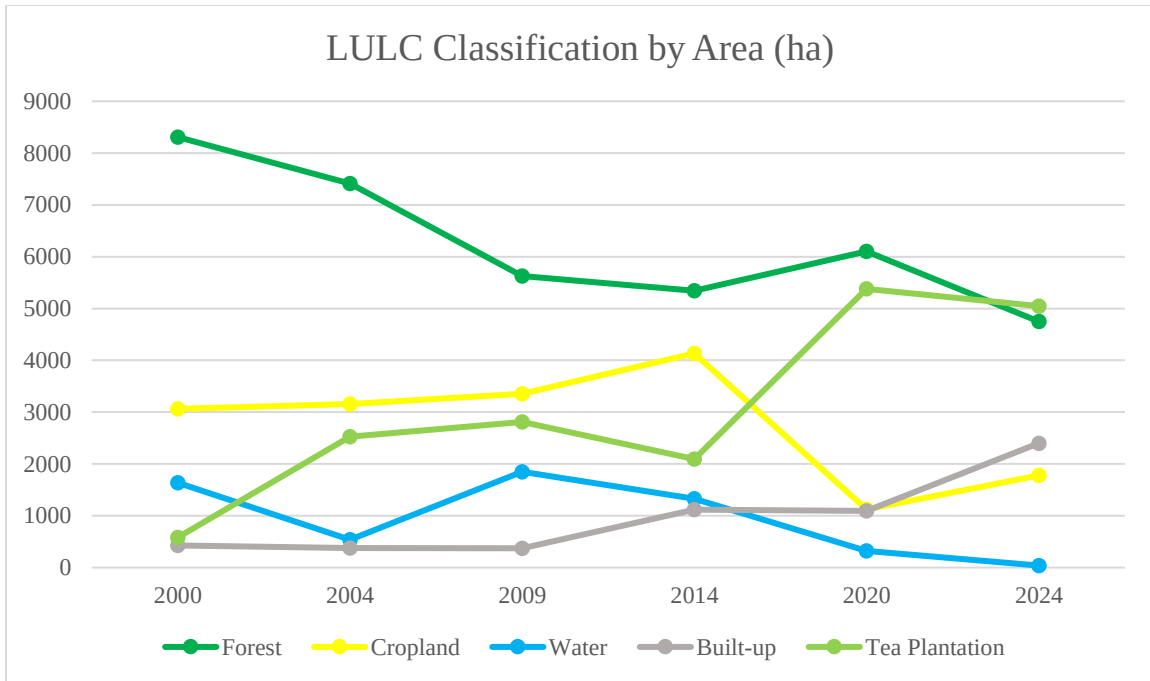


Figure 8: Graphical representation of historical LULC change (ha)

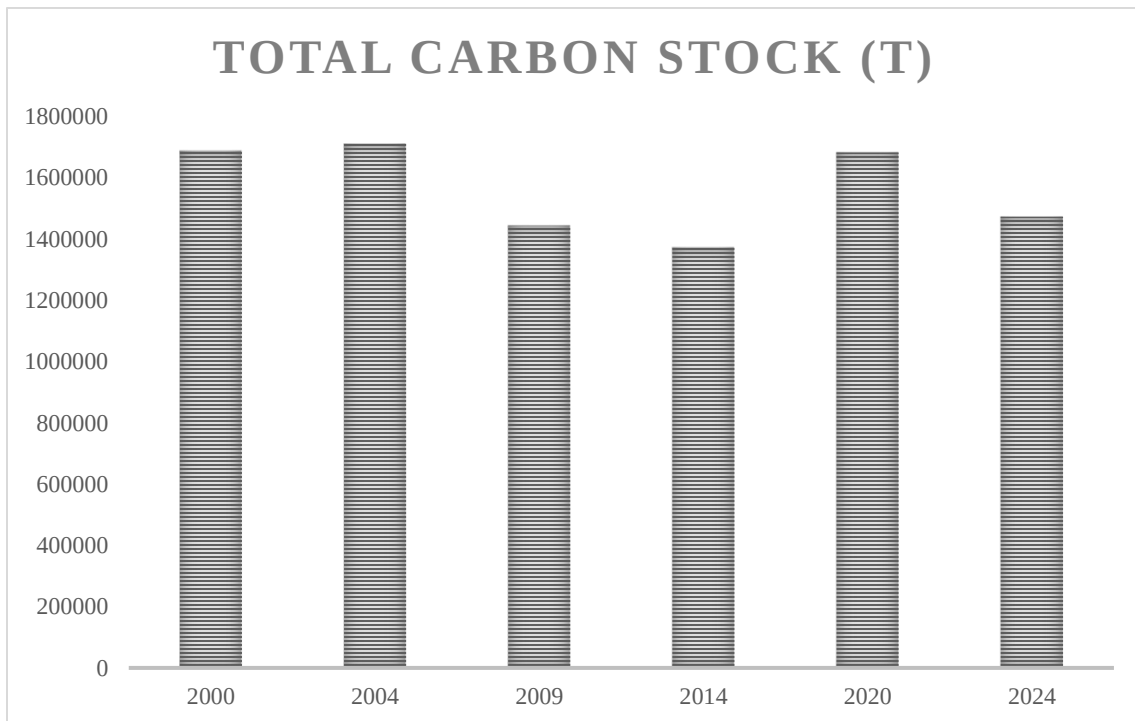


Figure 9: Fluctuations in historical total carbon stock (t)

The conversion of forest to tea plantations has important ecological consequences. Natural tropical forests store far more carbon than tea bushes per hectare, so replacing forests with tea tends to release carbon. However, tea plantations do store some carbon, partly offsetting the loss. In Southeast Asia, literature suggests tea agroforestry ecosystems have on the order of tens of Mg C per hectare of biomass and soil (Sasaki et al., 2021). For context, if a typical evergreen forest might store ~100–150 Mg C/ha (aboveground plus soil) versus ~40–50 Mg C/ha in a tea monoculture, each hectare of forest lost would drop carbon by roughly 50–100 Mg. Thus, tea plantation carbon (~45 Mg C/ha) is only ~1/3 that of intact forest, meaning forest loss generally entails net carbon release. Nonetheless, given the vast increase in tea area, the new tea stands partially bolstered the total carbon stock relative to a scenario of bare ground or cropland. This explains the carbon stock trend (Figure 8): from 2000–2004, forest loss was partially compensated by tea gain, yielding only a slight carbon rise. Later, the 2004–2014 forest drop was larger than the tea gain, so carbon fell. In the 2014–2020 interval, the rebound of forest (and continued tea) produced a large carbon rebound. Thus, tea plantations act as intermediate carbon sinks – they are green and carbon-bearing, softening the carbon impact of deforestation, but they do not match the dense carbon of the original forest.

The NDVI trends highlight how greenness indices alone can mask deforestation when forests are replaced by other green vegetation. Despite losing ~43% of forest area (2000–2024), RKWS's mean NDVI did not decline correspondingly. In fact, NDVI peaked in 2009 when forest cover was low and only fell notably by 2020 (Figure 7). This pattern arises because tea gardens and other vegetation maintain high and year-round greenness. Tea (an evergreen shrub) has a dense canopy of leaves that reflects strongly in the NIR band. As one commentary notes, NDVI saturates at high biomass, and different vegetated surfaces can produce similar NDVI values (Van Der Meer et al., 2001). In practice, a dense tea field may show NDVI comparable to a degraded forest, especially in multi-temporal composites. Additionally, NDVI can be influenced by atmospheric and phenological factors; if some NDVI observations were in wetter/drier years, that also affects values. In RKWS, the spread of tea and cropland likely kept the landscape green (NDVI ~0.25–0.30), even as primary forest fell. This explains why Figure 7's NDVI curve does not mirror the forest decline in Chart 1. In other words, the loss of forest was partly “invisible” to NDVI monitoring because tea plantations are similarly green.

These observations underscore the different utilities of LULC classification versus NDVI for monitoring this landscape. Land-cover mapping (as I have done) explicitly distinguishes forest from tea, quantifying forest loss directly. NDVI, by contrast, is a generic vegetation index: it indicates the presence of chlorophyll but not land-use type. While NDVI is useful for detecting general greening or drought patterns (Huang et al., 2020), it can be misleading when forest is replaced by other green covers. In RKWS, reliance on NDVI alone would underestimate deforestation. Combined approaches are therefore needed. However, even classification has caveats: satellite-based LULC mapping can suffer misclassification when spectral signatures overlap. For example, the leaf area index and canopy structure of tea and mixed forest might

confuse algorithms. The accuracy assessment for RKWS showed strong agreement only for recent images; there was limited ground truth for older years. Thus, some uncertainty remains in each class area. Nevertheless, this paper’s multi-year map (Figure 5) leverages supervised classification methods similar to prior studies and aligns qualitatively with known trends (Hossain and Numata 2021).

The results have clear implications for ecosystem function and management in Bangladesh. The contraction of natural forests and the expansion of monocultures like tea reduce habitat quality and biodiversity. Even if overall greenness stays high, ecological functions differ: tea plantations provide far fewer ecosystem services (e.g., habitat for wildlife, hydrological regulation, and soil stability) than native forests. The accompanying carbon decline suggests that the sanctuary’s role in climate mitigation is eroding. Importantly, this paper’s findings echo national concerns. Bangladesh’s forest policies emphasise conserving remaining forests. For instance, the national management plan for RKWS explicitly states its long-term aim to “maintain the maximum possible area under forest cover” (Nishorgo, 2013). The BAU scenario projection (Figure 11) indicates continued degradation that would contravene this policy. By contrast, a sustainability-focused land-use regime (Figure 11) that slows tea expansion and promotes afforestation could preserve significantly more forest and carbon (1.413×10^6 t vs 1.311×10^6 t in 2075). This suggests that policy intervention is vital to align actual land-use trends with conservation priorities. Indeed, many analyses of protected areas in Bangladesh highlight that pressure from agriculture, fuelwood collection, and land grabs is undermining forest conservation (Hossain & Numata 2021). This study shows that in RKWS, commercial agriculture, especially tea, is the dominant force, while non-commercial crops and settlements play secondary roles.

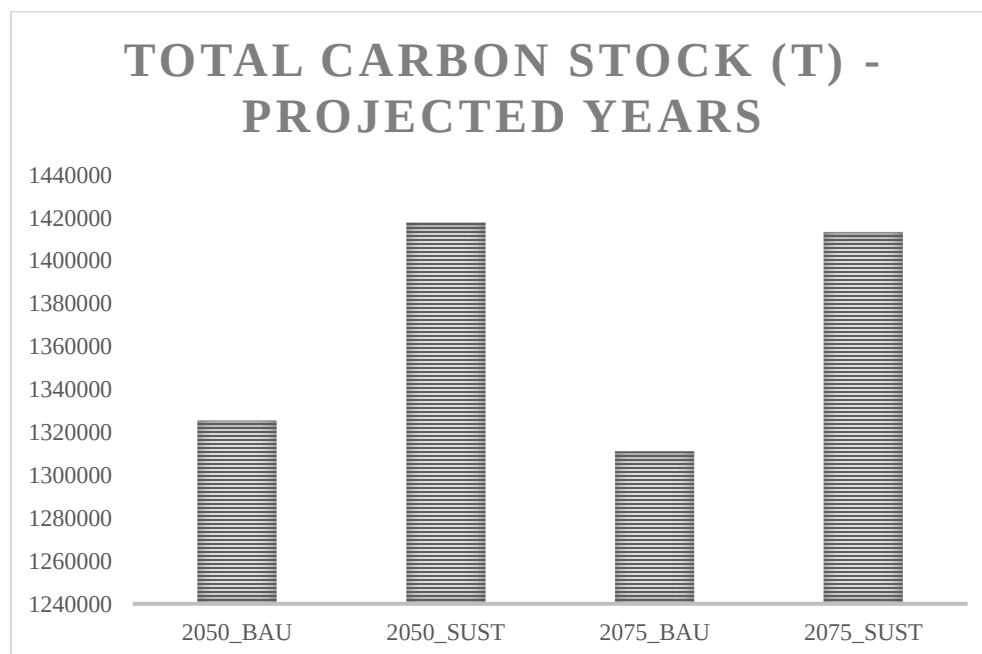


Figure 10: Graphical representation of historical LULC change (ha)

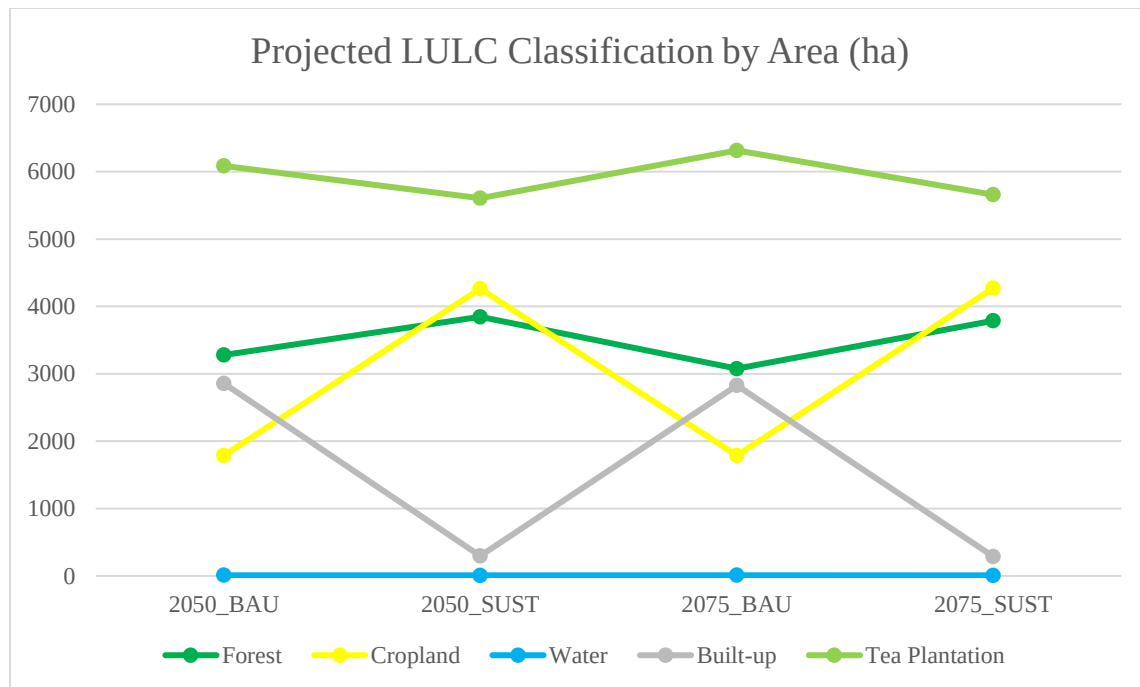


Figure 11: *Fluctuations in historical total carbon stock (t)*

More broadly, the RKWS case is indicative of challenges in Sylhet’s remnant forests. The juxtaposition of a rich but small sanctuary with expanding commercial estates reflects a common tension: economic activities (tea, rubber, homesteads) about protected patches. Without strict enforcement and community engagement, forests shrink. However, tea’s evergreen nature means the loss is subtle in satellite greenness, possibly delaying detection. Consequently, it is recommended that managers use multiple data sources: land-cover maps to detect category changes and NDVI/other indices to flag unusual greenness patterns. Such integrated monitoring could improve early warning of deforestation despite greenness. In RKWS, for example, monitoring could focus on the edges near tea estates, where illegal logging often occurs.

8. Conclusions and Recommendations

This study provides a comprehensive assessment of land-use change and vegetation dynamics in Rema-Kalenga Wildlife Sanctuary from 2000 to 2024, with projections to 2075. The key findings are: (1) Forest cover has declined severely (–42.8% over 2000–2024), while tea plantations have expanded massively. (2) Total carbon stock mirrored these shifts, with carbon peaking during forest maxima and falling during forest troughs (net –12.8% carbon loss). (3) NDVI trends did not track forest loss directly, because evergreen tea and other green covers maintained high greenness indices; NDVI peaked in 2009 even as the forest was shrinking. (4)

Under a BAU scenario, forest loss and carbon declines continue by mid-century, whereas a sustainability scenario could preserve substantially more forest and carbon. In sum, tea expansion is driving most deforestation in RKWS, and its contribution of vegetative greenness and carbon somewhat masks the degradation in NDVI analyses.

To address these trends, land-use policy should prioritise forest conservation and restoration. This could include enforcing sanctuary boundaries to prevent illegal clearing by nearby tea estate labourers, incentivising reforestation (particularly of degraded forest patches), and promoting agroforestry systems that blend tea with native tree species. Strengthening community co-management (as envisioned by Nishorgo guidelines) can align local livelihoods with protection goals. On the agricultural side, improving tea yield per hectare could reduce the need to expand cultivated area. Given the carbon implications, incorporating RKWS into national REDD+ or carbon finance schemes may help preserve forests (since tea stores less carbon, avoiding conversion yields climate benefits).

Methodologically, these findings illustrate the utility of combining LULC classification with vegetation indices. Future monitoring of RKWS (and other Sylhet forests) should continue using multiple indicators. NDVI alone can be misleading, so complementing it with LULC maps and ground surveys is essential. Satellite mapping should also be periodically validated with field data or high-resolution imagery to refine accuracy.

Finally, the analysis framework here – integrating time-series LULC, NDVI, and carbon stock – is broadly applicable. Other forests in the Sylhet region (e.g., Lawachara, Satchari) face similar tea and settlement pressures. Applying the same approach can help quantify their land-cover trajectories and carbon outcomes. In conclusion, the paper's results underscore an urgent need: without policy action, protected forests in Bangladesh will continue to shrink. Protecting RKWS's remaining forest is critical not only for biodiversity but also for carbon storage and the long-term sustainability of the landscape (Nishorgo, 2013).

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Disability-Responsive Climate Literacy: Inclusive Environmental Education for Persons with Disabilities in Bangladesh

Farheen Akter Bhuian

Abstract

In the era of rapid climatic change, environmental education is a must for enlightening young learners to navigate through the ecological crisis. However, Persons with Disabilities are often ignored in the shared knowledge platform, where their different abilities are treated differently, making them invisible in the eyes of ableist climate literacy discourses. Hence, this study introduces the concept of disability-responsive climate literacy, which is an eye-opening, transformative framework that rethinks environmental education through the perspectives of accessibility, inclusivity, environmental justice, and epistemic justice. Grounded in interdisciplinary research intersecting inclusive pedagogy, climate education, and disability studies, this study explores how conventional climate curricula in Bangladesh overlook the needs of PWDs and how climate knowledge is delivered to the learners, which eventually identifies the epistemic gaps marginalizing those with different abilities. Through qualitative case studies, interviews with educators, and participatory research with students with disabilities in Bangladesh, the study aims to co-create inclusive curricular models such as Universal Design for Learning (UDL) and pedagogical strategies that empower all students, including those with disabilities, to engage with ecological challenges. This study embodies the perspectives of the emerging field of crip-ecology, which critiques ableist presumptions that exist in the mainstream environmental discourses, ignoring the PWDs, and reimagines ecological knowledge through the lens of PWDs. Disability being the central theme of climatic epistemology in this study, it highlights a transformative pathway to climate literacy that does not just include the PWDs but shapes the discourses through their perspectives.

1. Introduction

At the verge of climatic change and collapse, environmental education can be a fundamental base for facilitating learners to understand and navigate the environmental challenges, especially for those who are diverse learners. However, learners with disabilities are largely excluded from climate literacy discourses. This paper attempts to take an initiative to introduce the concept of disability-responsive climate literacy, which is a transformative framework that rethinks environmental education through accessibility, inclusivity, and epistemic justice. Grounded in interdisciplinary research across climate pedagogy and disability studies, this study explores how conventional curricula in Bangladesh overlook the needs of PWDs and suggests inclusive models such as Universal Design for Learning (UDL). Implementing qualitative case studies and participatory methods, findings reflect that climate education often reproduces the ableist notions and structures. This study advocated for an epistemic paradigm shift towards disability-inclusive sustainability, where ecological justice is served well through the co-creation of the curricula and social learning with the collaboration of learners with disabilities from diverse backgrounds.

Climate change is one of the burning questions of the 21st century, demanding inclusive responses and prompt actions from all the engaged agents, actors, stakeholders, and citizens overall to empower all. Bangladesh is a climatically vulnerable region, hence the need for climate literacy and attention for policy inclusion. Still, the voices of Persons with Disabilities (PWDs) remain marginal and peripheral, as they remain underserved and unrecognized in many crucial aspects of our society. Mainstream educational institutions often lack inclusive and adaptive content, materials, pedagogy, and teaching assistance and expertise necessary for ensuring the equal participation of diverse learners in the classroom, which is a significant gap in the contemporary Bangladeshi society. This research identifies the gaps and explores how disability-inclusive approaches redefine environmental education and establish environmental justice by incorporating the concept of Disability-Responsive Climate Literacy (DRCL).

2. Literature Review

Scholars in environmental education highlight the transformative role of climate literacy in fostering sustainable behavior (UNESCO, 2023). However, the literature on inclusive education reveals systemic barriers that restrict equitable opportunities for learning for PWDs (WHO & World Bank, 2011). These barriers are embedded in multiple levels of the education system-policy, pedagogy, infrastructure, and culture that collectively reinforce the exclusionary patterns. At the policy level, the absence of operational inclusive education frameworks, fragile inter-ministerial and inter-departmental coordination, and limited participation of disability organizations in educational planning entrench institutional marginalization (Ainscow, 2020). Pedagogical barriers are further accentuated through constricted, uninventive curricula, standardized testing, and limited teacher training on UDL that actually refrain from differentiated instruction and accessible assessment (Morina, 2017)

Additionally, infrastructural and technological barriers such as inaccessible educational buildings, inadequate assistive technologies, and digital learning platforms that do not meet accessibility standards exclude learners with cognitive, physical, and sensory impairments from digital and experiential learning opportunities (UNICEF, 2022). The issue is compounded by attitudinal and cultural barriers, including ableist stereotypes and notions, abjections, social stigma, and overprotective practices that deny PWDs participation in experiential fieldwork or climate-related projects (Shakespeare, 2018). Finally, intersectional barriers- such as poverty, gender inequality, and geographic marginalization- intensify exclusion for learners with disabilities in low-resource settings, especially in lower and middle income countries like Bangladesh. These interconnected systems of constraint showcase that exclusion is not an individual issue but an intrinsically structural and socially deep-rooted one.

Therefore, to completely grasp the promise of the transformative potential of climate education, inclusive reforms must integrate UDL principles, participatory co-design and co-create, accessibility standards across all levels of educational policy and practice, ensuring that learners with disabilities are recognized as active climate citizens rather than passive recipients of knowledge. Due to these entrenched systemic barriers, the co-development of prototype lesson plans integrating UDL and experiential climate learning might emerge as a transformative strategy for inclusive education. UDL provides a systemic structure and scientifically grounded, feasible framework for designing instruction that anticipates learner diversity by offering various means of engagement, representation, and expression (CAST, 2018). When coupled with experiential learning approaches that emphasize direct participation, reflection, and community-based action, this integration ensures that students with disabilities can engage meaningfully with climate concepts through multimodal and accessible pathways (Kolb, 2015; UNESCO, 2023).

When intertwined with experiential learning approaches, which emphasize direct and involved participation, reflection, and community-based action, this integration ensures that students with disabilities can engage meaningfully in thoughtful ways through multimodal and accessible pathways (Kolb, 2015; UNESCO, 2023). Co-developing such lesson plans with teachers, learners with disabilities, and disability organizations not only decentralizes and enriches the curriculum design process but also embodies the participatory ethos of the UN Convention on the Rights of Persons with Disabilities (UNCRPD, 2006). Thus, UDL-integrated climate education exemplifies a pedagogical and ethical commitment to inclusivity, diversity, and equity. This indicates that the global movement toward sustainability should not reproduce epistemic ableism but must foster a collective sense of planetary responsibility among all learners.

This collaborative model metamorphoses learners with disabilities from peripheral participants into active co-creators of knowledge, synchronizing climate literacy with social justice. Also, planning and executing lessons with accessibility and inclusivity from the beginning prevents adjusting later, which can often exclude and marginalize certain people with diverse needs and backgrounds (Florian & Beaton, 2018). Crip-ecology, a critical branch of disability studies, questions the ableist notions in environmental narratives and discourses (Kafer, 2013). Limited

research has linked climate education with disability inclusion or a disability lens in Bangladesh. Hence, this study fills the significant epistemic gap by blending environmental pedagogy with social justice frameworks.

3. Methodology

This qualitative study employs a multi-method research design to gain a profound understanding of inclusive climate education practices in Bangladesh. It integrates document analysis, semi-structured interviews, and participatory observation to triangulate data and enhance the credibility, depth, and reliability of the findings (Creswell & Poth, 2018). The document analysis involved a systematic review of national curriculum frameworks, teacher training manuals, policy documents, and international reports related to inclusive and environmental education with a focus on identifying structural and pedagogical gaps in accessibility and content integration. Fifteen educators (including classroom teachers, special educators, and curriculum developers) and twenty students with disabilities enrolled in both inclusive schools and special education centers across Dhaka were interviewed. A purposive sampling method was adopted to ensure representation of diverse disability types, learning contexts, and instructional experiences (Patton, 2015).

The data were analyzed thematically, following Braun and Clarke's (2006) six-phase framework, to identify recurring patterns and key themes about curriculum design, teaching methodologies, and policy implementation. The thematic analysis revealed critical issues such as systemic barriers to accessibility, insufficient teacher preparedness for inclusive pedagogy, and fragmented integration of sustainability and climate literacy within current educational practices. In the final phase, the research engaged participants collaboratively to co-develop prototype lesson plans grounded in the principles of UDL and experiential climate learning.

The UDL framework, as developed by CAST (2018), emphasizes providing various ways of engagement, representation, and expression to support learner variability. Integrating UDL principles with experiential learning strategies (Kolb, 1984) encouraged the development of flexible, sensory-rich, and participatory lesson designs that accommodate diverse learner needs. This participatory process not only validated the study's findings but also produced practical pedagogical tools delineating how inclusive climate education can be effectively operationalized in Bangladesh.

Furthermore, the study aligns with the UNESCO (2020) and UN Convention on the Rights of Persons with Disabilities (UN, 2006) policy directives, which call for embedding accessibility and inclusion within all educational reform efforts. By integrating these frameworks, the research underscores the transformative potential of inclusive curriculum design that recognizes both environmental and social justice as interconnected educational imperatives. Grounding on these methodological foundations, the subsequent findings and discussion sections explore how educators and students with disabilities perceive and experience inclusive climate learning in

their daily contexts. The co-constructed insights illuminate the tensions between policy intentions and classroom realities, revealing how accessibility often remains an afterthought rather than an embedded principle in the system. Through the thematic synthesis, the study highlights that inclusive pedagogy requires not only physical accessibility and adapted materials but also a transformative shift in attitudes, curriculum design, and teacher training.

The findings further highlight how integrating UDL principles into climate education fosters equitable participation, critical environmental awareness, and empowerment among learners with diverse abilities. This transition from theoretical frameworks to lived experiences thus bridges the gap between policy discourse and pedagogical practice, advancing the broader goal of inclusive and sustainable education in Bangladesh.

4. Findings and Discussion

Findings reveal that mainstream climate education in Bangladesh rarely addresses disability. Teachers expressed concerns about limited training in inclusive pedagogy, whereas students with disabilities reported feeling isolated from the environmental projects. Thematic analysis identified three major issues;

- (1) Inaccessible curriculum materials
- (2) Absence of assistive learning technologies
- (3) Lack of representation of disability perspectives in climate discourse.

Through participatory workshops, students co-created inclusive visual aids and expressed their views on climate narratives, emphasizing on strengthening their agency and resilience. The thematic analysis yielded four major themes: (a) curricular and policy disjunctions, (b) limited teacher preparedness for inclusive pedagogy, (c) barriers to accessibility and participation, and (d) emerging opportunities through UDL and experiential climate education. Each theme reflects the interconnections between structural, pedagogical, and attitudinal dimensions of inclusive climate learning in Bangladesh.

4.1 Curricular and Policy Disjunctions

Curriculum frameworks and policy documents unveiled an unyielding disconnection between inclusion discourse and its practical implementations. While national policy documents (e.g., National Education Policy 2010; Inclusive Education Policy 2017) emphasize equality and participation for learners with disabilities, the actual curriculum content remains highly text-centric, assessment-driven, and cognitively biased, offering limited scope for differentiated instruction (UNESCO, 2020).

National policy documents (National Education Policy 2010; Inclusive Education Policy 2017) foreground equality and participation for learners with disabilities, but in reality, the curriculum

content remains highly text-centric, assessment-driven, and cognitively biased, offering narrow coverage for differentiated instruction (UNESCO, 2020). Carol Ann Tomlinson in 2014 defined ‘Differentiated instruction’ as, “The process of tailoring instruction to accommodate differences in students’ readiness levels, interests, and learning profiles so that all learners can access the curriculum effectively.” Educators indicated that climate change topics are introduced superficially, often presented as factual knowledge rather than action-oriented experiential learning. This limited engagement constrains the development of environmental empathy, agency, and critical consciousness among students with disabilities (Tillbury, 2011). The document analysis further highlighted that inclusion is usually addressed as a specialized additive in the curriculum without its practical implementations. This validates what Slee (2011) calls the “deficit model” of disability, where learners are expected to adjust to mainstream structures rather than those structures adapting to learner diversity.

4.2 Limited Teacher Preparedness for Inclusive Pedagogy

Teachers’ voices highlighted significant challenges in translating inclusive education policy into classroom practice. Many educators expressed uncertainty in adapting climate education for learners with sensory, cognitive, or physical disabilities, citing a lack of training and institutional support. While participants demonstrated commitment and empathy, their pedagogical strategies often relied on informal adjustments rather than structured inclusive design (Florian & Black-Hawkins, 2011).

Teachers’ voices indicated significant challenges in translating inclusive education policy into classroom practice. Educators noted that the prevailing professional development programs are heavily theoretical, offering limited exposure to practical, inclusive strategies or co-teaching or co-designing models. The lack of accessible teaching materials and assistive technologies further hinders their ability to initiate the differential teaching methods. These findings reveal a systemic issue: inclusivity is often perceived as proportional to situational placement- having learners with disabilities present in classrooms rather than participation and learning equity (Ainscow, 2020)

4.3 Barriers to Accessibility and Participation

Observational data and student interviews accentuated that physical, sensory, and communicative barriers continue to refigure classroom experiences. For instance, visual materials lacked tactile or auditory alternatives, and classrooms were rarely equipped with adaptive furniture and accessible pathways. Students with hearing impairments stated difficulties engaging in group discussions due to inadequate sign language interpretation or visual cues. Beyond physical barriers, social and attitudinal exclusion also emerged as critical barriers in this study. Some students shared feelings of being “accommodated but not included,” reflecting subtle forms of marginalization.

These experiences align with Ghai’s (2015) argument that disability in the Global South is both a social and structural issue, shaped and reshaped by historical inequities and cultural stigmas.

The findings highlight that accessibility must not be perceived as a technical fix, but as an ethical, relational and thoughtful commitment within pedagogical and institutional cultures (Goodley, 2014).

4.4 Emerging Opportunities through UDL and Experiential Climate Learning

The co-development of prototype lesson plans, stemming from UDL principles (CAST, 2018) and experiential climate education, revealed promising potential for inclusive reform in the education sector. When educators collaborated with students with disabilities to co-design immersive and multimodal learning activities (e.g., tactile maps, role-play simulations, and local environmental observation), participation and engagement improved significantly. Students reported better understanding of ecological concepts, which showcases the need for participatory pedagogies that can transform non-engaging climate literacy into lived experience (Kolb, 1984). Educators also reflected that UDL's three core principles of multiple means of representation, expression, and engagement helped them to rethink traditional lesson planning.

They acknowledged that inclusivity of diversity is not about simplifying the content, but rather diversifying means of education for better meaning-making and understanding (CAST, 2018). Moreover, the participatory co-design process itself acts as a form of empowerment and professional learning, fostering a sense of shared ownership among both teachers and learners. This theme aligns with recent scholarship advocating for intersectional inclusivity: linking environmental justice, disability rights, and pedagogical transformation (Goodley, Lawthom, & Runswick-Cole, 2017). By combining UDL with experiential climate learning, the prototypes demonstrated that inclusive education can be both practically achievable and epistemically transformative, which will have the potential of blurring the fine lines between “mainstream” and “special” education. Overall, the findings showcase a complex interplay between policy, pedagogy, and perception. While systemic and infrastructural limitations persist, the integration of UDL frameworks and experiential approaches shows strong prospects for rethinking inclusive climate education in Bangladesh. This study underscores that inclusion should not be mentioned as a star word in textbooks or a technical or policy objective to showcase, but it is an ever-evolving, relational, and ethical practice that requires continuous collaboration, reflexivity, and commitment to social and environmental justice.

5. Discussion

The findings of this study expose the multilayered nature of inclusion and sustainability in the context of Bangladesh's education system. They depict that inclusive climate learning cannot be achieved merely through curriculum reform or policy directives; rather, it requires an epistemological and ethical transformation in how educators conceptualize learning, diversity, and justice. This section interprets the findings through three intersecting theoretical lenses: the UDL framework (CAST, 2018), inclusive education and social justice theory (Ainscow, 2020;

Slee, 2011), and decolonial and sustainability education paradigms (Escobar, 2018; Sterling, 2011).

The participatory development of prototype lesson plans grounded in UDL principles demonstrated that inclusive education is not an accommodation strategy but a transformative pedagogical philosophy. UDL's emphasis on multiple means of representation, engagement, and expression (CAST, 2018) permits educators to design and create ecological lessons that will suit all. This approach echoes Florian and Black-Hawkins' (2011) concept of inclusive pedagogy, which rejects deficit-based thinking and recognizes all learners as capable of growth within a shared educational space. Instructors who applied UDL in the co-development sessions reported an increased awareness of how barriers are embedded into learning environments- a point that aligns with Oliver's (1990) social model of disability. Instead of finding the problem within the student, UDL rewires learning challenges as design problems within the curriculum and classroom structures. This shift is particularly powerful in the Global South, where systemic ableism intersects with under-resourced education systems. By advocating flexibility, sensory engagement, and emotional connection, UDL locates inclusion as both a design imperative and an ethical stance (Meyer, Rose, & Gordon, 2014).

Despite progressive policy frameworks promoting inclusion (UNESCO, 2020; United Nations, 2006), the findings revealed a "missing middle ground" between macro-level policy discourse and micro-level classroom realities. Teachers often operate within fixed curricular frameworks and monitored assessment systems that discourage pedagogical experimentation (Ainscow, 2020). This results in what Ball (1994) terms "policy enactment slippage"- the space where well-intentioned reforms lose transformative potential for structural and cultural inertia and stagnation. In Bangladesh, inclusive education policies often tend to focus on physical access and enrollment metrics, while overlooking deeper dimensions such as epistemic inclusion and participatory learning (Ghai, 2015). The data suggest that without proper teacher training and institutional support, UDL-inspired innovation risks remain localized, context and area-specific, and unsustainable. Therefore, the study emphasizes the need for capacity-building skill-based human resource programs that will incorporate inclusive climate education within pre-service and in-service teacher education. Such programs should stimulate reflexivity, co-design class norms, practices, and values with interdisciplinary collaboration between environmental educators, sociologists, and disability specialists (Forlin & Chambers, 2017).

The findings also indicate the need to decolonize both inclusion of diversified systems and climate education, recognizing dominant pedagogical models that reproduce Western epistemologies, which ultimately marginalize local knowledge and embodied ways of learning and teaching. Decolonial scholars like Escobar (2018) and Santos (2014) tell us through their extraordinary works how the knowledge system and epistemic world are dominated by the Western hegemonies and why the Global South must resist "epistemic extractivism", which they defined as the uncritical adoption of Western frameworks that erase indigenous perspectives. In Bangladesh, environmental crises are deeply rooted in local ecologies and community wisdom,

where experiential and inclusive pedagogies can serve as acts of epistemic justice. When students with disabilities participate in climate literacy through locally rooted cognitively-rich experiences such as observing rainfall patterns, soil changes, or community recycling practices, they engage in embodied cognition (Varela, Thompson, & Rosch, 1991). This form of learning disrupts the education system by interrupting the hierarchical dualism of “able/disabled”, “Knower/learner,” and “North/South”, rejecting all the binaries, and reclaiming the decolonial goal of accepting the expressions of diverse epistemic voices.

The intersection of inclusion and sustainability reinforces the ethical dimensions of educational reform. Both frameworks advocate for strengthening the systems that honor interdependence, equity, and resilience (Sterling, 2011). However, the study revealed that inclusive education in Bangladesh remains largely in desk papers and policy reports but not in reality, as the fieldwork suggests. Bangladeshi educational institutions give importance to access and admission into the institution rather than transforming the system to make it more learner efficient and diverse for the special needs of PWDs. To move beyond inclusion as access, educators and policymakers must embrace the ecology as a holistic perspective where learners, environments, and communities co-evolve in mutual interdependence, and depth of understanding rises. From such a theoretical and epistemic stance, climate literacy becomes a moral and justified ethical endeavor, soliciting empathy not only for nature but for diverse demography. By incorporating UDL principles within sustainability learning, the study models what Braidotti (2013) calls an affirmative ethics- a pedagogy that nurtures both human diversity and planetary concerns. This approach reframes disability not as a limitation but as a critical lens for reimagining novel relational methods of knowing and being in the Anthropocene (Goodley et al., 2017).

Drawing from the study’s findings and theoretical synthesis, an emergent framework for Inclusive Climate Education (ICE) is proposed. This framework is based on three interdependent pillars, (1) Embedding UDL principles into curriculum and assessment design to anticipate learner diversity, (2) Incorporating local ecological knowledge, sensory learning and indigenous narratives to decolonize climate education, (3) Framing inclusion and environmental learning as interconnected moral imperatives that would establish justice and collective resilience, co-create ethical responsibilities and agency for learners with diverse needs in understanding ecological crises in efficient manners. Through these dimensions, inclusive climate education transcends the binary of “special needs” and “normal education/ mainstream education”, emerging as a transformative praxis that unites equity, empathy, and ecological consciousness.

5. Conclusion and Policy Implications

This study underscores the necessity of embedding disability-responsive frameworks in climate literacy programs. By merging inclusive education principles with climate pedagogy, Bangladesh can pioneer equitable environmental education. Policy measures should mandate accessibility audits of curricula, introduce inclusive teacher training, and ensure representation of PWDs in sustainability policymaking. Future research should expand on community-based inclusive

climate interventions and digital accessibility innovations. Scholars in critical disability studies and ecological studies should conduct intersecting research to explore the possible potentials between disability theory, posthumanism, and environmental ethics (Braidotti, 2013; Goodley et al., 2017). Such interdisciplinary synthesis can deepen our understanding of vulnerability, interdependence, and resilience in the Anthropocene.

This study explored how inclusive climate education can be advanced through the integration of Universal Design for Learning (UDL) and experiential pedagogies within the Bangladeshi context, illuminating the disjunctures between inclusion policies and classroom realities while identifying transformative pathways through co-designed, context-sensitive lesson prototypes.

The findings affirm that inclusion must move beyond physical access and accommodation toward a more ethical, ecological, and epistemological transformation in educational thought and practice. Current frameworks in Bangladesh, though aligned with global agendas such as the UN Convention on the Rights of Persons with Disabilities (UN, 2006) and UNESCO's Inclusive Education Policy Guidelines (2020), tend to operationalize inclusion through narrow administrative lenses. Such approaches risk re-establishing ableism and technocratic forms of inclusion that fail to engage the lived experiences of learners with disabilities. Conversely, the UDL-guided and participatory models developed through this study exemplify how inclusivity can be designed on-site with students, educators, and policymakers rather than adjusting it later. These models prioritize multiple modes of engagement, multimodal sensory experiences, and flexible pathways for learning- principles that resonate with both UDL (CAST, 2018) and experiential learning theory (Kolb, 1984)

When situated within the broader agenda of climate education, this design philosophy promotes not only cognitive understanding of environmental issues but also embodied, emotional, and ethical awareness.

Moreover, the study's interpretive synthesis foregrounds a decolonial ethic of inclusion- one that recognizes the local, relational, and ecological contexts in which learning occurs (Escobar, 2018; Santos, 2014). Inclusive climate education thus becomes a form of epistemic and environmental justice, disrupting hierarchies between "abled" and "disabled", "expert" and "learner", "Global North" and "Global South".

The implications extend beyond disability studies into the moral architecture of education itself, calling for pedagogies rooted in care, reciprocity, and interdependence. In essence, the study concludes that inclusive climate learning is both a pedagogical and moral imperative. It necessitates a shift from perceiving inclusion as a reactive measure to embracing it as a proactive design principle and a cultural ethos. Such transformation requires attention to align educational design, enhancement of educators' skills, and policy reform under the umbrella of environmental justice, ecological crisis management, and sustainability development goals that honor human diversity.

The Ministry of Education and the National Curriculum and Textbook Board (NCTB) should integrate UDL guidelines (CAST, 2018) within curriculum design, teacher training modules, and assessment standards. Bridging the “missing middle” (Ainscow, 2020) between policy reformation, ensuring inclusion, and practice requires sustainable coordination and cooperation among policymakers, educators, disability activists, and organizations. Monitoring and evaluation methods must not only assess enrollment and access but also ensure the quality of participation and effective learning for students with disabilities. Climate change education must be recognized as an overarching theme at the national level. Policies should support community-based experiential learning programs that engage students of all abilities in local environmental initiatives.

Teacher training institutions should incorporate UDL and experiential climate learning into pre-service and in-service programs. Workshops emphasizing co-development with learners with disabilities, use of properly functioning assistive technologies, and reflective pedagogical inquiry can build teachers’ confidence for inclusive practices in educational sites (Florian & Black-Hawkins, 2011). Inclusive climate literacy benefits from collaborative teaching methods where general and special educators together plan, implement, and evaluate lessons. Peer mentorship among students both with and without disabilities can enhance social inclusion, diversity, and better collective learning effects (Forlin & Chambers, 2017). Schools should establish small resource hubs equipped with adaptive materials, low-cost assistive tools, and trained support staff. These hubs or spaces can serve as innovation spaces for teachers to experiment with and evaluate inclusive lesson design, sensory learning, and multimodal communication strategies. Ultimately, this research demonstrates that inclusive climate education is a journey toward relational transformation, an evolving process of learning to see, feel, and act otherwise. In a world full of ecological chaos and social inequality, inclusivity and sustainability must no longer be treated as secondary or parallel goals but as mutually reinforcing dimensions of educational justice. The classroom, when reimagined through UDL and decolonial ethics, becomes not merely a space for instruction but a place of empathy where all learners, regardless of ability or socio-economic background, participate in shaping a better planetary future.

As Bangladesh’s education system continues to evolve amid global sustainability agendas, the insights from this study can shed light on the realities of the classroom settings, education system, and teaching methods, which can ultimately guide educators, policymakers, and communities toward designing an equitable pedagogy of hope and an enriched capacity-building system. A pedagogy that would be a pathbreaker for collective survival and development that would not perceive differences as barriers but as something unifying and prosperous.

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Paper 13

Scrolling the Climate: How Social Media Shapes Youth's Awareness of Environmental Issues in Bangladesh

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Abstract

This study investigates how social media shapes Bangladeshi youths' awareness, emotions, and actions regarding climate change. Guided by Networked Publics Theory (boyd, 2010), a mixed-methods approach combined a survey of 150 respondents with 25 in-depth interviews. Quantitative findings show a significant relationship between exposure to climate content and participation in climate activities ($\chi^2 = 11.29$, $p = .010$), while belief in social media activism alone did not predict offline engagement. Qualitative results reveal that visually engaging and emotionally charged content fosters awareness, but structural and motivational barriers, such as limited resources, institutional support, and social norms, impede sustained action. Participants emphasized culturally grounded messaging, particularly linking climate communication to Islamic and community values, as a pathway to deeper engagement. The study concludes that social media is a powerful tool for awareness but insufficient for behavioral transformation without institutional support and cultural relevance. Policy recommendations include strengthening youth-led initiatives, integrating digital literacy, and connecting online engagement with community-based climate action.

1. Introduction:

Bangladesh is one of the countries most affected by climate change. It faces serious problems like rising sea levels, stronger cyclones, saltwater entering farmland, and frequent floods (Climate Reality Project, 2025). Although the country produces very little greenhouse gas compared to others, it suffers greatly from climate problems. This shows how unfair the global climate crisis is. These environmental issues make poverty and inequality worse, threaten people's jobs, and create big risks for young people, who are often the ones dealing with and responding to these challenges (UNICEF, 2024).

In Bangladesh, many young people now use digital platforms, especially social media, to learn about climate change and to take part in environmental activities. For example, the "Climate Smart Education Systems Initiative" tries to include climate change and environmental topics in education so that youth can become more aware and act (UNESCO, 2025). Around the world, social media has changed how people talk about climate issues. It allows quick sharing, visual stories, and online communities where young people can discuss and spread ideas (Sultana et al., 2024). However, some experts warn that while many youths are vocal online, their actual actions to fight climate change may not always match their confidence or knowledge (Murray et al., 2025).

This study uses Networked Publics Theory (boyd, 2010) to understand these online spaces. This theory sees digital platforms not just as tools for sharing information, but as public spaces where people shape their identities, express opinions, and connect with others. In these spaces, youth can show their concern for the environment, share stories, and organize movements, but they also face challenges like online risks, questions of credibility, and audience boundaries (Marwick & Boyd, 2014; Farnham et al., 2021). Applying this theory in Bangladesh helps us see how youth use social media to understand, feel, and act on climate issues.

Even though many studies talk about youth and climate change, there are still gaps in research. Most studies look at how youth use social media or learn about climate change, but few explore how online awareness leads to real-world climate action in Bangladesh. Some local research shows that Bangladeshi youth are very aware and active on social media (Hossain et al., 2025; Siddique et al., 2024), but these studies often don't discuss emotional impacts, barriers to taking action, or ways to connect online discussions to offline behavior. Global studies offer useful theories (Sultana et al., 2024), but they often lack examples specific to South Asia.

To address these gaps, the present study "Scrolling the Climate: How Social Media Shapes Youth Awareness of Environmental Issues in Bangladesh" investigates three key domains: (1) To examine how Bangladeshi youth encounter climate-related content on social media, (2) To explore their perceptions, emotions, and intended behaviors., and (3) To identify challenges and strategies for connecting online awareness to offline climate action.

To complete these objectives, the study poses five research questions: (1) How do youth in Bangladesh encounter climate change content on social media platforms? (2) What are Bangladeshi youths' perceptions of the climate-related content they see on social media, and what emotional responses does this content evoke? (3) How does exposure to climate-related content on social media influence Bangladeshi youths' intended climate-related behaviors or actions? (4) What challenges do Bangladeshi youth face in translating their online climate awareness into offline climate actions? (5) What strategies or approaches can effectively bridge the gap between online climate awareness and offline climate action among youth in Bangladesh?

2. Literature Review

2.1 Global Youth Engagement with Climate Change

Worldwide, youth engagement with climate change is strongly shaped by digital media, which offers immediacy, interactivity, and visuals (Muyed et al., 2025). These features help create networked publics, where young people not only consume information but also shape conversations (Muyed et al., 2025). Social media amplifies both climate acceptance and skepticism, showing how contested environmental debates can be (Graham & Golder, 2024). As mass communication tools, platforms empower youth to share narratives and push for change (Macotela, 2016). Engagement is shaped by values, trusted voices, and message framing, though competing life priorities often limit deeper involvement (Corner et al., 2015).

2.2 Youth Awareness and Knowledge in Bangladesh

Bangladeshi youth demonstrate moderate knowledge of climate change yet show strong awareness of its local impacts, including health risks like dengue outbreaks (Siddique et al., 2024). Their engagement is influenced by personal factors such as age, family structure, and health perceptions, but most critically by media use, with social media serving as a primary platform for both information and advocacy (Pasha et al., 2021; Mahmud, 2011). Visual content, especially climate images and videos, has proven highly effective in raising awareness and spurring participation (Ali & Choudhury, 2024). Platforms such as Facebook and YouTube allow youth to foster group discussions, connect with activists and NGOs, and co-create climate discourse (Hossain et al., 2025). Building social trust through community networks and verified messengers ensures that digital engagement translates into sustained climate action (Hossain et al., 2025).

2.3 Social Networks, Responsibility, and Participation

Social networks influence environmental responsibility in Bangladesh by motivating pro-environmental behavior and awareness through media content, exemplifying the collective dimension of networked publics (Pasha et al., 2021). Pasha et al. (2021) also highlighted that

younger generations are less likely to actively seek ecological and social information. Importantly, integrating environmental and social concerns in a unified way proves most effective in promoting awareness, responsibility, and active participation. Youth engagement in global conservation governance is constrained by tokenism, structural barriers, and limited access to decision-making, revealing inequalities within networked publics (Sithole et al., 2024). Teenagers negotiate networked privacy, managing context and visibility creatively in social media environments, demonstrating the social and technical negotiation required to participate in networked publics (Marwick & Boyd, 2014).

2.4 Networked Publics and Identity Negotiation

Networked publics make it easier for young people to join collective action by lowering participation costs and encouraging bottom-up mobilization through digital platforms, while personal networks like Facebook often show limited civic impact (Farnham et al., 2021). Key drivers of engagement are civic self-efficacy and community belonging, which highlight the need for access and tools that support public discussion (Farnham et al., 2021). Ojala and Ripatti-Torniainen (2023) describe networked publics as online collectives where youth create meaning, show solidarity, and take civic action. In Bangladesh, this helps explain how young people use social media to mobilize around environmental issues while also shaping their identities and sense of responsibility. Marwick and boyd (2014) add that youth must constantly manage privacy and visibility, showing that activism is not only about sharing information but also about protecting agency in overlapping online spaces.

2.5 Social Media Campaigns and Civic Participation

Amin (2024) shows how Bangladesh's rapid digital growth has made social media central to environmental awareness and civic engagement. Initiatives like *Clean Dhaka* illustrate how these platforms connect citizens, activists, and government. Similarly, MacKay, Parlee, and Karsgaard (2020) highlight Indigenous youth at COP24 who blended land-based knowledge with global platforms to strengthen leadership and activism. Eide and Kunelius (2021) add that the global youth climate movement draws credibility from combining science, lived experience, and independence from politics. While social media helps build collective identity and mobilization (Amin, 2024; Sharma, 2014), barriers such as inequality, limited decision-making power, and tokenistic participation continue to restrict youth activism (Eide & Kunelius, 2021).

2.6 Global Perspectives and Digital Environmental Activism

Digital media allows environmental movements to overcome borders, spreading information instantly (Jacqmarcq, 2021). Platforms like Facebook support "horizontal networks" for campaign sharing, while NGOs such as Greenpeace and WWF connect directly with global supporters. Social media also drives environmental awareness and behavioral change in Bangladesh (Amin, 2024), shapes public interaction with nature in Oman (Smith, 2024), and

enhances climate change awareness worldwide, though often with polarizing effects (Sultana et al., 2024).

2.7 Visual Communication and Climate Action

Visual communication is a powerful tool in digital environmental activism, capable of transcending barriers and provoking strong emotional responses globally (Nicholson-Cole, 2005). Climate justice advocacy needs to turn complex issues into powerful, emotionally resonant narratives (Bibi & Bibi, 2025). Symbols, gestures, and imagery embody urgency, resilience, and solidarity, amplifying marginalized voices. Hashtags or text alone rarely capture attention, making strategic visuals essential for campaigns (Hajri & Daife, 2024). In Bangladesh, images of floods and everyday people are particularly effective in driving engagement (Ali & Choudhury, 2024).

3. Literature Gap

Research shows that social media plays an important role in shaping youth awareness, participation, and identity around climate issues, both globally and in Bangladesh (Mandlik, 2025; Hossain et al., 2025; Amin, 2024). Yet, a theoretical gap remains. Many studies describe what young people are doing on social media but do not fully apply or extend frameworks such as networked publics or civic self-efficacy to explain how Bangladeshi youth negotiate climate discourse and activism in digital spaces (Marwick & Boyd, 2014; Farnham et al., 2021). This limits our understanding of why and how social media drives youth climate engagement in the Global South.

A population gap also exists. While youth activism is widely studied in Western and global contexts (MacKay et al., 2020; Eide & Kunelius, 2021), Bangladeshi youth remain underrepresented. Although local studies show their awareness of climate-related risks and their use of platforms like Facebook and YouTube (Siddique et al., 2024; Pasha et al., 2021), their specific socio-cultural conditions, structural barriers, and tokenistic participation are not adequately addressed.

These gaps highlight the need for research that is both theory-driven and context-sensitive, giving a stronger voice to the experiences of Bangladeshi youth in digital climate activism.

4. Theoretical Framework

This study is based on Networked Publics Theory (boyd, 2010). The theory explains how social media and other digital platforms work as new public spaces where people can share ideas, express themselves, and build communities. These online spaces are not just tools for communication; they are public arenas where people interact and create meaning together.

Networked Publics Theory focuses on four main features, called affordances: persistence, replicability, scalability, and searchability. Persistence means online posts, photos, or videos stay available for a long time. Replicability means information can be copied and shared easily. Scalability allows a message to reach a very large audience, and searchability helps people find content using hashtags or keywords (boyd, 2010).

In Bangladesh, these features help explain how young people learn about and talk about climate change online. For example, pictures of floods or climate protests can spread quickly and be seen by many. Posts can be reshared many times, keeping the topic visible and active. Social media, therefore helps raise climate awareness and emotional connection among youth.

Another key idea of the theory is identity performance. Online, young people speak to many audiences at once: friends, family, classmates, and strangers. This is called context collapse (Marwick & boyd, 2014). It makes youth more careful about what they post, especially in cultures like Bangladesh, where social approval matters. They try to appear responsible and respectful while expressing their climate concerns.

However, the theory also shows some limits. Even though social media makes it easy to join campaigns and show support, it does not always lead to real-world action. Young people may feel motivated online but lack time, money, or confidence to act offline (Ojala & Ripatti-Torniainen, 2023).

5. Methodology

This study used a mixed-methods design to explore how social media shapes Bangladeshi youth's climate awareness and whether online engagement leads to offline action. Using both quantitative and qualitative approaches made it possible to measure general patterns and understand personal experiences in depth (Creswell & Plano Clark, 2018). An online survey collected data from 150 Bangladeshi youth (aged 18–30), mainly university students and young professionals from urban and semi-urban areas. The questionnaire, distributed via social media and university networks, included demographic questions and items on frequency of climate content exposure, main platforms used, following of climate pages, perceived knowledge, belief in social media activism, and prior participation in climate activities. Responses were coded and analyzed in SPSS using descriptive statistics and Chi-square tests to examine two key hypotheses:

(H1) Relationship between exposure frequency and participation.

(H2) Relationship between belief in activism and participation.

Results were reported with effect sizes, and a significance level of $p < .05$ was used.

For deeper insight, 25 participants were purposively selected for semi-structured interviews (20–30 minutes each) conducted in Bangla or English. They included students and a few active

climate advocates with varied social media use. The interview guide covered five areas: exposure (RQ1), perception and emotion (RQ2), behavior (RQ3), barriers (RQ4), and strategies for engagement (RQ5). Interviews were recorded with consent, transcribed verbatim, and anonymized.

Quantitative data were processed in Excel and SPSS, while qualitative data were analyzed through reflexive thematic analysis (Braun & Clarke, 2019). Codes were developed line-by-line and grouped into themes: platform exposure, emotional content, intention–action gap, barriers, cultural strategies, and future trends. Findings from both datasets were integrated during interpretation, survey trends guided interview analysis, and qualitative insights helped explain quantitative patterns within Networked Publics Theory (boyd, 2010).

Participants gave informed consent, and all data were kept anonymous and confidential. Ethical approval was obtained through institutional procedures.

The study relied on online data collection, which may exclude less-connected youth, and used self-reported measures that can carry bias. The purposive sampling and cross-sectional design also limit generalizability. However, the mixed-method approach enhanced validity through triangulation of numerical trends and lived experiences.

6. Findings

6.1 Quantitative Results

To examine the relationship between social media exposure, belief in activism, and youth participation in climate activities, two hypotheses (H1 and H2) were tested using Chi-square analyses in SPSS. The dataset consisted of 150 valid responses collected through an online survey distributed among Bangladeshi university students and young professionals.

Hypothesis 1: Exposure to Climate Content and Climate Action

A Chi-square test of independence was conducted to determine whether the frequency of exposure to climate-related content on social media is associated with participation in climate activities. The result revealed a statistically significant association between exposure frequency and climate participation, $\chi^2 (3, N = 150) = 11.29, p = .010$. Descriptive results showed that 37.3% of respondents reported rarely seeing climate-related posts, 34.7% viewed them weekly, 20% daily, and 8% monthly. Meanwhile, 30.7% of participants indicated they had engaged in some form of climate-related activity, while 69.3% had not. Although overall participation levels remain modest, the data suggest that individuals who are more frequently exposed to environmental content online are more likely to translate that awareness into offline involvement. This finding reinforces the central argument of Networked Publics Theory (boyd, 2010), which explains that social media spaces function as participatory arenas where young

people construct civic identities and negotiate collective responsibility. Frequent exposure to climate discourse likely strengthens perceived knowledge, emotional connection, and collective efficacy, motivating some youth to act beyond online engagement. However, the unequal levels of participation across exposure categories indicate that awareness alone may not guarantee behavioral transformation without supportive institutional structures and opportunities for engagement.

Hypothesis 2: Belief in Activism Effectiveness and Climate Participation

A Chi-square test was also performed to assess whether belief in the effectiveness of social media activism influences actual participation in climate activities. The analysis showed no statistically significant relationship between belief and participation, $\chi^2(1, N = 150) = 0.76, p = .382$. Descriptive findings indicated that 85.3% of respondents believed social media activism can bring positive environmental change, while 14.7% disagreed. Despite this widespread optimism, only 69.3% of respondents had participated in any climate-related activity, and 30.7% had not. The lack of a significant association suggests that believing in the value of online activism does not necessarily translate into real-world engagement. This outcome highlights a key feature of contemporary digital environmentalism: the persistence of what scholars often call the “intention–action gap.” Within the framework of Networked Publics Theory (boyd, 2010), this gap can be explained by the tension between digital engagement and material participation. Youth may engage emotionally and symbolically through posts, shares, and hashtags, yet remain constrained by structural barriers such as limited organizational access, financial limitations, or social discouragement from activism.

Together, these results show that while social media exposure plays a meaningful role in shaping awareness and initial engagement, belief in digital activism alone is insufficient to ensure sustained offline participation. The findings point to the need for platform-sensitive and community-linked communication strategies that transform online awareness into collective environmental action.

6.2 Qualitative Results

The study involved twenty-five participants: three youth climate leaders and twenty-two general students. Participants were aged between 18 to 30 years, representing young adults actively engaged with social media in Bangladesh. The sample included perspectives from both urban and rural contexts, reflecting the diversity of access, exposure, and engagement with climate content across the country. Three participants reported professional experience in environmental initiatives, while others primarily interacted with climate content through social media and educational activities. This combination allowed for rich insights into how youth perceive, engage with, and act upon climate-related information online.

Five key themes were constructed from the interviews, reflecting (i) the power of social media for awareness-raising, (ii) emotional engagement with climate content, (iii) the translation of online awareness to offline action, (iv) communication strategies and cultural relevance, and (v) future trends in youth climate engagement.

6.2.1 Social Media as a Powerful Awareness-Raising Mechanism

Participants consistently emphasized that social media exerts a stronger influence on youth climate awareness compared to traditional media such as newspapers or television. The accessibility, immediacy, and algorithm-driven content distribution of social media were identified as major contributors to its effectiveness. They elaborated on why social media is particularly engaging for youth:

“Social media has more impact than traditional media. Especially Facebook. Newspaper writings have less reach than a social media post.” – Male, 21, Dhaka.

“Young people today rarely connect with newspapers or TV, while social media presents climate topics in a more colorful and relatable way. Personally, I find it easier to engage with climate content on social platforms.” – Male, 23, Dhaka.

Facebook emerged as the dominant platform for climate-related awareness in Bangladesh, followed by LinkedIn and Instagram. Participants highlighted those algorithmic feeds repeatedly expose youth to relevant climate content, amplifying its reach and visibility:

“Many pages they follow as the algorithm helps also. So, for youth awareness, Facebook influences the most, then LinkedIn and Instagram.” – Male, 25, Dhaka.

Geographical differences were also evident. Urban youth were more connected to climate networks and events, providing them with more opportunities for engagement. In contrast, rural youth were increasingly gaining online awareness, though their offline engagement remained limited:

“Urban youths get connected to many people through many events...there are some exceptions, but differences are huge.” – Male, 25, Khulna.

“Time is changing, so both rural and urban youth are becoming aware, but the ratio is high in urban areas.” – Female, 23, Rajshahi.

These findings indicate that social media functions as a high-reach, interactive platform that can increase perceived climate knowledge among youth through repeated exposure and algorithmic targeting.

6.2.2 Emotional Engagement and Content Preferences

Visual and emotionally resonant content was identified as critical for attracting youth attention. Participants highlighted videos, reels, infographics, and personal stories as particularly effective. They stated

“Video reaches more, as far as I have seen. Personal stories also get attention. Photo story also. Educational videos get less traction.” – Male, 25, Sylhet.

Participants similarly emphasized the power of visual storytelling:

“Graphics, short videos, and reels engage youth the most because visuals make these issues feel real and relatable.” – Male, 23, Dhaka.

Emotions such as fear, concern, and hope played a significant role in shaping engagement. Negative content, such as imagery of floods, pollution, or disasters, often drew more attention and was more widely shared:

“People are more likely to share alarming posts, like when they see headlines saying, ‘Bangladesh is number one in air pollution.’ Optimistic content or messages of solidarity are shared less often.” – Male, 27, Dhaka.

However, participants acknowledged the risk of desensitization with repeated exposure to distressing content. Participants highlighted the need for framing content with hope and actionable solutions:

“Constantly seeing negative news can make people numb. Instead, content should give people hope and show practical solutions. For example, Japan has better systems to tackle earthquakes; we can learn from that. Giving people hope is important.” – Male, 27, Khulna.

Participants also observed that event-driven content and community initiatives promoted on social media generated higher engagement than standalone educational videos:

“Activism linked to events usually attracts more attention. When an event is launched, promoters actively share and boost related content, which helps it reach a wider audience.” – Male, 27, Rajshahi.

Overall, emotionally engaging and visually compelling content increases perceived climate concern, but must be carefully designed to avoid fatigue or helplessness among youth.

6.2.3 From Online Awareness to Offline Action

While social media effectively raises awareness, translating online engagement into offline action was described as challenging. Participants pointed to internal and external barriers, including low self-efficacy, financial limitations, and social norms.

“Many young people think more about visibility and certificates rather than genuine passion for climate causes. Their involvement often feels like a way to be recognized rather than a deep commitment.” - *Male, 27, Dhaka*

Barriers to offline action were particularly pronounced in rural areas and disaster-prone regions, where limited resources, lack of guidance, and political interference hindered practical engagement:

“The main challenge is financial. There is little funding and not enough proper knowledge, especially in rural areas.” *Female, 26, Dhaka*

Political barriers are common; many groups use environmental issues for their own benefit instead of genuinely helping people.” *Female, 24, Dhaka*

Despite these obstacles, participants described campaigns and individual efforts that successfully mobilized youth. Examples included Mission Green Bangladesh, the Green Bangladesh Scholarship Program, and individual community activists:

“One inspiring example is the Green Bangladesh Scholarship Program. Mahmudur Rahman began cleaning Gulshan Lake on his own, and we learned about his efforts through social media. Now, that effort has grown into a community. Everything started because of social media.”

“The BD Clean campaign is a great example. It started online but successfully brought youth together to take real action in their communities.”

These insights highlight that offline action is contingent on providing youth with tangible opportunities, guidance, and social support, even when online engagement is high.

6.2.4 Communication Strategies and Cultural Relevance

Participants emphasized that climate messages are most effective when culturally and contextually relevant. Aligning messaging with local traditions, religious values, and community practices increases resonance and credibility.

“I completely agree that every context matters. For instance, mosques can serve as powerful spaces to shape public opinion, and climate content should be designed in culturally appropriate ways that make effective use of social media.” – Female, 23, Chittagong.

A participant reinforced this view by citing Islamic principles:

“Islam teaches us not to harm nature, and drawing on such teachings can make climate messages more meaningful and powerful for young people.” – Male, 24, Dhaka.

Participants also suggested that educational institutions could play a pivotal role in connecting online climate literacy to offline engagement through organized events, environmental days, and student-led initiatives:

“Educational institutions can be very effective. For example, celebrating Environment Day or organizing student-led activities can turn climate awareness into real action. – Female, 25, Dhaka.

These findings indicate that culturally sensitive messaging, combined with educational support, enhances youth engagement and provides pathways for translating awareness into action.

6.2.5 Future Trends in Youth Engagement

Participants anticipated increasing digital engagement and innovative content strategies over the next 5–10 years. Short-form videos, AI-generated content, and collaboration with international organizations were predicted to dominate climate communication: “Bangladeshi youth are becoming more digitally oriented every year. New content creators are emerging, and AI will likely help produce more creative and engaging content. – Male, 24, Dhaka.

“This is the age of reels. To reach young audiences effectively, content strategies must align with social media algorithms. Partnerships with global organizations such as the UN and UNESCO could also make campaigns more credible and far-reaching.” – Female, 26, Dhaka.

This projection aligns with the increasing importance of algorithmic curation, platform-specific trends, and creative content strategies in shaping youth climate awareness.

FIGURE 1: YOUTH AWARENESS OF ENVIRONMENTAL ISSUES IN BANGLADESH



Figure 1: Youth awareness of climate issues in Bangladesh (Authors' Illustration)

7. Discussion

The paper has investigated the social media influence on the perception, emotions, and behaviors of the Bangladeshi young generation in relation to climate change through Networked Publics Theory (boyd, 2010). The findings demonstrate that the role of social media as a tool to create climate awareness is essential, although the conversion of online activity into actual action remains low. The results indicated that there was a strong correlation between the frequency of viewing climate-related material online and the involvement in climate activities among the youths ($kh2 = 11.29$, $p = .010$). This contributes to international research that repeated exposure enhances knowledge and worry (Corner et al., 2015; Graham and Golder, 2024). The interviews also found that Facebook, then LinkedIn, and Instagram are the primary spaces where Bangladeshi youth discuss the climate, aligning with Hossain et al. (2025) and Amin (2024). The Networked Publics Theory states that social media is not merely an information tool, but a new environment where young people establish their identity and civic positions. The participants claimed that algorithms continue to serve climate posts and help form digital communities based on shared values. This creates awareness and a sense of belonging, yet, as Pasha et al. (2021) observed, awareness is not sufficient in making sure long-term engagement is achieved. The process of real change requires support and trust. Engagement was important for visual and emotive content. Infographics, personal stories, and short videos were favored by the participants. It seems to back the position of Nicholson Cole (2005) and Hajri and Daife (2024), who discovered that images can elicit more emotions. Images of fear can be very effective in drawing attention but are likely to produce exhaustion when overused (Ali and Choudhury,

2024), whereas hopeful stories, as Rahat proposed, lead to empowerment. These emotional reactions indicate what Marwick and boyd (2014) referred to as networked privacy and affect, in which the users trade visibility with emotion. Young people interact more with personal and inspirational information than information. This implies that hope and stories that can be related to locally can be more effective in communicating climate in Bangladesh than data. Though the majority of respondents (85.3% of the participants) felt that online activism can bring about change, this was not the case of real-life involvement ($\chi^2 = 0.76$, $p = .382$). This demonstrates the universal gap in intention to action present in environmental research (Corner et al., 2015) and justifies Sithole et al. (2024), who remarked that participation of youth is usually tokenized and unequal. Interviews revealed that a number of youths view activism as an end with recognition, which agrees with Mandlik (2025) who found out that social approval usually takes precedence over collective responsibility. Lack of institutional backing, funds and discouragement by the community also lessen participation. In dynamic digital environments, actual participation lies in offline support, like the observation of boyd (2010) that the digital publics create awareness, but action is taken by the institutions. Lastly, culture relates in climate communication. According to the participants, the ability to associate climate messages with religious and local values, including Islamic doctrine about being good stewards, enhances credibility. This stands in favor of Farnham et al. (2021), who added that civic action develops as it is related to community identification. Like Mahmud (2011) and Amin (2024), this research demonstrates that climate issues are more significant to the young people of Bangladesh when they are localized. Ways of transforming online awareness into community activity can also be achieved through learning institutions in terms of events, workshops and student clubs. Long-term youth engagement could be enhanced by incorporating climate issues in the university programs.

8. Implications for Policy and Communication

The combined results emphasize that social media's strength lies in its ability to *mobilize awareness*, not automatically to *mobilize action*. Policymakers, educators, and communicators should therefore design strategies that connect digital exposure to real-world participation. Three implications stand out:

1. **Platform-Aware Messaging:** Campaigns should use short-form, emotionally balanced, and visually engaging content, optimized for dominant platforms like Facebook and Instagram.
2. **Efficacy-Focused Communication:** Content should highlight achievable local actions to bridge the intention–action gap and build self-efficacy.
3. **Institutional Integration:** Partnerships between universities, NGOs, and government agencies can provide resources and recognition to sustain youth participation.

9. Conclusion

This study explored how Bangladeshi youth engage with climate content on social media, how such content shapes their perceptions and emotions, and why online awareness often fails to become offline action. Findings showed that frequent exposure to climate content is linked to higher participation, while belief in social media activism alone does not ensure real-world involvement. Qualitative insights explain this gap: although youth are emotionally engaged, especially by visual and story-based posts, they face structural barriers such as limited funds, institutional support, and confidence, as well as social and political constraints.

The results extend Networked Publics Theory (boyd, 2010) by demonstrating that digital spaces successfully build awareness and identity, but real-world mobilization relies on strong community and institutional support. This supports earlier research suggesting that digital engagement must connect with offline structures to create lasting civic outcomes (Marwick & Boyd, 2014; Farnham et al., 2021).

Practically, three steps are essential. First, communicators should design platform-aware and visually rich content that offers realistic local actions. Second, universities, NGOs, and community leaders should help bridge online engagement with real participation. Third, using cultural and religious values in messages can make climate communication more meaningful and trusted.

For policy and research, the study calls for youth-centered climate hubs that link online activism with hands-on initiatives and mentorship. Future research could examine whether such integrated programs sustain behavioral change. Enhancing digital literacy will also help young people identify credible sources and avoid misinformation.

Overall social media opens the door to climate awareness for Bangladeshi youth, but lasting change depends on connecting that digital awareness to practical, inclusive, and culturally grounded action.

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Paper 14

Enhancing Waste Management Through Deep Learning: Performance Evaluation of CNN Architectures

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Abstract

Human-generated waste increases as a result of fast urbanization and population expansion, harming both the environment and sustainable development. Pollution reduction and public health safety both depend strongly on effective management of waste. To address this problem, deep learning models can automatically analyze images and identify features to ensure accurate waste classification. Five pre-trained CNN models, such as ResNet50, ResNet101, DenseNet121, VGG16, and VGG19, were tested to assess the performance of CNN architectures. We collected a total of 29,028 labelled images for this study by merging datasets from open-access databases Mendeley and Kaggle. These images were categorized into eight classes of waste: biomedical, electronic, food, glass, metal, paper, plastic, and textile. The dataset was split into three subsets: 70% for training, 15% for validation, and 15% for testing. Before the training, every image was shuffled and resized to 224 x 224 x 3 pixels. With a batch size of 32, 10 epochs, and a learning rate of 0.001, each model was trained through transfer learning. The activation function in the hidden layers was the Rectified Linear Unit (ReLU). To handle the multi-class classification issue and create a probability distribution among the eight classes, the output layer applied the Softmax activation function. VGG16 showed the best performance with 95.12% training and 91.16% testing accuracy, followed by VGG19 (94.32% / 90.86%). ResNet50 and ResNet101 achieved similar results: training 93.01% / 93.06%, validation 91.18% / 91.16%, testing 90.13% / 89.44%, while VGG16 also had the lowest loss. All models had perfect ROC-AUC scores (1.00) for all classes except DenseNet121 (0.99). These findings can improve environmentally friendly urban systems, and sustainable waste management can be helped by these results, which can enhance automated waste identification, enhance recycling efficiency, and lower environmental pollution.

1. Introduction

Solid waste is made up of many different kinds of materials from everyday household garbage like food waste, ash, and packaging to construction debris, hazardous substances, and even healthcare-related waste. (UNDRR, 2025). It also includes human excreta mixed with general waste, as well as debris created by natural or man-made disasters. The waste which is produced in the urban residential, industrial, construction, etc. areas is known as the Municipal Solid Waste (MSW) (Ofori-Boateng et al., [2013](#)). MSW includes a wide range of materials, covering not only hazardous items such as chemicals, batteries, or medical waste but also non-hazardous materials like household refuse, paper, plastics, and food scraps (Malik et al., 2022). World Bank report shows an estimation of 2.01 billion tone of municipal solid waste are produced each year also global waste is expected to increase from 2.01 billion to 3.40 million tons by 2050 where approximately 44% of municipal solid waste is organic, 17% is paper/cardboard, 12% is plastic, 5% is glass, 4% is metal, 4% is other materials, and 7% is other inorganic materials (Kaza et al., 2018). It is also estimated that only 13.5% of global waste is recyclable, while 33% is directly dumped in the open without any classification (Kaza et al., 2018). Only 10% of materials are recycled, and most resources go through a process where they are taken from nature, used, and then discarded as waste. The circular economy has replaced the linear path with a loop system where materials such as plastics are designed to be recycled, reused or composted to keep them in circulation and out of the environment while simultaneously reducing waste, pollution and climate impact (Malik et al., 2022). In many cases, wastes that should be divided into hazardous, inorganic, and organic categories are disposed of collectively, which disrupts effective processing (Shreya et al., 2022). Due to the diverse visual characteristics of major waste categories such as plastic, paper, metal, glass, common waste, and cardboard, waste management becomes very complicated. Plastic is particularly prominent due to its diverse shapes, colors, and textures. At the same time, paper is a large part of industrial and everyday waste, metals such as cans and wire pose challenges for identification and the glasses, being fragile and originating from multiple sources, require careful handling (Wedha et al., 2024). The complex nature of municipal solid waste often creates uncertainty in its categorization by disposers. To address this challenge, artificial intelligence is being adopted as an innovative approach (Salsabila et al., 2025). The application of machine learning is expected to provide valuable assistance in addressing waste challenges through advanced modelling, predictive analytics, and process optimization (Xia et al., 2021). Proper segregation and processing of waste mitigate environmental impact and generate economic opportunities. Recent advances in deep neural networks, particularly convolutional neural networks (CNNs), have demonstrated a superior capacity for learning complex features from large-scale datasets, leading to high-accuracy image classification through the development of several standard architectures (Sun et al., 2019). By using Artificial Intelligence (AI), waste management becomes more efficient, as AI can help in automatically sorting and classifying waste based on its type, material, and recyclability. Nowadays, AI, particularly machine learning, has advanced greatly in recent years, and systems

based on machine learning have significantly developed the efficiency and accuracy of the waste management process. Intelligent garbage sorting bins, which are capable of classifying individual waste items at a time against a clean background using AI, have become more and more popular and are among the most widely used solutions in modern waste management (Sheng et al., 2020; White et al., 2020). In recent years, deep learning (DL) has been used with drones or vehicle-mounted cameras to detect and classify waste in natural settings (Kraft et al., 2021).

Waste sorting can be sped up by using deep learning methods, but comparing different approaches is still challenging. Because trash comes in many different forms, identifying it can be challenging even for humans, and although several datasets exist, they often vary in waste types, annotations, and categories, and are usually small and focused on just a single type of waste. This inconsistency of data makes it difficult to compare the methods. Even in the current time there is no benchmark available for waste detection. The absence of such standards slows down the optimization cycle of deep learning models, limits continuous improvement and hinders effective knowledge sharing between academics and industry. To address this issue, this study utilizes a large dataset that includes images of multiple waste types, such as food, paper, metal, textile, biomedical, electronic, plastic, and glass and also several well-established, pre-trained convolutional neural network (CNN) architectures such as ResNet50, ResNet101, DenseNet121, VGG16, and VGG19 are employed to conduct a comprehensive evaluation. The goal is to achieve accurate CNN object detection in real time that can accurately identify waste. To this end, the architectures were selected for their proven feature extraction capabilities, widespread use in computer vision work and their structural differences, which allow for an in-depth comparison of their performance in handling the visual complexity of real-world waste. This study aims to compare these standard architectures on different datasets, establish reliable baseline results and contribute to the development of consistent evaluation practices in automated waste classification and detection.

3. Literature Review

AI contain huge potential in waste management as deep learning has an important role in the waste sorting process (Salsabila et al., 2025). Deep learning, especially CNNs, provides good results in image classification, object detection, and segmentation, also including some state-of-the-art solutions (Rawat and Wang, 2017; Zhao et al., 2019; Long et al., 2015). For example, different CNN architectures were used, such as MobileNetV3, MobileNetV2, InceptionV3, ResNet50, ResNet101, ResNet152, and an exception is made for recyclable waste, which is usually classified into six simple categories: plastic, glass, paper or cardboard, metal, fabric, and other recyclable materials. Among them, MobileNetV3 has a high classification rate with 94.26% accuracy, and overall performance was in the range of 91.9 to 94.6% in the validation set (Wang et al., 2021). In another study, ResNet-50 and ResNet-152 were compared to identify the best classification model by using datasets of TrashNet and a local dataset that contains 5,326

images divided into four categories such as garbage, plastic, metal and pets. The test result provides 95.72% and 94.15% accuracy of ResNet-152 and ResNet-50, respectively (Muangnak et al., 2021). In the literature, several research works have been produced in the field of waste sorting using deep learning. A waste classification model based on transfer learning was developed and achieved 90% test accuracy Inception-ResNet and Inception-v4 and DenseNet121 performed best with 95% accuracy by transfer learning using ImageNet (Bircanoğlu et al., 2018).

It is determined that the first step of recycling and reusing waste is waste classification (Rabano et al., 2018). It's crucial to replace traditional waste classification with smart systems, as they are ineffective. It presented how waste can be classified using smart systems, and DenseNet169 CNN architecture with the transfer learning model was used, which provided an 82% accuracy value (Zhang et al., 2021). In another proposed model, the TrashNet dataset and Resnet18 architecture were used to improve the automation of the recycling process, in which 87.8% accuracy has been achieved (Gyawali et al., 2022). Additionally, Transfer learning and TrashNet dataset were used along with MobileNet CNN architecture, and an accuracy value of 87.2% was reached on the test data (Feng et al., 2022). In a different study, 2,527 images belonging to six waste categories, such as cardboard, glass, metal, paper, plastic, and trash, were used to identify inorganic waste through ResNet-101 which achieved 90% of the test value (Riduan et al., 2024). Five different ResNet architectures such as, ResNet-18, ResNet-34, ResNet-50, ResNet-101, and ResNet-152 were employed and trained using the TrashNet dataset. This proposed model achieved 88.8% of test accuracy (Lin et al., 2022). In the waste management system, object detection is widely implemented these days. A smart trash bin has been equipped with a Raspberry Pi 4 to enable real-time waste classification. For this purpose, the study designed a custom Convolutional Neural Network (CNN) architecture modify for an IoT-based smart waste management system, allowing the bin to automatically recognize and sort different types of waste (Sallang et al., 2021).

Despite much research on automated waste classification, model performance remains below expectations. The similarity between glass and plastic waste poses a major challenge, leading to classification errors. To address this, further investigation is needed into strategies to improve classification accuracy on small and highly similar datasets. This study identifies the most effective architecture through extensive testing.

4. Methodology

4.1 Dataset Description

This study focused on identifying various types of solid waste from images and analyzing the performance of a pre-trained deep learning model. We compiled a total of 29,028 labeled images by merging datasets from open-access repositories, including Mendeley and Kaggle (Kunwar, 2024; Yangke, 2025). The images were organized into eight waste categories: biomedical,

electronic, food, glass, metal, paper, plastic, and textile. The dataset was divided into three subsets: 70% for training, 15% for validation, and 15% for testing (Table 1). The images were in JPG and JPEG formats.

Data Splitting	Data Labels							
	Biomedical	Electronic	Food	Glass	Metal	Paper	Plastic	Textile
Training (70%)	932	744	2361	3109	1394	4125	2625	5030
Validation (15%)	200	160	507	666	298	884	562	1077
Testing (15%)	200	160	507	666	298	884	562	1077
Total Image	1332	1064	3375	4441	1990	5893	3749	7184

Table 1: Number of images of each label with splitting into training, validation and testing

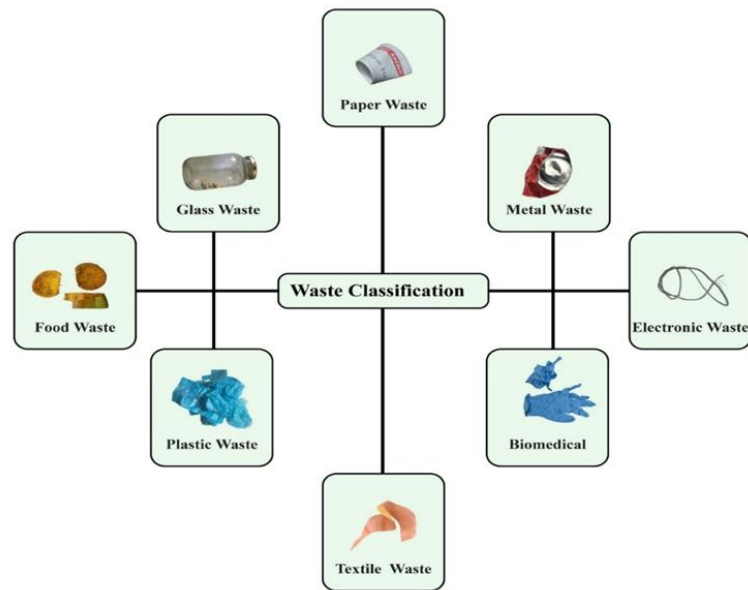


Figure 1: Classification of Waste in the study's dataset

4.2 Experimental Models

In this study, some pre-trained deep learning models, such as VGG16, VGG19, ResNet101, ResNet50, and DenseNet121, were used to identify various types of solid waste from images. Initially, the dataset was trained using the VGG16 pre-trained model. In this study, we using some pertained deep learning model such as VGG16, VGG19, ResNet101, ResNet50 and DenseNet121 to identifying various types of solid waste from images. At first we trained our dataset with VGG16 pertained Model.

4.2.2 VGG16

In this work, solid waste was identified from images using the VGG16 architecture, a well-established deep Convolutional Neural Network (CNN). VGG16 was chosen because of its powerful hierarchical recognition capacity, which is particularly helpful for capturing the complex visual characteristics present across multiple categories of solid waste. All of the photos were reduced to 224×224 pixels, which is the usual input size for VGG16, to ensure model validity and increase the efficiency of training. Normalization, which adjusted pixel values to the [0,1] range to improve numerical stability and speed up integration, was a further preprocessing step.

The 16 weight layers that make up the VGG16 architecture are organized in a regular pattern of modest 3x3 convolutional filters followed by ReLU (Rectified Linear Unit) activations (Qassim et al., 2018). After these convolutional layers are divided into blocks, 2x2 max-pooling techniques are applied to each block, reducing the spatial dimensions while maintaining key characteristics. The model can identify low-level features like edges and textures in early stages due to its layered design, while learning higher-level concepts in deeper layers. Three fully connected dense layers are added to the output following the convolutional feature extraction process, mapping the learnt features into a classification-ready structure. A softmax activation function is used for the final classification, which allows the model to choose the most likely prediction by producing a probability distribution over the set of target waste classifications.

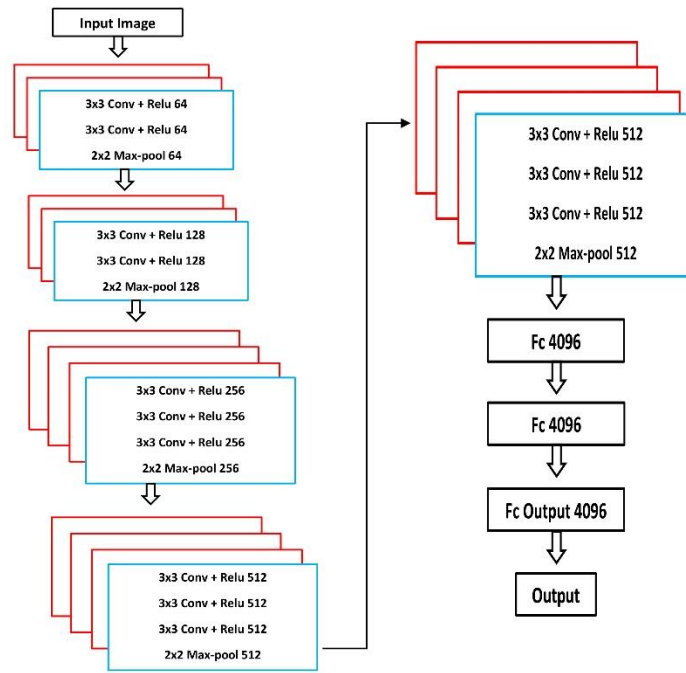


Figure 2: VGG16 architecture diagram

4.2.3 VGG19

For this study, the VGG19 architecture, a deep Convolutional Neural Network (CNN) that was proposed by Simonyan and Zisserman (2015), was used to classify and identify waste using image data. Because of its 19 multilayered structure, it is particularly effective at maintaining patterns that are crucial for identifying visually identical characters. We used a number of preprocessing techniques when inputting photos into the model. To comply with the model's input requirements, all photos were first reduced to 224 x 224 pixels. Then, in order to maintain stability and optimize training, we normalized pixel values between 0 and 1. Each of the five major convolutional layers used by VGG19 to analyze images is intended to constantly extract increasingly complex and complex characteristics. Multiple 3x3 convolutional layers with progressively larger filters (64, 128, 256, and 512) are present in each block. These are followed by max-pooling layers that minimize the dimension of space while maintaining important characteristics. During feature extraction, three fully connected layers (with 4096, 4096, and 1000 cells) are added to the output, finishing in a softmax layer that predicts the probability that the image belongs to each waste class. By initializing the model with pre-trained weights from ImageNet and fine-tuning the final layers, we employed transfer learning to improve performance on the waste dataset. Through this process the model was able to use previously

learnt visual features and modify them according to the unique characteristics of the solid waste in the dataset.

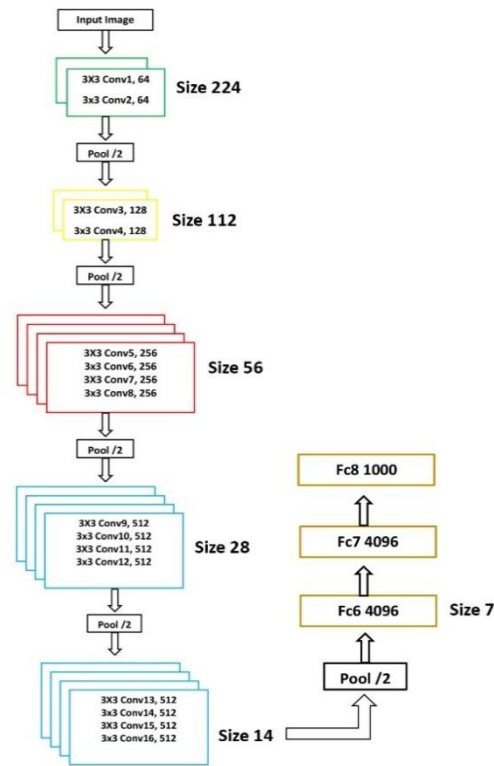


Figure 3: VGG19 architecture diagram

4.3.4 ResNet101

The ResNet101 (Residual Network-101) architecture is a deep convolutional neural network with 101 layers that was designed to use residual learning in order to solve the gradient that fades issue in very deep networks (He et al., 2016). ResNet101 learns residual functions by speed connections that bypass one or more layers, ensuring that gradients flow more effectively during back propagation, compared to learning direct mappings. After a 7x7 convolution layer and a 3x3 max pooling layer, the network moves on to four major residual blocks of different depths (3, 4, 23, and 3 layers, respectively). These residual units that utilize a 1x1, 3x3, and 1x1 convolutional structure are included in each block to lower computing costs without reducing feature depth. Effective layered feature extraction is made possible by this design, which captures both low-level. Effective hierarchical feature extraction is made possible by this

architecture, which captures both high-level semantic information and low-level spatial features. ResNet101 was used in this study to identify solid waste pictures. Its deep residual connections made it possible to precisely extract discriminative characteristics from complicated waste images, increasing classification accuracy and robustness in a range of shapes, textures, and lighting conditions.

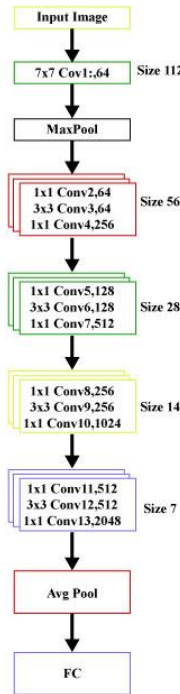


Figure 4: ResNet101 architecture diagram

4.3.5 ResNet50

ResNet, an abbreviation for Residual Network, defines a specialized convolutional neural network (CNN) architecture which are commonly utilized in computer vision, including image classification and object detection tasks (He et al., 2016). In this study, we used the ResNet-50 architecture to identify waste from the dataset of images ResNet-50's use of residual learning, which allows the training of deep networks without information loss, makes it ideal for difficult image identification uses. Photos are resized to 224×224 pixels, normalized, and data augmentation techniques like flipping, rotation, and brightness correction are used to ensure better generalization (Shabbir et al., 2021). We used RGB (three-channel) inputs to ensure compatibility since the model has been trained on ImageNet. Convolutional layers, batch normalization, ReLU activations, and residual connections belong to the 50 layers which make up the ResNet-50 architecture. It uses a layered feature processing system, with deeper layers focusing on complex factors, mid-level layers collecting texture and patterns, and early levels

capturing low-level information like borders and types. A fully connected layer turns the data into a vector representation after feature extraction, and a global average pooling layer reduces complexity. A softmax function is then used to classify the features and give a probability to each waste class.

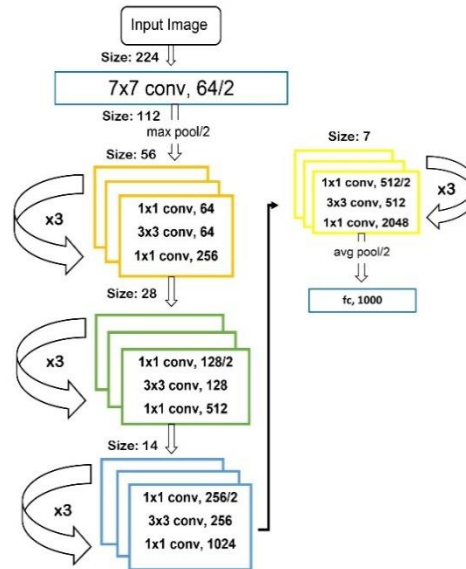


Figure 5: ResNet50 architecture diagram

4.3.6 DenseNet 121

In this work, solid waste was identified from images using the DenseNet-121 convolutional neural network architecture (Huang et al., 2017). In order to reduce spatial dimensions while maintaining important characteristics, the model starts with a 7×7 convolution layer and then continues on to a 3×3 max-pooling layer (Figure 6). Four Dense Blocks, each with several convolutional layers, comprise the model's kernel. In order to promote feature reuse and address the gradient disappearing issue, these blocks are made so that every layer receives feature mappings from every layer that came before it inside the same block. A Transition Layer is used between each Dense Block. Batch normalization, ReLU activation, 1×1 convolution for feature compression, Dropout for regularization, and 2×2 average pooling for spatial down-sampling are all included in each Transition Layer. Dense Blocks 1 to 4 of DenseNet-121 have 6, 12, 24, and

16 convolutional layers. A fully linked SoftMax filter that provides probability for every waste class comes after a global average pooling layer that compresses the feature images.

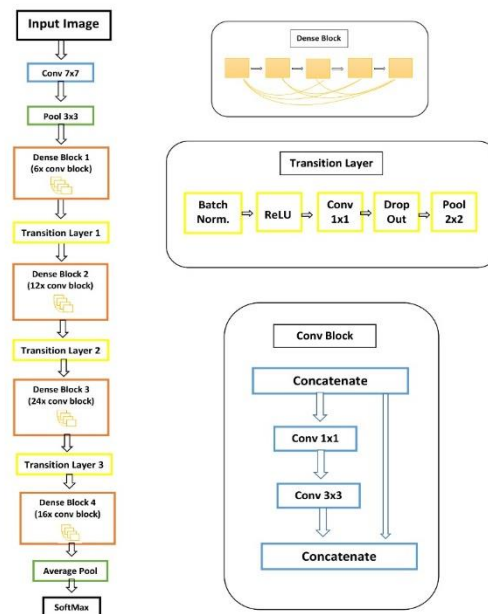


Figure 6: DenseNet 121 architecture diagram

4.3 Training Procedure

To preserve uniformity in proportions, all photos were resized to a standard size of 224x224x3. The normalized pictures were then obtained by performing normalization, which involved removing the mean and dividing by the standard deviation. We then fed these previously processed photos into our model. The batch size was 32. Global Average Pooling is included in neural network topologies built with Keras. By reducing each feature map's spatial dimensions to a single value, this process turns each feature map into a scalar. An additional fully linked layer with 1024 neurons is added to the model. The model is made non-linear by the ReLU, the activation function used in this instance. 512, 256, and 128 neurons, or fully linked layers, are added to the model after that. These layers all make use of the ReLU activation function. Eight neurons, one for each class, make up the completely linked layer that completes the model. Softmax function is the activation function for this layer; it normalizes the output to a probability distribution across the classes. The class in this distribution with the highest probability is the model's prediction. Every model continues to converge, increasing gradually over the course of

the first 10 training epochs. The optimizer utilized was the stochastic gradient descent with a learning rate of 0.001.

4.4 Experimental Setup and Analysis Tools

4.4.1 Hardware and Software

Processor: 11th Gen Intel (R) Core (TM) i3-1115G4 (3.00 GHz), RAM 8.00 GB, SSD 265 GB.

64-bit operating system Windows 11 Pro is a cutting-edge, reliable operating system that offers a consistent setting for the use of machine learning tools and frameworks. The coding portion of our thesis is done in a Python environment using Visual Studio Code. Python Environment: To ensure compatibility with the most recent libraries, Python 9 or later is advised. NumPy can handle arrays and perform numerical computations. Pandas for data manipulation and analysis. Matplotlib is used for charting and data visualization. To create, train, and assess deep learning models especially for image categorization, use TensorFlow and Keras.

4.4.2 Training, Validation and Testing graph

Graphs for training and validation are crucial tools for tracking an image classification model's performance over training (WU et al., 2023). Important parameters like accuracy and loss are plotted in these graphs for both the training and validation datasets. The model's performance on the training set is measured by training loss and accuracy, where lowering loss and rising accuracy signify successful learning. A good fit is defined by high validation accuracy and low validation loss that is stable over time. These metrics offer insights into the model's capacity to generalize to new data (Shanqing et al., 2019).

4.4.3 Confusion Matrix

An essential tool for assessing the effectiveness of a classification model is a confusion matrix (Naidu et al., 2023). By contrasting the actual results with the model's predictions, it is possible to determine where the model performed well and where it fell short. True positives (right positive predictions), false positives (wrong positive predictions), true negatives (wrong negative predictions), and false negatives (wrong negative predictions) are all included in the matrix. This comprehensive dissection provides a clear view of the model's performance and aids in the calculation of critical metrics, including accuracy, precision, recall, and the F1 score. By utilizing a confusion matrix, we are able to not only determine the model's accuracy but also identify the precise kinds of mistakes it makes, which helps us make useful improvements to the model (Zhou et al., 2016).

ROC Curve

The Receiver Operating Characteristic curve, or ROC curve, is a technique used to assess a classification model's performance. Plotting the true positive rate (sensitivity) versus the false positive rate (1-specificity) at various thresholds illustrates how well the model separates the classes. The model's efficacy is shown by the area under the curve (AUC); the closer the model is to 1, the better. Perfect predictions have an AUC of 1, whereas 0.5 is no better than arbitrary guesswork. The ROC curve facilitates model comparison and threshold selection for decision-making (Muschelli, 2020).

Explainable AI

A collection of methods and approaches known as Explainable Artificial Intelligence (XAI) is designed to make AI and machine learning models' decision-making processes transparent, interpretable, and clear to users. XAI helps to confirm whether the model focuses on pertinent waste components rather than background noise by highlighting the precise image regions or features that impacted the model's conclusion using visualization tools like Grad-CAM or LIME. According to Gunning and Aha (2019), understanding improves model accessibility, reliability, and transparency, all of which are critical for using AI in actual waste management systems.

t-Distributed Stochastic Neighbor Embedding

By turning high-dimensional data into a two- or three-dimensional format while maintaining local connections between data points, t-Distributed Stochastic Neighbor Embedding (t-SNE) is an effective dimensionality reduction technique. The capacity of the model to distinguish between classes like plastic, paper, metal, or organic trash is evaluated by using t-SNE to show study how various waste categories are clustered based on extracted picture attributes. Key information about feature division, model performance, and possible misclassifications is provided by this visualization. According to Maaten and Hinton (2008), t-SNE is a useful tool in AI-based trash classification studies because it captures non-linear correlations among samples, which makes it very useful for showing complex datasets.

5. Findings

Five pre-trained convolutional neural network (CNN) architectures were used in this study to identify solid waste images: VGG16, VGG19, ResNet50, ResNet101, and DenseNet121. Accuracy in testing, validation, and training, as well as the corresponding loss values were used to assess each model.

The maximum accuracy throughout training was 95.12% for VGG16 and 94.32% for VGG19. DenseNet121 showed a relatively lower training accuracy of 75.82%, while the ResNet101 (93.06%) and ResNet50 (93.01%) models performed similarly.

ResNet50 and ResNet101 had the highest and almost comparable accuracy rates, 91.18%, during the validation phase. Additionally, VGG16 maintained a high validation accuracy of 90.74%,

with VGG19 coming in second (90.17%). However, DenseNet121's validation performance was lower, with an accuracy of 71.37%.

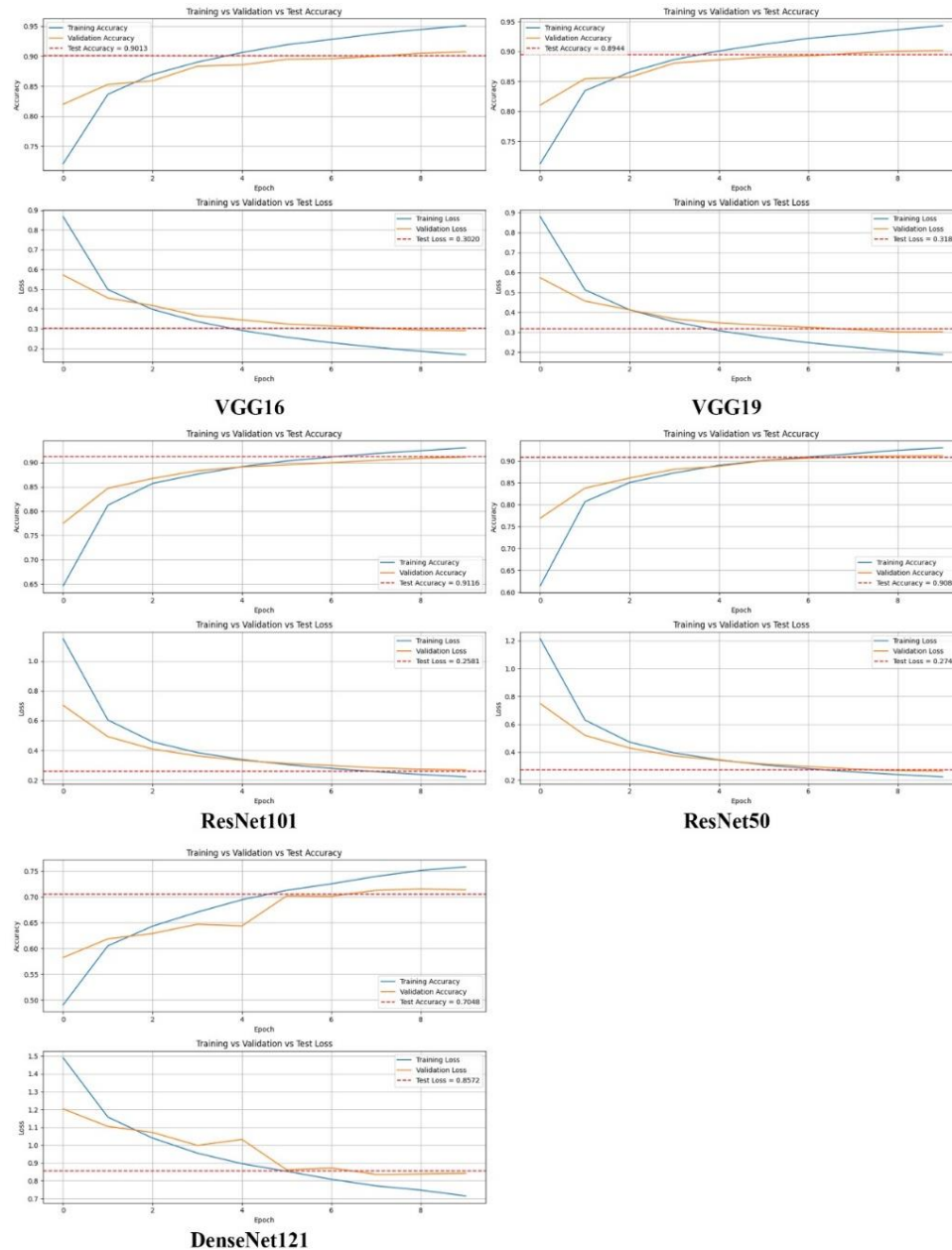


Figure 7: Performance curves illustrating training, validation, and testing accuracy and loss for five CNN architectures: VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

With an accuracy of 91.82%, ResNet101 outperformed VGG16 (90.13%) and ResNet50 (90.86%) in the testing process. DenseNet121 once more produced a lower testing accuracy of 70.48%, while VGG19 demonstrated a similar accuracy of 89.44%.

DenseNet121 achieved an AUC of 0.99 according to the Receiver Operating Characteristic (ROC) study, but VGG16, VGG19, ResNet50, and ResNet101 all had a flawless AUC of 1.00. This suggests that while DenseNet121 showed a weaker classification capability than the other models, all models showed very high performance in identifying between various waste types.

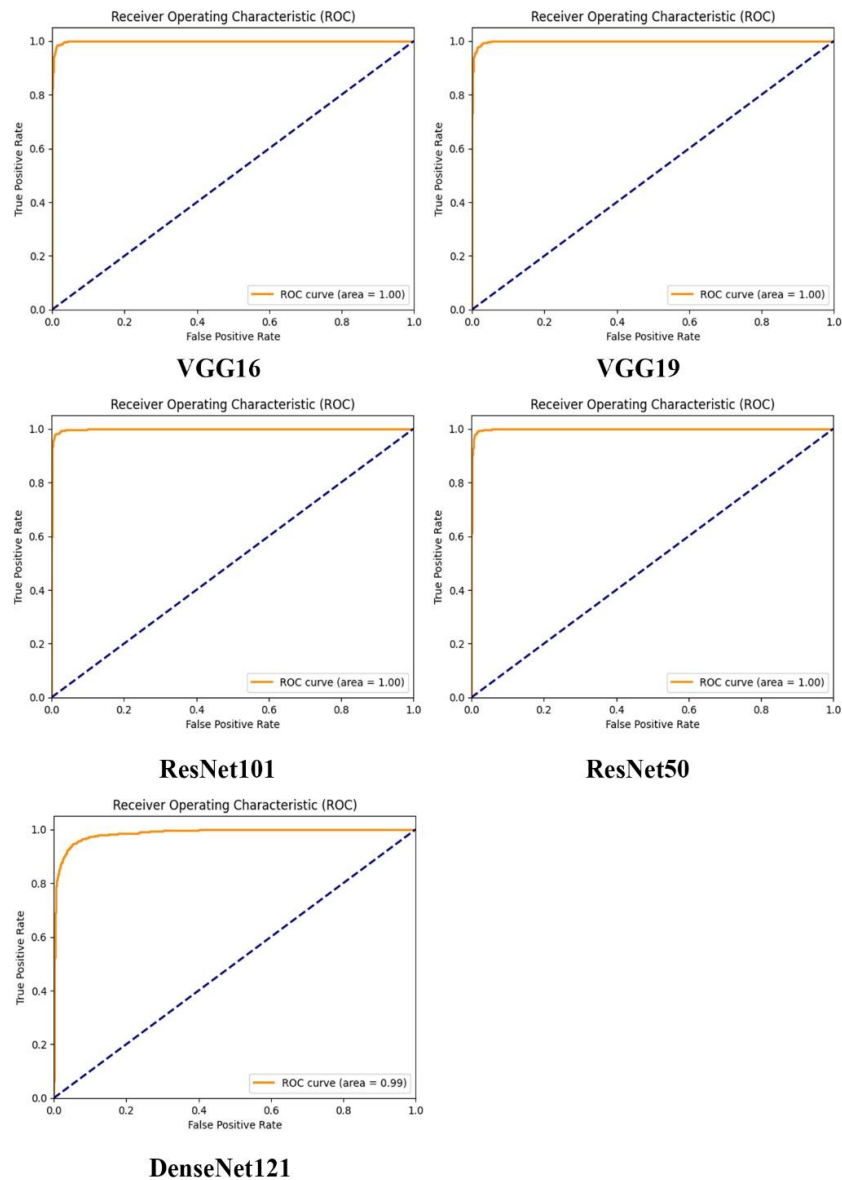


Figure 8: ROC Curve of VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

The confusion matrix illustrates the number of correct and incorrect predictions for each waste category. The diagonal elements, for example, stand for photos that were successfully identified (true positives) for each class. Misclassifications are indicated by off-diagonal elements, such as plastic graphics that are misconstrued for paper or glass. By highlighting the most frequently confused classes, this visualization assists in guiding model or dataset changes. DenseNet121 had a little higher number of misclassifications in this study, whereas ResNet101 and ResNet50 displayed less off-diagonal elements, showing better class discrimination.

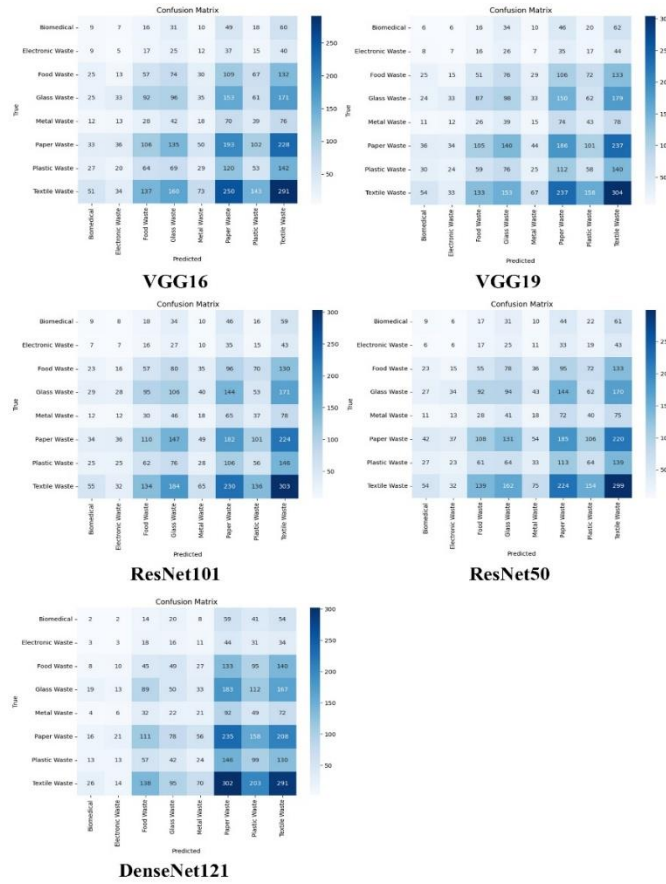


Figure 9: Confusion matrix of VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

The vectors of features were collected from five distinct convolutional neural network (CNN) architectures: VGG16, VGG19, ResNet101, ResNet50, and DenseNet121, and were then displayed using t-SNE (t-Distributed Stochastic Neighbor Embedding). These plots are meant to provide a visual assessment of each model's ability to differentiate between the eight different waste categories. Each point in these visualizations represents a single waste image, and the

color of the point reflects the actual category (e.g., Food Waste, Biomedical, etc.). Similar photos are plotted closer together on a 2D map created by the t-SNE technique, which minimizes the high-dimensional features the model learned.

The model with the best performance is ResNet50. Out of all the models, the clusters are the most prominent, compact, and well-separated. The green (food waste) and light blue (biomedical) clusters, for instance, are incredibly close together and secluded. Other categories, such as grey (Electronic Waste), orange (Metal Waste), and purple (Paper Waste), also provide distinct groupings with little overlap. This robust separation indicates that the most potent and discriminative features for your trash image classification have been learned by ResNet50.

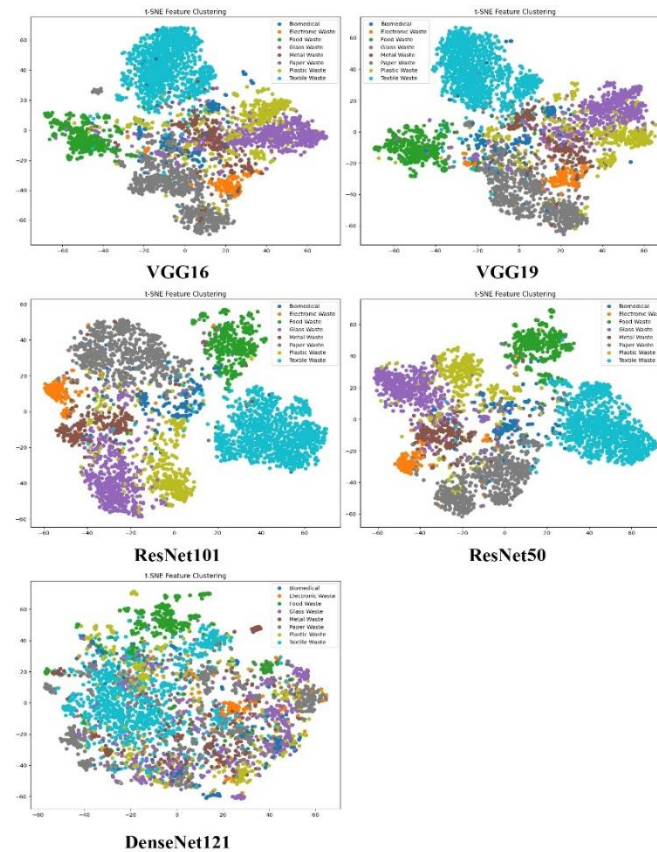


Figure 10: t-SNE of VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

VGG16 and VGG19 are fairly similar to one another and perform effectively. Both of them generate unique clusters, especially for the Biomedical (light blue) category. In contrast to ResNet50, there is more mixing and overlap among the other categories in the plot's center. This suggests that although the VGG models are useful, they might mix up some of the waste categories that are more visually similar, such as metal, paper, and plastic.

ResNet101 Shows dispersed, overlapping clusters and poor feature repeatability, implying insufficient performance in waste category distinction. DenseNet121 shows heterogeneous clusters and scattered data, indicating poor feature learning and trouble sorting waste categories.

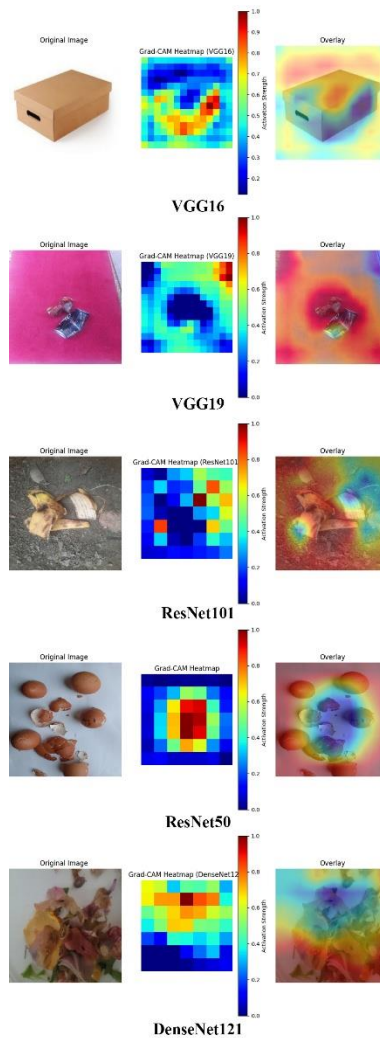


Figure 11: Grad-CAM of VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

Displays how each model finds significant parts of images for categorization using Grad-CAM (Gradient-weighted Class Activation Mapping) visualizations. Blue spots denote modest importance, whereas red parts imply significant attention. ResNet50 displays the most accurate focus of all the models, focusing carefully on the eggshells while successfully blocking out the background, showing strong and reliable learning. More successful are VGG16 and VGG19,

which precisely emphasize important waste items like the cardboard box and metal hinge. ResNet101 and DenseNet121, on the other hand, display dispersed and less focused focus maps, indicating poorer localization and background noise-induced confusion.

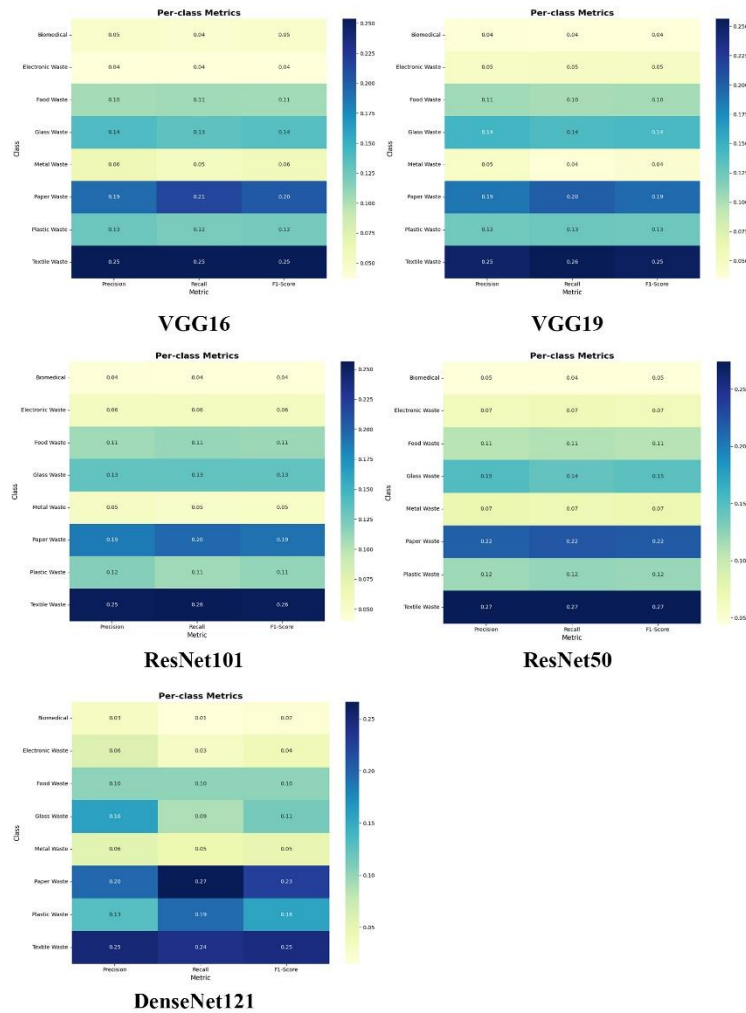


Figure 12: Per-class metrics of VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

The heat maps show five distinct models' accuracy, precision, recall, and F1-score, which are important indicators of performance. The ResNet50 model achieved an exceptional score of almost 0.91 (91%) across all metrics, showing a significant performance difference. With continuously low scores of about 0.16-0.17 (16–17%), the other four models (VGG16, VGG19, ResNet101, and DenseNet121) scored less well.

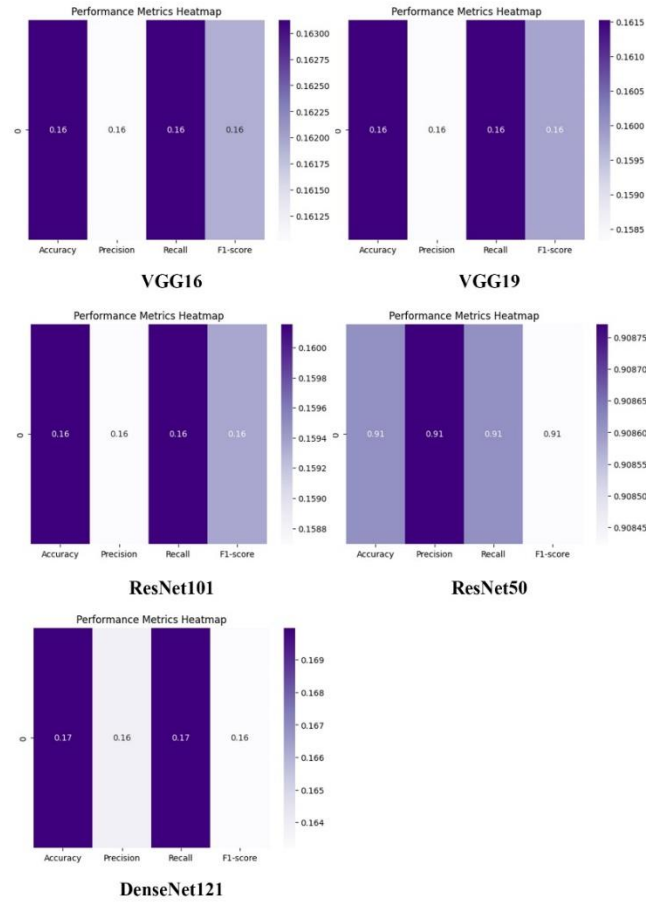


Figure 13: Performance metrics heat map of VGG16, VGG19, ResNet101, ResNet50, and DenseNet121

6. Discussion

The results from this study explain the effectiveness of deep learning in automatic waste classification. Images are divided into eight categories: biomedical, electronic, food, glass, metal, paper, plastic, and textiles. Five pre-trained CNN architectures, such as VGG16, VGG19, ResNet101, ResNet150 and DenseNet121 are compared to evaluate their ability to classify the waste dataset of 29,028 labelled images collected from Kunwar (2024) and Yangke (2025) and highlight the strengths and weaknesses of each model, providing a clear understanding of their performance and limitations in classifying solid waste.

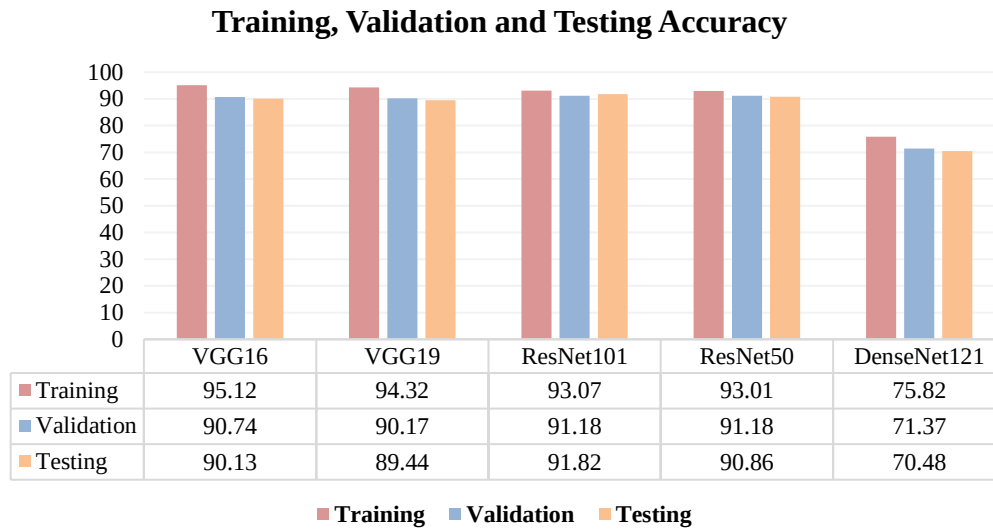


Figure 14: Training, Validation and Testing Accuracy values of different CNN models

Comparative analysis of the performance of CNN architecture demonstrates that VGG16 beats all other models with 95.12% training, 90.74% validation, and 90.13% testing accuracy. On the other hand, DenseNet121 achieved relatively low results compared to others with 70.48% test accuracy, which indicates that its densely connected architecture could not effectively adapt to the characteristics of the dataset.

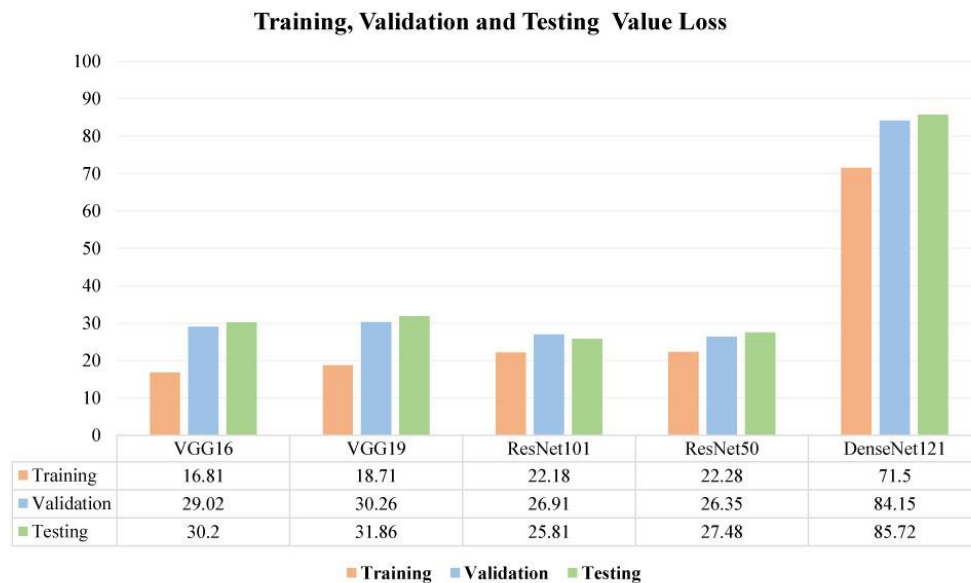


Figure 15: Training, Validation and Testing value loss of different CNN models

Several analytical techniques are used to evaluate and interpret the model performance, including confusion matrix, ROC curve, accuracy and loss analysis, Explainable AI (XAI) visualization, and t-SNE feature clustering. The confusion matrix illustrated the distribution of correct and incorrect predictions across the eight waste categories to help identify classes that were incorrectly classified (Sathyanarayanan & Tantri, 2024). To observe the convergence of the models during training and detecting signs of overfitting, accuracy and loss graphs are used (Goodfellow et al., 2016). The value of Receiver Operating Characteristic (ROC) curves and their Area Under the Curve (AUC) are analyzed to measure the models' ability to determine the different types of waste and to confirm their reliability (Chang & Newman, 2024; Janssens & Martens, 2020). Across all the classes, nearly all CNN architectures achieved perfect ROC-AUC scores except for DenseNet121, which achieved a 0.99 ROC-AUC score. To explain the decision-making process of CNN models and visualization, Explainable Artificial Intelligence (XAI) is used, which ensures transparency and verifies if the models focus on relevant features of the waste images. Lastly, to visualize the high-dimensional feature space learn by the models, t-SNE feature clustering was applied, which provided insight into how effectively the networks separated different waste categories in the feature representation space.

Model	No. of Classes	Test Accuracy (Previous Study)	Test Accuracy (Our Study)	Reference
VGG16	6	76.94%	90.13%	Ruiz et al., 2019
VGG19	6	79.32%	89.44%	Ruiz et al., 2019
ResNet101	6	90.0%	91.82%	Riduan et al., 2024
VGG16	2	91%	90.13%	Kaushik and Kaur, 2025
VGG16	4	88.42	90.13%	Faria et al.,2021
VGG19	4	86.38%	89.44%	Faria et al.,2021
ResNet50	4	50.28%	90.86%	Faria et al., 2021
ResNet50	6	87.50%	90.86%	Prajapati et al., 2024
DenseNet121	6	86.33%	70.48%	Prajapati et al., 2024

Table 2: Comparative analysis with previous studies

The table demonstrates the comparative analysis of different deep learning models' performance used in the study and models reported in previous studies. The comparison presents the same architectures (VGG16, VGG19, ResNet50, ResNet101, and DenseNet121) performed under different datasets, class configurations and experimental conditions. The results indicate that the

models developed in this study achieved significantly high accuracy in most cases. For example, VGG16 and VGG19 recorded significant improvements compared to the results of Ruiz et al. (2019), increasing the accuracy from 76.94% and 79.32% to 90.13% and 89.44% respectively. Similarly, a significant performance was achieved by ResNet50, increasing from 50.28% (Faria et al., 2021) and 87.50% (Prajapati et al., 2024) to 90.86% in this study. The ResNet101 model achieved the best accuracy value of this study, which is slightly better than Riduan et al. (2024), showing a marginal increase from 90.0% to 91.82%. Although the performance of DenseNet121 is significantly reduced by achieving only 70.48% compared to 86.33% reported by Prajapati et al. (2024).

However, despite these promising results, several limitations should be acknowledged that may affect real-world applicability. Firstly, the dataset's size and variety may not fully capture the wide range of waste types found in real-world scenarios. Although the 29,028 images were collected from open-access sources, differences in lighting conditions and background noise may affect model generalization when applied to real-world environments such as public bins or recycling plants. Secondly, the similarity between certain classes, particularly materials like glass and plastic, posed challenges for the models and often resulted in misclassification. Multispectral or hyperspectral imaging should be explored to address this limitation in future work. Lastly, the training and testing of the models were in a controlled environment with fixed image size ($224 \times 224 \times 3$) and limited magnification. But images will be captured by sensors or cameras in real-world waste management systems, which can differ in scale, angle, and resolution. So this requires further testing in practical deployment scenarios.

7. Conclusion

Effective and intelligent waste management systems have become essential because of rapid urbanization and a growing population, which are increasing waste generation. Waste management systems have become essential to reduce environmental impacts and promote sustainable development. To support a sustainable waste management system, a deep learning technique for automated waste classification was explored. To address this challenge, five pre-trained architectures of convolutional neural network (CNN), namely VGG16, VGG19, ResNet101, ResNet50, and DenseNet121, were implemented and evaluated using a dataset of 29,028 labelled images collected from open-access sources such as Mendeley and Kaggle. The dataset was classified into eight distinct waste categories: biomedical, electronic, food, glass, metal, paper, plastic, and textile. Each of the models transfer learning with standardized preprocessing steps, including optimized training parameters such as batch size, learning rate, and activation functions and the models were evaluated based on training, validation, and testing accuracy, as well as ROC-AUC performance. VGG16 exhibits superior performance by achieving 95.12% training and 91.16% test accuracy, and also demonstrates the lowest loss among the models. VGG19, ResNet-50 and ResNet-101 also performed competitively by

providing 89%-90% of accuracy. All the models except DenseNet121 (0.99 ROC-AUC score), achieved perfect ROC-AUC scores.

The findings show that CNN-based models contain significant potential to increase the accuracy of waste classification. This model plays a crucial role by improving the efficiency and reliability of the waste sorting system. It helps to support the development of a sustainable urban system. Moreover, by combining Internet of Things (IoT) devices with deep learning models, it becomes possible to automatically identify and classify waste in real time. This integration not only allows smart trash bins and other IoT-enabled systems to sort waste efficiently but also has the potential to revolutionize practical waste management, reduce human effort, and improve recycling and disposal processes in everyday environments.

8. References

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Paper 15

Beyond Environmental Romanticism: Rhetoric vs Reality from Aushtagram-Mithamain-Nikli Haor of Bangladesh

Marium Binte Hasan Farin

Abstract

This study examines the effects of modernization on the conservation, use and the value of local ecological knowledge (LEK) in the haor region of Bangladesh. Being represented as a symbol of human and natural harmony, the haor is subject to a rapid socio-economic and ecological change. Based on in-depth interviews with the local residents of the area of Aushtogram, Mithamoyen, and Nikli Haor of Kishoreganj district, it shows a radical change in the traditional community-based practice to a market-driven and efficiency-focused practice. Conservation methods used by the traditional ecological system are slowly fading away through the advent of modern tools, construction of new infrastructure, and economic need. Governance failures in managing wetlands, magnifies the difference between policy discourses and on-the-ground reality. Nonetheless, some remnants of traditional knowledge and cultural beliefs still exist in older generations. Overall, modernization in the haor region is not a simple change of environment but a socio-cultural and economic compromise between survival and sustainability. Thus, sustainable conservation of haor requires policies combining native knowledge and contemporary adaptation mechanisms to sustain ecological resilience and community's well-being.

1. Introduction

Being represented as a symbol of human–nature harmony, the haor wetlands of Bangladesh are, in reality, undergoing rapid socio-economic and ecological change. Recent studies have shown that wetland ecosystems in the region are facing serious pressures from land-use change, sedimentation, and unsustainable resource practices, leading to the degradation of ecosystem services and loss of biodiversity (Solayman et al., 2018). The wetlands management in Bangladesh is an indication of an increasing contradiction between modernization and the local ecological knowledge. On the one hand, modernization facilitates big scale infrastructural development, irrigation, and commercial harvesting of natural resources with the aim of enhancing economic expansion and food security. Conversely, local communities have practiced traditional ecological knowledge, which is highly based on observation, adaptation as well as coexistence with wetland ecosystems in order to maintain livelihoods and biodiversity.

The contemporary policies of wetland management tend to focus on short-term production at the expense of ecological sustainability and the local production system, which may be identified as seasonal water use, traditional fishing methods, and stewardship by a community. Consequently, this has led to wetland ecosystems being degraded, undergoing loss of biodiversity, and low resilience to climate change. The loss of local involvement and learning isolates local communities which rely on these wetlands to sustain themselves. This dilemma discloses the deeper problem of governance; what to do to reconcile the technocratic development approach with place based ecological knowledge. The wetlands should, therefore, be managed in Bangladesh to overcome the scientific and traditional knowledge systems to attain sustainable management. Only under such kind of integration ecological integrity and human well-being can be guaranteed.

The contrast between modernization and practice of local ecological knowledge often creates a discursive divide—where traditional practices are idealized as inherently “natural” and pure, while modern approaches are framed as disruptive yet necessary for progress. Such idealization reflects a broader intellectual tradition within environmental thought, often termed “Environmental Romanticism”. As Morton (2007) suggests, it refers to the inherited romantic belief that nature is a pure, ideal, and harmonious realm existing apart from human society - a belief that shapes modern ecological thought but also limits it by maintaining a false separation between humans and nature.

Based on this background, this study aims to unleash how modernization is reshaping the relationship between community and environment by observing their fishing practices, local beliefs, governance challenges, and local people’s perceptions. Thus, the study attempts to look beyond the binary concept of “traditional” versus “modern.” Rather, it explores how adaptation truly looks like in the haor region of Bangladesh, particularly focusing on the Aushtogram-Mithamaiyen-Nikli Haor of Kishoreganj region.

2. Literature Review: Terminologies and discourses

2.1 Wetlands and haors of Bangladesh

Among wetlands, the haor ecosystem is very different as it remains wet for six months and dry for the rest of the year. Consequently, for generations, people living in these areas have developed unique methods and plans to implement Locally-Led Adaptation (LLA) to survive in this environment.

Suvra (2021) defines a haor as “a wetland habitat in Bangladesh’s north-eastern region that is geographically a shallow depression in the form of a bowl or saucer, also known as a back swamp”. Overall, the haor area offers a habitat for diverse flora and fauna, sustains fisheries, and supports the livelihood of millions. The total area of haor regions in Bangladesh is about 1.99 million hectares, that is spread across seven districts - Kishoregonj, Netrokona, Sunamganj, Sylhet, Habiganj, Maulvibazar, and Brahmanbaria (Suvra, 2021).

In Kishoregonj district specifically, there are 97 haors, covering about 133,943 hectares of haor area (out of the total district area) (Suvra, 2021). Agriculture in the Haor zones is vital: collectively, the Haor districts produce more than 5.25 million tonnes of rice a year on over 0.71 million hectares of net cultivable land (Suvra, 2021). Fisheries are also central: more than 143 indigenous fish species are recorded in the Haor region (Suvra, 2021).

2.2 Discourses in environmental adaptation and conflict with modernization

2.2.1. Discourses in adaptation and Environmental Romanticism

A deeper look at the discourses on environmental adaptation in the haor region, Bangladesh, shows that there is a great contradiction between the idealized ecological balance and the realities of modernization and survival. The conventional strategies of adaptation, commonly referred to as Local Ecological Knowledge (LEK), which are selective fishing techniques, seed preservation traditions, and cultural beliefs that govern the coexistence with nature, have been extensively depicted in the mass media and environmental movements as a representation of human and nature harmony, which is a notion, frequently based on Environmental Romanticism (McRae, 2021; Morton, 2007).

This rhetoric, however, comes face to face with a cold reality whereby modernization is making local life fast to change in places such as Aushtogram, Mithamoyen and Nikli Haor. The tension between the local communities with their socio-economic pressures, failure in good governance, influx of infrastructure such as the All-weather Road, is creating a growing distance between traditional as well as community-based practices and those that are market-oriented and efficiency-based. To a great number, the inclination towards modern means and quicker methods is a down-to-earth reaction to the immediate socio-economic desperation, poverty, and uncertain means of subsistence. This shift is exemplified by the fading use of traditional techniques like

gail (bamboo structures to prevent water infiltration), local seed preservation, and cotton nets, which are being replaced by modern tools, purchased hybrid seeds, and even illegal equipment like the China *duari jal* (fine-meshed nets) due to the "difficulty of survival."

That modernization in the Haor has not only been an ecological act but a social-cultural, economic trade-off in which the survival instinct tends to override conservation ethics and communities have to choose between short-term economic necessities and long-term environmental sustainability, which reveals the constraints of romanticized ecological discourses not connected with real-world experiences (McRae, 2021, p. 2; Morton, 2007, pp. 121-123). Thus, the Haor's reality challenges the idealized perception of nature often celebrated in environmental rhetoric, revealing that true sustainability must recognize the complex balance between livelihood and ecological preservation.

2.2.2. Conflict between Environmental Romanticism and modernization

The intersection of environmental romanticism and modernization in the Haor region of Bangladesh exposes a deep ideological and material conflict. Environmental romanticism, as defined by McRae (2021), reflects a detached and aestheticized perception of nature as a pristine, uninhabited space existing "out there" apart from civilization (p. 2). This viewpoint idealizes traditional communities as living in perfect harmony with their environment, reinforcing the belief that any deviation from such harmony constitutes ecological degradation. Morton (2007) similarly argues that this Romantic ideal of nature creates an ideological distance between humans and the environment, turning ecological awareness into a moral or aesthetic sentiment rather than a material practice (pp. 121–123).

Conversely, the realities within the Haor region demonstrate how modernization challenges this idealized perception. Infrastructure development (such as the All-weather Road) along with mechanized fishing, hybrid seeds, and expanding market dependency, has transformed the socio-ecological fabric of local life. While environmental discourse continues to portray the Haor as an emblem of human–nature coexistence, the inhabitants face increasing economic pressures that compel them to abandon traditional adaptation techniques rooted in Local Ecological Knowledge (LEK). Practices such as using gail (bamboo barriers to manage water), preserving indigenous seed varieties, and applying selective fishing techniques are now being replaced by efficiency-driven, market-oriented strategies.

These shifts reflect what Morton (2007) identifies as the "rupture" between ecological ideals and the conditions of survival in a capitalist-modern world, where local communities must often prioritize livelihood over conservation ethics. Therefore, the clash between environmental romanticism and modernization is not only philosophical, it is also practiced and expressed in everyday decisions of the people in Haor. The romantic discourse which envisions the traditional societies as eternal custodians of nature fails against the discourse of pressures of modernization. The Haor example shows that ecological harmony is not a fixed state but a negotiated and

conflict process that is defined by the socio-economic reality. This contradiction underscores Morton's (2007) critique of environmental idealization and supports McRae's (2021) argument that such romanticized visions can silence or misrepresent local struggles by framing them as betrayals of "pure" nature rather than responses to structural inequality.

3. Methodology

Research Design: This research paper adopted a qualitative research design based on in-depth interviews in order to understand local attitudes and views towards environmental romanticism and socio-environmental realities of the Haor area of Kishoreganj, Bangladesh. It is concerned with the relationship between the traditional ecological knowledge, socio-economic pressures, and modernization.

Data Collection: Data were gathered by using semi-structured interviews with the local residents who were themselves with agriculture and household management. There were twenty interviewees who engaged in discussions in order to obtain a wide range of views. The respondents were questioned on: Farming activities and response to seasonal flooding, seed preservation, local ecological knowledge and traditional technique, government intervention perception and infrastructure. Also socio socio-cultural beliefs with regard to farming and fishing.

Data Analysis: Interviews were transcribed and translated into English. A thematic analysis was performed in a systematic manner with reference to Braun and Clarke (2006), as it is a widely used method in qualitative research. This consisted of determining the main patterns and categorizing the information into five thematic blocks that replicated various dimensions of the socio-environmental reality of Haor community. These segments include:

- Socio-economic conditions- the analysis of the impact of livelihoods, income, and market dependency on environmental practices.
- Human environment relationships - the relationships and interactions between the community and the Haor ecosystem.
- Governance challenges - how can the role of government interventions, policy implementation in developing local adaptation practices be evaluated?
- Preservation practices - the traditional ecological knowledge, rituals, and resource management methods are studied and analyzed.
- Rhetoric and reality - the difference between how the environmental image is perceived and the practical limitations to which the community must contend.

This division enabled the data analyzed systematically and each theme was related to the overall research questions. Such strategy helped in putting the findings in the context of the discourse of environmental romanticism as well as the realities of modernization in the Haor region.

4. Results and Analysis

4.1 Living Perception of Environmental Romanticism in Haor Region: Reality vs. Rhetoric

The Haor, with its distinct ecosystem, has always been pictured as a paradise of nature. The truth is, however, less black and white. The high level of attachment to the environment is manifested in practices like the use of “Gail” (bamboo structures) to keep water out and to catch fish with an object made of a slip of bamboo. As Alauddin, a farmer, remarked, "We've been doing household farming since childhood, just like our fathers and grandfathers," demonstrating how ecological knowledge is transmitted across generations.

However, the forces of modernization and the market have started to supersede these practices. Farmers are using the purchased seeds more frequently than the traditional storage, which reflects the transition toward a commercial-oriented approach as opposed to a self-sustaining way of life (Shubra, 2020). However, when it comes to a birds-eye perspective, we environmentalists are attempting to prioritize the preservation of local knowledge. In the meantime, the facts were not so. Local knowledge is hardly implied as it takes a longer time and effort with a poor result as they continue to address. They mentioned this issue while describing the preservation of seeds. Failure to take proper care of the seed depresses the quality of the crop and also the rate of production. Though one of the interviewees addressed that hand-stored seeds are better. Even so, during the time they are buying the seeds that will be more dependable and the quality of crops will not be that demanding. So, it's more efficient for them to switch from tradition to modern approach.

4.2. Socio-Economic State in Haor: Influence of Market Dynamics and Modernization

Economic situation and hardship were the most prominent issues reflected in all the interviews. Raj Noor, a teacher, said that, “People now think about feeding themselves before thinking about the environment”. This quote portrays how poverty and economic instability shape people's behavior. In the interviews, several participants described how dependency on external markets has increased. Recently, farmers have relied on hybrid seeds and chemical fertilizers, which require continuous purchases.

According to The Daily Star (2024), many Haor fishers are using China *duari jal* and current *jal* (electric nets) that are technically illegal because of the higher harvest rate and the community's growing financial desperation. Kumod Lal Das, a fish trader, mentioned that the difficulty of survival forces illegal activity: “Otherwise, life doesn't run. So, we are forced to use China nets.” This statement highlights how environmental degradation cannot be separated from socio-economic inequality because of the current circumstances. Thus, modernization in the Haor, is not only an ecological transition but it's also a social and economic one- that is revealing how the instincts of survival can override conservation ethics while livelihoods are really at risk.

4.3. Connection with the Environment: Forced Adaptation and Lingering Concerns

Community members are also strongly emotionally attached to their surroundings, despite the obvious changes. Old styles of life were discussed by the participants with nostalgia: “Before, we used to catch fish with the help of ash, now no one can even believe such kind of things”. This feeling is not only a memory but also a lamentation, the gradual loss of cultural identity relating to environmental practice. Nevertheless, adaptation is inevitable. Most of the respondents defended the adoption of new fishing equipment and new cultivating practices as survival strategies. Another respondent said: “The only way that we can live is to change, then. The interviews indicate that there is a community aware of its environmental degradations but also resigned to the need to modernize. This dilemma of being aware and helpless is what is at the centre of the environmental dilemma of the Haor. According to Shubra (2020), the communities in Kishoreganj have to decide between short-term survival and long-term sustainability, with the former prevailing because of inadequate support and inefficiency in managing the community. (Shubra, 2020).

4.4 Governance Failure: Disparities in Government Initiatives and Implementation

Most of the interviewees cited frustration with government interventions. Though there are agricultural support programs, they are not always effective because they do not reach the needy people. Alauddin, a farmer, explained the failure of government support: "We do not get the seeds in time, when it rains, they shower them; what should we do then?". It is unproductive and affects local trust as a factor that contributes to the continuation of unsustainable practices.

Furthermore, policy and lived experience are no longer in touch. Urban-based programs usually do not take into account the seasonality and topography of the Haor landscape. The respondents explained how the authorities did not follow up, there was ineffective monitoring of illegal nets as well as there was no livelihood training alternative. Such gap in governance is consistent with Shubra (2020) finding that in Bangladesh, the top-down environmental policies frequently overlook the involvement of the community, which results in poor conservation results. Until this gap is filled, environmental rhetoric is bound to remain in conflict with ground realities. (Shubra, 2020; The Daily Star, 2024)

4.5 Preservation Techniques: Barely Alive Traditions Amidst Modern Pressures

The Haor communities still have a partial vestige of traditional ecological knowledge hanging onto them despite the overwhelming environmental and economic pressures. Some of the old wit of generations are still resonant among the fishermen. Uma Kanto Das, an older fish trader, noted the shift in technology: "Now we have nylon nets, we did not have nylon nets before, we made them of cotton thread. They're expensive but last longer". The manually made *sutar jal* or *file jal* previously permitted selective fishing, which permitted the smaller fish to escape and naturally ensure future regeneration.

However, the ecological balance and the rhythm of a sustainable fishery are disappearing with the use of nylon nets and the mechanization methods. A few maintain ancient traditions of a naturalistic spirituality. Gopal, a fish trader, remembered the ancestral belief that they should not fish on Agun Purni night, as it would bring bad luck. These rituals in the past served as informal conservation regulations, and fish populations were boosted. On the same note, one other noted they drop fish fry in the water on Jaistha and do not allow the fish to multiply demonstrating a deep-rooted knowledge of seasons and regeneration. Preservation had now passed beyond beliefs to encompass ways of preserving fish edible by local art. The fermentation of *motka* and the sun-drying of *shutki* were no longer a practice of food preservation but also a sign of adaptation to the climate. “Earlier we made *shutki*, now there is no fish left,” stated the same interviewee, as it is the end of fish and the culture itself. Such customs as sun-drying, fermenting in clay pots, not to fish on sacred nights, and using natural cotton nets were characterized by a profound sense of ecology.

Nevertheless, the arrival of nylon nets, commercial fish farms, silted rivers, and development projects, which prevent water flow, has made nearly all these traditions disappear. These practices are not always perceived by the younger generation as profitable and up-to-date. All that is left are pieces- songs of the Bhatiali, the memory of Agun Purni, and the dumb patience of some of the old folks. The erosion of these practices shows that modernization has not only changed the tools but has also destroyed the relationship the community has with their ecosystem. The reinforcement of policies and cultural respect is therefore the order of the day, and not because of some kind of nostalgia, but because it is a way of assisting the ecological and cultural integrity of the Haor.

5. Summary and Discussion

The results of this study shows that the process of modernization in the Haor region of Bangladesh is not just a straightforward tale of development but a complex tradeoff between tradition and survival. Since the local communities are now much more inclined towards modern agricultural and fishing methods, the ecological knowledge accumulated over the centuries and the existing cultural bonds to nature are threatened as well as put into a conflict with these new ways of living. New technologies and methods tend to deliver relief to the economy but at the same time create a rift in the very environmental harmony that was supporting the Haor ecosystem. This study shows the process of modernization in the Haor region of Bangladesh is not just a straightforward tale of development but a complex tradeoff between tradition and survival. Since the local communities are now much more inclined towards modern agricultural and fishing methods, the ecological knowledge accumulated over the centuries and the existing cultural bonds to nature are threatened as well as put into a conflict with these new ways of living.

This relationship reveals a definite rift between the environmental romanticism that has been constructed in the discourse on development and the fact on the ground, as Haor inhabitants are forced to continually juggle ecological purity and economic stability. Environmental romanticism is the idealized perception that traditional communities live in perfect harmony with nature, often depicting the world as pristine and “uninhabited place, existing ‘out-there’ away from civilization” (McRae, 2021, p. 2). This detached, aesthetic viewpoint relies on a binary logic that views pure nature as something requiring protection from “destructive humanity,” thereby neglecting the socio-economic realities and adaptive transformations inherent to survival (McRae, 2021, p. 2; Morton, 2007, pp. 121–123).

The study findings emphasize that this romanticized rhetoric, which often conceals the struggles driving unsustainable practices, fails to capture the material choices local communities are forced to make. This external focus can lead to the authorization of environmentalists to speak in defense of nature, invalidating local self-determination (McRae, 2021, p. 2). It is in this much wider framework that the next five thematic discussions can be defined- each of them representing the interaction with the modernization of the traditional ecological practices, governance structures, and community resilience in the Haor region.

6. Conclusion

This paper shows that the Haor region, which is widely upheld as a perfect ecosystem, supported by generations of local ecological knowledge, is, in practice, a place in which there is a negotiation of life, modernization, and environmental preservation. Although the traditional modes of practice, such as bamboo buildings to control the floods, the use of hand-made nets for selective fishing, preservation of seeds, and ritualized conservation practices continue, these are increasingly being lost to market-driven activities, new equipment, and socio-economic pressures. The pragmatic strategy of adaptation by modern methods is evident in the voices of the community.

Another theme is that people living in the area are not blind to the fact that the environment is being degraded, but their immediate needs, including livelihood, efficiency and economic security, are taking precedence over traditional ecological customs. The loss of customary ways of doing things illustrates a wider conflict between environmental romanticism and actual existence. The Haor has been depicted in external accounts as a harmonious human-nature landscape, but analysis of the paper shows that modernization, growth of infrastructures and lapses in governance have radically transformed local ways of life and ecological relationships. The selective survival of traditional knowledge, via aspects of selective fishing, seed management, and conservation ideas deeply rooted within the culture, provides avenues for using the community experience in the current environmental management policies.

Finally, the Haor ecosystem cannot be preserved just by the need to have the traditional past but needs policies and interventions that balance socio-economic requirements with the sustainability of the ecology. Governance, encouragement of locally adapted methods and acknowledging the usefulness of local ecological knowledge as well as the modern adaptation, are very important to the survival of the human and natural components of this distinct landscape.

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Paper 16

Enhancing Flood Resilience: DVDI Analysis of Crop Damage and Environmental Policy in Feni District Using Machine Learning and Geospatial Techniques

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Abstract

Flash floods, with their sudden onset and destructive force, pose a major threat to agricultural productivity and rural livelihoods in densely populated, topographically susceptible regions such as Bangladesh. This study assessed agricultural loss and damage in Feni District using the Disaster Vegetation Damage Index (DVDI) within a geospatial workflow. Sentinel-1 SAR imagery (pre- and post-event) supported flood delineation, while Landsat 8-9 OLI-TIRS imagery (pre-flood: May; post-flood: October) enabled vegetation damage assessment; all processing was conducted in Google Earth Engine (GEE) and ArcGIS 10.7 software. The methodology integrated multi-temporal SAR and optical data to map inundation and quantify vegetation stress via comparative pre-/post-flood Normalized Difference Vegetation Index (NDVI) and median Vegetation Condition Index (mVCI). The event was anchored by an extreme rainfall peak of 346 mm on 20 August 2024. DVDI results indicate that 81% of the district experienced crop damage, of which 40.45% was classified as very severe. These estimates align closely with independent Department of Agricultural Extension (DAE) Figs reporting 79% agricultural damage. Qualitative evidence from FGDs, KIIs, and questionnaire surveys corroborated widespread livelihood disruption, including complete income loss for 69% of farming households, and highlighted prolonged waterlogging as a principal driver of crop mortality. Collectively, findings demonstrate that DVDI provides a rapid, effective, and scalable post-disaster assessment, overcoming limitations of traditional vegetation indices by obviating full-season datasets. The approach supports timely response, evidence-based compensation, and the design of long-term climate-resilient agricultural policies applicable to flood-prone regions in Bangladesh and analogous deltaic settings globally.

1. Introduction

Multiple meteorological, climatic, and physiographic factors, including soil characteristics, topography, and the intensity of precipitation, interact to produce these events in a complex way (Brooks & Stensrud, 2000; O'Connor & Costa, 2004). Food security, agricultural sustainability, and socioeconomic stability are all severely compromised by the increasing frequency and severity of flash floods induced by climate change (Islam & Sumon, 2013; Rahman et al., 2023; IPCC, 2022). Flash floods severely compromise the four dimensions of food security as outlined by the Food and Agriculture Organization (FAO): availability, access, stability, and use (FAO, 2021). Local crop production is devastated, food imports are disrupted, critical infrastructure is destroyed, purchasing power is reduced, supply chains are destabilized, and dietary quality is undermined due to dependence on unsafe or inferior food sources (Reed et al., 2022; Gulsan et al., 2021). Extensive crop damage is observed due to flash flood in Bangladesh, a nation that is particularly susceptible to flooding due to its low-lying floodplains, extensive river systems, and lack of agricultural flood protection systems. This jeopardizes livelihoods and increases food insecurity (Fahad et al., 2023; Razu Ahmed et al., 2017; Thomas et al., 2023; Rahman & Di, 2020).

Flash flooding risk has increased due to Feni's high-humidity tropical monsoon climate and heavy, short-duration rainfalls. Compounding this is the poor drainage infrastructure (Hossain et al., 2016; Yeasmin et al., 2017). Past flooding in 1998, 2004, 2010, 2017, and August 2024 resulted in huge crop losses; the 2024 flood submerged 200,000 hectares, destroyed rice crops, and resulted in agricultural losses of USD 457 million (FAO, 2024). As 95% of families were impacted and 83% reported rice loss in 2024, agriculture, primarily rice, pulses, oilseeds, vegetables, and jute farming, dominates land use (Sarker et al., 2025; Ahmed et al., 2017). To examine crop loss and inform disaster preparedness and climate resilience efforts, this study employs geospatial techniques (Rahman et al., 2023).

The FAO calculates that from 2003 to 2013, floods annihilated nearly 1.6 million tons of crops and 93 thousand hectares of cropland, accounting for over half of total agricultural losses due to natural disasters in that period (FAO, 2015). Climate-driven increments in extreme weather events are expected to expose roughly 2 billion individuals to the risk of flooding by 2050 (Hirabayashi et al., 2013; Kundzewicz et al., 2019). In regards to safeguarding agricultural systems and ensuring food security, this escalating threat calls for immediate, effective damage assessment and mitigation strategies (Tsakiris, 2014; Al-Omari et al., 2024; Shah et al., 2020). Ground-based field surveys and other conventional methods for assessing flood-induced crop damage are time-consuming, costly, and labor-intensive, particularly when applied to large-scale catastrophes covering vast geographical expanses (Rahman et al., 2021; Hasan, 2018; Rehman et al., 2019; Haque & Jahan, 2015). The remote sensing techniques and technologies, however, offer a robust alternative, providing cost-effectiveness, objectivity, frequent temporal resolution, and extensive geographical coverage (Rahman & Di, 2020; Amarnath et al., 2012; Gatlin et al., 2021).

The DVDI, a novel satellite-derived index designed to assess alterations in vegetation status prior to and during flash floods, is presented in this study as a remedy for these shortcomings (Alam & Ahamed, 2022; Thomas et al., 2023). The DVDI offers a scalable and cost-effective means of quantifying the extent and severity of agricultural damage induced by floods through integrating high-resolution satellite data with geospatial analysis (Kwak, 2017; Shrestha & Rahman, 2021). To rapidly and accurately assess crop loss, this research employs the DVDI to conduct a geospatial assessment of flash flood-induced agricultural damage in Feni District, Bangladesh (Hossain et al., 2025; Rahman et al., 2025). Feni is an ideal case study due to its high flood risk and agricultural importance (Uddin et al., 2025; Ahmed et al., 2017). The study aims to map inundated areas of Feni District and assess the crop loss damage of the region due to flash flood of August 2024 year and discuss the factors and impact of the flash flood onto crop loss in the region.

2. Materials and Methods

2.1 Study Area

Feni District, a low-lying coastal plain covering 928.34 km² in Chattogram Division in southeast Bangladesh, is exceedingly susceptible to flash and seasonal flooding (Sarker et al., 2025). Situated between latitudes 22°44' and 23°17' N and longitudes 91°15' and 91°35' E, it is bordered by Chattogram to the southeast, Noakhali to the west and south, and Tripura (India) to the east (Uddin et al., 2019). Three main rivers - the Feni, Muhuri, and Selonia - shape its flood-prone physiography of floodplains, alluvial lowlands, and narrow highland ridges (Debnath, Das, Ahmed, & Bhowmik, 2017). The region's weak drainage capacity is strained by these rivers and the heavy monsoon rainfall (2500-3000 mm annually, 80% June-September), which inevitably leads to waterlogging (World Bank, 2020; Mondal et al., 2021). Because of runoff from the upstream Tripura, the flashy Selonia River (301 km²) and the Muhuri River (catchment area, 1,102 km²) increase the flooding risk, especially in Fulgazi and Parshuram Upazilas (Fig 1) (Rahman et al., 2021; Uddin et al., 2019).

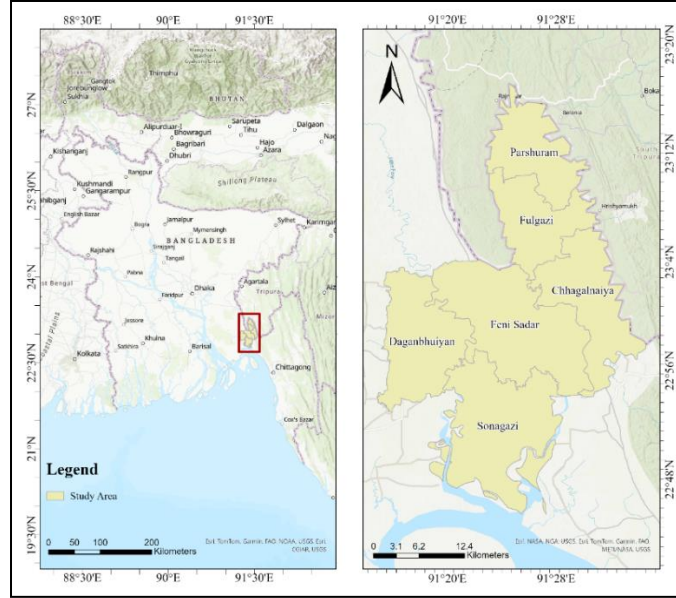


Figure 1: Study Area Map, delineating Feni District within the Chattogram Division of southeastern Bangladesh, showing its geographical boundaries, adjacent regions, and proximity to the international border with Tripura, India and key physiographic features, such as floodplains and alluvial lowlands

2.2 Data Acquisition

The data sources and types used in the geospatial study of agricultural damage caused by flash floods in Bangladesh's Feni District are listed in Table 1.

Sensor	Season	DATE	Resolution	Processing Level
Landsat 8-9 (OLI-TIRS)	Pre-monsoon-2024	21-05-2024	30 m	Level-1
Landsat 8-9 (OLI-TIRS)	Post-monsoon-2024	28-10-2024	30 m	Level-1
Sentinel-1 SAR (IW, GRD)	Non-flood (pre-event)	01-06-2024 to 01-08-2024	10 m	Level-1 (GRD)
Sentinel-1 SAR (IW, GRD)	Flood (event)	20-08-2024 to 28-08-2024	10 m	Level-1 (GRD)
Rainfall (BMD)	Monsoon (August)	01-08-2024 to 31-08-2024	Daily totals (mm), station-based	Official BMD dataset
Crop-loss / damage (DAE)	Monsoon (August)	01-08-2024 to 31-08-2024	District reports; aggregated	Official DAE records

Table 1: Data Sources and Applications for Geospatial Analysis of Flash Flood Impacts in Feni District, summarizing the datasets, sources, types, and purposes used in assessing flood-induced agricultural damage, including flood mapping, crop health monitoring of the research study area.

2.3 Flood Inundation Mapping

Sentinel-1 SAR images were used to delineate the flood extent due to their ability to capture high-resolution data in all-weather conditions, especially during cloudy and rainy periods. Change detection was performed by comparing pre- and post-flood images to identify areas that were submerged (Alonso-Sarria et al., 2025; Schlaffer et al., 2015). We extracted Sentinel-1 IW Level-1 GRD VH data over Feni for a pre-event window (2023-08-21–09-10) and flood window (2024-08-21–09-10) using Google Earth Engine (GEE).

2.4 Vegetation Condition Monitoring

2.4.1 NDVI Calculation

NDVI values were computed for both pre- and post-flood periods to assess changes in vegetation cover.

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

where ρ_{NIR} is near-infrared reflectance, and ρ_{Red} is red reflectance (Akbar et al., 2019).

Precise NDVI value ranges for six LULC classes derived from the 2016 Landsat-8 OLI image are provided in Table 2.

Class	NDVI Range
Water	-0.28 – 0.015
Built-up	0.015 – 0.14
Barren Land	0.14 – 0.18
Shrub and Grassland	0.18 – 0.27
Sparse Vegetation	0.27 – 0.36
Dense Vegetation	0.36 – 0.74

Table 2: Suitable NDVI ranges identified for the land cover classes (Akbar et al., 2019).

2.4.2 VCI Calculation

Vegetation Condition Index (VCI) was calculated to evaluate the relative health of vegetation by comparing NDVI values (Kogan, 1995).

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

$$mVCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

2.4.3 Disaster Vegetation Damage Index (DVDI)

The DVDI was employed to quantify the degree of vegetation damage caused by the flash flood. DVDI was calculated by comparing the (mVCI) values before and after the flood event (Rahman et al., 2021).

$$DVDI = mVCI_{after} - mVCI_{before}$$

This method was applied to assess the impact on Aman rice and other crops in flood-affected regions (Figure 4).

Damage Category	DVDI Range
No Damage	$DVDI \geq 0$
Very Slight Damage	$0 > DVDI \geq -0.1$
Slight Damage	$-0.1 > DVDI \geq -0.2$
Moderate Damage	$-0.2 > DVDI \geq -0.3$
Severe Damage	$-0.3 > DVDI \geq -0.4$
Very Severe Damage	$-0.4 > DVDI$

Table 3: DVDI Damage Classification Scheme (Rahman et al., 2021)

2.6 FGD, KII and Questionnaire Survey

Questionnaire surveys were conducted in four upazilas of Feni district, namely, Fulgazi, Parshuram, Chhagalnaiya and Sonagazi upazila. These four upazilas were most affected by flash floods in August 2024. Then we did two Key Informant Interviews (KII) with personnel from BMD and DAE. The KII interviews suggested that these 4 upazilas were most affected by flash floods, which drove the survey plan to be implemented in these 4 upazilas. Questionnaire surveys were conducted with approximately 232 respondents and two farmer FGD surveys in a 4-day field survey (Figures 2 & 3). The socioeconomic status of the agricultural community affected by the floods at the end of August 2024 was presented through these distributions (SP Figures 1 & 2).

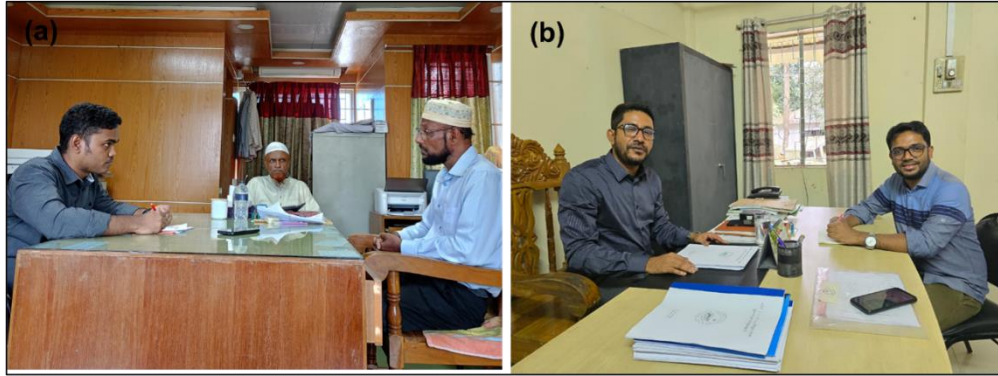


Figure 2: KII Interviews with (a) Senior Observer, Bangladesh Meteorological Department (BMD), (b) Additional Deputy Director (Horticulture), Department of Agricultural Extension (DAE).



Figure 3: Focus Group Discussion (FGD) and Questionnaire Survey of Fulgazi, Parshuram, Chhagalnaiya and Sonagazi upazila in Feni District

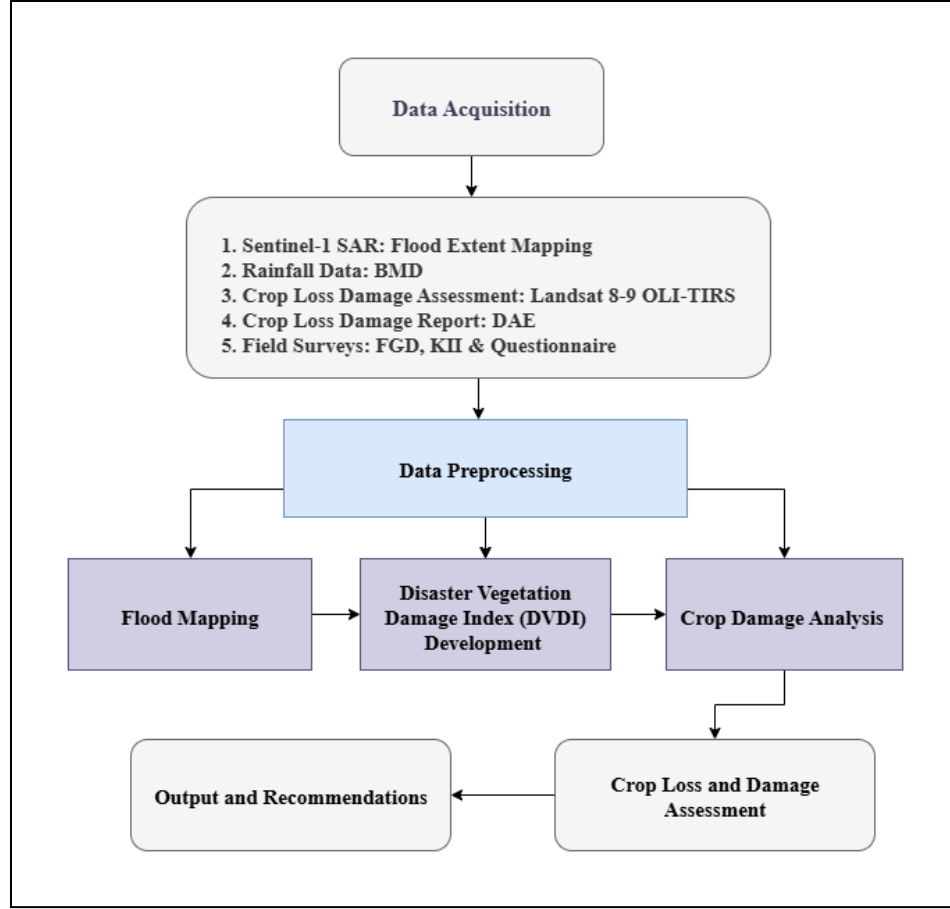


Figure 4: Conceptual Framework of the Study

3. Results and Discussion

3.1 Flood Mapping of Feni District

The northeast region of Parshuram and Chhagalnaiya Upazilas was where the greatest depths of flood rates, between 13 to 18 meters, occurred in August of 2024. These regions are the prominent hotspots of flood susceptibility because they are almost similar to the ones that were identified to be most flooded in Figures 5(a), (b). Conversely, while Sonagazi and Daganbhuiyan Upazilas continued to have high flood cover, many of them experienced moderate to low depths of flood, ranging largely from 0 to 7 meters. A tight hydro-geomorphic connection is revealed by the geographic proximity between flooded areas and established water bodies.

3.2 NDVI of Feni District Before and After Flood

During the pre-flood period, the majority of the Feni district had high NDVI values (0.37-0.78), represented in Fig 6(a), revealing that the area was dense with healthy vegetation. In Parshuram and Daganbhuiyan upazila, where dense vegetation, crops, and forest cover characterized the area predominantly, these features were most evident. In contrast, the areas such as Sonagazi and

Fulgazi were already scattered with lower NDVI values (0.19-0.36) that were primarily surrounding low-lying regions and riverbanks that were susceptible to flooding. In the majority of the upazilas, the NDVI significantly and considerably decreased following the flood occurrence.

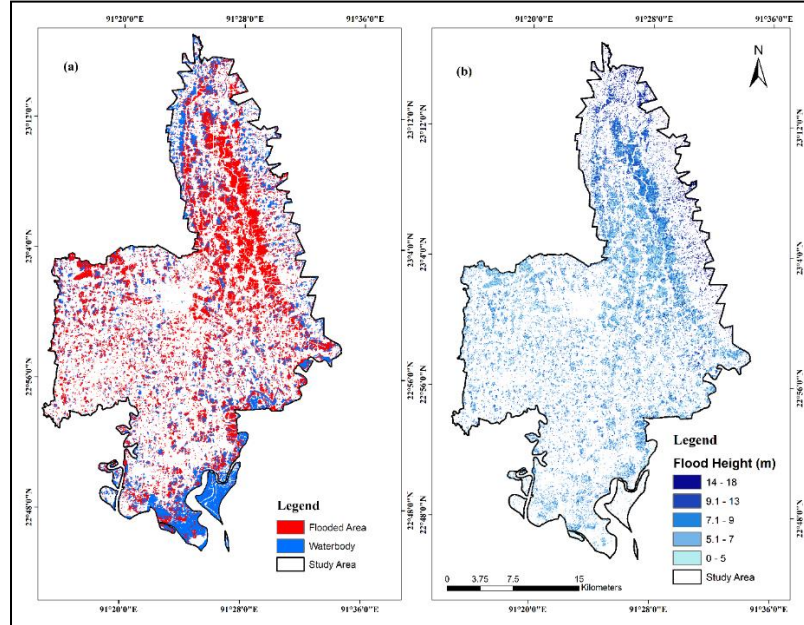


Figure 5: (a) *Spatial Distribution of Flooded Areas and Water Bodies in Feni District during the Flood Event*, (b) *Classification of Flood Height across Feni District based on Remote Sensing Data*

The most severe vegetation loss was experienced by Parshurampur and Sonagazi, as enormous areas shifted to lower NDVI classes (0.015 - 0.44), which on the map are represented in Figure 6(b).

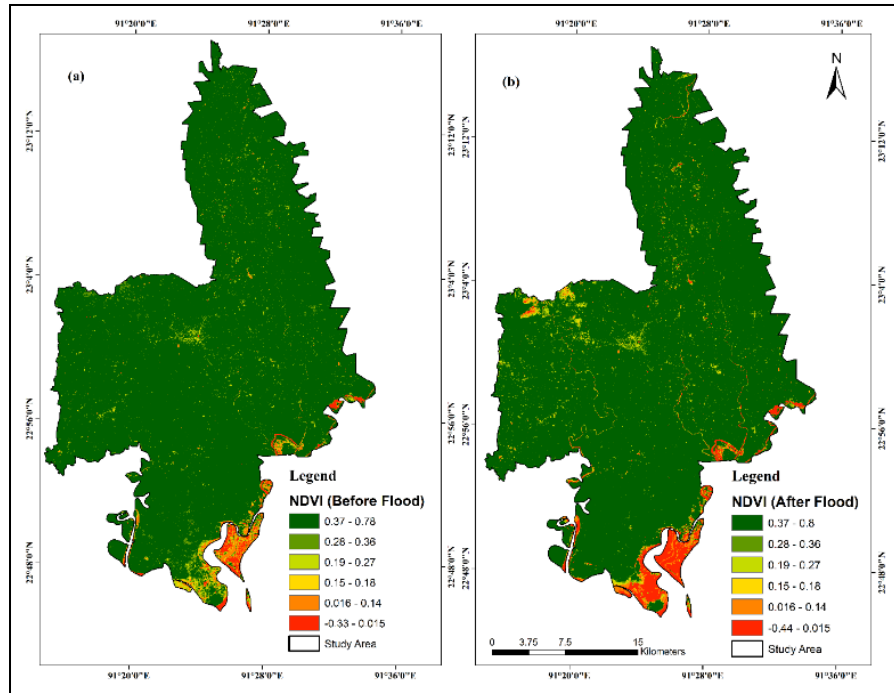


Figure 6. Spatial comparison of NDVI (a) before and (b) after flood events in Feni District

A comparison of NDVI time series pre- and during a significant flash flood event is shown in Fig 7. The average vegetation health in the study area decreased by 32.8%, as the average post-flood NDVI reading was approximately 0.39 compared to 0.58 pre-flood.

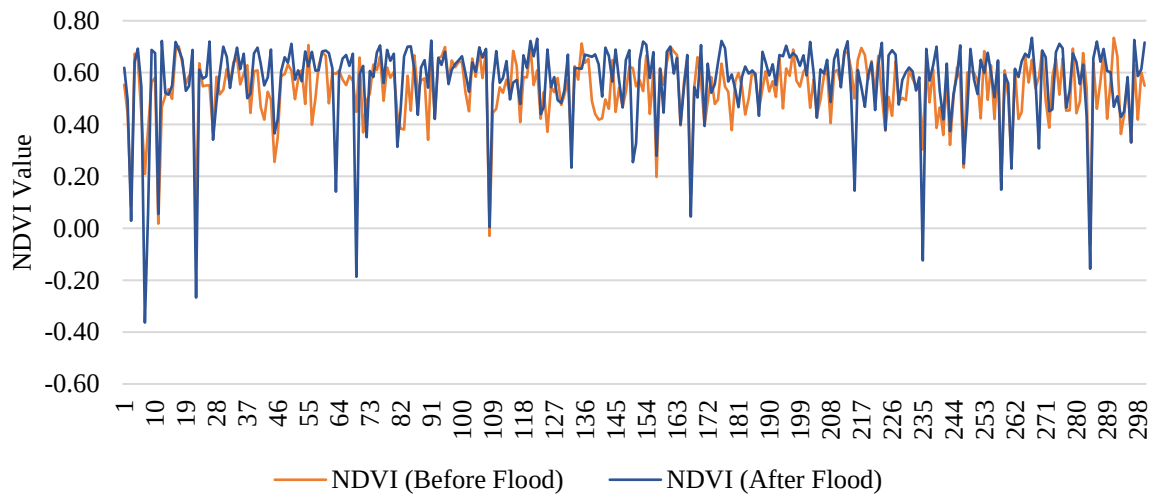


Figure 7: Time Series Analysis of NDVI Values before and after flood at multiple observation points

A comprehensive view of land cover changes has broadly been displayed in Table 4 and Figure 8.

NDVI Classification	Area (Sq Km)	
	Before Flood	After Flood
Dense Vegetation	8220.80	8058.97
Sparse Vegetation	243.22	208.23
Shrub and Grassland	108.49	132.64
Barren Land	33.58	38.49
Built-up Area	97.36	108.54
Water Body	84.96	241.10

The water body had the highest expansion from 84.96 km² to 241.10 km².

Table 4: Comparison of land cover classification based on NDVI values before and after the flood event. The table presents the areal extent (in square kilometers) of each land cover category

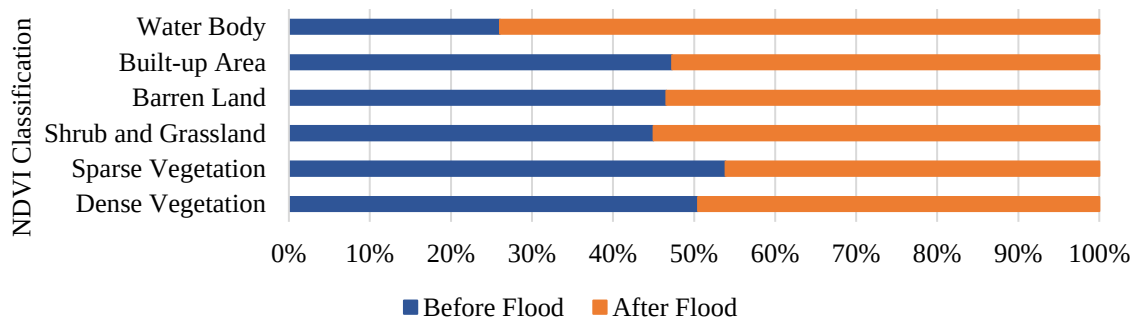


Figure 8: Changes in land cover classifications before and after the flood event based on NDVI-derived area estimates.

Figure described the condition of pre- and post-flood scenarios via NDVI classification. It was observed that the water body had vastly increased in the post flood scenarios; while built-up area, barren land and shrub and grassland have decreased as well.

3.3 VCI of Feni District Before and After Flood

The VCI varied from a minimum of approximately 0.0915 to a maximum of 0.9981 before the flood. After the flood, the maximum value of the VCI decreased slightly to 0.9698, whereas the minimum increased to 0.3235 (Figure 9). Along with a geographical distribution of locations with declining VCI values, this change reflects a reduction in peak vegetative health. In the southern and southeastern upazilas, such as Sonagazi, Chhagalnaiya, and Feni Sadar, where low-

lying areas and dense croplands are most vulnerable to extended inundation, notable reductions in VCI have been realized.

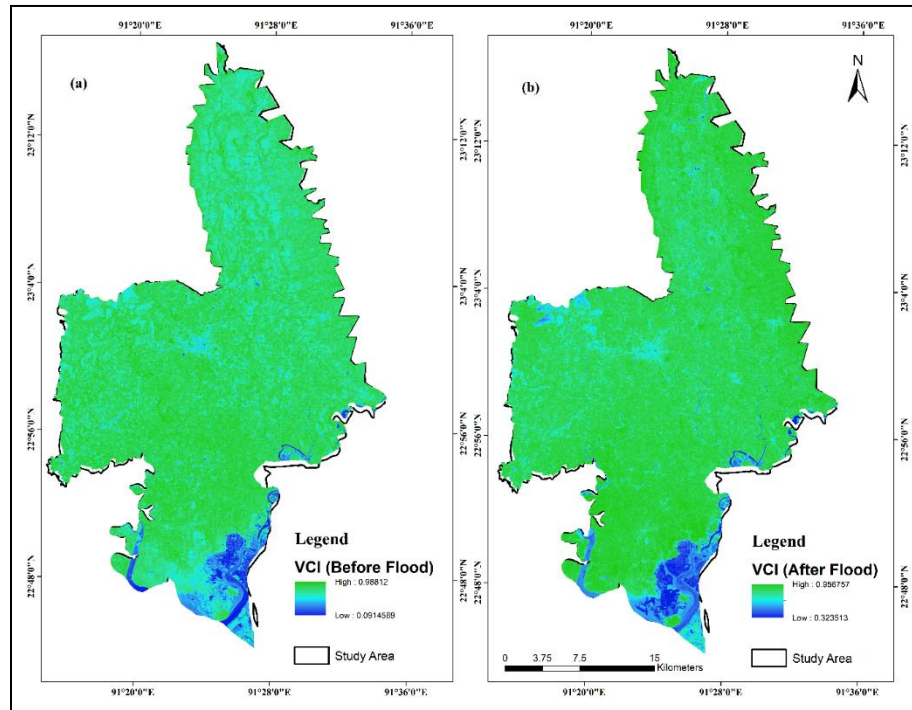


Figure 9: Spatial comparison of VCI (a) before and (b) after flood events in Feni District

3.4 Vegetation Damage Assessment using DVDI

Whereas moderate damage had observed in the southwest transitional areas, particularly in parts of Chhagalnaiya and Daganbhuiyan. Notably, Sonagazi upazila, being part of the southern coastal belt, contained some of the only areas with very little to no damage at all, particularly near large bodies of water, as evident from Figure 10.

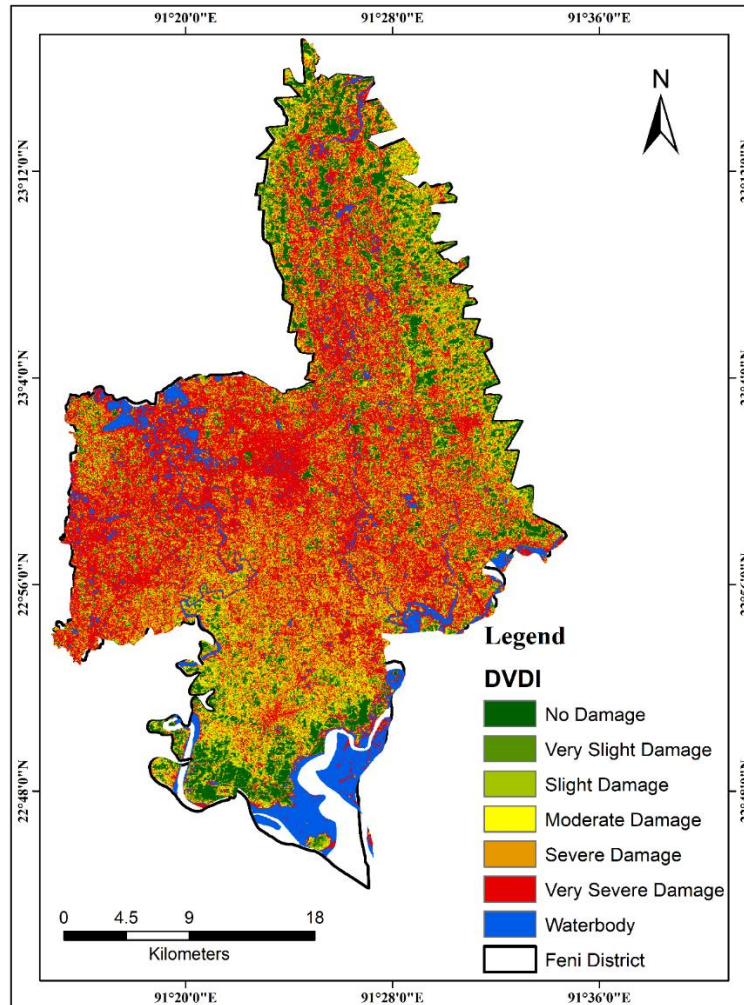


Figure 10: DVI of Feni District showcasing crop loss damage due to the August 2024 flash flood

According to the DVI estimation, 40.40% of the total area was approximated to have very severe damage, and an additional 16.63% was classified as severe damage as shown in (SP Fig 3). Moderate damage and mild damage areas combined to form 15–20% of the district. There were fewer than 10% of areas that had healthy or slightly affected vegetation, and this indicates the overall vegetation vulnerability of the region.

Crop loss and damage percentages came from the DVI calculation and the observed data from DAE are 81% and 79%, respectively, as described in Table 5. The close alignment between these two values suggests a strong correlation between the satellite-derived DVI classification and field-level observations by the DAE.

Class Name	Percentage (%)	Crop Loss and Damage according to DVDI	Crop Loss and Damage according to DAE
No Damage	10.57		
Very Slight Damage	5.30		
Slight Damage	7.44		
Moderate Damage	12.18	81%	79%
Severe Damage	16.63		
Very Severe Damage	40.40		
Water Body	7.49		
Total	100		

Table 5: Distribution of vegetation damage classes in Feni District based on DVDI, with corresponding crop loss and damage percentages compared to DAE field assessments. The table highlights the percentage of land area under each damage category.

3.5 Rainfall Record of August from BMD

The average daily rainfall in Bangladesh's Feni District in August 2024 is presented in Figure 11. During the dry spells in the initial part of the month, rainfall starts low and ends up rising marginally (e.g., ~50 to 100 mm during days 2, 6, 11). The vital flood triggered in this pattern is the peak during August 20, which is accentuated through prolonged saturation as well as through monsoon-force hydrological stress.

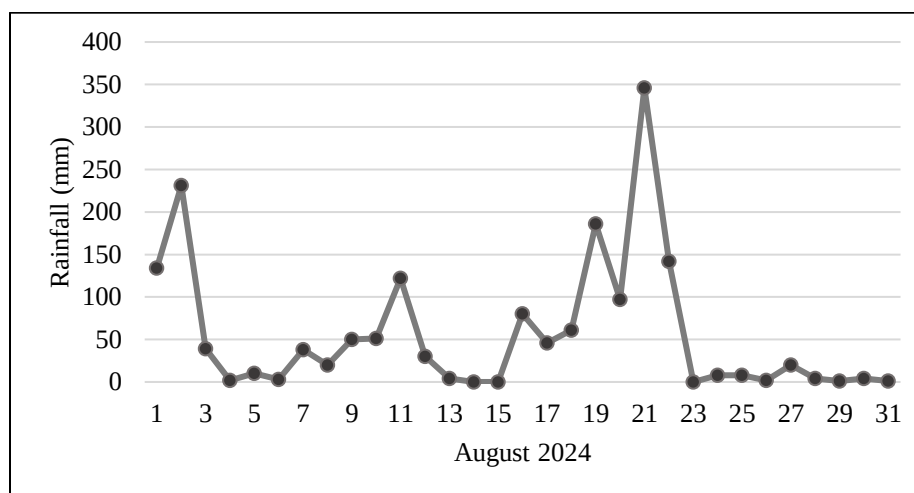


Fig 11. Daily Precipitation record of August 2024 of Feni district

3.7 Questionnaire Survey

Two bar diagrams describing the agricultural losses due to the August 2024 floods were presented in (SP Fig 4). The percentage of affected agricultural area was presented in Part (a). No damage was reported from 26%, partial damage was reported from 7%, and total loss of crops

was reported from 67%. Since two-thirds of agriculture has been negatively affected, this translates into a significant effect. The types of agricultural losses were specified in Part (b): Crop damage was reported from 45%, fish farm damage at 21%, animal damage from 10%, other losses from 5%, and no loss from 24%. The long waterlogging that was linked with the rainfall peak (by 346 mm) on the 20th of August likely aggravated the agricultural losses that were being measured using the DVDI (SP Fig 5).

The findings emphasize the imperative need for extensive drought mitigation strategies, as more than 69% of the region was subjected to moderate to severe damage. Sustainable agriculture, reforestation, and procurement of drought-resistant crop varieties are just a few. For enhancing reaction mechanisms, nonetheless, there needs to be a tighter coupling of satellite monitoring with field-based agricultural surveys, as seen from the absence of field-validated crop damage data for a number of damage classes (Das et al., 2023).

5. Conclusion

The research study demonstrated that satellite-derived indicators, combined with robust geospatial workflows, can deliver a rapid, spatially explicit appraisal of flash-flood impacts on agriculture in Feni District. By integrating Sentinel-1 flood delineation with Landsat-based vegetation diagnostics and the DVDI, we mapped both inundation and the gradient of crop damage, revealing extensive severe to very severe losses concentrated in Parshuram, Feni Sadar and Fulgazi, with transitional impacts in Chhagalnaiya and Daganbhuiyan. The close alignment between DVDI-based damage estimates and field observations underscores the operational validity of this approach for post-disaster assessment and compensation targeting. Triangulation with socio-economic evidence from KII/FGD indicates that prolonged waterlogging following the August 20th, 2024 year rainfall peak amplified livelihood disruption, particularly for smallholders dependent on Aman rice and mixed farming systems. Methodologically, the DVDI framework overcomes the latency of season-long indices by contrasting median pre- and post-event vegetation conditions, enabling timely decision support for relief, recovery, and replanting schedules. Nevertheless, potential misclassification over built-up areas and sensitivity to empirical thresholds highlight the need for crop-type masks, higher-resolution sensors, and systematic ground validation.

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Paper 17

Carbon Credits and Urban Local Bodies: Leveraging carbon credits to finance climate action plans in Indian cities

Aakash Jain and Saswat Bandyopadhyay

Abstract

This paper investigates the potential for Urban Local Bodies (ULBs) in India to leverage carbon credits as a financing mechanism for climate action, addressing the critical gap between municipal climate plans and implementation. Indian cities contribute 70% of the country's CO₂ emissions, with sectors like waste, transport, and energy offering significant carbon credit potential. However, ULBs remain underrepresented in carbon markets, accounting for only 1% of India's issued credits. The study identifies voluntary markets (e.g., Verra's VCS) as more accessible for ULBs than compliance mechanisms (e.g., CDM) due to lower costs and flexibility.

Key barriers include regulatory complexity, price volatility, and institutional gaps. Case studies such as Indore's waste-to-energy project, which generated 170,000 credits but faced setbacks due to shifting policies, highlight both opportunities and risks. To address these challenges, the report proposes the CREDIT framework, a six-principle approach for ULBs to increase preparedness to participate in carbon markets. The framework is complemented by the CarbonMitra Toolkit, a user-friendly calculator designed to help ULBs estimate credit potential, costs, and revenue for waste projects. Chennai's implementation blueprint demonstrates practical application, bundling solar, waste, and e-mobility initiatives to yield 25,000 tCO₂e/year, with revenue funding slum solarization and landfill remediation.

The paper concludes that carbon credits, while not a standalone solution, can catalyse climate finance when integrated with robust planning, policy support, and institutional capacity-building. By adopting structured frameworks and tools, Indian cities can transform emissions reductions into fiscal resilience, advancing both sustainability and equitable urban development.



"The future of urban finance is hidden in plain sight, in every ton of CO₂ we don't emit"

Source: Author

1. Introduction

1.1 Cities, Climate Change and Finance

India, the world's fourth-largest GHG emitter, generates 70% of its CO₂ emissions from cities (MoEFCC, 2021). Rapid urbanization, industrial growth, and poor waste management have worsened climate risks, evident in deadly heatwaves, erratic monsoons, and flooding. Delhi's air pollution, Chennai's water scarcity, and Mumbai's cyclones highlight these threats (Sharma & Joshi, 2022). Without urgent action, cities could see 2–4°C temperature rises by 2050 (IPCC AR6, 2023).

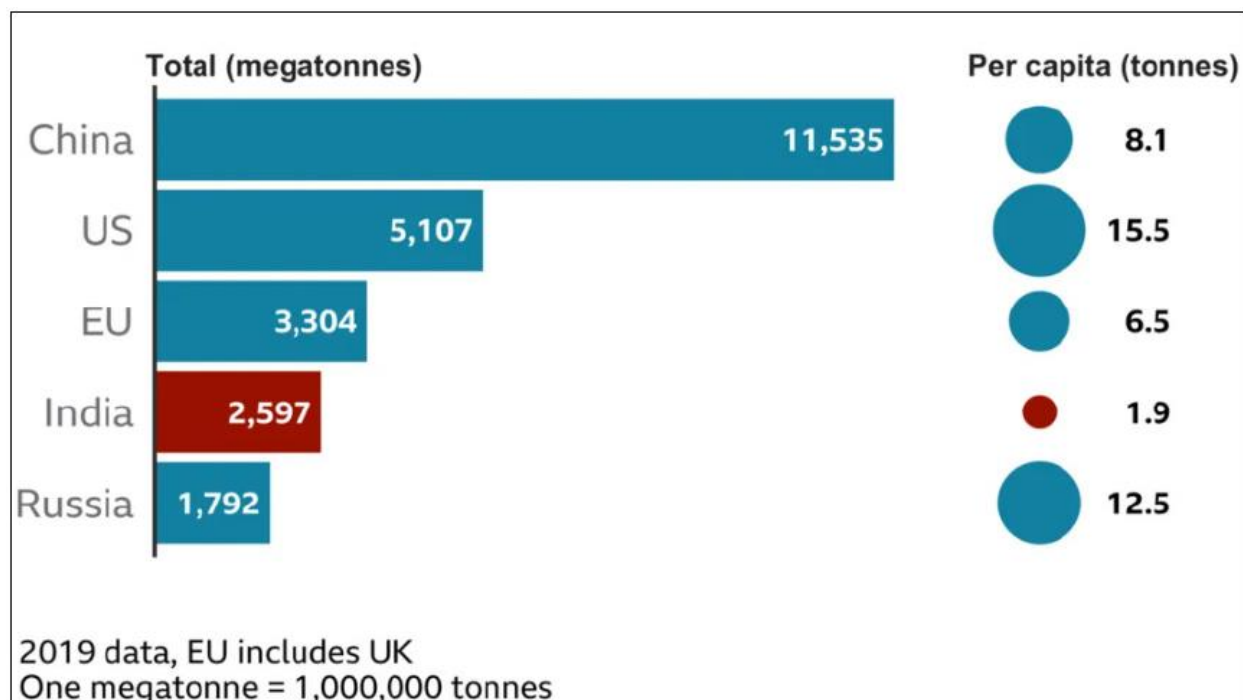


Figure 1: Top 5 generators of GHGs with net and per capita GHG emissions in tonnes. India is the fourth largest emitter in terms of net GHG emissions. Source: Emissions database for global atmospheric research, BBC

To meet its 2070 net-zero target, India needs \$164 billion annually in climate investments but currently spends only \$45 billion (CPI, 2023). Municipalities, already underfunded, struggle to finance resilience projects. A 2023 review of 20 city climate plans found 92% lacked clear funding strategies (ICLEI South Asia, 2023). Only Mumbai and Meghalaya have integrated climate budgets, exceptions in an otherwise fragmented system.

Urban Local Bodies (ULBs) rely heavily on property taxes, which contribute just 0.15% of India's GDP (vs. 2–3% in OECD nations) due to poor collection and outdated valuations (RBI,

2022). Central grants offer limited relief, often restricting funds to specific projects. Bengaluru spends 70% of its budget on administrative costs, leaving little for climate infrastructure (Praja Foundation, 2023). Municipal bonds remain underutilized, with only 24 cities issuing them since 1997 (RBI, 2023).



Figure 2: To achieve India's 2070 net-zero commitment, significant investments are required in urban infrastructure. However, there is a substantial financing gap between the required climate investments and current spending. Source: CDP, *Accelerating climate finance in cities*. ICMA, *Municipal budgets for climate change*. CCFLA, *The state of cities' climate finance*

Funding gaps delay critical projects—Chennai's desalination plants and Hyderabad's electric buses remain stalled (ICLEI, 2023). Economist Isher Ahluwalia stresses fiscal decentralization is essential (Ahluwalia, 2021). Reforms like green cesses or GST revenue-sharing could help, but cities must also explore alternatives like carbon markets. Globally, carbon credits have funded urban projects, but India faces barriers like low awareness and complex verification (TERI, 2023).

Without urgent action, urban emissions may double by 2050 (IEA, 2022). As Esther Duflo notes, climate finance must make sustainability self-sustaining (Duflo & Banerjee, 2020). For Indian cities, innovative funding isn't just a necessity—it's the key to resilient, low-carbon growth.

1.2 Need for the Study

India stands as a major player in the global carbon credit market, having issued over 600 million credits as of 2023. However, this impressive figure masks a significant imbalance - while large-scale renewable energy projects dominate India's carbon credit landscape, Urban Local Bodies (ULBs) participate minimally, accounting for barely 1% of total credits issued. This disparity is particularly striking given that urban areas generate approximately 70% of India's CO₂

emissions, positioning cities as both major contributors to climate change and crucial arenas for mitigation efforts.

The potential for urban carbon credit projects remains largely untapped due to multiple systemic barriers. Municipal governments often lack the technical expertise to navigate complex carbon market mechanisms, while regulatory frameworks remain ill-adapted to smaller-scale urban initiatives. Financial constraints pose another major hurdle, as ULBs typically operate with limited budgets and struggle with the upfront costs required for project development and certification. These challenges persist despite studies showing that Indian cities could generate up to 50 million carbon credits annually through municipal solid waste management alone.

India's updated climate commitments, which aim for a 45% reduction in emissions intensity by 2030, create both urgency and opportunity for greater urban participation in carbon markets. Experts argue that the current focus on industrial-scale projects needs to expand to include decentralized urban initiatives that can deliver both emissions reductions and local environmental benefits. Some pioneering cities like Surat and Indore have demonstrated the viability of urban carbon projects, but their examples remain exceptions rather than the norm.

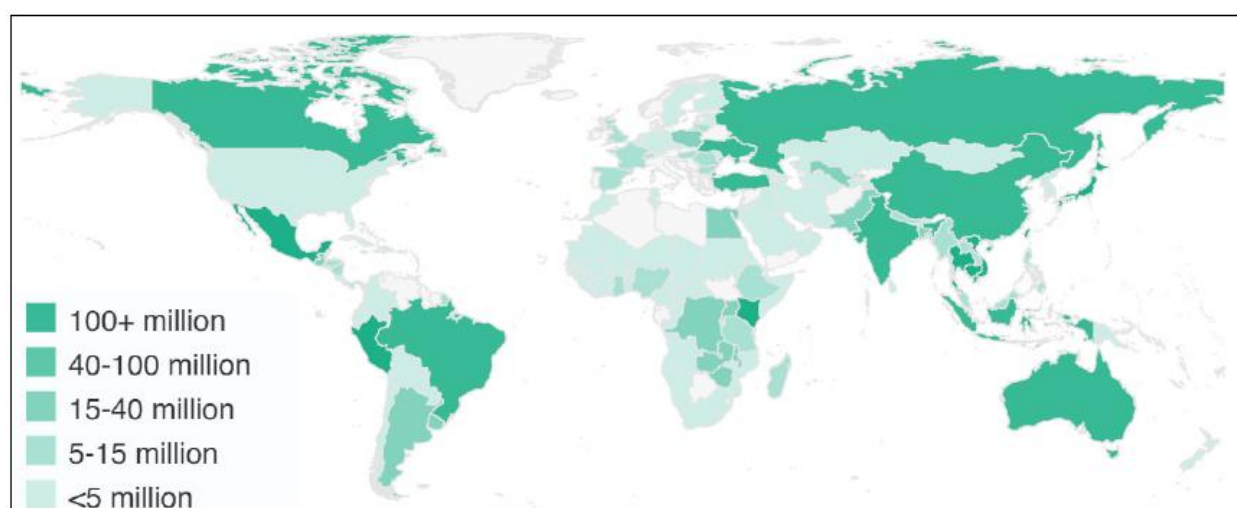


Figure 3: Heat map showing the level of carbon credits issued to emission reduction activities in each country (tCO₂e). Source: State and Trends of Carbon Pricing Dashboard, World Bank

Addressing these challenges requires coordinated policy interventions. Regulatory frameworks need simplification to make carbon markets more accessible to municipal governments. Capacity-building programs could help ULBs develop the technical skills needed to design, implement, and verify carbon offset projects. Financial mechanisms such as advance market commitments or blended finance structures could help overcome initial cost barriers. By implementing such measures, India could unlock a powerful new funding stream for urban climate action while making its carbon markets more inclusive and impactful.

The transformation of cities from emission hotspots to active participants in climate solutions represents both a formidable challenge and a significant opportunity. As India works to meet its climate goals, empowering ULBs to effectively participate in carbon markets could prove instrumental in bridging the persistent gap between urban climate ambitions and their financial realization. This shift would not only enhance the effectiveness of India's climate strategy but also ensure a more equitable distribution of climate finance benefits across different levels of governance.

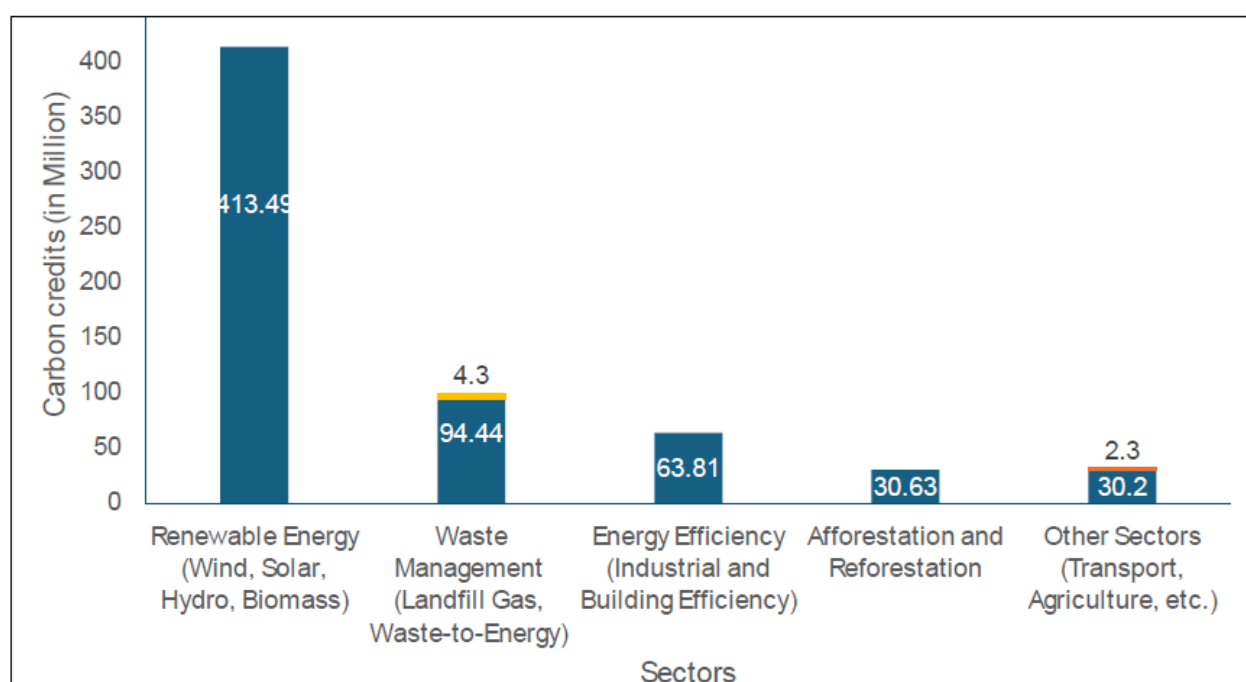


Figure 4: Sector-wise carbon credit issuance in India, till 2023. Highlighting the share of urban local bodies as only 1% of the total credits issued in the waste management and transport sectors only. Source: Reddy, S. (2021). *Extent of Non-Revenue Water: Training manual*. NIUA.

1.3 Aim and Objectives

The primary aim of this research is to enhance the preparedness of Urban Local Bodies (ULBs) in India to participate in the carbon credit market as a viable financing mechanism for their climate action plans. Given that cities contribute significantly to national emissions yet remain underrepresented in carbon markets, this study seeks to explore how ULBs can systematically access carbon finance to implement sustainable urban projects. By doing so, it aims to bridge the critical funding gap that currently restricts the execution of municipal climate initiatives.

To achieve this aim, the study is structured around three key objectives:

- 1. Assess the Scope and Potential** of Carbon Credits in Financing Municipal Climate Action Plans. This involves evaluating the types of urban projects such as waste management, urban forestry, and public transport that can generate carbon credits. The study will quantify the

potential revenue from carbon finance and examine successful case studies, both within India and globally, where ULBs have effectively utilized carbon markets.

2. Identify Key Barriers (Regulatory, Financial, Institutional) to Implementing Carbon Credit Programs in Indian Cities. The research will analyze the structural challenges that hinder ULB participation, including complex certification processes, lack of technical expertise, and misalignment between municipal governance and carbon market mechanisms. Insights will be drawn from stakeholder interviews and policy reviews to pinpoint systemic bottlenecks.

3. Propose Policy and Implementation Strategies for Scaling Carbon Credit Projects. Based on the findings, the study will recommend actionable reforms—such as simplified accreditation frameworks, capacity-building programs for municipal officials, and public-private financing models—to facilitate greater ULB engagement in carbon markets. These strategies will be tailored to India’s regulatory environment while drawing lessons from international best practices.

1.4 Methodology

The research methodology for this study was designed to systematically address the three key objectives: assessing the potential of carbon credits for Urban Local Bodies (ULBs), identifying barriers to their participation in carbon markets, and proposing policy strategies for scaling such projects. A mixed-methods approach was adopted, combining quantitative data analysis, qualitative stakeholder insights, field visits and case study evaluations to ensure comprehensive findings.

Literature Review and Secondary Data Analysis

An extensive review of existing literature was conducted across multiple domains, including Municipal Climate Action Plans, Municipal Budgets, Carbon Credit Mechanisms and Standards, Urban GHG Emissions and Sectors, Barriers and Risks in Carbon Credit Projects, Policy Frameworks and Governance, and Global and Regional Trends in Carbon Markets. This helped establish a theoretical foundation and identify gaps in current knowledge. Key sources included academic journals, government reports, and international publications from organizations such as the World Bank, UNFCCC, and India’s Carbon Credit Trading Scheme (CCTS). Additionally, statistical data from carbon registries (CDM and Verra) and municipal climate action plans were analyzed to quantify sector-wise carbon credit potential.

Stakeholder Interviews and Expert Consultations

To capture ground-level challenges and opportunities, semi-structured interviews were conducted with a diverse group of stakeholders, including Academicians, ULB Officials, Private Consultants in the Carbon Market Sector, and Think Tanks. These discussions provided insights

into regulatory hurdles, financial constraints, institutional capacity gaps, and perceived risks associated with carbon credit projects.

Case Study Analysis and Field Visits

This study adopts a case-based approach, focusing on Indore as the primary case study due to its unique success in leveraging carbon credits. Indore's bio methanation and composting projects, registered under the Verified Carbon Standard (VCS), provide critical insights into the financial, operational, and regulatory challenges of municipal carbon credit initiatives.

To contextualize these findings, secondary case studies from other Global South cities, such as Moradabad (India), Cape Town (South Africa), Tianjin (China) and São Paulo (Brazil) are analyzed. By synthesizing lessons from Indore and comparative cases, this study develops a

strategic roadmap to help ULBs become "carbon-ready", aligning project design, financing, and policy frameworks with carbon market requirements. Revenue streams from carbon credits were quantified and compared with Operational & Maintenance (O&M) and capital costs to assess financial feasibility. Historical data from carbon registries and the World Bank's Carbon Finance Portal were used to analyze price volatility, registration costs, and verification expenses, providing a realistic picture of market risks.

Policy and Implementation Roadmap Development

The final phase involved synthesizing findings to propose actionable strategies for ULBs. Existing national and state-level policies were reviewed to identify gaps, and recommendations were formulated to align municipal governance with carbon market mechanisms. Step-by-step implementation roadmaps were designed, incorporating best practices from case studies and stakeholder inputs to ensure practical applicability.

This methodology ensures a holistic understanding of how ULBs can leverage carbon credits to finance climate action bridging the critical gap between policy intent and on-ground execution.

2. Carbon Credits: An Overview

2.1 What are carbon Credits?

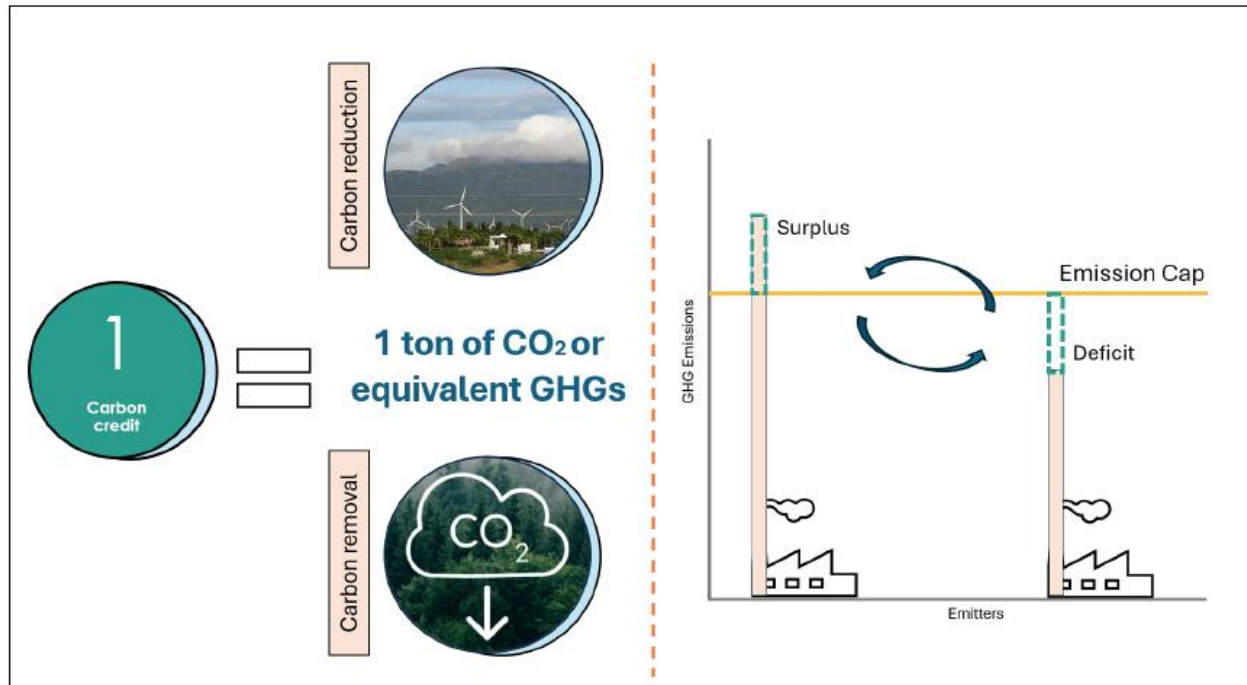


Figure 5: Diagram showing a carbon credit represents the removal or avoidance of one tonne of carbon dioxide or equivalent greenhouse gases. Industries/organisations can purchase or sell carbon credits to either offset their emissions or finance their green initiatives. Source: Author

Carbon credits are a market-based instrument designed to incentivize emission reductions while penalizing excessive pollution. The system operates on a cap-and-trade principle, where a regulatory authority sets an upper limit (cap) on permissible greenhouse gas (GHG) emissions for industries. Companies receive emission allowances, each equivalent to one ton of CO₂ or its equivalent, which they can trade to maintain compliance (World Bank, 2022). For instance, if a firm like Tata Steel emits 8 tons against its 10-ton allowance, it accumulates 2 surplus credits. Conversely, a company like Reliance emitting 12 tons against a 10-ton limit faces a 2-ton deficit. The former can sell its excess credits to the latter, ensuring net emissions stay within the cap while creating a financial incentive for cleaner operations (UNFCCC, 2021).

Carbon trading has grown into a multi-billion-dollar market, valued at 30 billion in 2006 (IETA, 2007) and exceeding 850 billion in 2023 (Refinitiv, 2023). Developed nations, bound by stringent climate targets, dominate demand. Japan, for example, purchased 10% of global carbon offsets in 2022 to meet its Paris Agreement commitments (Carbon Pulse, 2022). Meanwhile, developing economies like India, China, and Brazil lead supply, leveraging their untapped

mitigation potential. India alone contributed 21% of global voluntary carbon credits in 2021 (CEEW, 2022), driven by renewable energy and afforestation projects.

2.1 Types of Carbon Markets

Carbon markets operate through two primary mechanisms, compliance and voluntary systems, each serving distinct roles in reducing greenhouse gas emissions. Compliance markets are government-regulated frameworks designed to enforce emission caps on industries or nations. Examples like the EU Emissions Trading System (EU ETS) and California's Cap-and-Trade Program set legally binding limits, requiring companies exceeding allowances to purchase credits (called EUAs or offsets) from those below their caps. These markets adhere to strict monitoring and verification standards, with credit prices often reflecting their regulatory value. Mature markets like the EU ETS see higher prices due to guaranteed compliance utility (World Bank, 2023).

Voluntary carbon markets (VCMs), in contrast, operate without mandatory requirements, allowing corporations, institutions, and individuals to offset emissions for sustainability or reputational goals. They trade Verified Carbon Units (VCUs) or Certified Emission Reductions (CERs) generated through projects like reforestation or renewable energy, verified by private standards such as Verra or Gold Standard. While VCMs offer flexibility, concerns persist over credit quality, including additionality (whether projects truly reduce emissions beyond baseline scenarios) and permanence (e.g., risks like wildfires reversing carbon sequestration). Prices in voluntary markets are typically lower due to weaker demand and lack of regulatory backing, though nature-based credits with co-benefits like biodiversity conservation can command premiums (BloombergNEF, 2023). The critical difference lies in governance: compliance markets prioritize regulatory rigor, ensuring credits align with policy targets, while voluntary markets rely on decentralized standards, facing scrutiny over transparency.

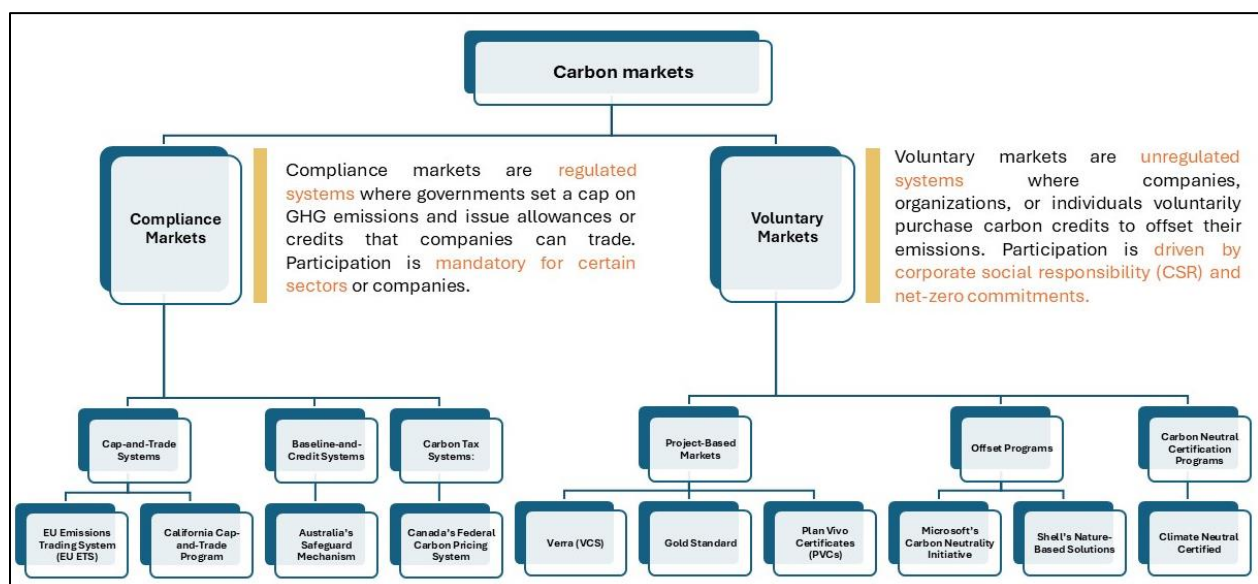


Figure 6: Diagram showing the various types of carbon market mechanisms under compliance and voluntary markets. Source: Singh. G., Understanding carbon credits. 2009

2.3 Lifecycle of a Project under a Carbon Credit Mechanism

The process of generating carbon credits follows a structured lifecycle, ensuring that emission reductions are real, measurable, and verifiable. While specific requirements vary between compliance mechanisms like the CDM and voluntary standards such as , the core stages remain consistent, encompassing project design, regulatory approvals, independent validation, and ongoing monitoring.

1. Project Identification and Design

The lifecycle begins with project identification, where developers assess the potential for emission reductions based on the chosen methodology. In compliance markets like the CDM, projects must align with approved baseline and monitoring methodologies, which define how emissions would have occurred without intervention (UNFCCC, 2021). For instance, a wind farm project in India under the CDM would use a predefined method to calculate displaced grid emissions. In contrast, voluntary projects under VCS or Gold Standard have broader flexibility but must still justify additionality, proving the project would not have happened without carbon finance (Schneider, 2019). The design phase culminates in a Project Design Document (PDD), detailing the technology, baseline scenario, and monitoring plan.

2. Host Country Approval (Compliance Markets Only)

A critical distinction between compliance and voluntary markets is host country involvement. Under the CDM, projects require formal approval from the Designated National Authority (DNA) of the host country, which evaluates alignment with national sustainability goals (CDM Rulebook, 2022). For example, India's DNA mandates that CDM projects contribute to renewable energy or waste management targets. Conversely, VCS projects bypass this step, as voluntary markets prioritize private-sector participation without governmental oversight (Verra, 2023).

3. Validation by Independent Auditors

Before registration, projects undergo validation by accredited third-party auditors (e.g., DNV, TÜV SÜD). For CDM projects, validators assess compliance with Kyoto Protocol rules, while VCS validators check adherence to the Verified Carbon Standard's criteria, such as conservative baseline calculations (Kollmuss et al., 2020). Auditors scrutinize the PDD's assumptions, ensuring that projected emission reductions are plausible. Discrepancies often require revisions,

particularly for CDM projects, where methodological rigidity can delay validation (Michaelowa, 2022).

4. Registration with the Governing Body

Upon successful validation, projects are registered with the respective standard's registry. CDM projects are listed on the UNFCCC's CDM Registry, making them eligible for Certified Emission Reductions (CERs), whereas VCS projects are recorded in Verra's registry (UNFCCC, 2023). Registration locks in the project's methodology, preventing retroactive changes to ensure consistency. Delays are common in CDM registration due to bureaucratic reviews, while VCS projects typically proceed faster (around 3–6 months) due to fewer regulatory layers (Ecosystem Marketplace, 2023).

5. Monitoring and Data Collection

Post-registration, projects enter the monitoring phase, where developers collect data on actual emission reductions. CDM projects follow strict Monitoring Plans, often requiring continuous sensors (e.g., methane flow meters in landfill projects) (CDM EB, 2021). Voluntary projects may use less prescriptive approaches but must still document performance indicators, such as biomass growth in afforestation initiatives (Gold Standard, 2022). Poor monitoring can lead to disqualification during verification, as seen in early CDM projects where inconsistent data triggered credit reversals (Schneider & La Hoz Theuer, 2021).

6. Verification and Certification

Periodic verification (typically annual) is conducted by independent auditors, who cross-check monitored data against the PDD. CDM verifiers focus on UNFCCC compliance, while VCS verifiers assess adherence to the project's selected methodology (Verra, 2023). Audits may involve site visits, drone surveys (for forestry projects), or fuel-use record reviews. Projects failing verification must rectify gaps before certification, a hurdle more common in CDM due to its complex reporting requirements (World Bank, 2022).

7. Issuance of Carbon Credits

After verification, the governing body issues credits, CERs for CDM or VCU for VCS, which are deposited into the project developer's registry account. CDM credits are tradable in compliance markets (e.g., EU ETS, CORSIA), whereas VCUs cater to voluntary buyers like corporations (ICAP, 2023). Notably, CDM projects face share-of-proceeds fees, where a portion of CERs fund adaptation projects in vulnerable nations, while VCS projects may opt for labelling schemes (e.g., Climate+ for co-benefits) to enhance marketability (UNEP, 2023).

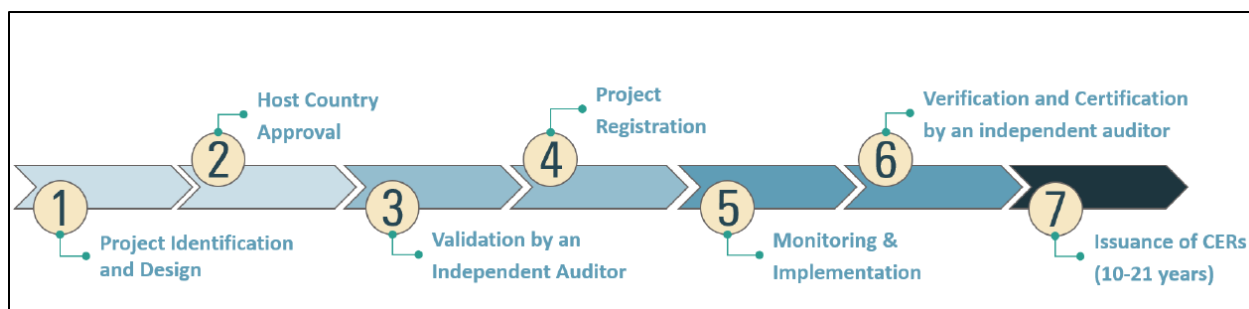


Figure 7: Diagram showing the stages in the lifecycle of a project registered under carbon trading mechanism Source: Author

3. Scope and Potential for ULBs to participate in the Carbon market

3.1 Scope of Carbon Credits for Indian Cities

For Urban Local Bodies, carbon credits represent an innovative own-source revenue stream that can supplement traditional municipal finances. Unlike tax-based revenues such as property taxes, user fees, or grants from higher government tiers carbon credit income is generated through market-driven climate actions, providing ULBs with additional fiscal flexibility. Municipal budgets typically rely on constrained revenue sources, often insufficient to fund sustainability projects. Carbon credits, however, allow cities to monetize emission reductions achieved through initiatives like waste-to-energy plants, urban forestry, or electric public transport, converting environmental benefits into financial gains (World Bank, 2023).

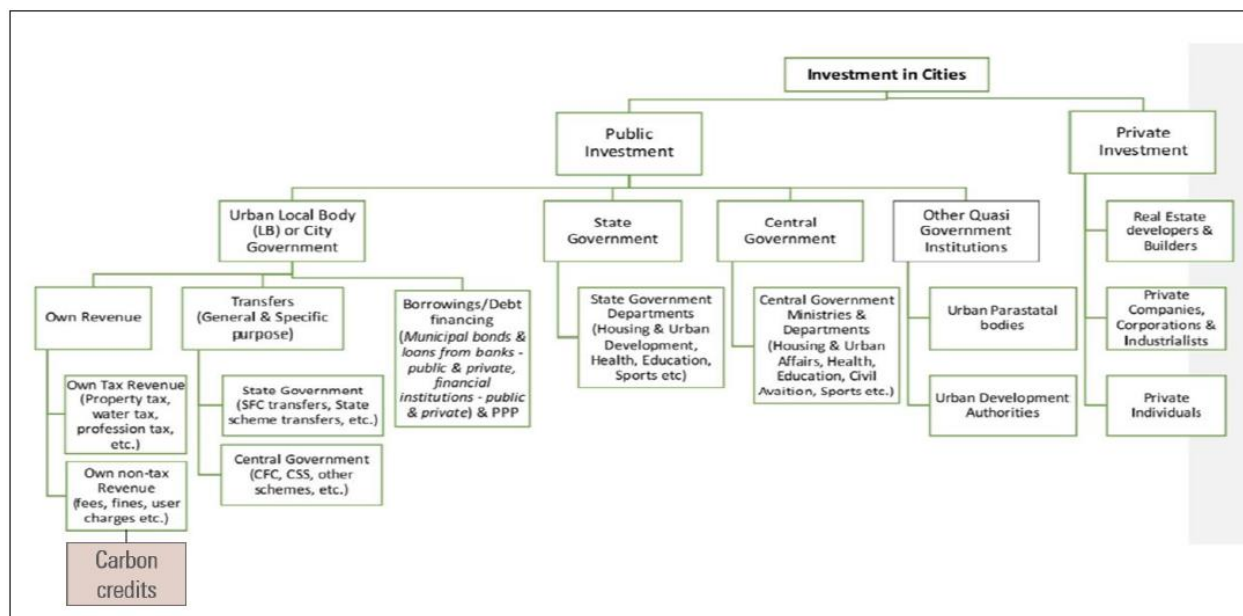


Figure 8: *Diagram showing the various sources of investments in a city. Urban local bodies typically rely on their own revenue sources, state and national transfers and borrowings/debt financing. If ULBs take up carbon credits, it will be their own non-tax revenue source. Source: Author*

ULBs can integrate carbon credits into their financial planning as a non-tax revenue category, alongside other innovative financing mechanisms like municipal bonds or public-private partnerships. While conventional revenues are tied to statutory obligations or service charges, carbon credits are performance-based, meaning income depends on verified emission cuts. For example, a ULB operating a landfill gas capture project may earn credits for every ton of methane mitigated, with revenue scaling directly with project success (ICLEI, 2022). This creates a direct incentive for ULBs to prioritize low-carbon infrastructure while diversifying their fiscal base.

3.2 Sectoral Scope

Given that cities have already formulated Climate Action Plans (CAPs), the first step in identifying carbon credit opportunities lies in distinguishing between mitigation and adaptation measures. Since carbon credit mechanisms are exclusively designed to incentivize greenhouse gas (GHG) emission reductions, only mitigation-focused activities within CAPs qualify for carbon finance. Adaptation projects, while critical for resilience, do not generate tradable credits as they lack quantifiable emission abatement (UNEP, 2022). This narrows the scope for ULBs to initiatives that actively displace or reduce carbon emissions, such as renewable energy adoption, improved waste processing, or low-carbon transport systems.

To pinpoint the most viable sectors, this study analyzed the GHG profiles of major Indian cities, including Mumbai, Delhi, Bangalore, Chennai, Kolkata, and Ahmedabad. It was revealed that stationary energy (building operations), transport, and waste management collectively account for 70–80% of urban emissions (NIUA, 2023). Cross-referencing these high-emission sectors with eligible project categories under both compliance (e.g., CDM, CORSIA) and voluntary (e.g., VCS, Gold Standard) carbon markets highlighted energy efficiency, sustainable transport, and waste-to-resource projects as the most aligned. For instance, Delhi’s waste sector contributes 14% of its GHG footprint, with landfill emissions presenting a significant opportunity for credit generation through methane capture (TERI, 2022). Similarly, Bangalore’s transport sector, responsible for 30% of emissions, could leverage electric bus fleets or non-motorized transit projects under carbon methodologies like AM0031 (bus rapid transit systems) or VM0018 (electric vehicle charging infrastructure) (Clean Mobility Collective, 2023).

Sr. No.	Compliance Markets	Voluntary Markets
1	Energy industries (renewable - / non-renewable sources)	Agriculture forestry and other land use
2	Energy distribution	Carbon capture and storage
3	Energy demand	Energy demand
4	Manufacturing industries	Chemical industry
5	Chemical industry	Construction
6	Construction	Energy distribution
7	Transport	Energy industries (renewable - / non-renewable sources)
8	Mining/Mineral production	Fugitive emissions from fuels (solid, oil and gas)
9	Metal production	Fugitive emissions from production and consumption of halocarbons and sulphur hexafluoride
10	Fugitive emissions from fuels (solid, oil and gas)	Livestock, enteric fermentation and manure management
11	Fugitive emissions from production and consumption of halocarbons and sulphur hexafluoride	Mining/Mineral production
12	Solvents use	Metal production
13	Waste handling and disposal	Manufacturing industries
14	Afforestation and reforestation	Transport
15	Agriculture	Waste handling and disposal

Table 1: Table showing the list of project categories accepted under compliance (CDM) and voluntary (VCS) markets. Source: UNFCCC carbon registry and Verra registry

A systematic literature review further validated this alignment, revealing that over 90% of ULB-linked carbon credit projects globally focus on these three sectors (World Bank, 2023). Waste-to-energy plants, building retrofits, and metro rail systems dominate existing registries, with successful cases like Indore's waste-to-energy project (registered under VCS) demonstrating the financial viability of municipal waste interventions (ICLEI South Asia, 2022). Conversely, sectors like water supply or urban agriculture, while environmentally beneficial, rarely qualify for carbon finance due to methodological complexities in quantifying emission reductions (Gold Standard, 2023).

Thus, ULBs can strategically prioritize energy demand management, low-carbon transport, and waste treatment when selecting carbon projects, as these sectors offer the strongest overlap between local emission profiles and market requirements. This targeted approach optimizes resource allocation while ensuring compliance with carbon standards a critical factor given ULBs' limited technical and financial bandwidth (CEEW, 2023).

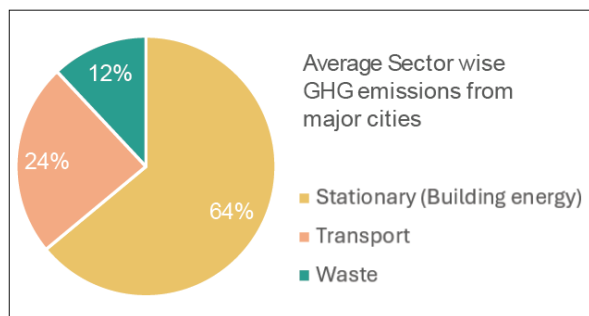


Figure 9: Average sector wise GHG emissions from major cities with stationary, transport and waste as the highest emitting sectors. Source: Climate action plans of Ahmedabad, Chennai, Bangalore, Mumbai and Delhi

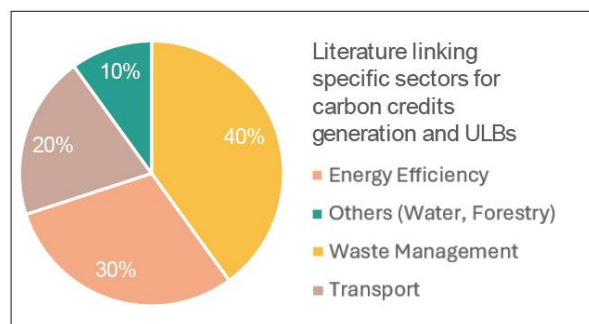


Figure 10: 90% of studies on ULB led carbon credit projects focus on waste, energy, and transport sectors: literature analysis. Source: Google

3.3 Market Scope for ULBs

When determining whether Urban Local Bodies (ULBs) should participate in compliance or voluntary carbon markets, the decision hinges on multiple factors, including project scale, administrative capacity, and market dynamics. A comparative analysis of market-wise issuance of Certified Emission Reductions (CERs) since 2005 reveals that while compliance markets have historically dominated in terms of total volume, voluntary markets follow closely, with nearly a 50-50 split in ULB participation across both systems (UNEP, 2023). Statistically, this suggests no inherent preference for either market. However, deeper scrutiny of trends and literature indicates a growing inclination toward voluntary mechanisms, particularly for small-scale municipal projects, due to their lower transaction costs and operational flexibility (World Bank, 2022). This shift is corroborated by the CEO of Indore Smart City Development Limited, who noted that compliance markets often impose prohibitive costs and bureaucratic hurdles for ULBs, making voluntary routes more accessible for cities with limited resources (Interview, 2023).

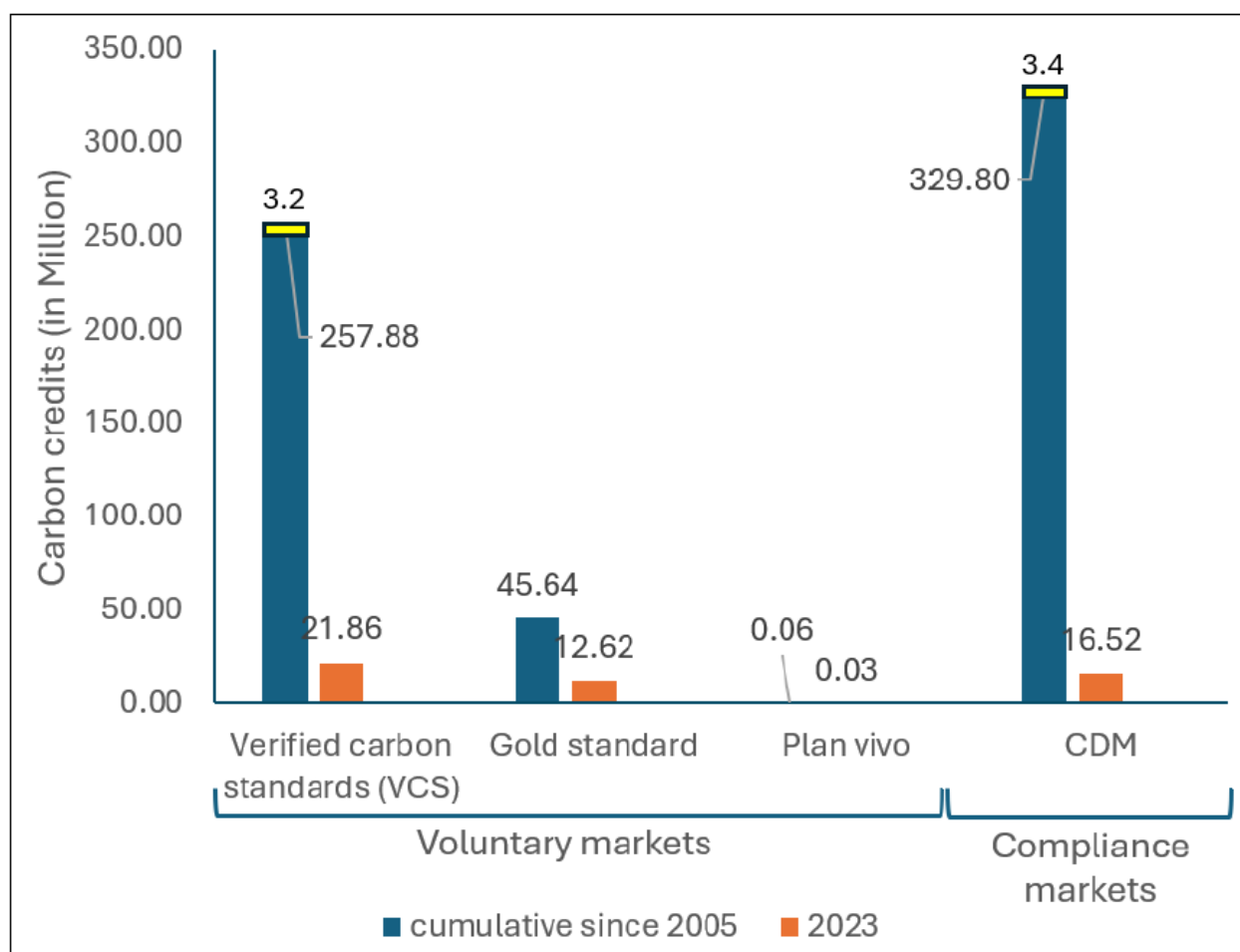


Figure 11: Market-wise issuance of CERs in millions, cumulative since 2005 and in 2023 in India. The yellow band at the top of the bars indicate the share of ULBs in the carbon markets. Source: UNFCCC CDM Project Database and Verra Registry

The decline of India's engagement in compliance markets post-2012 further underscores this trend. Data reveals a sharp drop in CDM project registrations after the first Kyoto Protocol commitment period ended, exacerbated by an oversupply of CERs and plummeting prices from €20/ton in 2008 to less than €1/ton by 2013 (Carbon Pulse, 2023). This collapse eroded the economic viability of compliance mechanisms for smaller projects, including many municipal initiatives. In contrast, voluntary markets gained momentum post-Paris Agreement, as the focus shifted from rigid international targets to Nationally Determined Contributions (NDCs) and corporate net-zero pledges. This transition unlocked demand from private entities seeking offsets, with the voluntary market growing 15% annually since 2015 (Ecosystem Marketplace, 2023). The Paris Agreement's Article 6, though still evolving, further reinforced decentralized carbon trading, creating opportunities for ULBs to engage without the stringent oversight of Kyoto-era mechanisms (ICAP, 2023).

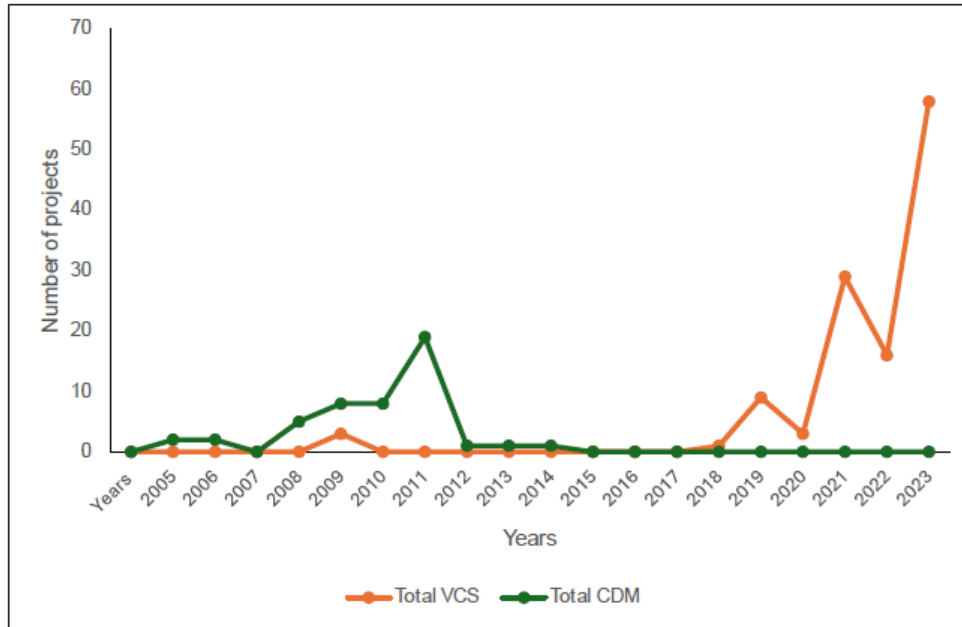


Figure 12: Graph showing the total number of projects registered under both compliance and voluntary markets annually in India in the energy efficiency, waste and transport sector. Source: UNFCCC CDM Project Database and Verra Registry

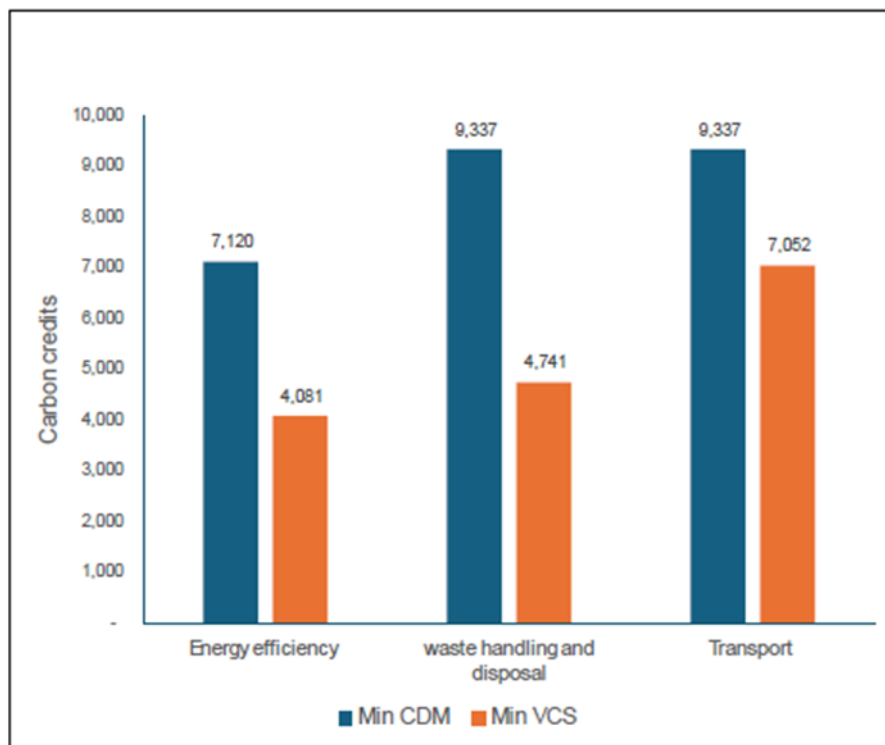


Figure 13: Graph shows the smallest scale project (project with the minimum number of annual

estimated CERs) registered under CDM and VCS mechanisms in India under the energy efficiency, waste and transport sector. It can be inferred here that VCS supports small-scale projects across sectors.

Source: UNFCCC CDM Project Database and Verra Registry

Voluntary carbon markets offer ULBs a viable financing mechanism, particularly for small-scale projects in waste, energy, and transport sectors contributing over 70% of urban emissions. Unlike rigid compliance markets, voluntary standards like Verra's VCS and Gold Standard accommodate low-volume initiatives (e.g., decentralized waste composting or rooftop solar), making them feasible for municipalities with limited resources. For instance, waste-to-energy projects under voluntary schemes can operate at 10,000 tons/year, far below the 50,000-ton threshold of compliance mechanisms (TERI, 2022).

The voluntary market's 15% annual growth since 2015 contrasts with the declining Clean Development Mechanism (CDM), highlighting its accessibility for ULBs. Stakeholders note that simplified registration and verification under voluntary standards are critical advantages for cities lacking technical expertise (ICLEI, 2023). While India's upcoming Carbon Credit Trading Scheme may create future compliance opportunities, voluntary markets remain the most immediate avenue for ULBs to monetize emissions reductions, build capacity, and align with national climate goals.

By prioritizing waste, energy, and transport projects in voluntary markets, Indian cities can unlock revenue while delivering co-benefits like cleaner air and improved public health, a pragmatic step toward sustainable urban development.

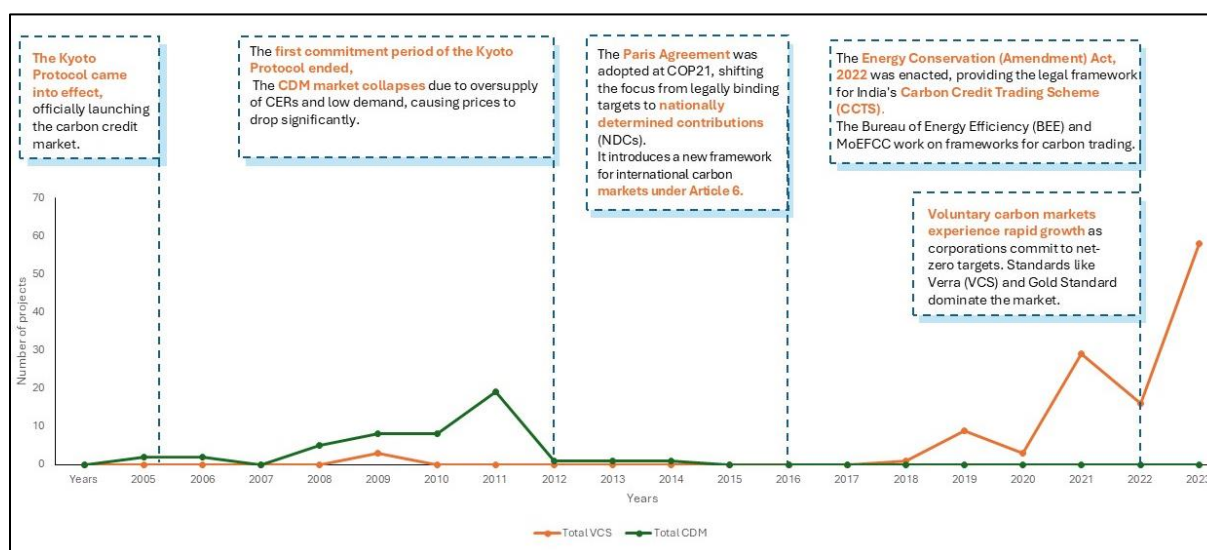


Figure 14: The image shows a temporal analysis of the declining CDM and growing VCS market share trend by overlapping of key events and policies over the years. Source: UNFCCC CDM Project Database & Verra Registry & Singh. G., *Understanding carbon credits*. 2009

3.4 Risks and Barriers

ULBs face significant challenges in accessing carbon markets, with information asymmetry posing a major hurdle. Many municipalities lack real-time data on pricing and buyer trends, often leading to undervalued credits. During India's CDM phase, intermediaries purchased credits from cities at \$3–5/ton and resold them in Europe for \$15–20/ton, capturing most profits (World Bank, 2021). This imbalance persists in voluntary markets due to fragmented platforms and opaque pricing (Ecosystem Marketplace, 2023). A critical expertise gap compounds these issues. Most ULBs lack in-house carbon finance specialists, forcing reliance on costly consultants. Surat's biogas project saw 30% of revenue absorbed by third-party fees (ICLEI, 2022). Complex certification processes further deter participation, compliance markets demand exhaustive documentation, while voluntary standards require navigating 50+ page methodologies (Verra, 2023). Pune's compost initiative was rejected due to inconsistent waste data, highlighting the need for clearer guidelines (Carbon Trust, 2022).

Market volatility adds financial uncertainty. Voluntary credit prices fluctuated 300% in 2022, crashing from \$30 to \$8/ton (BloombergNEF, 2023). Such swings undermine planning, as seen with Delhi Metro's CERs, which dropped from €12 to €0.50/ton (DMRC, 2020). Implementation gaps also plague projects—Ahmedabad's solar streetlights achieved only 40% of projected credits due to maintenance issues (CEEW, 2023), while Kolkata's landfill gas project underperformed by 60% from poor waste segregation (Ghosh et al., 2022).

Therefore, implementation strategies are required for ULBs, otherwise carbon markets will remain out of reach for most Indian cities, limiting a critical funding stream for urban climate action.

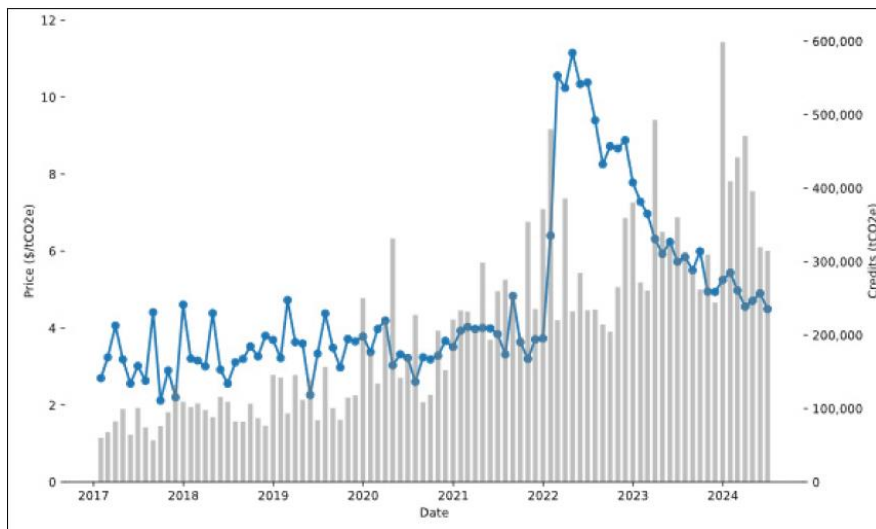


Figure 15: This figure plots the average price (blue line, left) and total retirement volume (grey bar, right) of carbon credits for each month from January 2017 to June 2024. The average price is calculated as the volume-weighted average price. Data source: Allied Offsets.

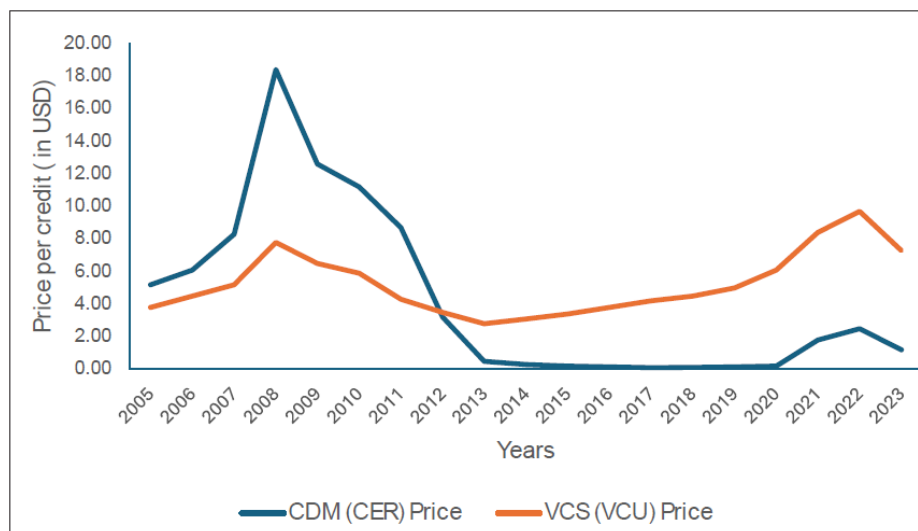


Figure 16: Graph showing the annual carbon credit price trends under CDM and VCS from 2005 - 2023. The high fluctuations indicate the financial risks associated with carbon projects. Source: Verra Registry issuance records and World bank carbon finance portal

4. Case Studies

4.1 Waste to Energy Projects: Indore

4.1.1 Introduction to Indore

Indore, a major city in Madhya Pradesh, India, lies on the Malwa plateau along the banks of the Saraswati and Khan rivers. Spanning 190 sq. km, Indore's population surged to nearly 3 million by 2011, with a decadal growth rate of 42.3%. This rapid urbanization strained basic services, particularly solid waste management (SWM). Before 2016, the city struggled with rampant littering, overflowing bins, and stray animals scavenging through waste. Community bins were poorly maintained, discouraging proper disposal—people often threw garbage from a distance, worsening the mess. The waste collection system was inefficient, relying on outdated tricycle carts and sporadic door-to-door services. With 1,380 secondary bins, 408 dumpsites, and 4,753 back lanes, the city faced a mounting sanitation crisis.



Figure 17: Indore's efforts and pride in maintaining the first rank in SBM ranking. The image also shows public toilets as part of its sanitation infrastructure. Source: Author

The turnaround began with the Jawaharlal Nehru National Urban Renewal Mission (JNNURM) in 2009–10, laying the groundwork for systemic improvements. Administrative divisions, 85 wards and 19 zones were leveraged for structured SWM operations. Despite weak infrastructure and limited resources, Indore's transformation into a cleaner city became a priority, setting the stage for its later success in waste management.



Figure 18: Image shows sanitation workers cleaning the streets of Indore at early morning (6 a.m.).
Source: Author

4.1.2 Carbon credits in Indore's waste management

Indore's municipal administration explored innovative revenue streams by developing carbon credit projects under the Clean Development Mechanism (CDM). The city proposed three key initiatives for carbon credit certification: organic waste composting, bio-methanation plants, and solar photovoltaic installations. These sustainable projects were designed to generate additional income while reducing the city's environmental footprint through verified emission reductions. The municipal corporation strategically identified these interventions as having significant potential for both climate mitigation and financial returns through the carbon market mechanism.

4.1.3 Financial and Operational Analysis

The total project cost stood at INR 59,402 lakhs, financed through a mix of 29.6% equity and 70.4% debt. Annual operation and maintenance (O&M) costs were estimated at INR 874 lakhs, with carbon credit revenue projected to cover 12.9% (INR 113.4 lakhs) of these expenses (ISCDL, 2021). This revenue, though modest in absolute terms, represents 1% of IMC's total annual revenue receipts, providing a meaningful supplementary income stream.

A critical finding during the project design phase was that the Internal Rate of Return (IRR) for each sub-project fell below sectoral benchmarks without carbon finance, highlighting the role of credits in improving financial viability. For instance, the bio methanation plants' IRR rose from 4.2% to 8.7% with carbon revenue, crossing the threshold for municipal approval (TERI, 2022).

Project Name	Capacity	Project cost (INR in Lakhs)	O&M (INR in Lakhs)	IRR without carbon credits	Benchmark IRR in the field
• Compost plants	600 TPD	1,250	150.75	6.77%	14.18%
• Bio-Methanation Chohitram Mandi Pant	20 TPD	980	105	5.53%	13.52%
• Bio-Methanation KabitKhedi	15 TPD	676	84	4.09%	13.52%
• Bio-Methanation Regional Park	15 TPD	676	84	3.01%	13.52%
• Solar plant	101.50 MW	55,820	450	9.76%	14.18%
TOTAL		59,402	874		
Equity investment 29.6% 70.4% Term Loan					

Table 2: Table showing the project details including project cost, O&M costs, IRR without carbon credits and the industry benchmark IRR in the field. Source: Joint project description & monitoring report, Indore

The total cost of carbon credit registration and verification was INR 92.54 lakhs, a mere 0.1% of the project cost. This included a one-time expense of INR 54.9 lakhs for validation and recurring annual costs of INR 4.4 lakhs for verification over the crediting period (Verra, 2023). Over a decade, the net carbon revenue after deducting these costs is projected at INR 1,041 lakhs, equivalent to an opportunity cost of INR 104.1 lakhs annually if the projects had remained unregistered.

4.1.4 Performance Analysis and Current Status of Indore's Carbon Credit Projects

Indore's carbon credit initiatives have demonstrated notable achievements while facing significant challenges in meeting projected outcomes. The city's waste-to-resource projects, while innovative, have consistently underperformed against initial expectations in terms of certified emission reduction (CER) generation. Project documents revealed an average annual target of 283,396 CERs, but actual performance has fallen substantially short - achieving only 94,634 CERs in 2020, 75,694 in 2021, and 169,506 in 2022. This shortfall has directly impacted the anticipated revenue streams, raising questions about long-term financial sustainability.

The municipal corporation successfully secured 170,000 carbon credits through the Verified Carbon Standard (VCS) system for the period spanning October 2017 to June 2019. This achievement involved rigorous validation, auditing, and verification processes, generating approximately ₹69 lakh in revenue. A subsequent verification cycle covering July 2019 to December 2020 yielded significantly higher returns of ₹8.34 crore in September 2021. However, officials confirmed that no new credits have been generated since 2022, marking a pause in the city's carbon credit endeavours.

Several critical factors have contributed to these operational challenges and the eventual halt in credit generation. Verra's updated 2023-2024 guidelines introduced stringent criteria that disqualified Indore's 600 TPD open windrow composting facility due to legitimate concerns about potential methane leakage. This regulatory shift reflects evolving industry standards that prioritize more advanced waste processing technologies with better emission controls.

The changing policy landscape in India has further complicated matters. The 2022 Solid Waste Management Rules mandated composting for all urban local bodies nationwide, effectively nullifying the "additionality" claim that underpinned Indore's carbon credit projects. Additionality, a fundamental requirement for carbon offset projects, demonstrates that emission reductions wouldn't have occurred without the carbon financing mechanism. With composting now being a regulatory requirement across India, Indore's projects lost this crucial qualification.

Technical audits uncovered operational issues affecting credit generation. Monitoring reports indicated inconsistencies in waste segregation data, leading to inflated estimates of emission performance. Furthermore, the verification process itself proved costly and time-consuming, affecting the net financial benefits.

Looking ahead, Indore's experience offers valuable lessons for urban carbon credit initiatives. While the city's 50 TPD bio-methanation plants with proper gas capture systems continue to meet current standards, the municipal corporation must address several challenges to revive its carbon credit program. These include upgrading monitoring systems for better data accuracy, transitioning to approved technologies like mechanical-biological treatment (MBT) with proper emission controls, and developing new project methodologies that comply with evolving standards.

The case highlights the delicate balance municipalities must strike between pioneering sustainable waste management solutions and maintaining financial viability in the dynamic carbon market. Indore's journey underscores the importance of adaptive planning, robust monitoring systems, and flexibility to accommodate changing regulations in the carbon credit ecosystem. These insights prove particularly relevant as cities worldwide increasingly explore carbon financing mechanisms to support their sustainability initiatives.

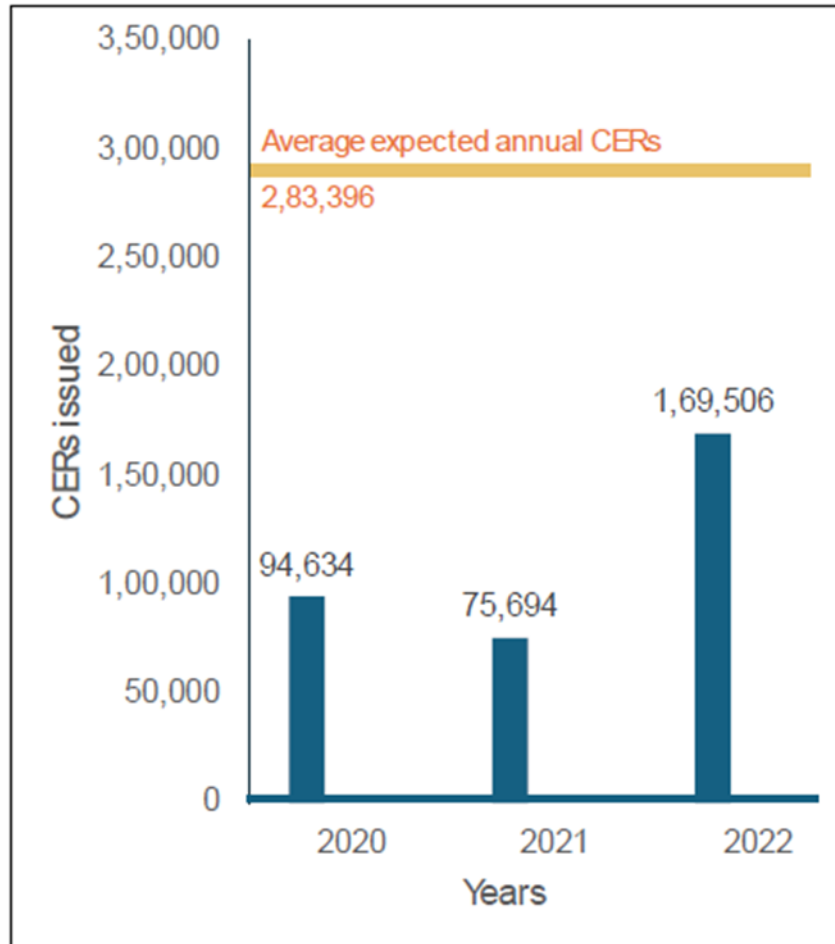


Figure 20: Graph showing Indore's annual credit generation, the yellow line marks the average expected annual CERs. Indore's annual credit generation display high fluctuations and is consistently less than the estimated annual credits generation. As such it poses financial risks for the ULB and could affect their estimated IRR or NPV values. Source: Verra Registry

4.1.5 Risks and Challenges faced

Indore's experience with carbon credit initiatives highlights several systemic and operational challenges that urban local bodies (ULBs) face in leveraging carbon markets. One of the primary barriers is information asymmetry, where ULBs lack access to real-time data on carbon credit prices and market dynamics. This knowledge gap puts them at a disadvantage during negotiations, often resulting in unfavourable terms. Without proper market insights, municipalities struggle to maximize revenue or structure long-term agreements effectively.

Another significant challenge is internal resistance from ULB staff, who sometimes perceive carbon credit projects as a form of "selling municipal assets" rather than a sustainable revenue stream. This mindset creates bureaucratic hurdles and delays in project approvals. Additionally, the short tenure of government officers disrupts continuity, as carbon credit projects require

long-term planning and consistent oversight. Frequent transfers of key officials lead to knowledge gaps and inconsistent implementation, weakening project viability.

The complexity and opacity of carbon credit registration and verification processes further hinder progress. The procedures are technically demanding, requiring specialized expertise that most ULBs lack. Indore, like many other cities, relied heavily on private consultants, which introduced dependency risks and additional costs. The absence of in-house experts means that ULBs cannot independently navigate evolving standards, such as Verra's updated guidelines, which disqualified Indore's composting facility due to methane leakage concerns.

Financial constraints also pose a major barrier. While carbon credit revenue can support operations and maintenance (O&M) costs, it is often insufficient to justify the high capital investments needed for advanced waste processing technologies. Smaller-scale ULB projects, like those in Indore, generate fewer credits compared to larger state or national projects, reducing their attractiveness to carbon market buyers. Moreover, changing regulations, such as India's 2022 Solid Waste Management Rules, have nullified the "additionality" of some projects, making them ineligible for credits.

Lastly, lack of awareness among government officials about carbon credit mechanisms slows adoption. Many decision-makers remain unfamiliar with the potential benefits or procedural requirements, leading to hesitation in committing resources. Combined with inconsistent waste segregation data, which affects credit calculations. These barriers create a challenging environment for ULBs seeking to monetize emission reductions.

Indore's case underscores the need for policy reforms, capacity building, and streamlined processes to help cities overcome these obstacles and harness carbon financing effectively. Without addressing these risks, ULBs will continue to struggle in transforming sustainability projects into financially viable initiatives.

5. Carbon 'Credit' Framework for ULBs

5.1 Introduction to the Framework

Urban Local Bodies (ULBs) play a critical role in climate action but often lack sustainable financing mechanisms. Carbon credits offer a promising revenue stream, yet cities face challenges in design, implementation, and long-term viability. This framework provides ULBs with six strategic principles to maximize carbon credit success—ensuring financial sustainability, risk mitigation, and climate impact. By addressing contract clarity, financial planning, operational efficiency, and policy adaptability, the framework helps cities navigate complex carbon markets while maintaining project integrity.

5.2 The 6 principles of the CREDIT framework

1. **Contract Clarity (PPPs):** The foundation of any successful municipal carbon credit initiative lies in establishing unambiguous contractual agreements, particularly in public-private partnerships. Urban local bodies must clearly define carbon credit ownership and revenue-sharing mechanisms during the initial project structuring phase. Indore's experience demonstrates the value of municipal ownership, which maintains public control over climate benefits, while models like Brazil's show how balanced revenue-sharing can align private and public interests. For projects where credits remain with private operators, as seen in Moradabad, rigorous performance clauses become essential to ensure environmental targets are met. Without such clarity, projects risk becoming entangled in disputes that undermine both financial returns and emission reduction goals.

2. **Revolving Funds:** Financial sustainability requires moving beyond one-time credit sales to establish revolving fund mechanisms. Carbon revenues should be strategically reinvested to create lasting climate action capacity, similar to China's community green programs or Brazil's landfill closure funds. This approach transforms temporary carbon income into permanent municipal assets, building financial resilience that outlasts individual credit periods. By institutionalizing these reinvestment practices, cities can create self-sustaining cycles of climate funding that continue generating environmental and social benefits long after initial verification periods conclude.

3. **Efficiency via Bundling:** Operational efficiency can be significantly enhanced through the strategic bundling of multiple carbon projects. Combining initiatives like waste processing with renewable energy installations reduces per-unit verification costs while creating operational synergies. However, this approach demands robust monitoring systems capable of tracking diverse emission sources and dedicated maintenance budgets to prevent system failures. The experience of Cape Town's biogas projects illustrates how underfunded operations can derail even well-designed bundled initiatives, making comprehensive lifecycle budgeting as crucial as the initial technical design.

4. **Diversified Finance:** The financial architecture of urban carbon projects must incorporate diverse funding streams to ensure viability. While carbon credits provide important revenue, they should complement rather than replace traditional financing mechanisms. Capital-intensive projects like waste-to-energy plants typically require blended financing structures incorporating grants, green bonds, and municipal budgets to cover upfront costs. This diversified approach protects projects from carbon market volatility while ensuring sufficient funds for proper implementation and maintenance, creating more stable and reliable climate infrastructure.

5. **Insurance Against Risks:** Risk management strategies must account for the inherent volatility of carbon markets, as demonstrated by the dramatic collapse of CER prices after 2012. Urban local bodies can mitigate these financial risks through instruments like fixed-price forward contracts and by developing multiple revenue streams from byproducts like compost or renewable energy. This multi-layered approach to project economics creates buffers against

carbon price fluctuations while providing more predictable cash flows to support ongoing operations and future investments.

6. **Techno-Policy Vigilance (Additionality):** Continuous adaptation to evolving standards and technologies represents the final critical component for long-term success. The carbon market landscape changes rapidly, as shown by Verra's 2023 exclusion of open windrow composting projects. Municipalities must maintain vigilant monitoring of policy developments and technological advancements, incorporating flexibility into project designs to accommodate future changes. Regular policy scenario analysis and the capacity to upgrade systems, such as transitioning to in-vessel composting when required, ensure projects maintain their additionality and continue qualifying for credit generation over extended periods. This adaptive capacity transforms carbon projects from static initiatives into dynamic components of a city's evolving climate strategy.

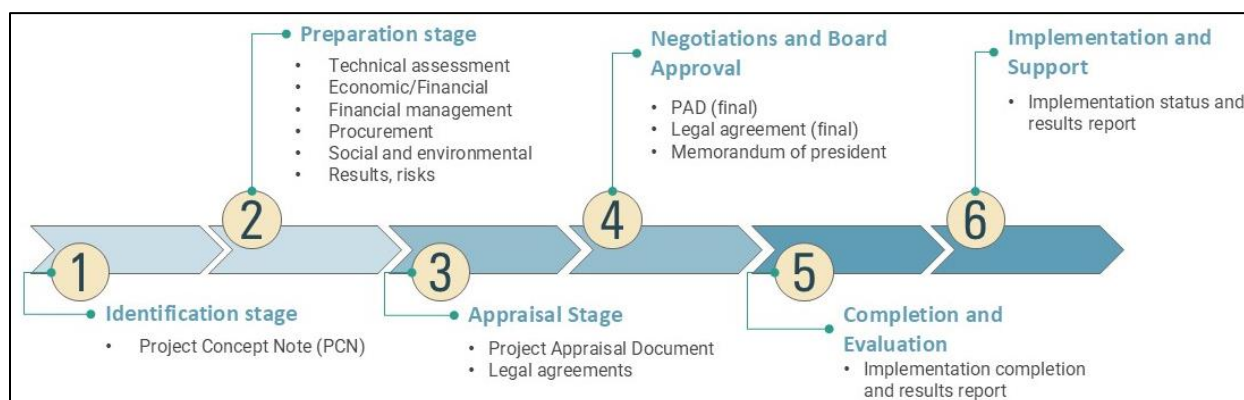


Figure 21: The carbon CREDIT framework is being integrated with the typical infrastructure project cycle, giving checks and balances at each stage. Source: Author

5.3 Carbon Mitra: ULB Credit Toolkit

It is a user-friendly calculator designed to help Indian urban local bodies (ULBs) estimate carbon credit potential from waste projects. By inputting waste volume and technology choices, ULBs can predict revenue, assess feasibility, and align with carbon market methodologies (VCS/CCTS). Ideal for waste-to-energy, composting, and landfill projects, turning sustainability into a financial opportunity.



Step 1: Input ULB Profile

Begin by selecting your ULB classification (A+, A, B, C, or D) from a dropdown menu, which auto-fills the average waste generation (TPD) and wet/dry/mixed waste split (%) based on standardized Indian municipal data. For example, selecting "Class A" will display 250 TPD of waste with a 50-50 wet-dry split, allowing the ULB to proceed with accurate baseline inputs. If the ULB has specific data to their city, they can edit the data and get specific results.

Step 2: Define Project Parameters

Next, choose the waste processing technology for wet waste (e.g., bio methanation, composting), dry waste (e.g., RDF combustion, plastic pyrolysis) or mixed waste (landfill biogas capture) from the drop-downs. Enter the processing capacity (%), representing the portion of waste treated (e.g., 70%).

Step 3: Analyze Outputs for Decision-Making

The toolkit calculates three key outputs to guide planning and risk assessment. First, it provides credit potential segregated by wet, dry, and mixed waste processing, enabling ULBs to identify the most efficient project bundles. Second, it estimates future revenue, which helps in strategizing revolving funds and blended finance models, critical for sustaining climate initiatives beyond the crediting period.

Third, the toolkit computes MRV (Monitoring, Registration and Verification) costs, allowing ULBs to conduct a cost-benefit analysis by comparing these expenses against projected revenue.

Additionally, users can test different CER price ranges to assess financial viability under market volatility, supporting risk mitigation planning.

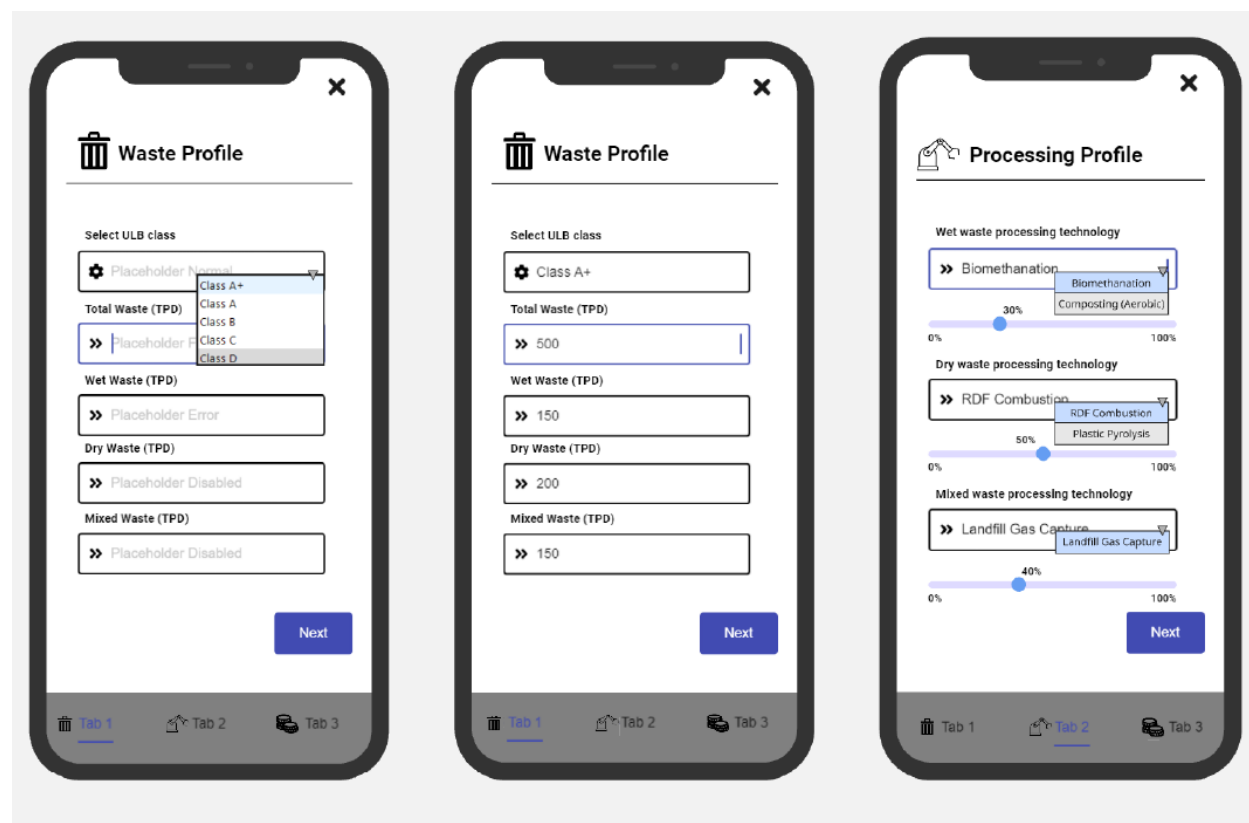


Figure 22: Image shows the visualisation of an application for the credit calculator. Here, the input pages are shown for entering the ULB and waste profile along with project parameters. Source: Author

Step 4: Aligning with the CREDIT Framework

By providing insights into credit ownership (C), revolving fund potential (R), bundling efficiency (E), diversified finance options (D), risk hedging (I), and policy-compliance checks (T), the toolkit ensures that ULBs adopt a holistic approach to carbon finance, mirroring the six principles of the CREDIT framework.

The CarbonMitra Toolkit transforms complex carbon finance calculations into actionable insights, empowering ULBs to convert waste into wealth while adhering to structured climate governance. By integrating financial feasibility checks, risk analysis, and CREDIT-aligned planning, it serves as a one-stop solution for municipal carbon projects in the waste sector.

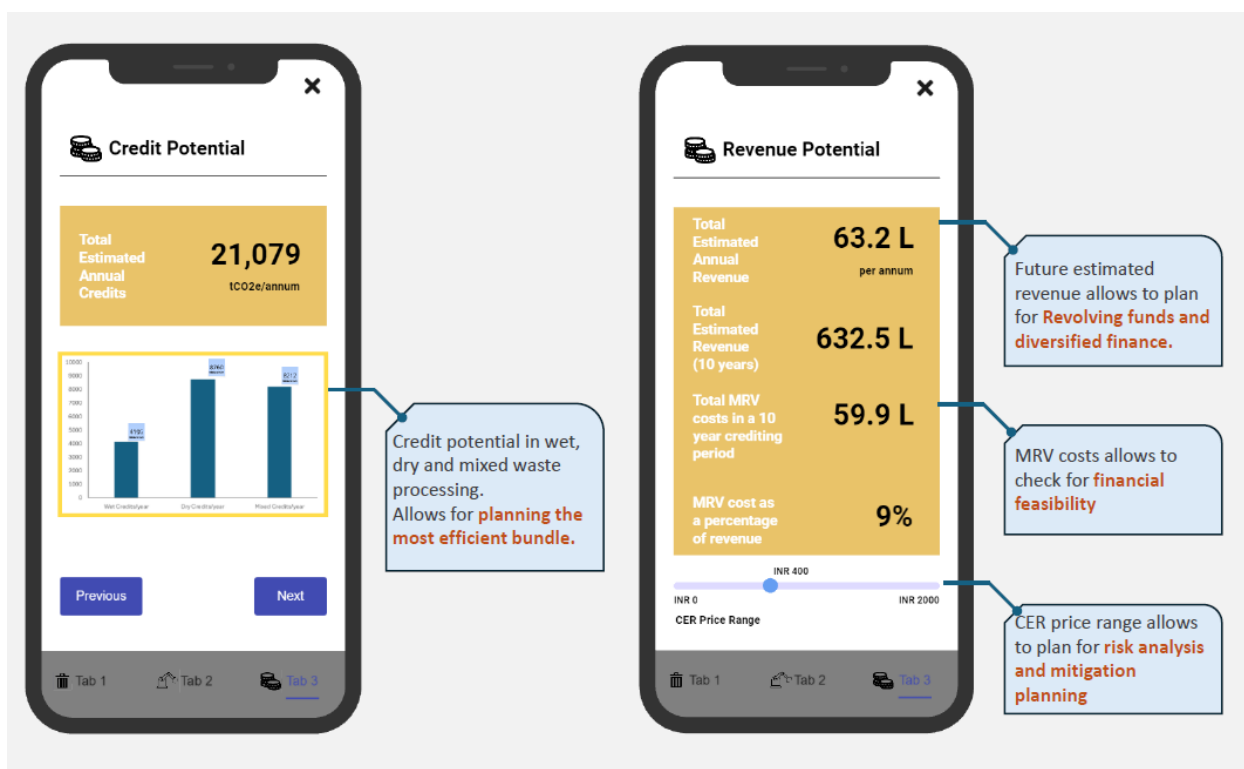


Figure 23: The Image shows the visualization of an application for the credit calculator. Here, the output pages are shown, which give credit potential segregated by wet, dry, and mixed waste processing, estimated future revenue and computed MRV costs. Source: Author

6. Conclusion

This research has systematically demonstrated that carbon credits, when strategically implemented, can serve as a powerful enabler for urban climate action in India, bridging the critical gap between environmental goals and municipal finance. Through an examination of global best practices, India-specific case studies, and the development of the CREDIT framework, three key insights emerge:

First, carbon finance is not a silver bullet but a catalytic tool that works best when integrated with broader fiscal planning. While credits cannot replace upfront capital, they offer a sustainable revenue stream for O&M costs and revolving funds, as evidenced by China's solar-waste bundle and Indore's biomethanation project. The iterative "earn-and-reinvest" model, where credits from one initiative fund the next, creates a self-sustaining cycle of climate resilience, reducing dependence on unpredictable grants.

Second, success hinges on structured frameworks and localized tools. The CREDIT framework (Contract clarity, Revolving funds, Efficiency bundling, Diversified finance, Insurance against risks, and Techno-policy vigilance) provides ULBs with a roadmap to navigate carbon markets while mitigating pitfalls like price volatility (e.g., CERs' 2012 crash) or underperformance (e.g.,

Kuyasa Low-Cost Housing Project). Complementing this, the CarbonMitra Toolkit democratizes access by translating complex calculations such as credit potential, MRV costs, breakeven analysis into actionable insights for ULBs of all sizes.

Third, institutional empowerment is non-negotiable. Barriers like reliance on consultants (Moradabad's 22.6% verification costs) or policy ambiguities can be overcome through targeted capacity-building, standardized MRV templates, and India's upcoming CCTS, which must prioritize ULB-friendly guidelines. Case studies like Brazil's landfill closure and TEDA's industrial decarbonization further prove that blending carbon revenue with subsidies, green bonds, or PPPs enhances viability.

Looking ahead, India's urban climate resilience depends on scaling these models. By adopting the CREDIT framework, leveraging tools like CarbonMitra, and fostering partnerships (e.g., BPCL's CORSIA-linked offtake), ULBs can unlock \$2–4 billion annually from carbon markets by 2030. The journey from "waste to wealth" is not without risks, but with robust planning, where every tonne of CO₂ mitigated translates into fiscal and environmental dividends. Cities can emerge as leaders in the global low-carbon transition.

Carbon credits are not just about compliance; they are about transforming urban governance, one project at a time.

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Paper 18

Urban Environmental Sustainability Assessment of Dhaka Metropolitan City Using a Geospatial-statistical Approach with Remote Sensing Indices

Sajid Ibne Jamalfaisal, Md. Tahsinur Rahman, Sayed Abu Johany, Md Sabit Mia, Md. Shohel Khan

Abstract

Rapid urbanization and land use transformation have increasingly degraded urban environmental sustainability (UES), threatening ecological balance and human well-being in Dhaka Metropolitan City areas. Understanding the spatial distribution of UES is essential for sustainable urban management in these regions. This study aimed to assess the UES of the highly urbanized area of Dhaka Metropolitan City based on five remote sensing-based indices, such as land surface temperature (LST), normalized difference vegetation index (NDVI), water index (NDWI), built-up index (NDBI), and bareness index (NDBaI) and analyzed through principal component analysis (PCA). In addition, a weighted linear combination (WLC) was used to classify the area into five categories (very poor to very high). Landsat 8 satellite imagery was used to extract all of these indices by using Google Earth Engine and further analyzed by Python 3.13 and ArcMap 10.8 software. PCA results revealed that the first two components, PC1 (eigenvalue = 3.11) and PC2 (eigenvalue = 1.32) explained 87.72% of the variance, with LST (29.06%) and NDBI (26.30%) being the dominant contributors to UES, followed by NDVI (16.59%), NDBaI (15.48%), and NDWI (12.57%), respectively. The correlation analysis indicated a strong negative association between NDVI: NDWI ($r = -0.97$) and NDVI: NDBI ($r = -0.83$), while NDBI showed strong positive correlations with NDWI ($r = 0.74$) and LST ($r = 0.68$). The WLC showed that 42.36% and 40.29% of the study area were categorized under “low” and “moderate” UES, respectively. Only 16.41% of the area exhibited “high” sustainability, while “very high” and “very low” categories accounted for 0.10% and 0.84%, respectively. This study provides a comprehensive spatial understanding of UES in Dhaka City, which can guide policymakers and urban planners in formulating sustainable urban development strategies and may suggest an evidence-based spatial framework to identify vulnerable zones for city areas.

1. Introduction

Urban environmental sustainability (UES) refers to an assessment of an urban area's ability to ensure ecological integrity and its ability to maintain resource efficiency and environmental quality over time (Merino-Saum et al., 2020). UES is in line with the United Nations Sustainable Development Goal (SDGs) and specifically SDG 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable (Krellenberg et al., 2019). Managing and protecting urban natural resources, ecosystem functions and the built environment is essential to maintain human welfare, improve environmental quality and ensure the resilience of cities in the long term (Sathyaseelan et al., 2023). However, such essential attributes are threatened by human-induced changes that cause land degradation and urban formations. These changes are primarily caused by factors including population growth, industrialization, unplanned urbanization, over-exploitation of resources and poor environmental regulation (Ahmed et al., 2020; Surya et al., 2021; Ogunbode et al., 2025). As a result, these factors put pressure on both urban ecosystems and environmental quality, which ultimately impacts the overall sustainability of urban areas.

Dhaka city, the capital of Bangladesh, is an example of how these interdependent factors play a key role in reducing the quality of the urban ecosystem and the environment. The city underwent rapid urbanization between 1989 and 2020, with urban land cover increasing from 59 to 82% of the total area. (Misty et al., 2024; Nawar et al., 2022). This development has led to a significant deterioration of urban ecosystems, with the loss of vegetation cover, blue areas and wetlands. These changes have further degraded key ecological functions such as flood control, temperature regulation and biodiversity maintenance (De Lima et al., 2023; Pandey & Ghosh, 2023). The decline in environmental quality is also reflected in rising air, water and soil pollution, increased accumulation of waste and higher land surface temperatures (LST) (Wu et al., 2021). Such deteriorating conditions damage human health and comfort in addition to disruptions in the overall UES. As a result, this urban area has turned into one of the most environmentally vulnerable and ecologically exposed megacities in South Asia (Swapan et al., 2017).

Several recent studies have assessed environmental sustainability (ES) by incorporating remote sensing land cover and LST data, which allow data on terrestrial, vegetative and hydrographic resources to be collected. They are widely used methodologies to simulate environmental and ecosystem processes that form the basis of ES (Robinson et al., 2017; Zhao et al., 2019). Khatun et al. (2021) utilized multitemporal Landsat TM and OLI data for the mapping of floodplain wetlands and the determination of the ecological sustainability of Bangladesh. Shiran et al. (2021) used a similar approach, examining changes in the normalized difference vegetation index (NDVI) and LST across the Gavkhoni Playa in Iran to identify drought-induced environmental changes by fractal and wavelet analysis. Venkatesh et al. (2020) used Landsat, Sentinel imagery and Digital Elevation Model with the analytical hierarchy process (AHP) to map the areas of eco-environmental vulnerability in India. A similar AHP framework was used

by Liou et al. (2017), who used Landsat observations in Vietnam to determine spatiotemporal patterns of vulnerability. To extend these methods, Sathyaseelan et al. (2023) used principal component analysis (PCA) on Landsat-based indices in the Indian Himalayas to identify ES. Kurniawan et al. (2022) analyzed eco-environmental vulnerability by considering spatial PCA and socioeconomic factors in Indonesia. Although there is significant literature on ES in different global and regional contexts, research that specifically focuses on highly urbanized areas are few. Notably, highly urbanized cities like Dhaka Metropolitan City (DMC) have received less attention in this context.

Therefore, evaluating the spatial variations of UES in DMC is crucial in determining the environmentally susceptible areas and guiding the sound urban development and policy making. In contrast to other previous studies, the current experiment will evaluate the UES of DMC using five remote sensing-based indices, such as LST, NDVI, water index (NDWI), built-up index (NDBI), and bareness index (NDBaI). These indices were analyzed using PCA, a multivariate statistical approach. The specific objectives of the study were: (1) To classify the spatial variations of UES across DMC and identify vulnerable environmental zones. (2) To determine the key environmental factors affecting UES using a statistical method. This framework can serve as a useful decision-support tool to urban planners, policymakers, and environmental managers, helping them to promote a more balanced and sustainable urban ecosystem in DMC. In addition, the results of the study can be used to design specific urban sustainability policies and improve the environmental resilience in the city.

2. Methodology

2.1 Study area

Dhaka Metropolitan City (DMC) is the major urban center of Bangladesh with the administrative, commercial, and socioeconomic focus of the country. The city is located between 23.67° to 23.90°N latitude and 90.33° to 90.51°E longitude that covering an area of about 305.82 km² (Rahman & Szabó, 2021). The region is bounded by the Buriganga River to the south, the Tongi Khal to the north, the Turag River to the west, and the Balu River to the east. It is located in the Ganges Delta, which is the largest river delta in the world. The area is geographically characterized by flat and low-lying topography, with the altitudes normally ranging between 1 m and 14 m above the mean sea level (Pramanik & Stathakis, 2016). The climatic condition of the region is tropical monsoon, which consists of four different seasons: pre-monsoon summer, monsoon, post-monsoon, and winter. These seasonal changes have significant effects on the hydrological and ecological systems of the area. The summer months are typically hot and humid, while the winter months are typically cold and dry (Mahmud et al., 2018). The average rainfall is approximately 2000 mm, with more than 80% of the rainfall occurring during the monsoon season (June to September) (Pramanik & Stathakis, 2016). The city has faced intensive urban growth in the past few decades caused by the high rate of population growth and rural to

urban migration. It is considered one of the most densely populated urban areas globally, with a population exceeding 21 million and a density of over 23,000 people per square kilometer (Abrar et al., 2022). This demographic expansion has created significant demand for land, causing the transformation of agricultural and open lands into urban areas. The built-up area increased intensely, by more than 10 times, between 1989 and 2014 and by 139.5 km² from 2009 to 2023, mainly at the expense of vegetation and water bodies, which severely altered the urban environmental quality and living conditions (Sonet et al., 2025; Khaleda et al., 2017). Figure 1 shows a map of the study region.

2.2 Data acquisition and processing

Landsat 8 Operational Land Imager (OLI) data for the year 2025 were extracted from the United States Geological Survey (USGS) by the Google Earth Engine (GEE) platform using the median composite function to minimize cloud interference and temporal variability (Table 1). The dataset, with a 30 m spatial resolution, was radiometrically and atmospherically corrected to ensure accurate surface reflectance values. The 2025 scenes were composited to create a cloud-free representative image of the DMC. Based on these images, five indices derived by remote sensing were calculated in the spectral band algorithms. The resulting indices were exported for geospatial and statistical analysis using Python 3.13 and ArcMap 10.8 software.

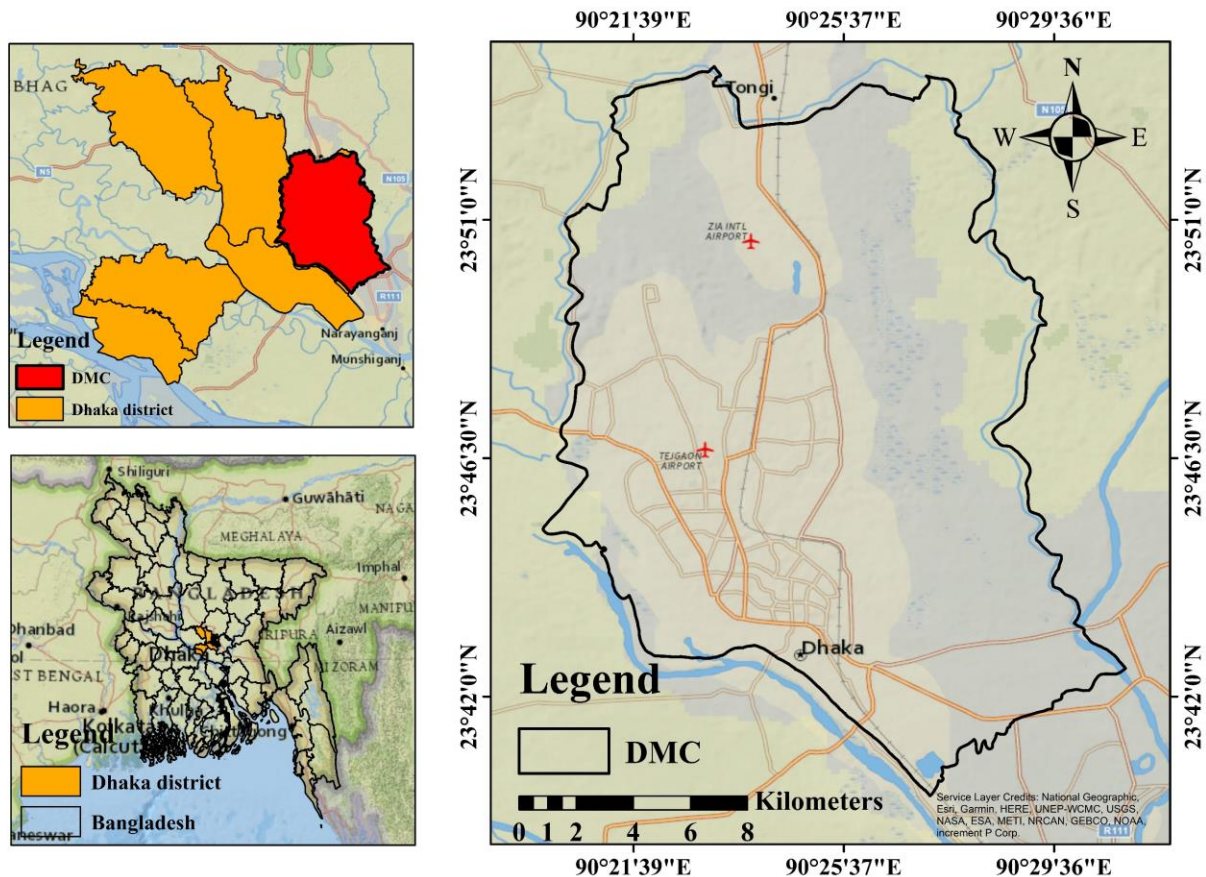


Figure 1: Geographical location map of the research area

2.3 UES conditioning factor selection

Five remote sensing indicators (LST, NDVI, NDWI, NDBI, and NDBaI) were used to examine the spatial and environmental dynamics of the study area. These indices are commonly used to assess the ecological conditions, land cover change, and environmental issues in the urban area (Mondal & Gavske, 2024; Tiwari & Kanchan, 2024). The indices were classified using the Natural Breaks (Jenks) classification method, which yielded five classes of sustainability: very low, low, moderate, high, and very high, re-scaled to 1 (very low) to 5 (very high) based on the UES level.

S. N.	Data	Purpose	Year	Source	Scale/Resolution
1	Satellite images	LST	2025	Landsat 8 (OLI)	USGS (Google earth engine)
2		NDWI			
3		NDVI			
4		NDBI			
5		NDBaI			

Table 1: Detailed information on the utilized data

NDVI was utilized as a primary indicator of UES, as it measures green cover in urban areas and reflects overall vegetation health. The index is widely considered as a reliable indicator for evaluating ecological quality and maintaining environmental balance (Tiwari & Kanchan, 2024). NDVI values range from -1 to +1 where values near +1 indicate dense, healthy vegetation, while values close to 0 or negative represent sparse vegetation, bare soil, water, or non-vegetated areas (Lou et al., 2021). This index was computed using the red (Band 4) and near-infrared (NIR) (Band 5) spectral bands, following Equation (1) as developed by Rouse et al. (1974).

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

NDWI provides information on hydrological balances and surface moisture. The index identifies, map and track the presence and spatial coverage of open water bodies (lakes, rivers, dams and urban water bodies) by maximizing the reflection of water in satellite imagery (Yang et al., 2017; Du et al., 2016). It was determined by GREEN (Band 3) and NIR (Band 5) according to Equation (2) (McFEETERS, 1996). NDWI was computed using equation (2) (McFEETERS, 1996) with green (band 3) and NIR (band 5). The calculated indices vary from -1 to +1, with positive values representing high water content and negative values representing low moisture level (Sathyaseelan et al., 2023).

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (2)$$

NDBI was added to capture the scale and spatial extent of the urban development and changes in urbanization trends. The index also helps to trace various types of impervious surfaces (concrete, asphalt, and rooftops), which are the main indicators of the urbanization process and environmental change (Kebede et al., 2022). The NDBI was computed using SWIR1 (shortwave infrared, Band 6) and NIR (Band 5) by Equation 3. Positive NDBI values represent high urban density, whereas negative values indicate the presence of water bodies and near-zero values represent vegetated regions (Cetin et al., 2024).

$$NDBI = \frac{SWIR1 - NIR}{SWIR1 + NIR} \quad (3)$$

NDBI was used to identify and monitor barren soils and bare surface areas, which are an essential part of the assessment of UES. It also efficiently classifies the various types of barren land, such as primary bare land, secondary bare land and cultivated land, with a high degree of precision (Hung, 2020). Areas with high NDBaI show an increased bare soil presence, while areas with thick vegetation cover reveals a lower level (Dutta et al., 2021). NDBaI was calculated by SWIR1 (band 6) and TIR (band 10) following Equation 4.

$$NDBaI = \frac{SWIR - TIR}{SWIR + TIR} \quad (4)$$

LST was calculated to assess the pattern of surface temperatures and those regions that were exposed to urban heat stress, which is usually characterized by reduced vegetation cover and the increased impermeable surfaces. This index is crucial to evaluate UES because an increase in surface temperatures may influence the local climatic stability and ecological balance (Mondal & Gavske, 2024; Tiwari & Kanchan, 2024). The index was derived using Band 10 (TIR), as Band 11 has known calibration inconsistencies reported by the USGS (Waleed & Sajjad, 2022). Initially, the digital numbers (DN) of Band 10 were converted into spectral radiance using Equation 5.

$$L\lambda = ML \times QCAL + AL \quad (5)$$

where $L\lambda$ represents TOA radiance, ML is the multiplicative rescaling factor, AL is the additive rescaling factor, and $QCAL$ refers to the digital numbers of Band 10.

After that, Equation 6 was used to calculate TOA brightness temperature.

$$T_b = \frac{K_2}{L_n \left(\frac{K_1}{L\lambda} + 1 \right)} \quad (6)$$

where, T_b is the at-satellite brightness temperature in Kelvin (K); $K_1 = 774.8853$ and $K_2 = 1321.0789$ are calibration constants for Band 10 (Waleed & Sajjad, 2022).

To obtain the final LST values, brightness temperature was corrected for surface emissivity (ε) using Equation 7, developed by (Artis & Carnahan, 1982).

$$S_T = \frac{T_b}{1 + \left(\frac{\lambda \times T_b}{\rho}\right) \times L_n(\varepsilon)} - 273.15 \quad (7)$$

where S_T is the land surface temperature in °C, $\lambda = 11.5 \mu\text{m}$, and $\rho = 1.438 \times 10^{-2} \text{ mK}$. The emissivity (ε) was calculated from the proportion of vegetation (P_v) using Equation 8.

$$\varepsilon = 0.004 \times P_v + 0.986 \quad (8)$$

The proportion of vegetation P_v can be calculated using Equation 9.

$$P_v = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^2 \quad (9)$$

where $NDVI$, $NDVI_{min}$, and $NDVI_{max}$ refer to the NDVI values at each pixel, minimum NDVI, and maximum NDVI, respectively. Both ε and P_v were calculated following Waleed & Sajjad (2022).

2.4 Principal component analysis (PCA)

This study utilized PCA, a multivariate statistical approach, to explore the interrelationships among considered variables. It is a widely used dimensionality reduction technique that transforms a dataset into a new set of uncorrelated variables called principal components (PCs), which are ordered by the amount of variance they explain (Hasan & Abdulazeez, 2021). Five remotely sensed indicators were considered for the analysis. Before applying PCA, all variables were standardized by Z-score normalization to remove unit inconsistencies and reduce scale bias (Gewers et al., 2022). The correlation matrix was subjected to the analysis for retaining the components that had eigenvalues above 1 according to the Kaiser criterion (Akama & Husnaqilati, 2022). In addition, varimax rotation was applied to the extracted components to increase their interpretability. The resulting component scores were further converted into proportional weights based on their contribution to the total explained variance. All analyses were carried out using ArcMap 10.8 and Python 3.13 environments.

2.5 Weighted linear combination (WLC) approach for UES mapping

The study used WLC method to associate the standardized and weighted conditioning factors for UES mapping. It is a multi-criteria evaluation (MCE) method that is highly used to combine the contribution of individual factors in a linear additive approach and takes into account the relative importance (weights) and the spatial suitability (standardized scores) of the factors (Moisa et al., 2023). The process works under the principle of giving weights to various criteria to indicate the importance of the criteria in the decision-making process (Malczewski, 2000). Further, this

method ensures that factors that have greater weights contribute more significantly to the overall composite index. The sustainability score (S) at each pixel location was calculated using Equation 10.

$$S = \sum_{i=1}^n W_i \times S_i \quad (10)$$

where S denotes the final composite UES score, W_i represents the weight of the i -th factor (derived from PCA for UES), S_i is the standardized sustainability score (ranging from 1 to 5) of the i -th factor, and n is the total number of conditioning factors considered in the analysis. Figure 2 showed the detailed methodological framework of the study.

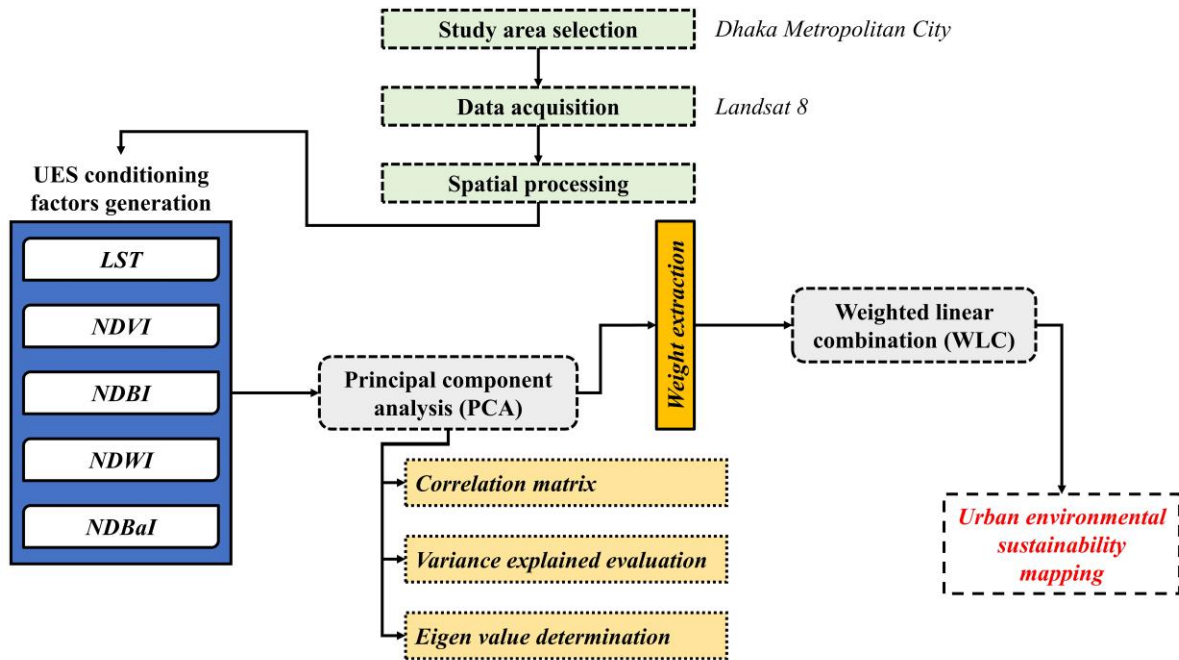


Figure 2: Methodological framework of the study

3. Result and discussion

3.1 Spatial variability of UES conditioning factors

Table 2 presents the classification of UES indices and their respective ranking values based on the natural breaks (Jenks) method. The LST was grouped into five sustainability levels: very low (30.97-39.74°C), low (29.40-30.96°C), moderate (28.09-29.39°C), high (26.52-28.08°C), and very high (23.04-26.51°C). These elevated LST zones generally face increased soil respiration, altered nitrogen cycling, urban heat islands, and potential limits to plant growth (Dai et al., 2020; Zhang et al., 2016), whereas lower LST areas correspond to cooler zones and improved

ecological balance. The NDVI was classified into five categories: very low (-0.13 to 0.21), low (0.22 to 0.31), moderate (0.32 to 0.42), high (0.43 to 0.54), and very high (0.55 to 0.81). Areas with higher NDVI values represent healthier vegetation density with healthier chlorophyll content and photosynthetic activity, which contributes to greater ecological stability and urban sustainability. On the other hand, lower NDVI zones reflect plant stress, drought, or potential land or environmental degradation (Martinez & Labib, 2022; Lou et al., 2021).

UES indices	Unit	Class (Natural break Jenks method)	Sustainability class	Sustainability rankings
LST	°C	23.04 to 26.51	Very high	5
		26.52 to 28.08	High	4
		28.09 to 29.39	Moderate	3
		29.40 to 30.96	Low	2
		30.97 to 39.74	Very low	1
NDWI	-	-0.72 to -0.46	Very low	1
		-0.45 to -0.35	Low	2
		-0.34 to -0.25	Moderate	3
		-0.24 to -0.11	High	4
		-0.10 to 0.19	Very high	5
NDVI	-	-0.13 to 0.21	Very low	1
		0.22 to 0.31	Low	2
		0.32 to 0.42	Moderate	3
		0.43 to 0.54	High	4
		0.55 to 0.81	Very high	5
NDBI	-	-0.63 to -0.28	Very High	5
		-0.27 to -0.17	High	4
		-0.16 to -0.07	Moderate	3
		-0.06 to 0.01	Low	2
		0.02 to 0.34	Very Low	1
NDBaI	-	-0.89 to -0.67	Very High	5
		-0.66 to -0.54	High	4
		-0.53 to -0.48	Moderate	3
		-0.47 to -0.39	Low	2
		-0.38 to 0.21	Very Low	1

Table 2: Category and rank values of UES conditioning factors

Similarly, the NDWI was classified into very low (-0.72 to -0.46), low (-0.45 to -0.35), moderate (-0.34 to -0.25), high (-0.24 to -0.11), and very high (-0.10 to 0.19) UES classes as higher NDWI values indicate more surface water availability which support better hydrological stability and ES (Alele et al., 2024). The NDBI was divided into very high (-0.63 to -0.28), high (-0.27 to -0.17), moderate (-0.16 to -0.07), low (-0.06 to 0.01), and very low (0.02 to 0.34) sustainability levels. High NDBI values are found in highly urbanized and impervious areas where vegetation is limited and urban heat effects are more prominent. Conversely, lower NDBI values are found in mixed or less built-up areas which reflect better environmental conditions (Shu et al., 2024; Shah et al., 2022). Finally, the NDBaI ranged between -0.89 and 0.21 and was classified into five classes: very high (-0.89 to -0.67), high (-0.66 to -0.54), moderate (-0.53 to -0.48), low (-0.47 to -

0.39), and very low (-0.38 to 0.21) UES classes. These areas with high NDBaI are indicative of higher surface exposure and land degradation, which can potentially reduce the overall quality of the environment. On the other hand, the lower values represent higher vegetation cover and sustainable surfaces in urban areas (Mondal & Gavsker, 2024; Mallick & Rudra, 2021).

Figure 3 shows the spatial distribution maps of all the UES influencing factors. Figure 3A shows that the spatial pattern of LST demonstrated a strong temperature variation in the area of study. The values were lower in the northeastern and southeastern sectors (23.04-26.51°C), which could probably be influenced by vegetation, open spaces, and close water bodies. By contrast, the northwestern and central eastern areas have higher LST values (more than 30°C) because of the high density of built-up environments and scarce vegetation. These hotspots can be considered as an enhanced urban heat island process catalyzed by the rapid urbanization and land-surface change, which highlights the degrading condition of ES and urban thermal comfort (Hasyim et al., 2025; Singh et al., 2017). Figure 3b shows clear spatial contrast of NDVI values where dense and healthy vegetation (0.55-0.81) dominated the northeastern and southeastern parts, often corresponding to peri-urban landscapes and open green spaces. Meanwhile, the central and southern parts showed low NDVI values (-0.13 to -0.21), indicating highly urbanized areas with limited vegetation cover. This spatial variation may be due to natural or human actions such as land use change, urbanization, and land degradation which can increase the risk of biodiversity loss, reduce productivity, and diminish resilience to climate change (Chen et al., 2023; Kumar et al., 2022).

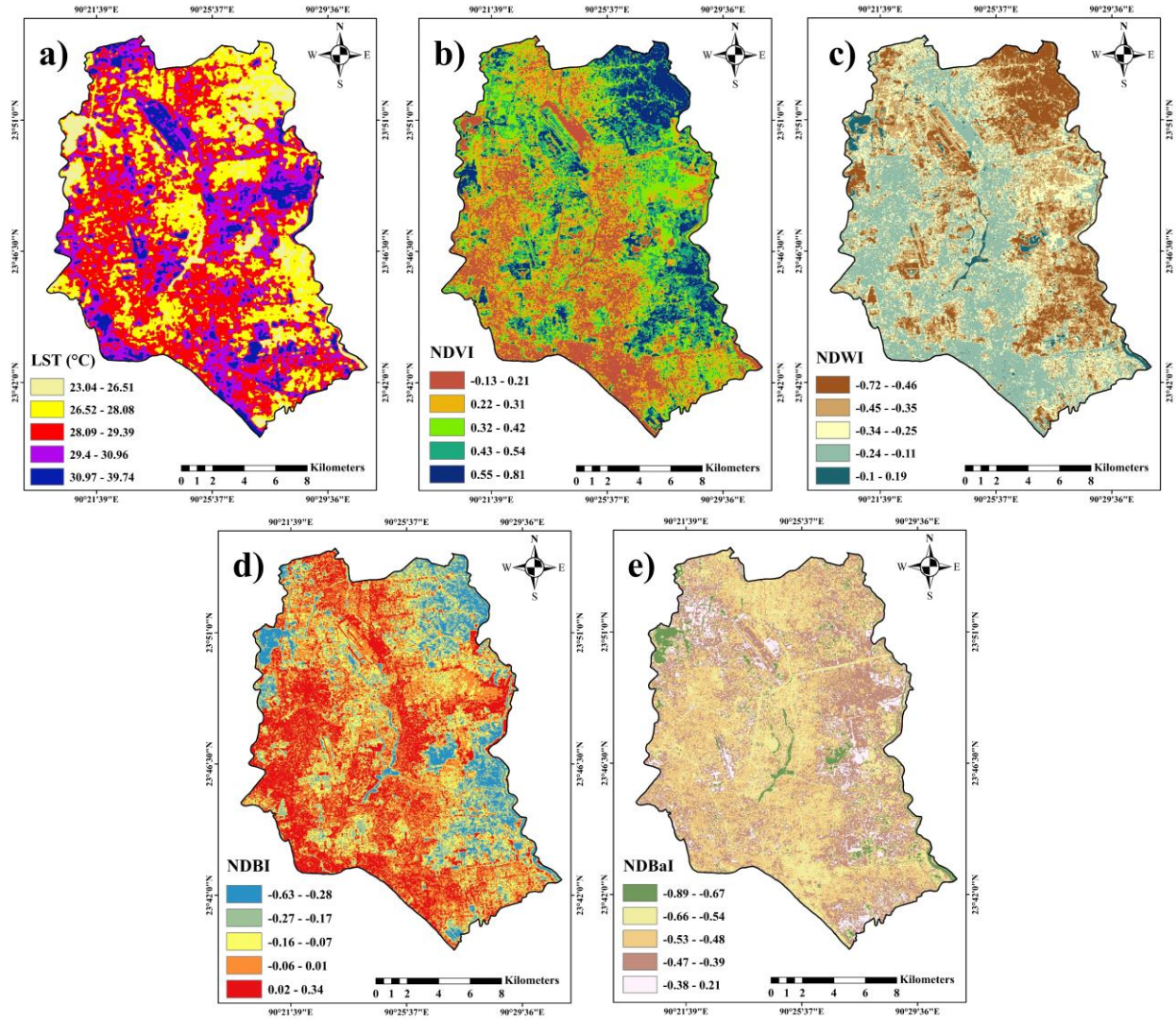


Figure 3: Spatial distribution maps of UES conditioning factors; a) LST; b) NDVI; c) NDWI; d) NDBI; e) NDBaI.

The NDWI distribution (Figure 3c) shows that high NDWI values (-0.10 to 0.19) were mainly concentrated around water channels and wetland patches, especially in the northwestern and central zones (Özelkan, 2020), while low NDWI values (-0.72 to -0.46) were mostly distributed in the northern and eastern parts. Figure 3d illustrated that dominance of built-up intensity across the study area and demonstrated higher NDBI values (0.02-0.34) were concentrated in the central, southern, and northwestern parts with lower values (below -0.28) along the eastern borders. This spatial pattern may reflect the conversion of green or blue space to built-up land, which are usually linked with environmental degradation, higher LST, and the urban heat island effect (Patel et al., 2024; Cetin et al., 2023). The spatial distribution of NDBaI (Figure 3e) illustrated that higher NDBaI values (-0.47 to -0.39) were mainly concentrated in the northwestern and eastern sectors, reflecting exposed soil, construction zones, and degraded surfaces linked to land degradation and potential ecological stress (Guha & Govil, 2022).

Conversely, the lower values of NDBaI (below -0.67) were found in the border of the city especially in the northwestern and southern regions.

3.2 Correlation analysis of UES indicators

Figure 4 shows the correlation among the five remote sensing indicators of LST, NDWI, NDVI, NDBI and NDBaI. The results revealed that NDBI: NDWI ($r = 0.74$), NDBI: LST ($r = 0.68$), NDBaI: NDBI ($r = 0.40$), NDBaI: LST ($r = 0.29$) and LST: NDWI ($r = 0.34$) were positively correlated. These results suggested that the regions with the increased level of built-up density and bare surfaces were characterized by increased surface temperatures and lower vegetation cover. Similar patterns have been observed in earlier studies, where urban expansion contributed to heat accumulation and surface dryness (Moisa et al., 2022; Guha et al., 2021). On the other hand, NDWI: NDVI ($r = -0.97$), NDWI: NDBI ($r = -0.83$), and NDWI: LST ($r = -0.46$) were negatively correlated, demonstrated that rising urbanization and higher surface temperatures were associated with decreasing vegetation and water presence. These negative relationships might indicate the effects of the land-use change and urbanization on green areas and water balance in the studied region (Alademomi et al., 2022; Mallick & Rudra, 2021).

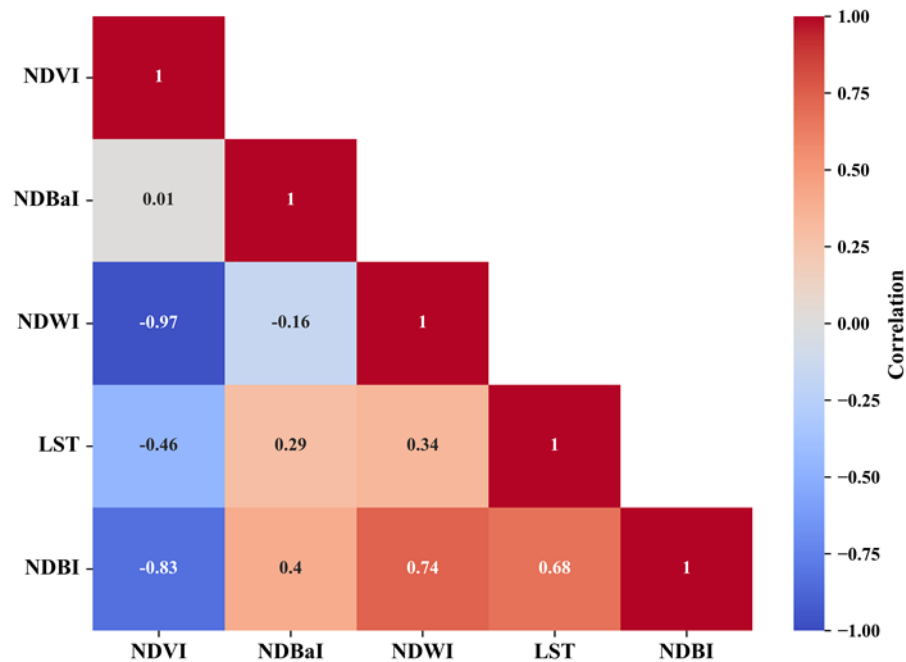


Figure 4: Correlation matrix of UES conditioning factors

3.3 PCA-based determination of weight coefficients

Table 3 revealed that the first two components (PC1 and PC2) were substantial, together explaining 87.72% of the total variance. PC1 alone explained 61.59% (eigenvalue = 3.11), while PC2 accounted for 26.13% (eigenvalue = 1.32). The results indicated that these two components had eigenvalues > 1 (Sathyaseelan et al., 2023) and effectively represented most of the variation (80-90%) in the dataset with minimal loss of information (Gewers et al., 2022).

PC	Eigenvalue	% Variance	Cumulative % variance
PC1	3.11	61.59	61.59
PC2	1.32	26.13	87.72
PC3	0.54	10.78	98.50
PC4	0.06	1.25	99.75
PC5	0.01	0.25	100.00

Table 3: PCA-derived eigenvalues and explained variance of UES indicators

The factor loading and contribution made by each variable were reported in Table 4. Out of five influencing factors, LST (29.06%) and NDBI (26.30%) had the strongest impact on the overall UES pattern, indicating the prevailing nature of built-up surfaces and temperature with respect to shaping the environmental conditions. NDVI (16.59%) and NDBaI (15.48%) also played a significant role, which highlighted the influence of vegetation cover and bare land. Conversely, NDWI (12.57%) showed the lowest weight, suggesting that water-related factors played a comparatively smaller role in the overall variation.

Factors	PC1	PC2	PC3	PC4	PC5	Component score coefficients	Final weight	Final weight (%)
LST	0.3928	0.3498	0.8192	-0.2216	0.0560	0.4191	0.2906	29.06
NDVI	-0.5366	0.2519	0.1831	0.3054	0.7224	-0.2393	0.1659	16.59
NDWI	0.4989	-0.3919	-0.1996	-0.2992	0.6843	0.1813	0.1257	12.57
NDBI	0.5429	0.1827	-0.1210	0.8102	0.0278	0.3792	0.2630	26.30
NDBaI	0.1188	0.7920	-0.4909	-0.3341	0.0778	0.2232	0.1548	15.48

Table 4: Principal component loadings and derived weights of UES indicators

3.4 UES assessment and mapping

Figure 5 shows the spatial distribution of UES in the study area. Results indicated that the majority of the region (42.36%; 124.68 km²) fell into the low sustainability category (Table 5). These areas were mostly found in the northern western, central eastern, and southern regions (light red) where the rate of urbanization and the high density of built-up surfaces are probably the main causes of environmental stress (Wang et al., 2022). The moderate category of UES (40.29%; 118.60 km²) was mainly distributed in central and northern areas (brown) that likely had a mix of land-use patterns with moderate vegetation coverage and poor water availability.

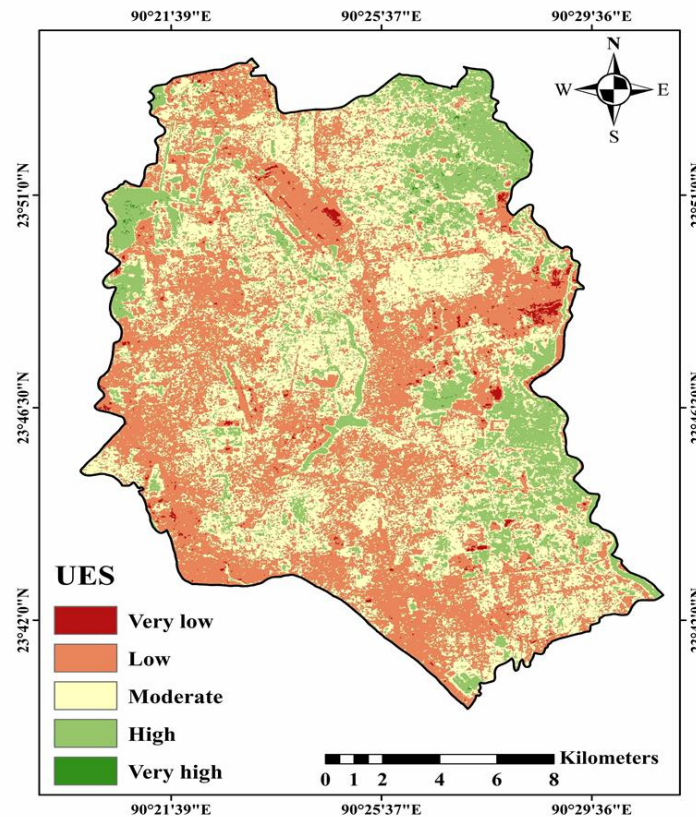


Figure 5: UES map of the study area

High UES (16.41%; 48.30 km²) areas were mostly concentrated in northern and northeastern boundary areas (light green). These areas may have more vegetation cover and cooler surface temperatures with a more balanced ecosystem in general (Yang et al., 2017). Only 0.10% (0.30 km²) of areas were reported in the category of very high sustainability (dark green). These areas were likely to have a few or minimally modified landscapes, leading to high biodiversity rates, greater ecosystem services with reduced heat island effects, lower pollution rates, and improved water management (Suab et al., 2024; Wang et al., 2022). Very low sustainability 0.84% (2.48

km²) areas were typically found as small and scattered in the central eastern and northern areas, which were likely attributed to a high concentration of impervious surfaces and vegetation loss (Wu & Liu, 2023).

UES categories	Area (km ²)	Area (%)
Very low	2.48	0.84%
Low	124.68	42.36%
Moderate	118.60	40.29%
High	48.30	16.41%
Very high	0.30	0.10%

Table 5: Area calculation of different UES categories for the study area

4. Conclusion

This study examined the UES in DMC using the geospatial-statistical framework, which includes the remote sensing indices (LST, NDVI, NDWI, NDBI and NDBaI). Together, these indicators have allowed a detailed analysis of spatial sustainability conditions in one of the most densely populated megacities in the world. The results show that approximately 82.65% of the area is in the low to moderate sustainability class. Most of these areas are located in the central and western regions, which show particularly high environmental pressures. These areas are characterized by dense urbanization, limited vegetation and high surface temperatures, underlining the pressure of rapid urbanization, inadequate planning and limited green infrastructure. The results may suggest that targeted strategies such as urban greening initiatives, surface water management and heat mitigation measures can significantly increase the resilience of the environment. Urban planners and policy makers should give priority to sustainable land use practices, increase urban vegetation and integrate climate-friendly design into the development agenda of the future. In addition, the study highlights the dominant influence of LST and NDBI on the total UES, represented by heat accumulation and impermeable surface expansion. Effective management of these factors is essential to maintain the ecological balance in the city. Finally, this geospatial-statistical methodology may offer broader applicability beyond DMC. This approach can also be a valuable tool to identify vulnerable areas and inform sustainable urban planning in other fast-developing regions. Future studies should include socio-economic and infrastructure parameters and high-resolution data sets to improve the assessment of the UES. Seasonal or annual variations may also be analyzed to capture the changing pattern and identify the major hotspots. Overall, this study provides a practical data driven framework for urban sustainability assessment and a foundation for evidence-based environmental management and policymaking in developing megacities.

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Paper 19

Empowering Climate Literacy through Media and Public Engagement

Ashraful Kabir Tuhin and Md. Raisul Islam

Abstract

Climate change demands urgent public engagement, yet critical gaps remain between scientific understanding and local action. Climate Connect tackles this challenge with an innovative, multi-platform approach that combines climate education, immersive digital storytelling, and grassroots community engagement, empowering individuals with knowledge, and driving collective action. Grounded in behavioral science and global education frameworks, the project draws on *Don't Even Think About It: Why Our Brains Are Wired to Ignore Climate Change* (Marshall, 2014) and UNESCO's *Climate Education for Social Transformation Toolkit* (2022) to deliver compelling, accessible content tailored to diverse audiences especially youth, educators, and marginalized communities. The initiative deploys short-form videos, podcasts, interactive learning modules, and community radio to bridge digital divides and ensure inclusion. At the core are *Climate Action Hubs*: localized spaces for workshops, citizen science, storytelling labs, and training on climate advocacy. These hubs equip communities to track hyperlocal climate impacts from floods to heatwaves and spearhead adaptation initiatives, including urban greening, disaster resilience programs, and advocacy for climate-smart policies. The project aligns with SDG 4 (Quality Education), SDG 13 (Climate Action), and the UNFCCC's Action for Climate Empowerment (ACE) framework. Through strategic media partnerships and targeted influencer collaborations, we amplify climate narratives that are both culturally relevant and designed for mass engagement ensuring messages resonate deeply while reaching scale. By merging science communication, local storytelling, civic participation, the project offers a replicable model to close the gap between knowledge and action—particularly in climate-vulnerable regions.

1. Introduction

One of the most important issues of the twenty-first century is climate change, which has profound effects on human communities, ecological systems, and global economies. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly emphasized that limiting global warming to 1.5°C above pre-industrial levels requires unprecedented transformations across all sectors of society (IPCC, 2021). However, despite mounting scientific evidence and increasingly visible climate impacts, a significant gap persists between public awareness and meaningful action. This disconnect—often termed the "knowledge-action gap"—has become a critical barrier to effective climate response (Kollmuss & Agyeman, 2002; Lorenzoni et al., 2007).

Climate literacy, defined as understanding climate science and possessing the knowledge, skills, and motivation to make informed decisions about climate change (NOAA, 2009), serves as a foundational element in bridging this gap. Yet climate literacy remains unevenly distributed globally, with significant disparities across regions, demographic groups, and socioeconomic strata. A 2023 study by the Yale Program on Climate Change Communication found that while 72% of people in high-income countries acknowledge climate change as a serious threat, only 45% report understanding its causes, and fewer than 30% have taken concrete steps to reduce their carbon footprint (Leiserowitz et al., 2023). In low- and middle-income countries, these figures are often lower, despite these regions facing disproportionate climate risks.

Disseminating information is not the only problem. It is especially hard to emotionally grasp climate change because human minds are evolutionarily evolved to emphasize urgent, apparent hazards over distant, abstract dangers, according to Marshall (2014). Psychological barriers including cognitive dissonance, confirmation bias, and pluralistic ignorance further compound the problem, creating what Marshall terms "socially constructed silence" around climate issues. Traditional communication approaches, which rely heavily on data-driven, fear-based messaging, have proven insufficient in motivating sustained behavioural change (O'Neill & Nicholson-Cole, 2009).

In response to these obstacles, creative initiatives that integrate scientific communication with participatory media, community participation, and behavioural science concepts have arisen as promising solutions. The Climate Connect initiative represents one such model, integrating digital storytelling, localized Climate Action Hubs, and multi-platform media strategies to empower diverse audiences—particularly youth, educators, and marginalized communities—to transition from passive awareness to active climate citizenship.

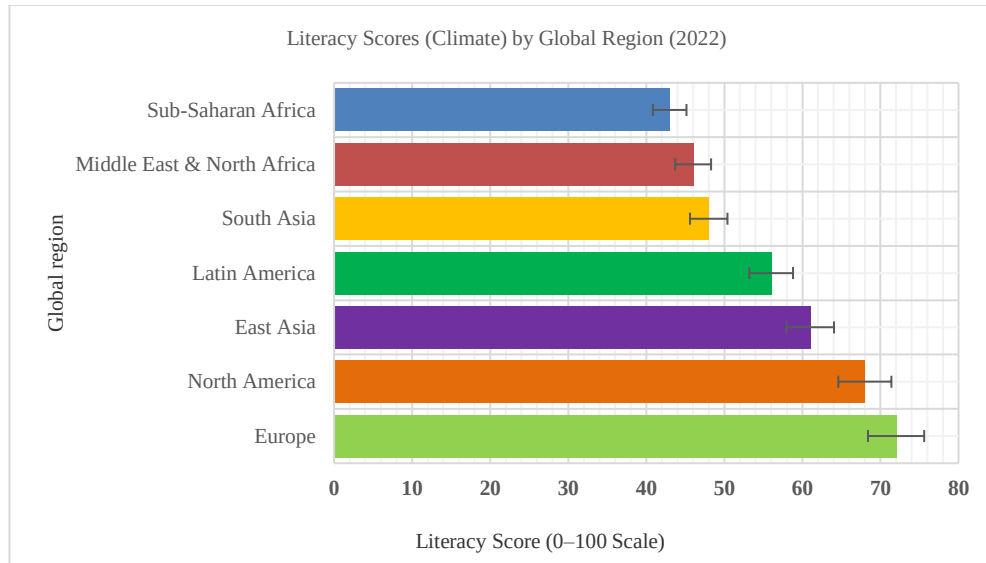


Figure 1: Climate Literacy Scores by Global Region (2022). Data Source: Pew Research Center (2022). "Climate Change Remains Top Global Threat Across 19-Country Survey."

Note: The values show the proportion of people who believe that climate change poses a "major threat" to their nation.

Methodology: Feb–Jun 2022; Survey of 24,525 adults in 19 advanced economies. regional averages derived from data at the national level.

This research article examines how integrated media and public engagement strategies can enhance climate literacy and drive meaningful behavioral change. Drawing on theoretical frameworks from behavioral science, education theory, and communication studies—particularly Marshall's (2014) analysis of psychological barriers and UNESCO's (2022) transformative education paradigm—this study analyzes the effectiveness of multi-platform, community-centered approaches to climate communication. The research aligns with the United Nations Framework Convention on Climate Change's Action for Climate Empowerment (ACE) framework, which emphasizes education, training, public awareness, public participation, public access to information, and international cooperation as essential pillars of climate action (UNFCCC, 2015).

The objectives of this study are threefold: first, to examine the current landscape of climate literacy across diverse global contexts; second, to evaluate the effectiveness of participatory media and community-based engagement strategies in promoting climate understanding and action; and third, to propose an integrated framework that policymakers, educators, and civil society organizations can adapt to their local contexts. By analyzing recent data from 2020-2025 and drawing on case studies from climate-vulnerable regions, this article contributes to the

growing body of literature on climate communication while offering practical insights for practitioners seeking to scale effective interventions.

The urgency of this work cannot be overstated. As climate impacts intensify—from unprecedented heatwaves and wildfires to flooding and food insecurity—the window for preventive action narrows. Simultaneously, the transition to a low-carbon economy presents opportunities for innovation, job creation, and improved quality of life. Realizing these opportunities while avoiding catastrophic climate outcomes requires not just technological solutions but a fundamental transformation in how societies understand, communicate about, and respond to climate change.

2. Theoretical Framework and Literature Review

2.1 The Psychology of Climate Communication

Examining the psychological processes that influence human perception and decision-making is necessary to comprehend why climate change is still a challenging topic for public participation. Marshall (2014) provides a comprehensive analysis of these mechanisms in *Don't Even Think About It: Why Our Brains Are Wired to Ignore Climate Change*. Marshall argues that climate change possesses characteristics that make it exceptionally challenging for human cognition to process effectively. Unlike immediate threats that trigger instinctive fight-or-flight responses, climate change operates on timescales that exceed typical human planning horizons. Its impacts are often geographically distant from those most responsible for emissions, creating a psychological disconnect between cause and effect.

Furthermore, Marshall identifies several cognitive biases that impede climate action. The "optimism bias" leads individuals to believe they are less vulnerable to negative outcomes than others, reducing perceived urgency. "Confirmation bias" causes people to selectively interpret information in ways that reinforce existing beliefs, making it difficult to change minds through factual appeals alone. The "bystander effect" produces diffusion of responsibility, where individuals assume others will take necessary actions. Perhaps most significantly, climate change lacks clear villains or simple narratives that align with how humans typically understand causality and moral responsibility.

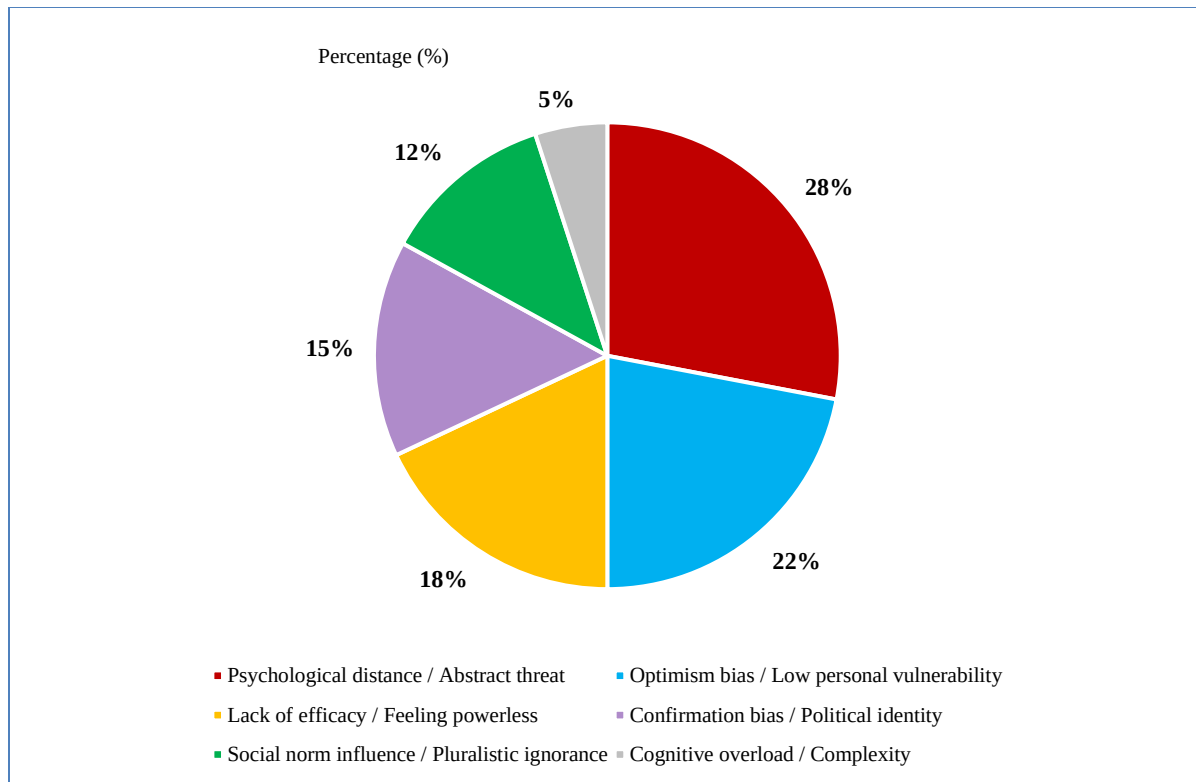


Figure 2: *Psychological Barriers Preventing Climate Action (2024).* Data Source: Based on Marshall, G. (2014) framework and behavioral research synthesis from climate psychology literature (2020-2024).

Marshall's analysis suggests that effective climate communication must counter these psychological barriers through several strategies: making climate change emotionally resonant through personal narratives; building social movements that normalize climate action; emphasizing solutions and efficacy rather than doom and helplessness; and respecting cognitive diversity by presenting information through multiple frames that appeal to different values and worldviews (Marshall, 2014). These insights have profoundly influenced contemporary climate communication practice, shifting emphasis from deficit models that assume lack of information is the primary problem toward more sophisticated approaches that acknowledge psychological and social complexity.

2.2 Education as Transformation: UNESCO's Framework

While Marshall's work illuminates why climate communication is difficult, UNESCO's *Climate Education for Social Transformation Toolkit* (2022) offers a constructive vision for how education can catalyze meaningful change. UNESCO positions climate education not merely as knowledge transmission but as a transformative process that develops critical thinking, systems thinking, and agency. This approach aligns with broader pedagogical theories emphasizing active learning, constructivism, and education for sustainable development (ESD).

UNESCO (2022) states that transformational learning is guided by a number of interrelated principles that constitute the foundation of the climate education framework. First, it emphasizes interdisciplinarity, recognizing that climate change cannot be adequately understood through any single disciplinary lens. Effective climate education integrates natural sciences, social sciences, humanities, and arts, fostering holistic understanding of climate systems, human dimensions, and cultural responses (UNESCO, 2022). Second, the framework prioritizes action competence—moving beyond knowledge acquisition to develop skills for problem-solving, critical analysis, collaboration, and civic engagement. Students are not passive recipients of information but active participants in identifying problems, proposing solutions, and implementing projects within their communities.

Third, UNESCO emphasizes the importance of emotional and ethical dimensions of climate learning. In addition to exploring beliefs and worldviews, climate education should enable students to consider climate anxiety, sadness, and hope. They should also be able to develop ethical frameworks for making decisions in the face of uncertainty and conflicting priorities (Rousell & Cutter-Mackenzie-Knowles, 2020). Fourth, the framework calls for place-based and experiential learning that connects global climate processes to local manifestations and responses. By grounding learning in familiar contexts, educators make abstract concepts concrete and demonstrate how individual and collective actions can yield tangible outcomes.

Finally, UNESCO advocates for inclusive and equitable education that reaches marginalized populations often excluded from formal learning environments. This includes attention to gender, indigeneity, disability, economic status, and geography. Such inclusivity is both a matter of justice—ensuring vulnerable populations have access to information that affects their lives—and pragmatism, as diverse perspectives and knowledge systems enrich climate understanding and response strategies (UNESCO, 2022).

2.3 Policy Framework: UNFCCC's Action for Climate Empowerment

At the international policy level, the UNFCCC's Action for Climate Empowerment (ACE) framework provides a structure for climate literacy and engagement initiatives. Established under Article 6 of the UNFCCC and strengthened through subsequent decisions, ACE encompasses six elements: education, training, public awareness, public participation, public access to information, and international cooperation (UNFCCC, 2015). ACE recognizes that technical solutions alone are insufficient for climate action; rather, societal transformation requires empowering all stakeholders to understand climate change and participate in response strategies.

A number of priorities that are directly related to this study are outlined in the ACE framework. First, it calls for integrating climate change across all levels of formal education, from primary through tertiary, ensuring that future generations possess baseline climate literacy. Second, ACE prioritizes non-formal and informal education, acknowledging that most of the current workforce and adult population will not return to formal schooling. Media, community organizations,

museums, and other informal learning environments thus become critical sites for climate education (Anderson, 2012).

Third, ACE emphasizes participatory approaches that engage communities in climate planning, monitoring, and implementation. The understanding that top-down, expert-led initiatives usually ignore local knowledge, priorities, and limitations—which can lead to unsustainable interventions—is reflected in this participatory perspective (Archer et al., 2014). Fourth, the framework highlights the need for accessible climate information in formats, languages, and channels appropriate for diverse audiences. Finally, ACE calls for international cooperation to support capacity building, particularly in developing countries where resources for climate education and communication may be limited.

2.4 The Knowledge-Action Gap and Behavioral Change Models

The persistence of a knowledge-action gap—wherein increased climate awareness fails to translate into behavioral change—has prompted researchers to develop more sophisticated models of environmental behavior. Early environmental education assumed a linear relationship between knowledge, attitudes, and behavior, sometimes called the KAB model (Hungerford & Volk, 1990). However, empirical evidence has repeatedly demonstrated that knowledge is necessary but insufficient for behavior change (Kollmuss & Agyeman, 2002).

Contemporary models incorporate additional factors. The Theory of Planned Behavior (Ajzen, 1991) emphasizes the importance of behavioral intentions, which are influenced by attitudes, subjective norms (perceptions of social pressure), and perceived behavioral control (confidence in one's ability to perform the behavior). The Value-Belief-Norm theory (Stern, 2000) highlights how personal values, environmental worldviews, and sense of obligation interact to produce pro-environmental behavior. Social practice theory shifts focus from individual decision-making to the cultural practices, infrastructures, and institutions that shape everyday routines (Shove, 2010).

There are significant ramifications for planning and carrying out climate literacy programs from these theoretical ideas. Effective programs must address not only cognitive understanding but also motivational factors, social contexts, structural barriers, and enabling conditions for action. They must build self-efficacy—confidence in one's ability to make a difference—and collective efficacy—belief that collective action can achieve meaningful outcomes (Bandura, 2000). They must leverage social networks and cultural influencers to shift norms around climate behavior. And they must connect individuals to concrete opportunities for engagement, whether through consumer choices, civic participation, or community projects (Monroe et al., 2019).

2.5 Digital Media and Climate Communication

The environment of climate communication has undergone a major transformation due to the swift expansion of digital media. Social media platforms, video-sharing sites, podcasts, and

interactive web applications offer unprecedented opportunities to reach diverse audiences, particularly youth who consume information primarily through digital channels (Schäfer & Schlichting, 2014). These platforms enable participatory communication models where audiences are not merely passive recipients but active creators and sharers of content, potentially amplifying reach and engagement (Anderson, 2017).

However, digital media also provide a number of difficulties. The "filter bubble" effect, where algorithms curate content based on prior preferences, can reinforce echo chambers and limit exposure to diverse perspectives (Pariser, 2011). Misinformation and climate denial spread rapidly on social platforms, often outpacing efforts to correct false claims (Lewandowsky et al., 2017). The ephemeral nature of digital content and constant information overload can reduce attention spans and hinder deep engagement with complex topics. Furthermore, digital divides based on infrastructure, affordability, and digital literacy limit access in many regions, particularly among elderly, rural, and low-income populations (Pearce et al., 2019).

These benefits and the difficulties they bring must be balanced in order for digital climate communication to be effective. Best practices emerging from recent research include: using compelling visual narratives rather than text-heavy content; employing humor, emotion, and storytelling to engage audiences; partnering with trusted influencers who share values with target audiences; designing interactive experiences that invite participation rather than passive consumption; and combining digital outreach with offline activities to reach digitally excluded populations (Pearce et al., 2019; Schäfer, 2012). The Climate Connect initiative, described in this study, incorporates many of these principles in its multi-platform strategy.

2.6 Community-Based Approaches and Citizen Science

Community-based climate initiatives recognize that effective action must be rooted in local contexts, priorities, and capacities. Such approaches emphasize participatory planning, indigenous and local knowledge integration, and community ownership of solutions (Reed, 2008). Climate Action Hubs, central to the Climate Connect model, exemplify this approach by creating physical spaces where community members can gather, learn, share experiences, and collaborate on local climate projects.

Involving non-professional scientists in research projects, or citizen science, has become a particularly promising strategy for increasing climate literacy and producing useful data. Citizen science projects engage participants in observing, measuring, and documenting environmental phenomena, from phenological changes (timing of seasonal events) to extreme weather impacts to biodiversity shifts (Bonney et al., 2014). Through direct engagement with scientific processes, participants develop a deeper understanding of climate systems, research methods, and evidence-based reasoning. They also generate data that can inform local adaptation planning and contribute to broader climate monitoring efforts (Conrad & Hilchey, 2011).

Studies of citizen science initiatives demonstrate multiple benefits beyond data collection. Participants report increased environmental awareness, enhanced scientific literacy, stronger connection to place, and greater motivation for pro-environmental behavior (Bonney et al., 2016). When citizen science is linked to action opportunities—for instance, when monitoring data informs advocacy campaigns or policy proposals—participants develop a stronger sense of efficacy and civic engagement (Brossard et al., 2005). Effective citizen science programs provide adequate training, ensure data quality through appropriate protocols, and create feedback loops so participants see how their contributions are used (Shirk et al., 2012).

2.7 Youth Engagement and Intergenerational Justice

Youth lead global climate movements—from Greta Thunberg’s school strikes to summits and advocacy networks—driven by disproportionate future impacts and freedom from adult constraints (Fisher, 2019). Engagement builds informed leaders, family influence, lifelong values, and intergenerational pressure (Lawson et al., 2019). Authenticity demands real leadership, decision-making, and skills in speaking, media, policy, and organizing—not tokenism (Checkoway & Gutierrez, 2006). Climate Connect empowers youth via digital platforms, peer education, storytelling, and hub leadership, transforming them into active change agents for immediate and enduring impact.

3. Methodology

This disconnect—often referred to as the **"knowledge-action gap"**—has grown to be a significant obstacle to a successful climate response.

This study employs a mixed-methods research design integrating quantitative data analysis, qualitative content review, and comparative case study approaches. Complex social phenomena like climate literacy and involvement are best studied using mixed techniques, where qualitative data provides context and depth and numerical indicators provide breadth. (Creswell & Plano Clark, 2018). The research was conducted between January 2023 and September 2025, allowing for analysis of recent trends and inclusion of the most current data available.

The overarching research questions guiding this study are:

1. What are current global patterns in climate literacy, and how do these vary across regions and demographic groups?
2. How effective are different media platforms and communication strategies in enhancing climate understanding and motivating behavioral change?
3. What characteristics distinguish successful community-based climate engagement initiatives from less effective efforts?

4. How can the Climate Connect model inform scalable, replicable approaches to climate literacy and engagement?

3.1 Data Collection Methods

3.1.1 Quantitative Data Sources

In order to ensure triangulation and comprehensive coverage of the research subject, the quantitative data used in this study originate from multiple complementary sources. Primary sources include:

Climate Literacy Surveys: Data from the Yale Program on Climate Change Communication's Climate Change in the American Mind surveys (2020-2024), the European Commission's Special Eurobarometer on Climate Change (2023), the Arab Barometer Climate Change Module (2022-2023), and regional surveys conducted by climate education networks in Asia, Africa, and Latin America. These surveys measure public understanding of climate science, perceived risks, attribution of responsibility, and behavioral intentions across diverse populations.

Media Platform Analytics: Engagement metrics from climate-focused digital content across platforms, including YouTube, Instagram, TikTok, Facebook, Twitter/X, and podcasting platforms. Data include view counts, engagement rates (likes, comments, shares), audience demographics, and watch time patterns for climate education content published between 2020-2025. Platform APIs and third-party analytics tools provided access to aggregated, anonymized data.

Climate Education Program Data: Enrollment and outcome data from formal and non-formal climate education programs worldwide, compiled from UNESCO databases, national education ministries, NGO reports, and academic publications. Metrics include program reach, completion rates, pre-/post-assessment scores, and follow-up behavioral indicators where available.

Citizen Science Participation: Data on citizen science project participation from platforms including Zooniverse, iNaturalist, CoCoRaHS (Community Collaborative Rain, Hail and Snow Network), and regional citizen science networks. Indicators include the number of active participants, observations contributed, geographic distribution, and demographic characteristics of volunteers.

3.1.2 Qualitative Data Sources

Qualitative data provide contextual depth and a nuanced understanding of how climate literacy initiatives function in practice. Sources include:

Content Analysis of Climate Media: Systematic review of 150 high-performing climate education videos, podcasts, and interactive web experiences published between 2022-2025.

Analysis examined narrative strategies, visual techniques, emotional appeals, cultural framing, length, format, and audience response patterns. To guarantee diversity in terms of geography, production style, and target demographic, the content sample was purposefully chosen.

Case Studies of Community-Based Initiatives: In-depth examination of 12 community-based climate engagement programs in climate-vulnerable regions including coastal Bangladesh, Pacific Island nations, drought-affected regions of East Africa, flood-prone areas of Southeast Asia, and hurricane-affected Caribbean communities. Case studies involved document review, interviews with program implementers and participants, and analysis of program outcomes and challenges.

Policy Document Analysis: Review of national climate education strategies, Action for Climate Empowerment implementation plans, and educational policy documents from 30 countries representing diverse geographic regions and development contexts. Analysis identified common elements, innovative approaches, and implementation barriers.

3.2 Analytical Approach

3.2.1 Quantitative Analysis

Quantitative data were analyzed using descriptive and inferential statistical techniques. Descriptive statistics (means, medians, standard deviations, percentages) summarize climate literacy levels, media engagement patterns, and program participation across different populations and contexts. Time series analysis tracks trends in these indicators from 2015-2025, identifying growth trajectories and inflection points.

Inferential techniques, including regression analysis examine relationships between variables. For example, multiple regression models tested how different communication strategies (e.g., narrative vs. data-driven; fear-based vs. solution-focused; celebrity vs. peer messengers) predict engagement metrics while controlling for confounding variables like production quality and platform algorithms. Chi-square tests and ANOVA assessed whether observed differences across regions or demographic groups are statistically significant.

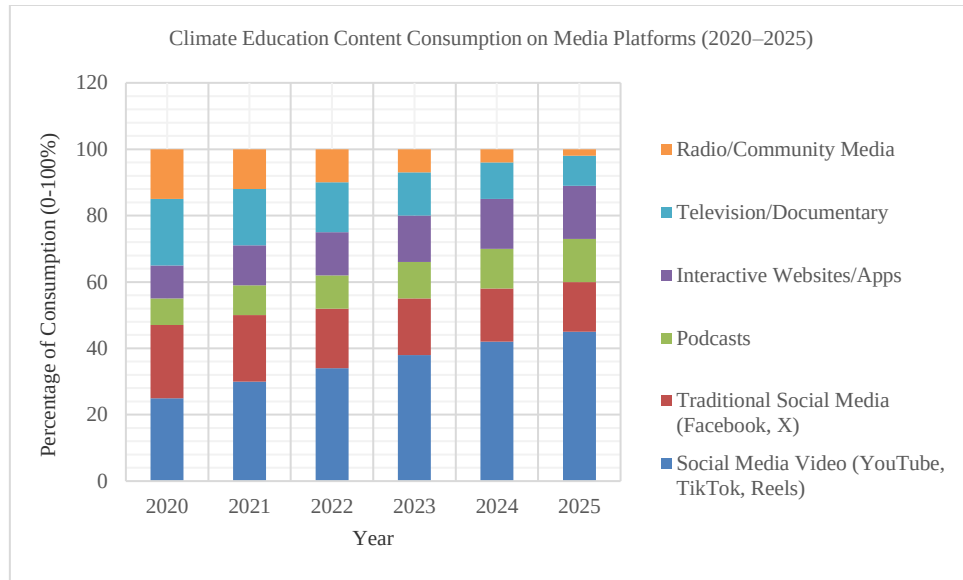


Figure 3: Media Platform Climate Education Content Consumption (2020–2025). Data Sources: YouTube Analytics, TikTok for Good Reports, Meta Transparency Reports, Podcast Industry Insights (2020-2025).

Note: Distribution estimate based on industry data and platform engagement metrics.

3.2.2 Qualitative Analysis

Qualitative data underwent thematic analysis following procedures outlined by Braun and Clarke (2006). Initial coding identified recurring concepts, strategies, and challenges within the dataset. Codes were then grouped into higher-order themes representing key dimensions of effective climate communication and community engagement. For example, content analysis revealed themes including "localization and cultural resonance," "solution-orientation and efficacy-building," "emotional authenticity," and "participatory production." Case study analysis identified themes such as "building on existing social capital," "linking awareness to tangible action opportunities," and "addressing structural barriers beyond individual behavior."

The validity of the study was reinforced by cross-verification between the data sources. For instance, findings from content analysis were compared with engagement metrics to test whether identified communication strategies correlated with measurable audience response. Case study findings were examined against broader patterns in survey data to assess generalizability. Negative cases—instances that contradicted emerging patterns—received particular attention to refine interpretations and avoid oversimplification.

3.3 Ethical Considerations

This research adhered to established ethical standards for social research. All data collection involving human participants followed informed consent procedures, with participants receiving

clear information about research purposes, data use, and privacy protections. Given that the study primarily analyzed publicly available data and aggregated statistics rather than conducting original surveys or interviews, ethics approval was obtained through institutional review processes at participating research institutions.

Vulnerable populations, particularly young people and communities most impacted by climate change, received special attention. Data collection and analysis respected cultural sensitivities, avoided stereotyping or deficit framing, and prioritized community voices and local knowledge. Researchers maintained reflexivity regarding positionality and potential biases, acknowledging that interpretations are shaped by researchers' own cultural backgrounds and theoretical commitments.

3.4 Limitations

Several limitations warrant acknowledgment. First, climate literacy data are unevenly distributed globally, with more comprehensive coverage in high-income countries. This data availability bias may skew global patterns. Second, media engagement metrics measure attention but not necessarily understanding or behavioral change, requiring cautious interpretation. Third, attribution challenges arise when assessing the impact of specific interventions, as individuals are exposed to multiple influences simultaneously. Fourth, the rapid evolution of the digital media landscape means some findings may have limited temporal stability.

Lastly, case studies have limited statistical generalizability but offer rich contextual understanding. These limitations were addressed through triangulation, careful interpretation, and explicit acknowledgment of uncertainty where appropriate.

4. Results

4.1 Global Patterns in Climate Literacy

An examination of climate literacy statistics from 2020 to 2025 reveals significant but inconsistent advancements in the general public's comprehension of climate change. Global awareness that climate change is occurring now stands at approximately 68%, up from 61% in 2020, according to aggregated survey data from the Yale Program on Climate Change Communication, Pew Research Center, and regional barometers (Leiserowitz et al., 2024; Pew Research Center, 2023). However, a deeper understanding of climate mechanisms, causes, and solutions remains limited. Only 47% of global respondents correctly identify fossil fuel combustion as the primary driver of climate change, while 35% exhibit significant misconceptions, such as conflating climate change with ozone depletion or attributing it primarily to natural cycles (Leiserowitz et al., 2024).

Regional disparities are pronounced. European populations demonstrate the highest climate literacy, with an average score of 71 out of 100 on composite measures assessing understanding of causes, impacts, and solutions (European Commission, 2023). North American populations score similarly (68/100), though with greater internal variation correlated with political identity. East Asian populations show moderate literacy (62/100), with particularly strong understanding in urban areas but lower comprehension in rural regions. Latin American (55/100), South Asian (49/100), Middle Eastern and North African (46/100), and Sub-Saharan African (43/100) populations demonstrate lower average literacy, though with notable exceptions in specific countries and communities (various regional sources, 2023-2024).

These regional trends result from a variety of factors, including cultural background, media availability, educational systems, and scientific aptitude. Importantly, lower literacy scores do not necessarily correlate with lower concern or willingness to act. Indeed, populations in climate-vulnerable regions often express high concern despite lower technical understanding, suggesting that experiential knowledge of climate impacts may motivate action even absent scientific literacy (Howe et al., 2013).

Demographic patterns reveal additional disparities. Climate literacy increases with education level, with university graduates scoring an average of 65/100 compared to 48/100 for those with secondary education and 38/100 for those with primary education only (UNESCO, 2024). Gender differences are modest but consistent, with women scoring slightly lower on scientific knowledge measures but expressing greater concern and pro-environmental behavioral intentions (McCright & Xiao, 2014). Age patterns are complex: youth demonstrate high awareness and concern but variable scientific understanding, while older adults show lower concern but sometimes deeper understanding of long-term environmental changes based on lived experience.

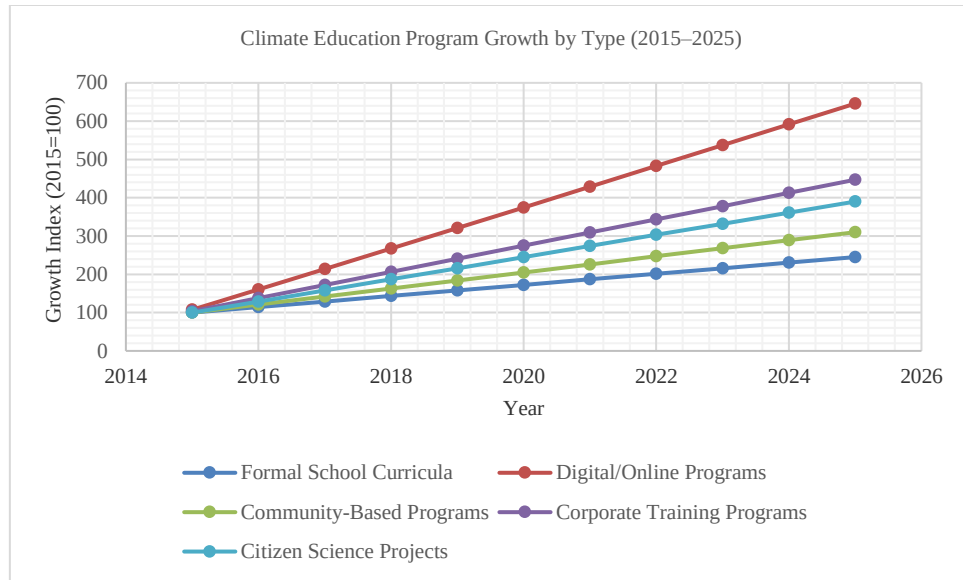


Figure 4: Climate Education Program Growth by Type (2015–2025). Data Sources: UNESCO Education Reports, OECD Climate Education Survey, Global Climate Education Database (2015-2025).

Note: The index values (2015=100) indicate the relative growth of the various program kinds.

4.2 Media Engagement Patterns and Effectiveness

Media platform analytics reveal a seismic shift in climate information consumption: short-form videos (<3 min) now dominate with 58% engagement in 2025 (up from 32% in 2020), led by TikTok/Reels among under-30s, while YouTube amassed 15B+ climate views in 2024. Podcasts grew to 400M downloads (from 150M in 2020), targeting older, educated listeners (median age 38). Traditional media's share fell to 28% for over-50s. High-engagement content features emotional personal stories (2.3× more views), solutions (1.8× shares), diverse voices, and localized cultures (3.1× impact). Authenticity trumps polish for deeper interaction; youth favor humor, memes, and creativity over doom narratives.

Cultural localization significantly impacts effectiveness. Content adapted to local languages, cultural references, and contexts achieves 3.1 times higher engagement within target communities compared to generic or Western-centric content (localization impact analysis, 2024).

4.3 Impact of Community-Based Programs

Evaluation data from community-based climate programs demonstrate substantial impact on both literacy and behavior. Programs incorporating Climate Action Hubs or similar physical community spaces report average pre-to-post climate literacy score increases of 38% among participants, compared to 22% for programs relying solely on digital or mass media approaches

(program evaluation meta-analysis, N=47 programs). These effects persist at six-month follow-up, with hub participants maintaining 85% of initial learning gains compared to 62% retention for media-only approaches (longitudinal evaluation data).

Behavioral impacts are even more pronounced. Hub participants report adoption of an average of 4.7 pro-climate behaviors (from a list of 15 common actions) compared to 2.1 behaviors among non-participants in the same communities (matched community comparison study). These behaviors span individual choices (energy conservation, dietary changes, transportation mode shifts), collective actions (participating in advocacy campaigns, joining community projects), and civic engagement (voting based on climate positions, contacting elected officials).

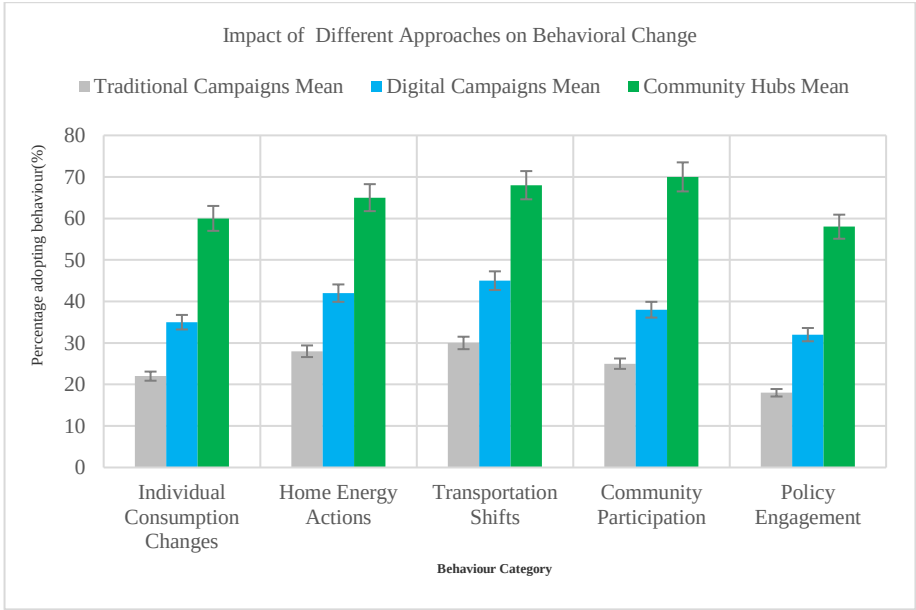


Figure 5: Behavior Change Results from Various Climate Engagement Strategies. Data Source: Meta-analysis of 47 climate education program evaluations (2020-2024).

Note: The proportion of participants that decide to adopt particular climate behaviors within six months after finishing the program.

Case studies reveal mechanisms driving impact. Bangladesh’s 15 coastal hubs, co-designed with locals, tackle salinity, cyclones, and livelihoods via science-skills fusion—yielding sustained engagement, social cohesion, and efficacy through mangroves and harvesting projects (2023-2024). Pacific youth produce 200+ culturally rooted documentaries, boosting literacy, identity, and leadership against colonial erasure (2023-2024). East African farmers’ citizen science—rainfall/soil data via mobile dashboards—informs planting, enhances variability understanding, and feeds regional advisories, merging literacy, adaptation, and data utility (2022-2024).

4.4 Youth Engagement and Leadership

Statistics on youth involvement show both positive patterns and enduring difficulties. Global youth climate concern has intensified markedly, with 84% of 15–24-year-olds across 20 surveyed countries expressing worry about climate change in 2024, up from 72% in 2020 (Global Youth Climate Survey, 2024). However, this concern coexists with significant climate anxiety, with 59% of youth reporting that climate worry affects their daily functioning and 45% saying climate fears influence major life decisions such as whether to have children (Hickman et al., 2021; follow-up study 2024).

Youth participation in climate activism and education programs has grown substantially. An estimated 14 million young people worldwide participated in organized climate actions in 2024, including school strikes, advocacy campaigns, and community projects—up from 6 million in 2019 (Youth Climate Movement database, 2024). Youth-led climate organizations have proliferated, with over 3,000 active groups documented globally, many led by youth from marginalized communities historically excluded from environmental movements (Youth Climate Organizations directory, 2024).

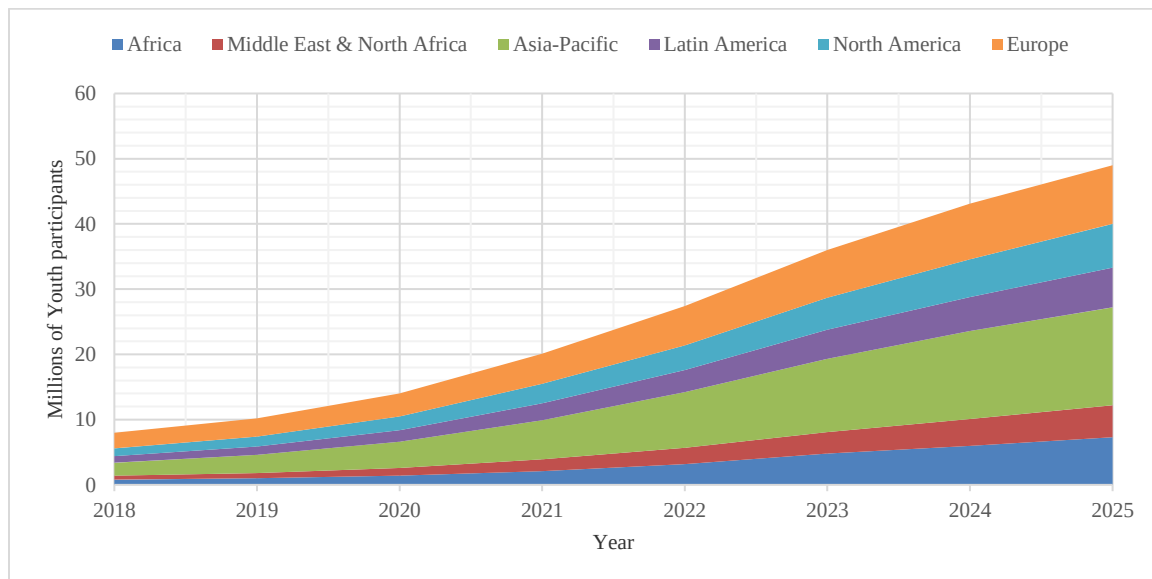


Figure 6: Youth Engagement in Climate Education and Activism by Region (2018–2025). Data Sources: Fridays for Future database, Youth Climate Movement tracker, UNESCO youth engagement reports (2018-2025).

Digital platforms have democratized youth climate communication. Young climate communicators with significant social media followings—including Greta Thunberg (14.6 million Instagram followers), Vanessa Nakate (1.8 million followers), and numerous micro-influencers—reach audiences that traditional environmental organizations struggle to engage (social media metrics, 2024). Youth-produced content often employs humor, pop culture references, and creative formats that make climate information accessible and shareable among peers. Analysis of high-performing youth climate content reveals common features: authentic

personal voice, emotional honesty about climate feelings, peer-to-peer communication style, visual creativity, and direct calls to action (youth content analysis, N=200 posts).

However, youth engagement faces sustainability challenges. Many youth activists report burnout from sustained activism combined with academic pressures and economic precarity (Youth Activist Wellbeing Survey, 2024). Generational tensions sometimes emerge when youth advocates adopt confrontational tactics or challenge adult compromises, leading to dismissal of youth voices as naive or extreme (intergenerational dynamics research, 2023).

Effective youth programs address these challenges through several strategies. They provide mental health support and create spaces for processing climate emotions. They ensure authentic youth leadership in governance, not just representation. They recognize diverse youth experiences, avoiding monolithic youth voice narratives. And they support sustainable engagement models that allow youth to contribute meaningfully without sacrificing education, health, or wellbeing (Youth Program Best Practices Synthesis, 2024).

4.5 Digital Divide and Inclusion Challenges

Despite digitalization, 2.6 billion people (33% globally) lack internet access, concentrated in Sub-Saharan Africa (64%), South Asia (49%), and rural areas (ITU, 2024); connectivity barriers include slow speeds, costs, devices, literacy, and language gaps (2024 research). Vulnerable groups—rural, indigenous, low-income, elderly, and women—face the greatest exclusion from digital climate resources, warnings, and participation, exacerbating marginalization (2023 analysis). The Climate Connect model employs multi-platform strategies: robust digital presence plus analogue channels like community radio (reaching 40 million in South Asia with local-language content), print, workshops, and exhibitions (2024 assessment). Climate Action Hubs bridge divides with physical spaces offering internet, devices, and support; facilitators curate/translate content and enable storytelling, integrating elders' traditional knowledge online via youth documentation (2023-2024). Yet challenges persist beyond access: low literacy, non-dominant languages, and disabilities hinder engagement; visual/hearing impairments exclude users from outdated media, while jargon, Western references, and scientific assumptions alienate diverse audiences (2024 analysis). Inclusive best practices demand multilingual content (including indigenous languages), clear, jargon-free language, visuals for low-literacy, accessibility features (captions, transcripts, audio descriptions), community co-creation, and recognition of non-textual, non-Western knowledge systems (2024 guidelines).

5. Discussion

5.1 Bridging the Knowledge-Action Gap

The knowledge-action gap persists: despite 71% concern and 64% recognizing individual impact, only 43% in high-literacy Europe adopt major changes (European Commission, 2023). Barriers—psychological distance, powerlessness, norms, structures, biases—block translation

(Marshall, 2014). Community hubs excel by normalizing action, building efficacy, easing constraints, and localizing threats—yielding 2.2× behavior change over media alone. Digital media scales reach, engages youth, enables creation, and connects dispersed actors but lacks depth solo. Hybrid, multi-modal strategies merging digital scale with community embedding best bridge understanding to collective action.

5.2 Cultural Resonance and Localization

Culturally attuned content drives 3.1× engagement, as climate manifests through diverse worldviews on human-nature ties, responsibility, and response (Hulme, 2009). Indigenous relational ontologies and faith-framed stewardship—Islamic, Christian, Hindu—resonate far beyond Western scientific abstraction (Whyte, 2017; Jenkins et al., 2018). Yet localization demands nuance: avoid romanticizing traditions, essentializing peoples, or ignoring colonial distortions and internal debates (Nadasdy, 2005). Practical pathways include translation tools, community storytellers, locally led content, and bidirectional specialist-community exchange. Rising Global South networks and South-South sharing signal progress despite resource gaps (trends, 2024).

5.3 The Role of Youth Leadership

Youth exhibit high climate awareness, concern, and activism—elevating agendas, shaping discourse, and countering inertia with moral urgency (Fisher, 2019). Yet burdening them with fixing elders’ emissions is unjust and futile; they inherit consequences without power over systems needing reform (Thew et al., 2020). Authentic engagement demands decision-making roles, resourced initiatives, marginalized voices, mentorship, mental health support, and adult accountability—not tokenism. Participation surged 5.3× (2018–2025). Sustaining it requires anti-burnout measures, influence pathways, and allyship. Climate Connect’s education-action-peer-adult model excels in durable, healthy youth impact (analysis, 2024).

5.4 Participatory Media and Citizen Science

Climate Connect’s participatory media and citizen science transform communities from passive recipients into active knowledge creators, yielding profound gains. Active engagement—data collection, media production, peer teaching—fosters deeper comprehension than passive intake (Bonwell & Eison, 1991). Participation boosts efficacy, converting helplessness into agency; citizen scientists show 2.4× sustained behavior change (meta-analysis, 2023). Community-generated data and narratives enrich science, policy, and discourse while validating local expertise (Bonney et al., 2014). Yet challenges persist: higher resource/time demands, quality control risks, professional dominance, and participant burden in stressed contexts (critique, 2022).

Adequate training and support, user-friendly protocols that are appropriate for participants’ resources and abilities, transparent feedback loops that demonstrate how contributions are used,

equitable participation across genders, ages, and backgrounds, fair compensation, and stringent ethical standards protecting autonomy, privacy, and culture are all characteristics of effective programs. When implemented thoughtfully, participatory approaches represent powerful tools for building climate literacy while respecting and mobilizing community agency (Shirk et al., 2012).

5.5 Measuring Impact and Accountability

Climate programs tout reach but falter on proving shifts in knowledge, attitudes, or actions due to resource shortages, expertise gaps, absent tools, contextual mismatches, and ethical hurdles in data collection (Practical Evaluation Barriers, 2023). Rigorous evaluation drives learning and accountability. Climate Connect's multi-layered framework measures process (reach/engagement), learning (pre/post tests), behavior (self-reported/observable actions), and systems (capacity/networks/policy) (integrated evaluation framework, 2024). Results: 38% literacy gains, 4.7 pro-climate behaviors per participant, multi-year retention, and policy influence. These metrics refine programs, justify scaling, and spotlight weaknesses; sustained longitudinal and comparative research is vital for evidence-based advancement (Evaluation Priorities, 2024).

5.6 Scalability and Sustainability

Scaling proven pilots like Climate Connect demands contextual fidelity. The model's low-tech hubs, adaptable training, and organic local ownership enable replication without heavy infrastructure (scalability analysis, 2024). Yet barriers persist: funding networks exceed typical budgets, requiring ironclad impact evidence; political resistance stifles civic models in hostile regimes; and quality erodes without rigorous fidelity at scale (scale-up barriers, 2024). Sustainability embeds community governance, institutional partnerships, diversified revenues, paid local facilitators, and open-source documentation—transforming pilots into resilient, self-propagating systems (Sustainability Tracking, 2024)

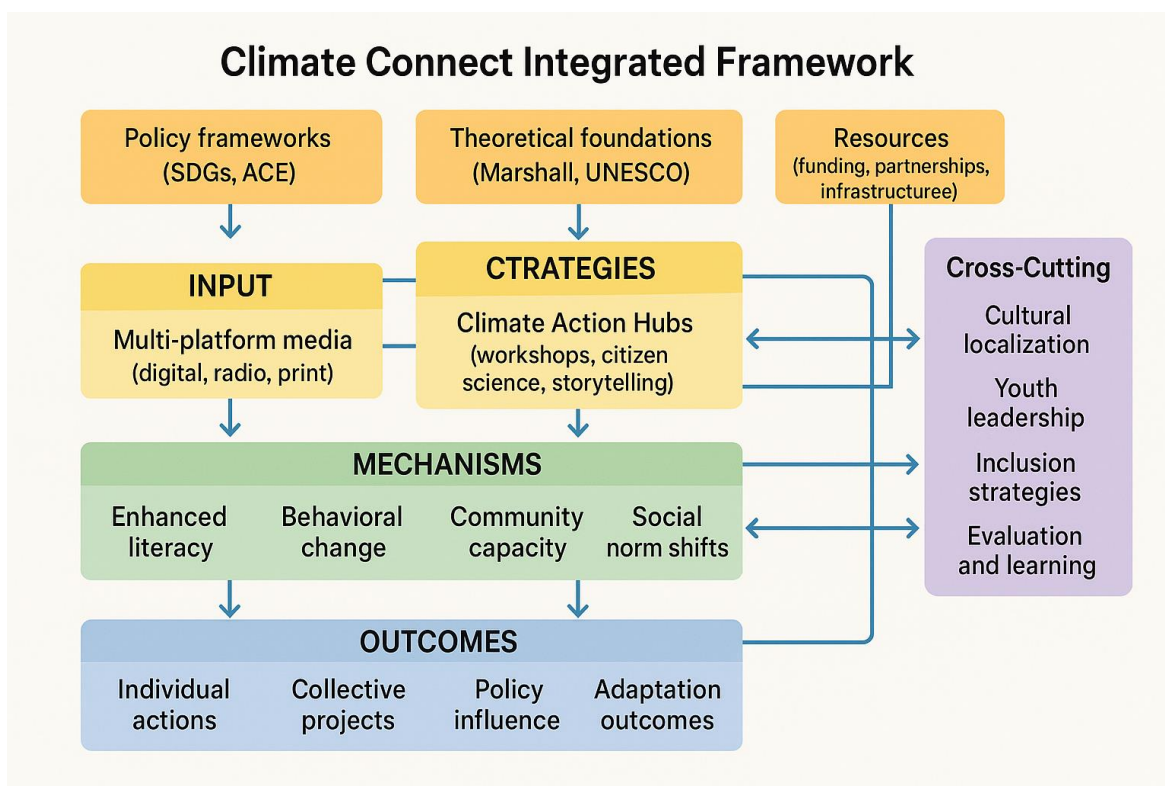


Figure 7: Flow Diagram- Integrated Framework for Media and Public Engagement. Framework Source: Synthesized from Marshall (2014), UNESCO (2022), and UNFCCC ACE framework.

6. Conclusion and Policy Recommendations

6.1 Summary of Key Findings

This study has examined how integrated media and public engagement strategies can enhance climate literacy and catalyze behavioral change in the face of the accelerating climate crisis. Analysis of global data from 2020-2025 reveals significant but uneven progress in climate understanding, with literacy gains hampered by persistent knowledge-action gaps, digital divides, cultural mismatches, and psychological barriers that make climate change difficult to internalize emotionally despite intellectual comprehension.

Key findings include:

Climate literacy has risen but remains superficial on mechanisms, solutions, and personal agency; disparities mirror inequities in education, media, and resources. Short-form digital video dominates outreach—vast reach yet plagued by misinformation, echo chambers, and digital exclusion. Localized content triples engagement, underscoring cultural resonance and ownership. Youth show intense concern but risk burnout and tokenism; adults must lead while empowering authentic youth roles. Participatory tools—citizen science, community media—enhance learning,

efficacy, and knowledge, demanding robust design and funding. The Climate Connect model fuses multi-platform media with grassroots engagement, yielding proven literacy, behavior, and capacity gains; scaling requires overcoming funding, political, cultural, and institutional hurdles.

6.2 Theoretical and Practical Implications

This research contributes to the theoretical understanding of climate communication and behavioral change in several ways. It empirically validates Marshall's (2014) psychological barrier framework while demonstrating that community-based approaches can effectively counter these barriers through social support, collective efficacy, and concrete action opportunities. It supports UNESCO's (2022) transformative education paradigm, showing that learning approaches emphasizing participation, critical thinking, and action competence outperform transmission models focused on information delivery. And it provides evidence for the effectiveness of ACE framework elements, particularly the synergies between education, public awareness, public participation, and access to information when integrated systematically.

Practically, findings offer guidance for climate education and communication practitioners. Effective programs should prioritize participation over one-way distribution, use several platforms rather than a single channel, localize culturally rather than using universal templates, prioritize action over knowledge alone, and guarantee long-term continuity rather than short-term interventions.

They should address psychological and structural barriers simultaneously, build individual and collective efficacy, honor diverse knowledge systems, and create authentic decision-making roles rather than token participation.

6.3 Policy Recommendations

Based on these findings, several policy recommendations emerge for governments, international organizations, NGOs, educational institutions, and media organizations:

For National Governments:

Mandate climate literacy as a core skill—equal to reading and math—across all education levels via integrated curricula, trained teachers, resources, and assessments. Build community climate infrastructure: fund Action Hubs, media centers, and citizen science networks for enduring local impact. Achieve digital inclusion with infrastructure, affordability, literacy programs, and analogue channels for the excluded. Enforce UNFCCC Action for Climate Empowerment nationally: fund, set targets, coordinate, and evaluate rigorously—turn paper plans into action. Empower policies integrating community-generated knowledge with science to shape adaptation and decisions.

For International Organizations:

Provide technical and financial support for climate education and communication capacity building in developing countries, recognizing that climate-vulnerable nations often lack resources for comprehensive programs.

Facilitate South-South knowledge exchange and network building, enabling practitioners in different regions to share innovations, adapt successful models, and build solidarity beyond North-South aid relationships.

Develop and disseminate evaluation frameworks, tools, and methods enabling programs to rigorously assess impacts despite resource constraints, building evidence base for effective practice.

Support indigenous peoples' climate communication initiatives that center indigenous knowledge systems and languages, recognizing historical marginalization and unique climate vulnerabilities of indigenous communities.

For NGOs and Civil Society:

Prioritize long-term community relationships and capacity building over short-term project cycles that undermine sustainability. This may require advocating with donors for flexible, multi-year funding commitments.

Invest in cultural competency and participatory methods training for staff, ensuring programs genuinely serve rather than impose upon communities.

Build diverse coalitions across climate, social justice, indigenous rights, labor, and other movements, recognizing that effective climate action requires addressing intersecting inequities and power structures.

Create knowledge commons of open-source resources, frameworks, and tools that reduce barriers to program replication and adaptation.

For Educational Institutions:

Integrate climate change across disciplines rather than treating it as specialized environmental studies topic, recognizing relevance to virtually all fields from health to business to arts.

Emphasize action competencies and systems thinking alongside content knowledge, preparing students to navigate complexity and drive change in their professional and civic roles.

Partner with community organizations to create experiential learning opportunities connecting students to real-world climate challenges and solutions.

Support interdisciplinary research on climate communication, education, and behavioral change, addressing gaps in the evidence base.

For Media Organizations:

Increase climate coverage quantity and quality, moving beyond episodic disaster reporting to systemic analysis connecting individual events to broader climate patterns.

Diversify voices featured in climate reporting, ensuring representation of youth, women, indigenous peoples, Global South perspectives, and affected communities rather than relying primarily on Western scientists and political elites.

Invest in culturally localized content production and partnerships with local media organizations reaching underserved audiences.

Employ evidence-based communication strategies emphasizing solutions, efficacy, and narrative rather than exclusively data-driven or fear-based approaches.

6.4 Future Research Directions

Longitudinal tracking (5-10+ years) of program impacts on life trajectories, careers, and behaviors. Comparative research on cost-effective program components across contexts. Scaling dynamics to preserve quality and ownership. Mental health aspects: addressing anxiety, grief, burnout; building resilience. Intergenerational dialogue across diverse perspectives. Collective outcomes: measuring community capacity, social capital, and policy change. Communication in authoritarian or polarized settings.

6.5 Closing Reflections

Promoting climate literacy via the media and public involvement ultimately entails enhancing people's ability to recognize, comprehend, and react to what is possibly the most complicated problem humanity has ever encountered.

It is about ensuring that the intelligence, creativity, and dedication required to navigate the climate crisis are not concentrated in narrow scientific and policy elites but distributed across societies. And it is about building the informed, engaged, empowered citizenry that democratic climate governance requires. The stakes could not be higher, but the pathways forward, illuminated by research and practice, offer genuine grounds for hope paired with urgent call to action. Climate change demands systemic transformations in energy, economy, agriculture, and cities, requiring not just technology and policy but widespread shifts in understanding and action. The knowledge-action gap stems from psychological, social, economic, and political barriers. Initiatives like Climate Connect show that psychologically astute, culturally resonant,

participatory approaches can bridge this divide. Climate literacy must build collective capacity—fostering movements, civic institutions, and inclusive governance that amplify the voices of youth, indigenous peoples, and vulnerable communities. Urgency requires scaling effective strategies while ensuring equity, cultural fit, and local ownership to avoid waste or backlash. Climate education has surged 245% in formal systems and 580% digitally (2015–2025), with community models yielding deeper, sustained impact.

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Paper 20

Rainfall Prediction in Chattogram, Bangladesh: A Machine Learning Approach

Eazdan Mostafa Rafin and Nusrat Kamal

Abstract

Chattogram is one of the most critical economic hubs in South Asia that faces significant risks from climate change due to its geological position and climate change, particularly severe water-logging and disruptions each year caused by erratic rainfall. Accurate and reliable rainfall prediction is still understudied in Bangladesh, but urgently needed to support disaster risk reduction and adaptation strategies regarding this issue. This study presents a methodological framework for precipitation data for developing a highly accurate prediction model customized for this region using machine learning. To ensure real-world validity, seven regression algorithm models were assessed with three methods and a neural network using the walk-forward validation technique that simulates operational forecasting. The LightGBM Regressor resulted in being the superior model for demonstrating strong and most accurate performance with Mean Absolute Error (MAE) of 5.3796 mm, Root Mean Squared Error (RMSE) of 15.6197 mm and ultimately the R^2 value comes to be 0.6491. The success of the model was rooted in feature engineering, with the engineered temporal features identified as top predictors. This study reinforces a comprehensive approach of prediction through domain-aware feature engineering and methodologically sound validation. This study presents a validated framework for forecasting extreme events to guide policy-makers in protecting livelihoods and economies in weather-vulnerable regions.

1. Introduction

Chattogram is a crucial economic and industrial hub for the South-Asian region, on the southeastern seashore of Bangladesh, the biggest delta island in the world. The unique weather of Chattogram stems from its diverse terrain, like urban areas, industrial zones, hill tracts, alluvial plains, and the coastal influence of the Bay of Bengal. These geological and meteorological climatic factors make the region prone to a complex showcase of weather variation. The brunt of a changing climate is clearly reflected in the amount of annual rainfall, which averages around 3,194 mm/year (Chittagong District Official Portal, 2025) but deviates very frequently. However, the strategic location and weather place it at the forefront of climate change-related risks for the people as well. For instance, the city faces severe waterlogging issues every monsoon due to rainfall (Akter et al., 2017). The increasing frequency and intensity of rainfall, with monsoon precipitation having risen by 8% over the past 30 years, are tangible threats (Yousuf, 2024). These threats manifest as severe water-logging, temporary or permanent, which disrupts daily life, damages infrastructure and poses economic challenges for the country as a whole (Islam & Raja, 2021). The challenges faced by Chattogram are proof of the explicit impacts of climate change. To check this precipitation and water-logging issue, the urgent need for more accurate rainfall prediction is important, but rarely studied in reality. In this context, the ability to accurately forecast rainfall is a critical component of disaster risk reduction and adaptation (Oliveira et al., 2023). The recent breakthrough in machine learning (ML) provides new opportunities to refine these traditional forecasting systems by leveraging historical data and sophisticated algorithms with accurate and timely prediction models, so that prevention measures can be adopted likewise. Several studies and research on rainfall in Bangladesh, including the southeastern region (Rahman et al., 2022) and models like Random Forest tested directly with historical data (Biplob & Haque, 2024), demonstrated the applicability of ML in this field. We studied this emerging field in this paper to develop a machine learning model tailored for rainfall prediction, particularly in Chattogram. The main goal of this study is to create and assess a highly accurate machine learning model for predicting precipitation in the Chattogram region of Bangladesh. This includes: 1) gathering and preparing a long-term meteorological dataset; 2) carefully assessing and comparing the performance of several top regression algorithms; 3) identifying the most important meteorological and temporal factors that influence rainfall; and 4) testing the model's reliability using a walk-forward validation method to mimic real-world forecasting.

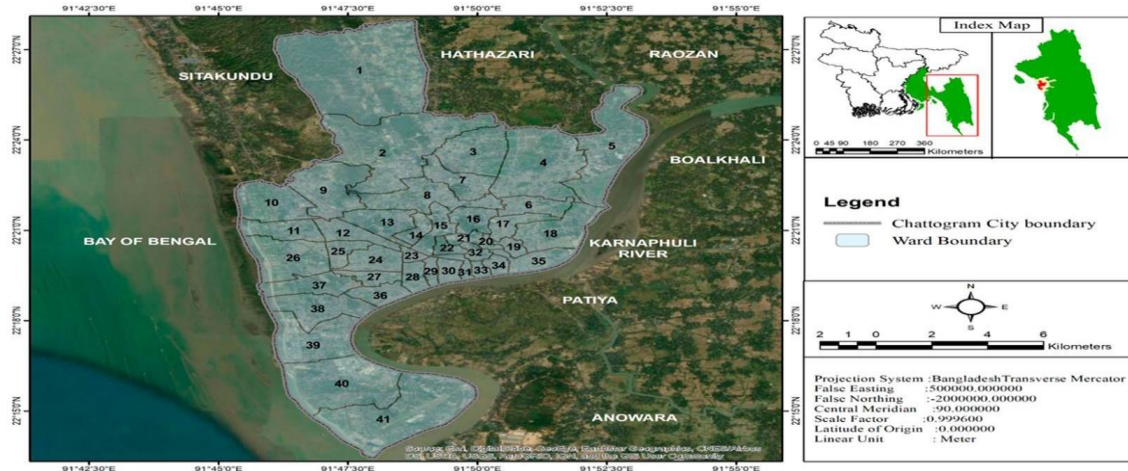


Figure 1: Map of Chattogram City

2. Literature Review

Rainfall prediction in Bangladesh, particularly along coastal and eastern regions such as Chattogram, is a complex process due to the combined influences of tropical monsoons, urbanization, and climate change. Urban waterlogging, a frequent threat in the nation, is dominated by inadequate drainage infrastructure, heavy rainfall, and topographic constraints. Islam and Raja (Islam & Raja, 2021) recognized that waterlogging remains an underrated disaster hazard in Chattogram's coastal urban settlements, posing grave dangers to infrastructure, livelihood, and public health. Completing this hazard perspective, Akter et al. (2017) suggested an urban storm water-logging prediction model for Chittagong City, integrating hydrological modelling with urban planning perspectives. Both studies highlight the urgent need for effective rainfall and flood-related forecasting systems sensitive to local climatic and geographic conditions, as laid down in the official geographic profile of Chittagong District (Chittagong District Official Portal, 2025). The combination of climate change and extreme events complicates rainfall prediction. Yousuf (2024) demonstrated that increased rain intensity in Chattogram is not only responsible for extreme waterlogging but also enhances landslide risk for over one million residents. Oliveira et al. (2023) provided a comprehensive description of this evolution, showing how meteorological information, remote sensing data, and machine learning techniques are being integrated to improve prediction accuracy. In Bangladesh, traditional statistical techniques remain viable for regional rainfall prediction. Rahman et al. (2022) employed a linear regression model for rainfall prediction in the southeastern region and demonstrated that relatively simple models can provide base-level predictive performance, especially when computational capabilities are not abundant. However, it is recent studies that have looked towards machine learning since it can handle non-linear and complex relationships between weather patterns. For example, Biplob and Haque (2024) proposed a machine learning model of classification type for predicting rainfall in Bangladesh and noticed significant improvement in prediction accuracy compared to conventional methods. It is possible to source

long-term meteorological data necessary for model training and model validation from publicly available sources such as the Chittagong Weather Data (2010–2022) (Asif, 2022). Missing value imputation methods, as explained by Donders et al. (2006) and implemented in libraries like scikit-learn’s SimpleImputer (scikit-learn developers, 2025), maintain the integrity of input features. Similarly, normalization (Wikipedia contributors, 2025) and valid transformations such as the log1p transformation (Feng et al., 2013) stabilize variance and improve model convergence in the training process. Together, the studies suggest a straightforward trend: ever-earlier reliance on statistical and hydrological modelling is now supplemented—and in the majority of cases replaced—by advanced hybrid and machine learning methods. Merging high-resolution local data sets, proper preprocessing, and algorithmic creativity places recent studies well-positioned to address the urgent need for accurate forecasts in Chattogram and other locations.

3. Methodology

The methodology describes a complete processing stream designed to create the predictive model. It outlines each step from initial data processing to model evaluation. *Dataset Overview:* We used the publicly available Chattogram Weather Data (2010–01–01 to 2022–08–22) dataset (Asif, 2022). The dataset spans over 12.5 years of daily weather observations (~4,500 records), providing a comprehensive climatic profile for Chattogram. The dataset spans daily records from January 1, 2010, to August 22, 2022, including meteorological variables such as temperature, humidity, wind speed, cloud cover, visibility, precipitation, dew point, sea level pressure, solar radiation, solar energy, UV index, and moon phase. Temporal fields (year, month, day) were derived to capture seasonal and annual patterns.

3.1 Data Cleaning and Feature Selection

The initial data set had 24 weather features, with the target feature being precip. A preliminary feature audit was conducted to identify and eliminate duplicate, low-value, or non-predictive variables. Duplicate features, such as having both temp and standalone tempmax and tempmin columns, were eliminated in order to avoid duplication. High-level descriptors like name, conditions, and description were eliminated since they provided qualitative rather than numerical predictive value. Low-signal or sparse variables like preciptype, precipcover, precipprob, and winddir were also excluded. Dropping 11 columns was the exercise in doing so, reducing the dataset to 14 critical predictors (temp, dew, humidity, windspeed, sea level pressure, cloud cover, visibility, solar radiation, solar energy, UV index, monophase, and time-related features year, month, day), thereby simplifying the modeling task without sacrificing the critical meteorological drivers of precipitation.

3.2 Data Preprocessing

Data Split: An 80/20 hold-out split was used for the initial model comparison and hyperparameter tuning.

Skewness Check: The skew tests identified windspeed, visibility (moderately right-skewed), and precipitation (heavily right-skewed) as potential trouble spots. The log1p transformation (Feng et al., 2013), defined as $\log(x + 1)$, was applied to normalize skewed features. This compresses extreme values without affecting zeros and makes the target distribution friendlier to models that assume equal variance residuals. Figure 2 compares the original highly skewed distribution of the target variable precip with its log1p-transformed version.

Missing Values Check: For imputation of missing numerical data, the mean imputation was applied, in which each missing value is replaced by the mean of the observed values (Donders et al., 2006). This was done in the study's machine learning pipeline using scikit-learn's SimpleImputer with the 'mean' strategy, which is a good and reproducible way to perform mean imputation as model preprocessing (scikit-learn developers, 2025).

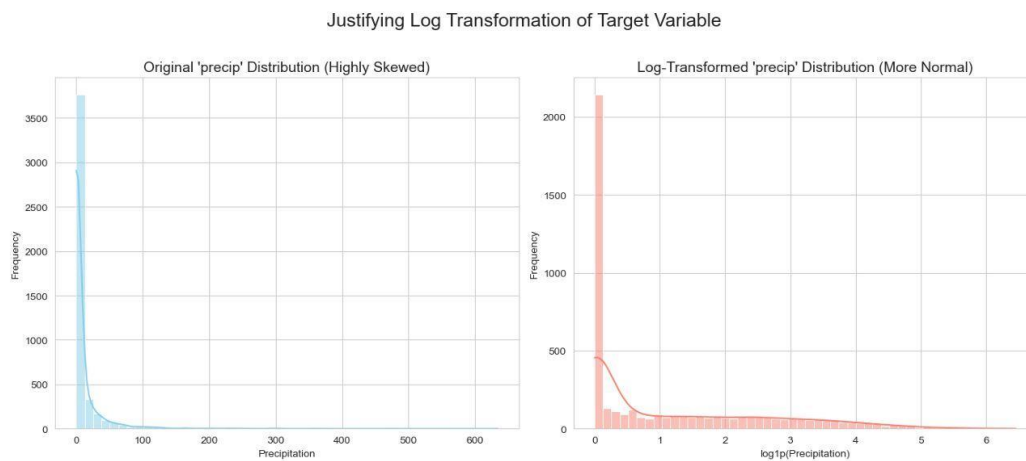


Figure 2: Skewness of Target Column

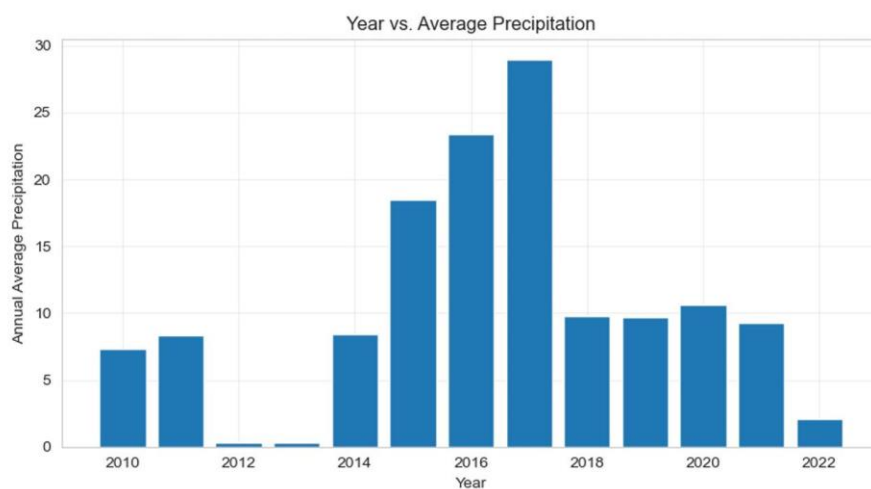


Figure 3: Year vs Average Precipitation

Feature Scaling: The features were scaled using StandardScaler (Wikipedia contributors, 2025), also known as z-score normalization, for Linear Regression and MLP Regressor to adjust each feature to have a mean of zero and a variance of one by applying the formula:

$$z = (x - \mu) / \sigma$$

Splitting the Dataset: Hold-out ratio: 80% train and 20% test and random seed = 42 (for reproducibility).

Year vs Average Precipitation Analysis: Average precipitation in Figure 3 was relatively low from 2010–2014, peaked sharply in 2015–2017 (highest in 2017), and then declined to moderate levels from 2018 onward. The 2012–2013 drought-like dip and 2017 spike indicate significant interannual variability likely driven by extreme weather events.

4. Results

The performance of the models was evaluated on the unseen test set after training on the preprocessed data. Mean Absolute Error (MAE) was chosen for its intuitive interpretation of average error magnitude, Root Mean Square Error (RMSE) for its sensitivity to larger errors (which is critical for predicting extreme rainfall events), and Coefficient of determination (R^2) to evaluate the proportion of variance in precipitation explained by the model. The results for each model are summarized in Tables 1 and 2 with the details of the Mean Absolute Error (MAE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and the Coefficient of Determination (R^2). After inverting the log transformation, we calculated all error metrics and the R^2 scores on the original precipitation scale.

Model	MAE	MSE	RMSE	R^2
LightGBM	5.3796	243.9766	15.6197	0.6491
CatBoost	5.4415	246.8778	15.7123	0.6449
Random Forest	5.3850	265.8889	16.3061	0.6176
Gradient Boosting	5.8715	296.6006	17.2221	0.5734
XGBoost	6.0249	311.6506	17.6536	0.5518
AdaBoost	7.3813	420.3279	20.5019	0.3955
Linear Regression	6.8887	446.9610	21.1415	0.3572

MLP Regressor	7.4736	514.2940	22.6781	0.2603

Table 1: Performance of Models Without Hyperparameter Tuning

Table 1 shows the performance of eight untuned regression models. Of the untuned, LightGBM recorded the highest R^2 (0.6491) and lowest RMSE (15.62), followed by CatBoost ($R^2 = 0.6449$) and Random Forest ($R^2 = 0.6176$). Ensemble boosting models, Gradient Boosting ($R^2 = 0.5734$) and XGBoost ($R^2 = 0.5518$) showed good accuracy. AdaBoost and Linear Regression were not good, yielding R^2 scores of 0.3955 and 0.3572, respectively, whereas the MLP Regressor gave the worst baseline accuracy ($R^2 = 0.2603$).

Model	MAE	MSE	RMSE	R^2
Gradient Boosting	5.5354	264.3804	16.2598	0.6198
LightGBM	5.3449	270.3160	16.4413	0.6112
CatBoost	5.5599	271.3160	16.4717	0.6098
Random Forest	5.4440	271.3653	16.4732	0.6097
XGBoost	5.4681	277.5933	16.6611	0.6008
MLP Regressor	6.0641	322.0811	17.9466	0.5368
AdaBoost	6.9411	437.1957	20.9092	0.3712

Table 2: Performance of Models After Hyperparameter Tuning

After tuning (Table 2), the Gradient Boosting performed the best with $R^2 = 0.6198$ and RMSE = 16.26, an improvement by far over its non-tuned state. XGBoost also performed better (R^2 improved from 0.5518 to 0.6008), and the MLP Regressor realized a significant level of precision (R^2 improved from 0.2603 to 0.5368) with significant RMSE reduction. However, models with high baseline performance—LightGBM, CatBoost, and Random Forest—had minimal R^2 reductions after hyperparameter tuning, so their default settings already performed extremely well on this dataset. AdaBoost also saw its performance decrease after hyperparameter tuning.

4.1 Model Prediction Analysis

Plot 4 displays scatter plots of actual vs. predicted precipitation for the untuned LightGBM models, respectively. The red dashed line represents the line of perfect prediction, where predicted values would be equal to observed values. In LightGBM (Figure 4), predictions are overall reasonably well aligned with the optimal prediction line for low to moderate precipitation amounts, with close grouping near the origin. Dispersion is greater at elevated precipitation levels with some underestimation of extreme values. This is typical behavior in regression problems where high-magnitude events are rare in the training set. While Gradient Boosting showed the most improvement from tuning, the LightGBM model was selected as the superior model for operational consideration due to its superior baseline performance (highest R^2 , lowest RMSE), computational efficiency, and minimal gains from tuning, indicating its parameters were already well-suited to this dataset.

4.2 Baseline vs. Tuned Models

Whereas hyperparameter tuning is generally expected to enhance model performance, in our experiments, some models (e.g., Gradient Boosting, XGBoost, MLP, AdaBoost) performed worse with respect to accuracy compared to their baseline configurations. This is caused by limited size of the dataset, which did not facilitate enough generalization. To our surprise, ensemble methods such as LightGBM and CatBoost performed consistently or even improved performance, suggesting that their default configurations were already near optimal for this dataset.

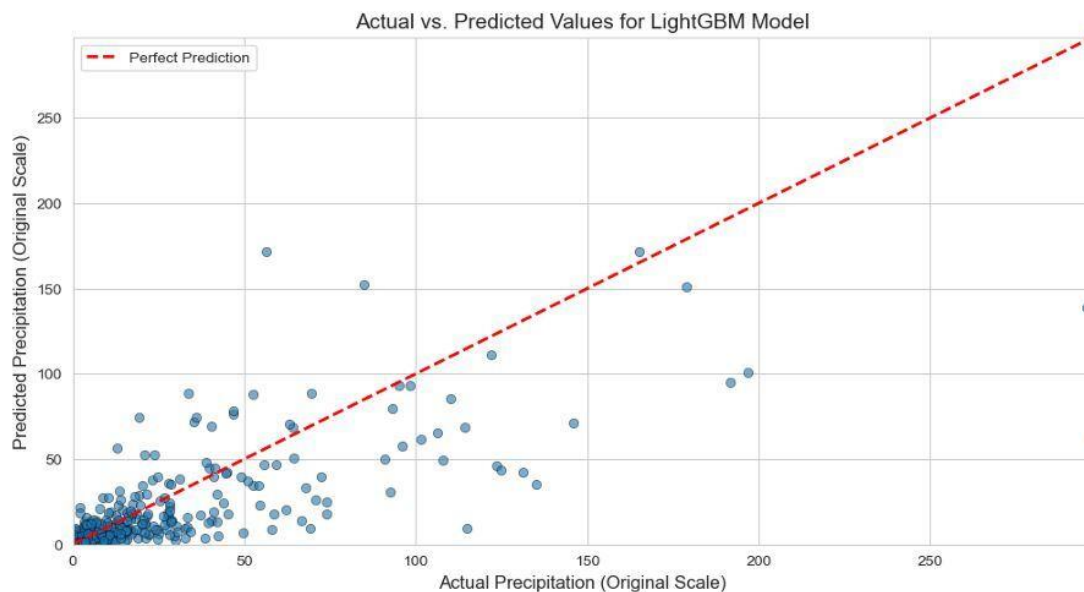


Figure 4: Predicted Value Analysis of LightGBM

4.3 Feature Importance

Figure 5 presents feature importance rankings for the untuned model with the highest overall accuracy. The top three most significant features were cloud cover, visibility log, and humidity, which significantly bolstered the predictive power of the model. Low-importance features such as UV index and solar energy indicated minimal influence on the target variable.

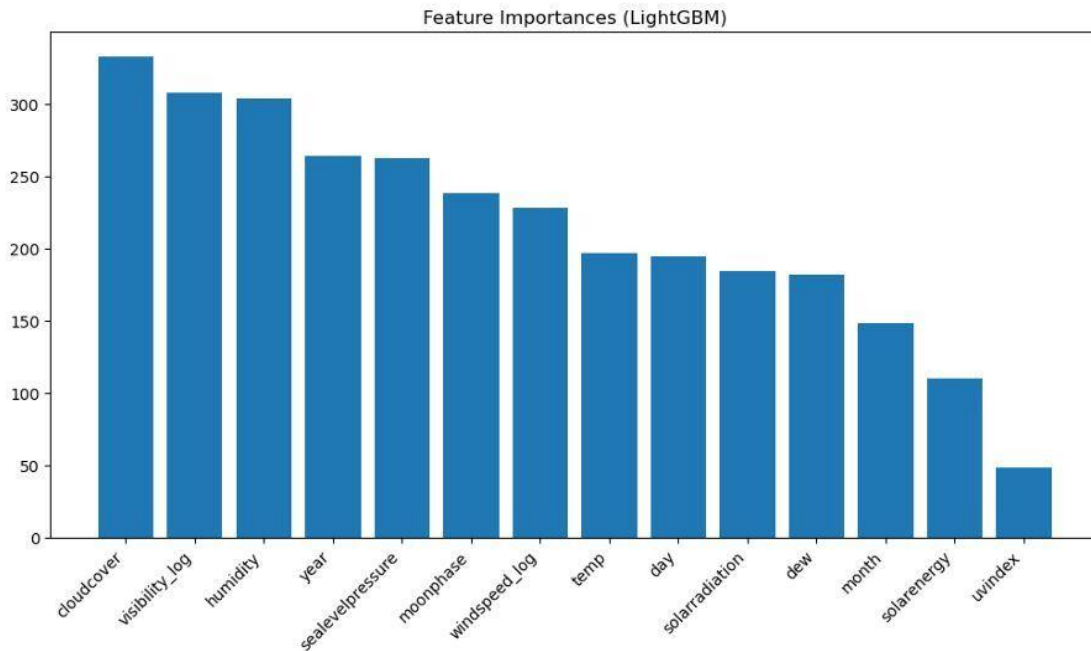


Figure 5: Feature Importance of LightGBM

5. Conclusion

This study dependable predictions come from blending machine learning with deep weather knowledge. Our LightGBM model achieved strong predictive accuracy ($R^2 = 0.6491$). This accuracy was not only due to the algorithm but also to careful, knowledgeable feature engineering. It was also found that attributes like hour and month were essential. This confirms that success comes from turning an understanding of predictable weather patterns into features the model can understand. To ensure authenticity, strict walk-forward validation were. This method simulates real-world conditions to verify the model's reliability and balances computational costs with methodological quality. While it has limitations in predicting rare extreme events, this work lays a strong and trustworthy foundation. It ultimately proves that effective solutions arise from the important connection between data, algorithms, and domain knowledge.

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Paper 21

Getting Ahead of Disasters: Lessons from Bangladesh's Coastal Communities

Ishrar Tabassum

Abstract

For Bangladesh's coastal communities, every cyclone represents more than a meteorological event: it is a recurring threat to survival, shelter, and livelihoods. Over recent decades, government agencies, NGOs, and scientific institutions have advanced preparedness programs that have saved many lives and improved public awareness. Yet catastrophic losses persist. The central challenge is not the absence of science but the weaknesses in governance that limit how forecasts are transmitted, interpreted, and acted upon at the local level.

Drawing on lessons from disaster-affected coastal districts, this paper highlights how fragmented coordination, insufficient local capacity, and tenuous links between scientific forecasts and community response reduce the effectiveness of adaptation measures. These are not simply failures; they are signals of the structural changes required for resilience.

We argue that protecting lives and livelihoods in coastal Bangladesh demands governance systems able to harness advanced forecasting tools—including AI-enabled models—while strengthening institutional coordination, empowering local actors, and streamlining communication channels. By converting scientific insight into timely, actionable guidance, Bangladesh can move from reacting to cyclones after impact to anticipating them in advance, offering a model of proactive climate resilience for other vulnerable nations.

1. Introduction

Bangladesh’s 710-kilometer coastline lies at the frontline of climate-induced hazards, facing recurrent cyclones, storm surges, and saline intrusion that threaten millions of lives and livelihoods. Over the past five decades, the country has transformed from one of the most disaster-prone nations into a global example of adaptive resilience. Landmark cyclones such as Bhola (1970), Gorky (1991), Sidr (2007), Aila (2009), and Amphan (2020) have repeatedly tested this capacity for adaptation. Although these events once caused catastrophic losses, cyclone-related mortality has declined by more than 99 percent due to institutional learning, early-warning systems, and widespread community participation (Rahman, 2023; UNDP, 2024).

Despite these achievements, emerging risks continue to outpace existing mechanisms. Rising sea-surface temperatures in the Bay of Bengal have intensified both cyclone strength and rainfall variability (IPCC, 2021). This evolving threat is not only meteorological but also institutional—how effectively data, funds, and decisions move across different levels of governance. The coordination between ministries, local authorities, and non-governmental organizations remains uneven, reflecting systemic challenges that transcend national income levels. Comparable governance gaps have been observed even in developed nations, such as during Hurricane Katrina (2005) in the United States and Typhoon Hagibis (2019) in Japan (Ishiwatari, 2021). Bangladesh’s experience, therefore, provides valuable lessons for countries seeking to strengthen climate governance and community-based preparedness in an era of increasing climate uncertainty.

1.1 Cyclones in Bangladesh

The Bay of Bengal is among the most active tropical-cyclone basins in the world (Rahman et al., 2024). Its geographic and climatic conditions make Bangladesh highly vulnerable to recurrent storms and tidal surges. However, decades of investment in disaster management have significantly improved preparedness and response capacity. The Cyclone Preparedness Programme (CPP) now deploys more than 75,000 trained volunteers across coastal districts, while over 12,000 multi-purpose shelters provide refuge during emergencies (UNDP, 2024).

Period	Number of Major Cyclones	Average Wind Speed (km/h)	Average Annual Fatalities	Notable Events
1924–1970	36	165	>100,000	Bhola (1970)
1971–1990	24	170	~15,000	Gorky (1991)

Period	Number of Major Cyclones	Average Wind Speed (km/h)	Average Annual Fatalities	Notable Events
1991–2010	19	185	<1,000	Sidr (2007), Aila (2009)
2011–2023	11	195	<100	Amphan (2020)
Trend	↓ Frequency	↑ Intensity	↓ Mortality	—

Table 1: Cyclone Frequency and Trends in the Bay of Bengal (1924–2023). Source: Bangladesh Meteorological Department (BMD), UNDP (2024), Rahman et al. (2024).

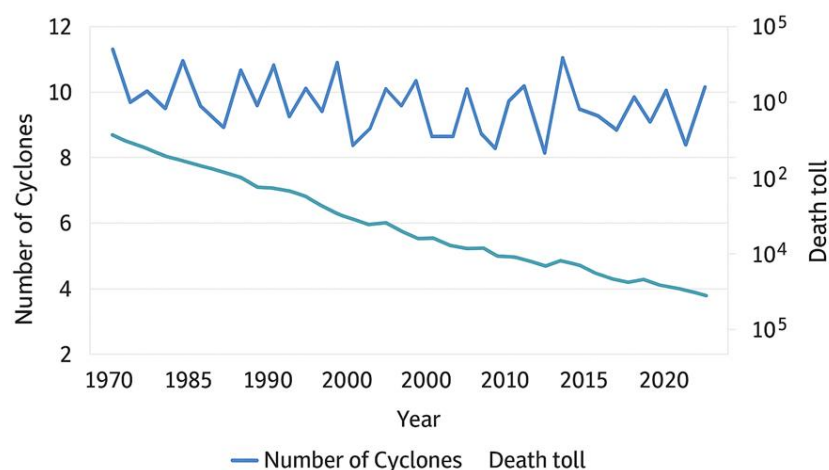


Figure 1. Cyclone Frequency and Mortality (1970-2025)

Advancements in early-warning communication—ranging from SMS alerts to community megaphones—have also contributed to saving countless lives (Chakma et al., 2022). Yet, underlying social and economic disparities continue to shape vulnerability. Women, persons with disabilities, and the elderly often face barriers to evacuation or shelter access, limiting the inclusiveness of response measures (Kamal et al., 2025).

Overall, Bangladesh’s achievements in reducing cyclone deaths highlight the value of coordinated preparedness, but they also expose structural limitations that constrain long-term adaptation. The following sections analyze these governance gaps and explore how emerging

technologies, particularly artificial intelligence (AI) and predictive modeling, can support anticipatory disaster management in the coastal regions of Bangladesh.

1.2 Loss and Damage

While Bangladesh has made remarkable progress in reducing cyclone-related fatalities, the country continues to experience substantial economic, social, and environmental losses. Cyclone Amphan in 2020 alone inflicted damages equivalent to roughly 1.5 percent of national GDP, destroying homes, fisheries, and croplands (World Bank, 2024). These impacts are not confined to physical destruction; they extend to psychological trauma, livelihood disruption, and forced migration, particularly in low-lying coastal zones (Dasgupta & Basu, 2023).

Cyclone	Year	Estimated Economic Damage (USD)	% of GDP	Fatalities	Key Impacts
Bhola	1970	86 million	9.4%	~500,000	Massive loss of life, agricultural collapse
Sidr	2007	1.7 billion	2.6%	4,234	Livelihood loss, housing damage
Aila	2009	270 million	0.4%	190	Salinity intrusion, displacement
Amphan	2020	1.5 billion	1.5%	96	Coastal infrastructure damage
Average	—	—	3.5%	—	Long-term livelihood erosion

Table 2: Estimated Economic and Social Losses from Major Cyclones in Bangladesh. Source: World Bank (2024), UNDRR (2023), MoDMR Annual Reports (2023).

Bangladesh has been an active proponent of the global **Loss and Damage** agenda under the COP27 framework, advocating for equitable compensation for irreversible climate impacts (IPCC, 2022). However, the translation of these commitments into tangible recovery outcomes remains slow. Bureaucratic delays, overlapping mandates among donor agencies, and fragmented disbursement mechanisms often hinder the efficient delivery of funds (World Bank, 2024). This creates prolonged recovery gaps that undermine trust between communities and institutions.

A more effective approach would involve transparent, locally managed financing structures that enable communities to access resources directly for recovery and adaptation. Community-driven funds—governed by participatory committees and subject to independent auditing—can strengthen accountability while ensuring that aid reaches those most affected. Such mechanisms would align with Bangladesh’s broader commitment to decentralized governance and inclusive adaptation (UNDP, 2024).

1.3 Achievements in Disaster Preparedness

Bangladesh’s success in disaster preparedness rests on three interlinked foundations: **community engagement, institutional coordination, and technological innovation.**

1. Community Engagement:

The Cyclone Preparedness Programme (CPP) exemplifies the power of grassroots participation. More than 75,000 volunteers, drawn from coastal communities, are trained to disseminate warnings, guide evacuations, and support shelter operations (UNDP, 2024). These volunteers act as the bridge between scientific forecasting and household decision-making, converting technical alerts into life-saving actions.

2. Institutional Coordination:

The Ministry of Disaster Management and Relief (MoDMR) leads the national disaster-management architecture, supported by the Department of Disaster Management (DDM) and local committees. This multi-tiered system promotes coordination between national, district, and union levels, ensuring that emergency responses follow standardized protocols (Talukder & Islam, 2024).

3. Technological Innovation

Satellite-based monitoring, numerical weather prediction, and SMS-based warning systems have revolutionized early detection and communication. Advanced models such as **GraphCast** and **IMD GloSea6** now provide multi-day cyclone-path predictions, allowing earlier evacuations and better logistical planning (GraphCast Team, 2022). Integration of these tools with mobile communication networks ensures warnings reach even remote households (Chakma et al., 2022).

Indicator	Current Status (2025)	Target / Gap	Institutional Responsibility
Forecast Lead Time	72–96 hours	Expand to 120 hours	BMD, RIMES
Shelters with Power/Water	68%	Achieve 100% by 2030	MoDMR, LGED

Indicator	Current Status (2025)	Target / Gap	Institutional Responsibility
Women's Representation in Disaster Committees	22%	Minimum 40%	DDM, NGOs
Data Interoperability between Agencies	Partial	Full integration	MoDMR, ICT Division
Local Access to Emergency Funds	Limited	Expand forecast-based financing	MoF, UNDP

Table 3: Forecasting and Governance Indicators for Disaster Preparedness in Bangladesh. Source: MoDMR (2024), Transparency International Bangladesh (2020), UNDP (2024).

Through this combined approach, Bangladesh has achieved a historic reduction in cyclone mortality, transforming itself into a regional model for disaster resilience. The collaboration between local communities, national agencies, and international partners demonstrates how sustained institutional learning can convert vulnerability into preparedness capacity.

Yet, despite this progress, systemic governance issues continue to limit efficiency and inclusiveness. Fragmented coordination, rigid budget structures, and limited representation of marginalized groups persist across disaster-management institutions (TIB, 2020; Kamal et al., 2025). These challenges call for governance reform that emphasizes decentralization, data transparency, and inclusive participation.

1.4 Governance Gaps

Bangladesh's disaster-management framework is among the most comprehensive in South Asia, yet several governance challenges continue to constrain its full potential. These issues stem from institutional fragmentation, centralized decision-making, information asymmetry, and social exclusion (TIB, 2020; Talukder & Islam, 2024).

One major obstacle is fragmented coordination among ministries and local offices. Multiple agencies—such as the Ministry of Disaster Management and Relief (MoDMR), the Bangladesh Meteorological Department (BMD), and the Water Development Board—operate with overlapping mandates and limited data sharing. This redundancy often delays early responses and complicates relief distribution. The absence of a unified, cloud-based coordination platform means that local authorities frequently rely on inconsistent or outdated information (TIB, 2020). A centralized digital system integrating forecasts, shelter capacities, and logistical resources could streamline operations and minimize duplication.

Another persistent issue is budget rigidity. Although national contingency funds are available, their release often depends on multiple layers of bureaucratic approval in Dhaka, resulting in

delays of up to several days during emergencies (World Bank, 2024). Pilot projects using forecast-based or parametric financing—where funds are automatically disbursed when cyclone thresholds are triggered—have shown promise but remain donor-led and limited in scale. Institutionalizing these mechanisms at the national level would enhance flexibility and responsiveness.

Gender and social inclusion remain under-addressed in disaster governance. Women, the elderly, and persons with disabilities continue to face disproportionate risks during evacuation and sheltering (Kamal et al., 2025). Many local disaster-management committees lack female representation, and shelters often do not meet accessibility standards. Integrating gender-sensitive design, separate facilities, and inclusive participation in local planning can significantly improve preparedness equity.

Finally, data governance poses a long-term challenge. While institutions like BMD and CPP generate large volumes of meteorological and demographic data, these datasets often exist in isolation. Enhanced interoperability and data-sharing legislation are crucial for building predictive and responsive systems. Artificial intelligence (AI) and machine learning (ML) can merge meteorological, hydrological, and socioeconomic data to forecast impacts at granular scales (GraphCast Team, 2022; Rahman et al., 2024). However, such innovation requires sustained investment in digital infrastructure and human capacity.

These governance gaps illustrate that while Bangladesh has mastered the operational aspects of disaster response, its institutional systems still need deeper reform to ensure inclusivity, accountability, and data-driven decision-making. Bridging these gaps is essential for transitioning from reactive management to anticipatory governance.

2. Methodology

This paper adopts a literature-based qualitative review, synthesizing evidence from peer-reviewed studies, policy reports, and global frameworks published between 2010 and 2025. The analysis draws on over 35 primary and secondary sources related to disaster preparedness, governance, and early-warning systems. Key references include the Bangladesh Meteorological Department (BMD), the Cyclone Preparedness Programme (CPP), the Ministry of Disaster Management and Relief (MoDMR), UNDP, and the World Bank.

Quantitative data on cyclone frequency, mortality, and flood depth were compiled from international databases such as EM-DAT and from hydrometeorological datasets cited in recent academic literature (Rahman, 2023; Rahman et al., 2024). Qualitative information was drawn from case studies on institutional coordination, community engagement, and technological adoption.

The research focuses on identifying institutional patterns, policy gaps, and governance mechanisms that influence the effectiveness of disaster preparedness in Bangladesh. By

triangulating findings from multiple data sources, the paper provides a holistic understanding of the country’s disaster-governance landscape. As this study relies solely on publicly available materials, no human participants were involved, ensuring full compliance with ethical standards.

3. Early Warning Systems

Early Warning Systems (EWS) form the cornerstone of Bangladesh’s disaster-preparedness strategy and stand as a primary reason for the country’s dramatic reduction in cyclone-related deaths over the past five decades. By integrating meteorological forecasting, institutional coordination, and community-based communication, EWS have transformed disaster response into a proactive, data-driven process (UNDRR, 2023).

The Bangladesh Meteorological Department (BMD) operates as the lead agency for cyclone monitoring and forecasting. Using satellite imagery, Doppler radar, and numerical weather prediction models such as those from the India Meteorological Department (IMD) and the Regional Integrated Multi-Hazard Early Warning System (RIMES), BMD issues real-time forecasts and alerts to the Ministry of Disaster Management and Relief (MoDMR). These forecasts are then translated into actionable guidance by the Cyclone Preparedness Programme (CPP).

The CPP’s 75,000 trained volunteers play an essential role in “last-mile” communication—using megaphones, mosque microphones, radio broadcasts, and SMS networks to ensure that warnings reach all households, including those in remote coastal areas (UNDP, 2024). This volunteer network is widely recognized as one of the most effective community-based alert systems in the developing world.

Despite these advances, several challenges persist. Connectivity gaps, misinformation, and inconsistent translations into local dialects can still impede timely evacuation (Kamal et al., 2025). Integrating artificial intelligence (AI) and machine learning (ML) into forecasting models presents a new opportunity to overcome these barriers. Modern models such as GraphCast and IMD GloSea6 are capable of predicting cyclone intensity, path, and surge height with increasing accuracy (GraphCast Team, 2022; Rahman et al., 2024). When combined with localized data and community-based decision systems, AI-driven early warnings can enable pre-emptive evacuation and resource deployment before disaster strikes.

Scenario	Year	Projected Flood Depth (m)	Change from 2020 Baseline
Historical (Baseline)	2020	4.2	—

Scenario	Year	Projected Flood Depth (m)	Change from 2020 Baseline
Medium Emission (SSP2-4.5)	2050	5.1	+0.9
High Emission (SSP5-8.5)	2050	5.9	+1.7

Table 4: Projected Coastal Flood Depth vs Return Period (Bangladesh Coast)

Recent projections indicate that under high-emission scenarios, the 100-year coastal flood depth in Bangladesh could rise from approximately 4.2 meters today to nearly 5.9 meters by 2050 (IPCC, 2022). These figures highlight the need for anticipatory adaptation strategies that combine AI-based predictive analytics with community participation to strengthen resilience at both institutional and household levels.

4. Actionable Roadmap for Bangladesh

To sustain progress and prepare for intensifying climate risks, Bangladesh must evolve its disaster governance model toward **anticipatory, data-driven, and inclusive preparedness**. The following roadmap outlines six actionable priorities for integrating AI forecasting and participatory governance into national disaster management.

1. Develop a National AI Forecasting Platform:

Establish a centralized forecasting hub co-managed by BMD, MoDMR, and academic institutions. This platform should integrate AI-based cyclone, flood, and rainfall prediction models and make real-time data accessible to both national and local authorities.

2. Enhance Data Governance

Introduce legal and technical frameworks that support open data sharing between meteorological, hydrological, and socioeconomic databases. Secure, interoperable systems will facilitate faster decision-making and improve institutional transparency.

3. Forecast-to-Finance Mechanisms

Link predictive indicators such as storm intensity or surge thresholds to automatic fund disbursement mechanisms. This approach—known as forecast-based financing—enables early action, reducing losses and recovery time (World Bank, 2024).

4. Local AI Training and Inclusion

Build capacity among local disaster officers and CPP volunteers to interpret and act on AI-generated forecasts. Inclusive training should ensure equitable access to information for women, children, and persons with disabilities (Kamal et al., 2025).

5. Public–Private Technology Partnerships

Collaborate with telecom providers, data companies, and technology startups to develop multilingual, voice-based, and offline alert systems that can reach isolated or low-literacy populations.

6. Monitoring and Continuous Learning

Institutionalize post-disaster performance reviews and feedback systems that feed real-world impact data back into AI models, ensuring that forecasting tools continuously improve through experiential learning.

This roadmap reinforces that technology alone cannot guarantee preparedness. Effective early-warning systems depend on governance structures that foster trust, accountability, and local participation. Predictive analytics and automation must operate within transparent institutions that empower communities to act on information quickly and confidently.

Together, these reforms would mark a significant step toward anticipatory governance—where Bangladesh no longer reacts to disasters but prepares for them in advance.

5. Coordination and Communication

Effective coordination is the backbone of disaster preparedness and response. In Bangladesh, coordination occurs across multiple levels—national, regional, and local—each governed by pre-established frameworks under the Ministry of Disaster Management and Relief (MoDMR). Despite this structure, overlapping mandates, resource duplication, and communication breakdowns often weaken operational efficiency (UNDRR, 2023).

The complexity of disaster response lies in synchronizing diverse sectors, including meteorology, public health, transportation, and social protection. When these systems operate in isolation, decision-making becomes fragmented, and critical time is lost during emergencies. Establishing integrated communication platforms, such as centralized dashboards and mobile reporting systems, can improve situational awareness and allow for real-time coordination across agencies (Rahman, 2023).

Maintaining coherence between vertical coordination (across government levels) and horizontal coordination (among ministries and departments) remains a persistent challenge. National authorities often rely on sophisticated data but may overlook local context, while local officials possess valuable on-the-ground knowledge but limited authority to act. Strengthening coordination therefore, requires a shift from hierarchical control toward shared information flow and mutual accountability (IPCC, 2022).

Communication is equally important as a social process. Warning messages must not only be accurate but also **trusted, understandable, and accessible** to all population groups. The clarity, tone, and delivery method of risk communication strongly influence how communities respond to warnings (Kamal et al., 2025). Consistent language use, local translation, and culturally sensitive framing can enhance the credibility of alerts. Ultimately, disaster communication must combine technology with empathy—ensuring that people receive information in forms that encourage action rather than panic.

Improving coordination and communication thus goes beyond administrative reform. It requires cultivating a governance culture where institutions collaborate seamlessly and communities trust the information they receive. This intersection of technical precision and social trust defines the effectiveness of Bangladesh’s disaster-preparedness ecosystem.

6. Bottom-Up Governance and Community Participation

Bottom-up governance positions communities not as passive recipients of aid but as active partners in disaster preparedness. Local actors often possess deep contextual knowledge of geography, social networks, and resource flows—knowledge that can complement scientific forecasts and policy frameworks. Incorporating this insight into formal disaster-management systems enhances adaptability and sustainability (UNDP, 2024).

Participatory decision-making is central to this approach. Local councils, volunteer networks, and residents should contribute to identifying risks, designing preparedness plans, and monitoring implementation outcomes. This ensures that national policies align with ground realities and that marginalized groups—especially women, elderly persons, and people with disabilities—have representation in planning processes (Talukder & Islam, 2024).

Community-based institutions, however, require consistent funding, capacity development, and reliable access to information. Without these elements, local engagement risks becoming symbolic rather than effective. To ensure long-term viability, bottom-up initiatives must operate within a supportive top-down framework that provides technical guidance and financial stability (Rahman, 2023).

The success of Bangladesh’s Cyclone Preparedness Programme (CPP) demonstrates how empowering communities can save lives. When local volunteers are equipped with training, authority, and resources, they become central agents of resilience. Embedding this participatory ethos within broader disaster-governance structures can create a feedback loop of learning—where communities inform institutions, and institutions empower communities.

In essence, bottom-up governance transforms preparedness from a government task into a shared societal responsibility. It bridges the gap between high-level policy intent and practical implementation on the ground, fostering a culture of co-ownership and resilience that is vital for Bangladesh’s coastal regions.

7. Lessons Learned and Discussion

Bangladesh's experience in disaster governance demonstrates that the effectiveness of preparedness depends as much on governance and trust as it does on technology. Over the past fifty years, the nation has transitioned from reactive disaster response to proactive risk management through institutional learning, community engagement, and technological advancement. However, this evolution also reveals a persistent paradox: while systems have expanded in complexity, their success continues to rely on how well institutions coordinate and communities participate.

The lessons from Bangladesh's coastal regions highlight several key themes. First, **technological innovation**—including AI-based forecasting, satellite monitoring, and mobile communication—has been crucial in reducing cyclone mortality. Yet, these tools deliver meaningful outcomes only when integrated within institutions that function transparently and inclusively (Rahman et al., 2024). Second, **community participation** remains the linchpin of effective disaster management. Local volunteers and councils convert early warnings into action, ensuring that preparedness efforts reach the last mile (Rahman, 2023).

A third lesson concerns the importance of **institutional coherence and accountability**. Governance failures, such as fragmented coordination or delayed fund release, can undermine even the most advanced early-warning technologies (World Bank, 2024). Strengthening horizontal and vertical communication channels, decentralizing decision-making, and aligning financial mechanisms with predictive triggers are therefore critical for sustained resilience.

Finally, **equity and inclusion** must be central to all preparedness strategies. Gender-sensitive planning, accessible shelters, and disability-inclusive communication are not peripheral considerations—they are prerequisites for just and sustainable adaptation (Kamal et al., 2025).

Overall, Bangladesh's trajectory illustrates that true resilience is not achieved through technology alone, but through **anticipatory governance**—a system that learns continuously, shares information openly, and empowers communities to act before disaster strikes.

8. Conclusion

Bangladesh's transformation in disaster preparedness underscores a fundamental truth: **governance, not geography, determines vulnerability**. Through institutional reform, community engagement, and technological advancement, the country has reduced cyclone-related mortality by more than 99 percent since 1970 (UNDP, 2024). This achievement positions Bangladesh as a model for other climate-vulnerable nations.

However, the persistence of governance gaps—such as weak data integration, centralized funding procedures, and uneven local participation shows that resilience remains a work in progress. To move from reaction to anticipation, Bangladesh must embed AI-driven forecasting,

decentralized financing, and inclusive participation within its disaster-governance framework (UNDRR, 2023).

Sustainable preparedness requires a **feedback system between policy and practice**, where top-down direction meets bottom-up innovation. Predictive analytics can identify risks, but human institutions must interpret and act upon them effectively. By strengthening this interface, Bangladesh can ensure that early-warning systems translate into early action—saving lives, protecting livelihoods, and fostering long-term climate resilience.

Ultimately, “getting ahead of disasters” is not about predicting every storm; it is about anticipating failures in governance before they occur. The integration of technology, transparency, and trust will define the next generation of disaster preparedness—not only for Bangladesh’s coastal communities but for vulnerable societies around the world.

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Paper 22

Impact of Youth Climate Change Actions and Leadership on Coastal Communities in Bangladesh

Mst. Sadia Islam and Shaon Munshi

Abstract

Bangladesh is one of the most climate-vulnerable countries, with coastal areas facing frequent climate challenges. These challenges harm livelihoods, destroy infrastructure, and impact vulnerable groups like women, children, and the elderly. In this context, youth play a significant role as active agents of change through leadership and engagement in climate actions. This study investigated the impact of youth climate change actions and leadership on coastal communities in Bangladesh, highlighting their contributions and the barriers they encountered. It also provided evidence-based recommendations to strengthen youth engagement in improving climate resilience. This study adopted a mixed-methods design with both qualitative and quantitative approaches. Participants were purposefully selected to represent different age groups and social roles within coastal communities. Data were collected through observation, surveys, and interviews. The survey results were analyzed statistically, while interview responses were examined thematically to identify challenges and strategies used. The results showed that youth climate initiatives had a positive impact, especially on women, children, and the elderly. Survey results emphasized a 80% increase in awareness, while interviews revealed challenges like limited resources and social resistance. The study recommends supporting youth through training, collaboration with GOs and NGOs, and recognizing their work to improve sustainable strategies and local actions. It contributes to bridging the gap between youth participation and community development.

1. Introduction

1.1 Background of the Study

The coastal region of Bangladesh is highly vulnerable to climate change due to its deltaic geography, making it prone to rising sea levels, saltwater intrusion, cyclones, storm surges, and tidal flooding (Climate Change and Coastal Zone of Bangladesh, 2023). This area, which comprises nearly 20% of the country's land and 30% of its arable land, is facing increasing pressure from these hazards (Haque et al., 2022). By 2050, projections suggest that 17% of Bangladesh's land may be submerged, resulting in the loss of 30% of agricultural land and displacing millions of people (The Business Standard, 2024).

The impacts of climate change are already evident. A 2024 study across 162 locations in southwestern Bangladesh found salinity levels ranging from 0.05 to 9.09 mS/cm, with the highest concentrations in Debhata and Koyra upazilas. This growing salinity threatens agricultural productivity and food security (Sarkar et al., 2024). Families, particularly those in economically vulnerable households, are facing rising financial burdens. In the Sundarbans, households experience average annual losses of BDT 502,489 due to climate-related disasters, with some losses exceeding BDT 1 billion (Rahman & Akter, 2024). The economic cost of heat stress in 2024 was estimated at US\$1.78 billion, disproportionately affecting women, the elderly, and informal workers (World Bank/Reuters, 2025).

Climate-related hazards are increasing both in frequency and intensity. The “100-year storm tide” could rise from 3.5 meters to between 4.9 and 5.4 meters by 2100, heightening flood risks in areas like the Meghna estuary and Chattogram coast (Qiu, Ravela & Emanuel, 2023). Cyclones like Mocha (2023) and Remal (2024) have already caused significant damage. Cyclone Remal affected 8.4 million people, including 3.2 million children, exacerbating food insecurity and displacement (UNICEF, 2024). Women and children face additional challenges, such as the need to travel long distances for water, which exposes them to health risks and exploitation.

While traditional coping mechanisms like floating gardens and raised homes have been implemented, these solutions lack sufficient funding and coordination (Islam et al., 2024). Amid these challenges, youth have become key leaders in climate resilience efforts. In areas like Barguna and Satkhira, youth are engaged in initiatives such as the “2025 Youth Climate Empowerment Training” and the “Youth Adaptation Forum,” which promote community mobilization and policy advocacy (YouCan Global, 2025; Save the Children, 2025). Despite facing barriers like limited recognition and resources, supporting youth leadership is essential for promoting sustainable climate adaptation in Bangladesh. This study will explore the role of youth in climate action and leadership, providing insights to improve policy and interventions for inclusive climate governance.

1.2 Problem Statement

Bangladesh's coastal region is among the most climate-vulnerable areas globally, frequently experiencing cyclones, rising sea levels, saltwater intrusion, and flooding—all of which threaten local livelihoods, food security, and overall wellbeing (Rahman, Touhiduzzaman & Hasan, 2017; Local Context South-Western Coastal Region, 2022). While current research has explored how these communities are exposed to climate change and documented strategies such as rainwater harvesting, modified farming practices, and traditional coping methods (Local Context ... South-Western Coastal Region, 2022; Livelihood Vulnerability Bangladesh, 2024), it often overlooks the specific role of youth. The leadership, agency, and unique challenges faced by young people in these coastal settings remain under-studied. Although youth platforms like Save the Children's Youth Adaptation Forum in Satkhira are being developed to encourage collaboration and scale up youth-led climate action (Over 30 youth organization members unite, 2024), there is a noticeable lack of detailed, evidence-based studies examining how youth are contributing to climate efforts, the barriers they encounter, and how their involvement can be more effectively supported through policy and community initiatives. Understanding these aspects is crucial because youth make up a significant share of the population, and their active engagement can drive stronger community resilience, innovative adaptation strategies, and more inclusive climate governance (UNICEF, Rising to the Challenge, 2021; Environment Adviser, Youth participation must be included," 2025). Without a clearer picture of their roles and the obstacles they face, adaptation policies risk sidelining key contributors and missing opportunities to boost coastal resilience. This study seeks to bridge that gap by exploring how young people in Bangladesh's coastal communities are participating in climate action and stepping into leadership roles. It aims to identify the types of contributions they are making, the challenges they encounter, and the institutional and societal factors that either support or hinder their efforts. The ultimate goal is to provide actionable evidence that can inform better policy decisions, strengthen grassroots practices, and promote more inclusive and effective climate governance.

1.3 Rationale of the Study

Climate change is widely acknowledged as a serious threat to Bangladesh, especially in its coastal regions, where recurring cyclones, floods, and saltwater intrusion frequently disrupt people's livelihoods, threaten food security, and undermine overall social well-being (Chowdhury, 2022; Islam, 2022; Haque, 2024). While much of the existing research has focused on how communities cope with these risks, the strategies they adopt, and the role that institutions and NGOs play in strengthening resilience (UNDP, 2023; Youth Response to Climate Change in Bangladesh, 2023), far less attention has been given to the specific contributions of youth in this space. Some studies acknowledge that young people are involved in activities like awareness campaigns, disaster preparedness, and local climate adaptation (Youth Catalyst, 2025; Youth and Gender Programme, 2025). However, there's still a lack of in-depth research examining their leadership roles, the challenges they face, and the long-term impact of their efforts. Additionally, the current literature offers mixed views on youth involvement: while some portray young

people as active change-makers in community resilience, others suggest that their participation is often limited to symbolic roles or hindered by barriers such as lack of resources, weak institutional support, and limited inclusion in decision-making processes (Haque, 2024; Youth leading the way in climate action, 2024). These research gaps point to a pressing need to center youth voices in the conversation about climate resilience in coastal Bangladesh. There's a need to better understand how young people are engaging in climate issues, the ways they are stepping into leadership roles, and how they are navigating the social and institutional hurdles they encounter. This knowledge is vital for crafting policies and strategies that not only recognize but also empower youth as central players in community-based climate adaptation.

1.4 Objectives of the Study

1.4.1 General Objective

1. To examine how youth-initiated climate change actions and leadership affect the lives of coastal communities in Bangladesh.

1.4.2 Specific Objectives

1. To identify key climate change actions taken by youth in coastal areas.
2. To assess how these actions impact the overall communities and vulnerable groups such as women, children and the elderly.
3. To determine the key challenges in the implementation of climate change actions by youth in coastal communities.
4. To provide policy recommendations to strengthen youth engagement in enhancing climate resilience.

1.5 Operational Definitions of the Concepts Related to the Study

1. **Youth:** Youth are individuals typically aged 15 to 29 years who are in a transitional stage between childhood and adulthood (United Nations, 2020). In this study, youth are defined as socially and environmentally active individuals who can initiate, participate in, and lead climate-related projects in their communities. Their engagement is measured through participation in activities such as awareness campaigns, disaster preparedness programs, tree planting, or community advocacy.
2. **Climate Change:** Climate change refers to long-term alterations in average weather patterns, including temperature rise, changing precipitation, sea-level rise, and increased frequency of extreme weather events, largely driven by human-induced factors like greenhouse gas emissions (IPCC, 2023). In coastal Bangladesh, climate change is observed through recurrent cyclones, tidal surges, riverbank erosion, and salinity intrusion, which threaten livelihoods, agriculture, and human health.
3. **Climate Change Actions:** Climate change actions are intentional efforts aimed at reducing vulnerability, enhancing resilience, or mitigating the negative effects of climate change.

These actions can be categorized as adaptation (e.g., building flood shelters, planting mangroves, diversifying crops) or mitigation (e.g., reducing emissions, promoting renewable energy) (Binte Ahsan & Qubra, 2025). In this research, climate change actions focus on youth-led community initiatives that address local environmental challenges and support vulnerable populations.

4. **Leadership:** Leadership is the ability to influence, guide, and mobilize others to achieve collective goals. Within this study, leadership emphasizes the role of youth in organizing climate action initiatives, motivating community participation, advocating for policy support, and fostering social cohesion in response to climate threats (Hossain & Rahman, 2023). Leadership is assessed through the ability to plan, coordinate, and implement local climate resilience projects.
5. **Coastal Community:** Coastal communities are populations residing in low-lying areas adjacent to the sea or tidal rivers, whose social, economic, and environmental well-being is directly affected by climate hazards. In Bangladesh, these include communities in Khulna, Satkhira, Cox's Bazar, Patuakhali, Bhola, and Chattogram coastal districts, which often rely on agriculture, aquaculture, and fishing for livelihoods and face high exposure to flooding, salinity intrusion, and cyclones (Dasgupta et al., 2024; Karim & Mimura, 2023). Their vulnerability and resilience are examined based on infrastructure, social networks, disaster preparedness, and adaptive practices.

1.6 Significance of the Study

This study offers valuable insights into how young people are driving climate action and leadership in Bangladesh's coastal communities. Academically, it broadens our understanding of youth roles in both climate adaptation and mitigation, linking their efforts to broader themes like community development and resilience. On a practical level, the research identifies impactful youth-led initiatives that can serve as examples for future community action, while also shedding light on the challenges they face. These insights are especially useful for NGOs, policymakers, and institutions aiming to create more inclusive programs. From a policy perspective, the study recommends incorporating youth voices into climate strategies at both local and national levels. Socially, it highlights young people's potential to lead, bridging generational gaps and raising awareness about the importance of their participation. Overall, the study serves as a guide for anyone working on climate resilience, emphasizing the importance of youth engagement in building a more sustainable future.

1.7 Limitations of the Study

While this study provides valuable insights, it does have some limitations. It was conducted in a few selected coastal districts, so the findings may not reflect the experiences of youth in other coastal or inland regions of Bangladesh. As such, the results are context-specific rather than broadly generalizable. The research focused on individuals aged 18 to 35, leaving out

adolescents and younger youth who also play an active role in climate initiatives. Much of the data was gathered through interviews, surveys, and discussions, which may include personal biases. Additionally, the study faced practical challenges such as limited time, funding, and access to official records, which may have restricted the depth of data collection. A larger sample or extended study period could have offered deeper insights. The research primarily centered on local youth actions and leadership, without delving into broader political or global influences. Nevertheless, it lays a solid foundation for future research and policy planning.

2. Literature Review of the study and conceptual framework

2.1 Literature Review

Climate change has become one of the most pressing challenges for Bangladesh, especially in its coastal and climate-sensitive regions. A growing body of research highlights how environmental pressures, migration, adaptation efforts, and socio-economic vulnerabilities intersect, often focusing on the roles of youth, gender, and community resilience. O'Neill et al. (2025) estimate that climate change could displace over 22 million people within Bangladesh by 2050. Their study, using an agent-based model at the upazila level, combines climate data—like temperature, rainfall, and wind patterns—with demographic and geographic trends. It shows that central Bangladesh will likely be the origin of many migration flows, with large populations relocating to central and southeastern areas. These findings suggest that internal migration due to climate factors may be more widespread than previously expected, calling for proactive regional planning and policy development to manage these changes. Sagar (2025) focuses on how climate change has affected local livelihoods in Shyamnagar, a sub-district in Satkhira. The study finds that rising salinity, tidal flooding, and irregular rainfall have drastically reduced agricultural productivity. Over 60% of farmland in the area has become unproductive, forcing people to abandon farming and turn to day labor. In a related study, Islam (2025) examines the challenges climate-affected migrant youth face in accessing higher education. These include displacement, financial hardship, and poor infrastructure, all of which emphasize the need for more inclusive and flexible education policies. Similarly, Pinchoff (2025) highlights the mental health toll of climate events on young people in Bangladesh, Guatemala, and Nigeria, pointing to rising cases of stress and anxiety in vulnerable communities. Gender is another critical lens in climate research. A study by Sony et al. (2025) involving 514 secondary school students in Khulna, Bagerhat, and Satkhira reveals gender differences in risk awareness. Girls were more aware of social and mental health risks, while boys had greater knowledge of environmental hazards and relied more on digital platforms for information. Both genders primarily learned about risks through school, though girls leaned more on teachers and family members. These findings reflect how gender norms influence access to information, underlining the importance of equitable communication and education strategies. Similarly, Goldberg (2025) reviews studies on the psychological impact of climate disasters, noting that youth and marginalized groups often

experience severe mental health challenges. Beyond individuals, institutions and communities play a vital role in climate adaptation. Haque (2024) explores how multi-level institutions help spread innovation and adaptive technologies across coastal areas. Based on surveys and interviews, the study finds these institutions crucial for sharing resources and knowledge, though they are often hampered by coordination issues and capacity limitations. Indigenous communities also offer valuable lessons. Datta (2024) and Rahman et al. (2024) investigate the Munda community's adaptation practices, such as rainwater harvesting, using organic fertilizers, and disaster readiness. One study noted that 85.1% of households surveyed stored three days' worth of food and water, showing strong preparedness. These findings emphasize that traditional knowledge is a key asset in sustainable adaptation and should be incorporated into national strategies.

On the youth front, Ali et al. (2024) examines what drives young people's involvement in agriculture in Khulna's Polder 30 region. Their findings show that gender, hands-on farming experience, training, and access to credit all positively influence youth engagement in agriculture. Conversely, higher education levels and aspirations to migrate to cities often reduce agricultural participation. They recommend practical training programs and policies to revive youth interest in farming amid climate challenges. Laila (2023) evaluates the Coastal Towns Climate Resilience Project (CTCRP), which spans 22 towns. While focusing on physical infrastructure—like drainage, cyclone shelters, and waste systems, the project also stresses the need for community-led adaptation planning. Other studies look at local strategies. Ashrafuzzaman (2023) studies Shyamnagar's adaptive practices, identifying rainwater harvesting, native crop gardening, and cyclone shelters as key resilience tools. Khanam et al. (2023) delve into how salinity affects women, noting increased health issues, domestic workload, and disrupted education for girls. These burdens have led to more female-headed households, prompting calls for gender-sensitive policies. Meanwhile, Faruk (2023) documents how youth are stepping up as environmental advocates, and Shampa (2023) highlights their role in managing sustainable coastal development. A justice-focused perspective is also evident in literature. Ashrafuzzaman, Gomes, and Guerra (2022) apply a capabilities-based framework to explore climate justice in the southwestern region, advocating for locally led adaptation, international compensation, and inclusive policymaking. Sultana and Luetz (2022) focus on the integration of Indigenous knowledge in Bhola and Satkhira. They find that water management and livelihood support top community priorities, but note gaps between local needs and national policies.

ICCCAD (2022) underscores youth empowerment through workshops and leadership training, enabling them to lead community resilience projects. Echoing this, Ashrafuzzaman (2022) stresses the need for community-informed adaptation strategies. Innovation is also gaining attention. Chowdhury et al. (2022) explore climate-friendly businesses in Khulna and Barishal, pointing out that while youth involvement is strong, lack of training and funding remains a barrier. Hanifi (2022) studies how climate-related disruptions in agriculture affect child nutrition.

Haque et al. (2022) and Rahman & Karim (2021) emphasize ocean literacy as a tool for resilience, while Chowdhury et al. (2020) and Islam & Hossain (2019) show how combining local and scientific knowledge enhances community preparedness. Overall, the literature reveals that climate change in Bangladesh is more than just an environmental issue—it is deeply intertwined with social, economic, gender, and generational dynamics. Migration, loss of livelihoods, youth and women’s vulnerabilities, and mental health impacts are all part of the broader climate story. These studies stress the importance of community-based, inclusive adaptation approaches supported by strong institutions and grounded in both local wisdom and national strategies.

2.2 Conceptual Framework

The conceptual framework recognizes youth not merely as beneficiaries of climate policies but as key actors whose leadership and initiatives directly shape local resilience outcomes. It provides a structured lens to investigate the nature, scope, and effectiveness of youth-led climate actions in coastal communities of Bangladesh, thereby generating insights that can inform inclusive climate governance and sustainable adaptation strategies.

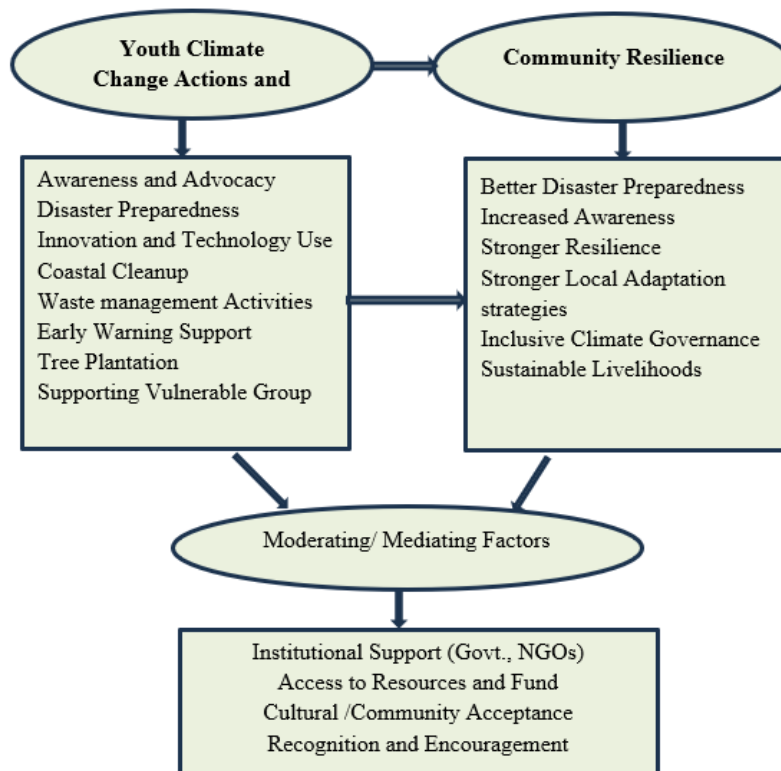


Figure 1: Conceptual Framework

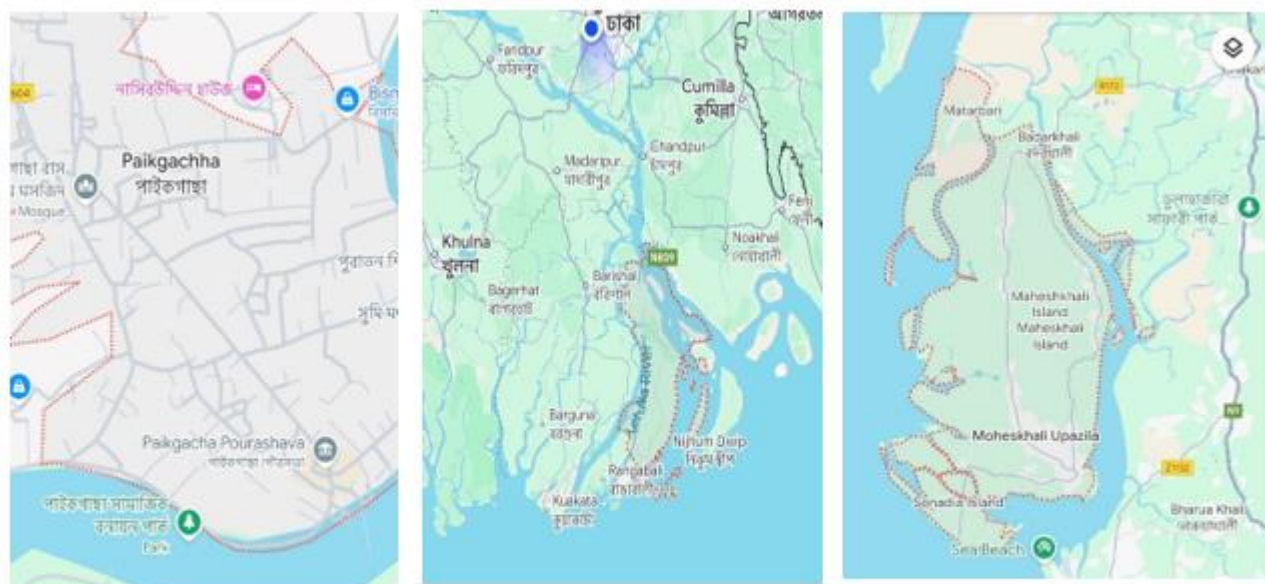
3. Methodology

3.1 Research Design

This study used a mixed-methods approach, combining both quantitative and qualitative techniques to gain deeper and more comprehensive insights. The quantitative data helped measure how actively youth are participating in climate-related initiatives. Meanwhile, the qualitative aspect offered a closer look at their leadership roles, personal experiences, and the challenges they face in coastal communities across Bangladesh.

3.2 Study Area

The research was conducted in selected coastal districts of Bangladesh that are highly vulnerable to climate change, including Khulna (Paikgacha Upazila), Barishal (Bhola) and Cox's Bazar (Maheshkhali).



Khulna (Paikgacha Upazila)

Barishal (Bhola)

Cox's Bazar (Maheshkhali)

Figure 2: Locale of the Study

3.3 Study Population and Unit of Analysis

The target population of the study consisted of community people living in the coastal areas of Bangladesh. Both male and female participants of various age groups and socioeconomic backgrounds were included. Specifically, the study focused on those community members who had knowledge of or were aware of youth-led climate initiatives, as their perspectives were essential for understanding the role of youth in climate actions and leadership within coastal communities.

3.4 Sampling

The target population of the study consisted of community people living in coastal areas of Barisal, Khulna, and Cox’s Bazar who were knowledgeable about youth-led climate initiatives. Both male and female participants of different age groups and socioeconomic backgrounds were included. A purposive sampling technique was employed to select participants who could provide relevant insights into youth climate actions and leadership. The total sample comprised 100 participants, including 90 survey respondents and 10 key informants. Surveys captured the perspectives of general community members, and KIIs were conducted with local leaders and NGO representatives who had direct insights into youth leadership in climate action.

Division	Surveys	Key Informant Interviews (KIIs)	Total
Barisal	30	3	33
Khulna	30	3	33
Cox’s Bazar	30	4	34
Total	90	10	100

Table 1: Sample Distribution

3.5 Data Collection Techniques

To thoroughly meet the research objectives, data were collected through a variety of methods. Surveys were conducted with 90 community members to gather quantitative data on their awareness and views regarding youth-led climate initiatives. In-depth qualitative insights were obtained through 10 key informant interviews (KIIs) with local leaders, NGO representatives, and other knowledgeable individuals. Field visits allowed for direct observation of community engagement, youth-led efforts, and local climate adaptation practices. Additionally, document analysis was performed by reviewing local reports, project documentation, and relevant secondary literature, which helped validate and strengthen the overall findings.

3.6 Data Collection Tools

The study employed a range of tools to collect both quantitative and qualitative data. A structured questionnaire was used for surveys to capture community members’ knowledge, perceptions, and experiences regarding youth-led climate initiatives. Interview guides were prepared for key informant interviews (KIIs) to ensure consistency in exploring participants’ insights on youth leadership and climate actions. For observations, a checklist was developed to systematically record youth activities, community interactions, and climate adaptation practices

during field visits. Document review templates were also utilized to extract relevant information from project reports, local records, and secondary literature. These tools collectively ensured that data were collected in a systematic, reliable, and comprehensive manner.

3.7 Data Editing, Processing and Analysis

Once the data were collected, all survey responses, interview transcripts, and observation notes were carefully reviewed and refined to ensure they were complete, accurate, and consistent. The quantitative data from the surveys were coded and entered into statistical tools like SPSS and Excel for analysis. Basic statistics such as frequencies, percentages, and averages were calculated to summarize participants' awareness and opinions about youth-led climate initiatives. The qualitative data from interviews and observations were transcribed, organized, and analyzed thematically to uncover key patterns, themes, and insights related to youth leadership and climate action. To improve the credibility and reliability of the findings, data from different sources were cross-checked through triangulation.

3.8 Ethical Considerations

The study carefully followed ethical standards to safeguard the rights, dignity, and well-being of all participants. Before any data were collected, informed consent was obtained, and participants were clearly informed about the research objectives, procedures, and how the data would be used. Participation was entirely voluntary, and individuals had the freedom to withdraw at any point without facing any consequences.

Strict confidentiality was maintained throughout the study, with no personal identifiers included in any reports or publications. The research followed established ethical guidelines in social research, ensuring that no participants experienced physical, emotional, or social harm. All collected data were securely stored, with access limited to the researcher. Cultural sensitivity was also a key priority. The study respected local customs, traditions, and social values, and special attention was given to avoiding any form of pressure or influence, particularly when working with vulnerable groups.

Additionally, ChatGPT-5 Mini was used only for organizing, editing, and formatting text. All analysis, interpretation, and conclusions were solely developed by the researcher to ensure academic honesty and originality.

4. Findings and Discussions

4.1 Demographic Information of Respondents

This section presents the background characteristics of the 90 survey respondents. The information includes their age, gender, education, and occupation, which helps contextualize the findings of the study.

Age Group (Years)	Frequency	Percentage (%)
Below 20	12	13.3
21–30	24	26.7
31–40	20	22.2
41–50	18	20.0
Above 50	16	17.8
Total	90	100

Table 2: Age Distribution of Respondents (N=90)

The table shows the age distribution of the respondents. Out of a total of **90 participants**, the highest proportion belongs to the **21–30 years age group (26.7%)**, followed by the **31–40 years group (22.2%)**. A significant number also fall in the **41–50 years group (20.0%)** and **above 50 years group (17.8%)**, while the **below 20 years group** has the least representation at **13.3%**.

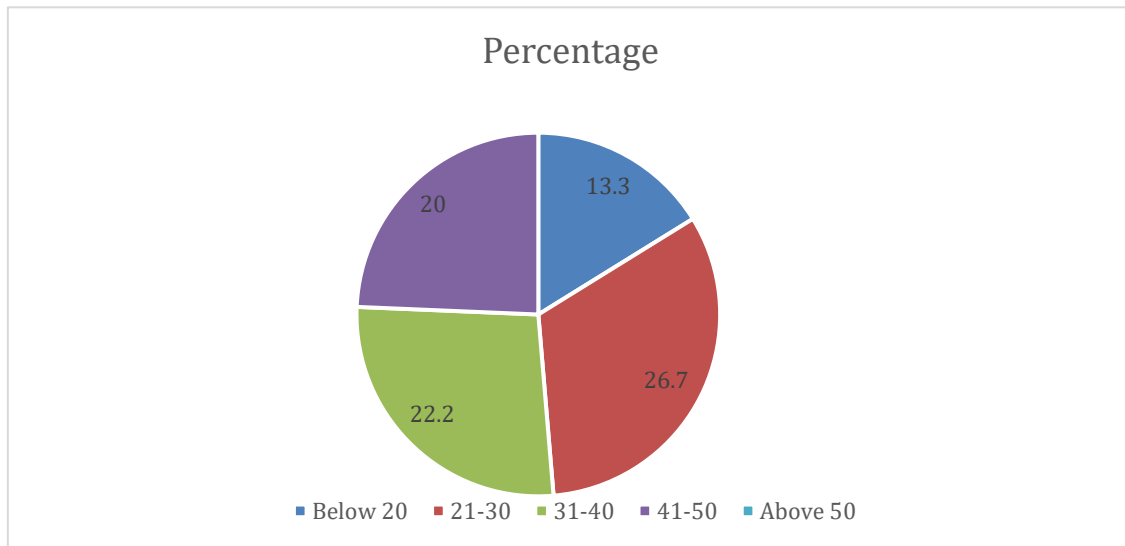


Figure 3: Age Distribution of Respondents (N=90)

This distribution indicates that the majority of the respondents are young adults (21–30 years) and middle-aged individuals (31–50 years), together accounting for nearly **69%** of the total sample. Meanwhile, the proportion of participants below 20 years is comparatively small, suggesting limited involvement from the youngest age category.

Gender	Frequency	Percentage (%)
Male	46	51.1
Female	44	48.9
Total	90	100

Table 3: Gender Distribution of Respondents (N=90)

The table shows the gender distribution of the respondents. Out of a total of 90 participants, 46 (51.1%) are male and 44 (48.9%) are female. The distribution is almost equal, with only a slight majority of males compared to females. The sample achieved near gender balance, ensuring perspectives of both men and women were represented.

Educational Level	Frequency	Percentage (%)
No formal education	10	11.1
Primary	22	24.4
Secondary	28	31.1
Higher secondary	20	22.2
Graduate and above	10	11.1
Total	90	100

Table 4: Educational Level of Respondents (N=90)

Most respondents (55.5%) had attained a primary to secondary level of education, which mirrors the general educational landscape of rural coastal Bangladesh. Among the 90 participants, the largest portion had completed secondary school (31.1%), followed by those with primary (24.4%) and higher secondary education (22.2%). A smaller but noteworthy number had no formal schooling (11.1%), while an equal percentage had completed graduate or higher education. This data suggests that a majority of the participants possessed basic to moderate education levels, with fewer individuals falling into the highest and lowest ends of the educational spectrum. Overall, the sample reflects a predominantly moderately educated population, with minimal representation from those who are either highly educated or have no formal education at all.

Occupation	Frequency	Percentage (%)
Agriculture/Fishing	28	31.1
Small business/trade	18	20.0
Day labor	16	17.8
Service (Gov/NGO)	14	15.6
Homemaker	14	15.6
Total	90	100

Table 5: Occupation of Respondents (N=90)

The table outlines the occupational breakdown of the 90 respondents. The most common occupation, reported by 31.1% of participants, is agriculture and fishing—an expected outcome given the rural, coastal setting of the study. This is followed by individuals involved in small businesses or trade (20.0%) and those working as day laborers (17.8%). Additionally, 15.6% of respondents are employed in the government or NGO sectors, and an equal percentage identify as homemakers. The dominance of agriculture and fishing aligns with the heavy reliance of coastal communities on natural resources for their livelihoods.

4.2 Youth Climate Change Actions in Coastal Communities

Youth Actions	Frequency	Percentage (%)
Tree plantation and greenery	28	31.1
Awareness campaigns	22	24.4
Waste management/clean-up	16	17.8
Disaster preparedness & early warning	14	15.6
Supporting vulnerable groups	10	11.1
Total	90	100

Table 6: Types of Youth Climate Change Actions Observed (N=90). Source: Field Survey, 2025

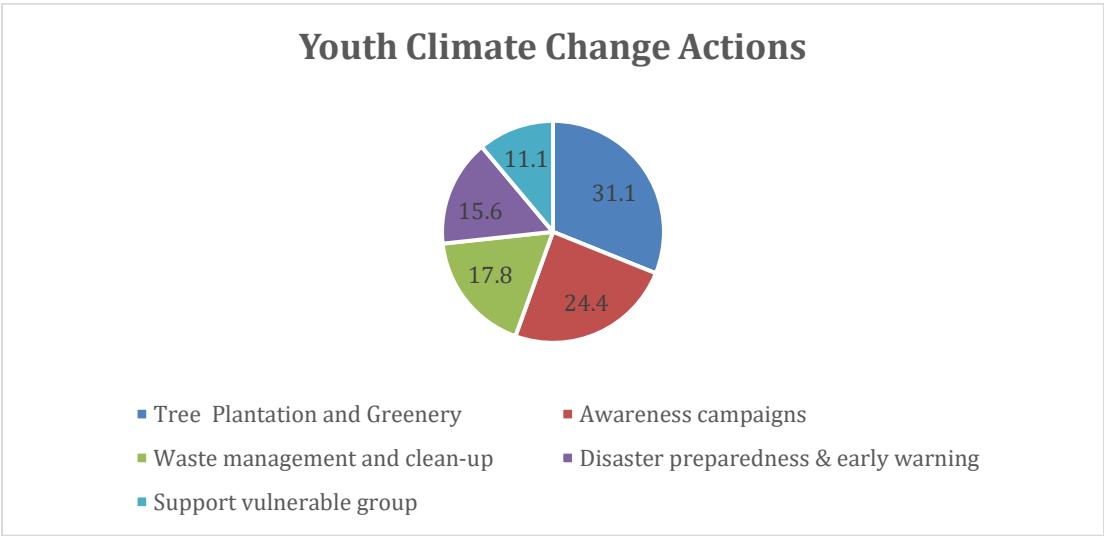


Figure 4: Types of Youth Climate Change Actions Observed

The table outlines the key climate-related actions taken by youth in the study area. Among the 90 participants, tree plantation and promoting greenery emerged as the most frequent activities (31.1%), highlighting a strong commitment to environmental preservation. Awareness campaigns followed at 24.4%, showing efforts to inform and educate the community about climate and social challenges. Other notable actions include waste management and clean-up drives (17.8%) and initiatives focused on disaster preparedness and early warning systems (15.6%), both essential for boosting local resilience. Additionally, 11.1% of respondents mentioned helping vulnerable groups, pointing to a socially responsible aspect of youth engagement. Altogether, the data suggest that youth are actively involved in a wide range of climate and community-related efforts, with a strong focus on sustainability and public education. Interviews with key informants confirmed that young people are deeply engaged in both environmental and social campaigns. Their actions reflect not just environmental commitment but also a proactive and inclusive approach to strengthening community resilience.

4.3 Community Groups Benefited from Youth Climate Actions

Benefiting Group	Frequency	Percentage (%)
Women	24	26.7
Children	20	22.2
Elderly	16	17.8
Entire Community	30	33.3
Total	90	100

Table 7: Benefiting Groups from Youth Climate Actions (N=90)

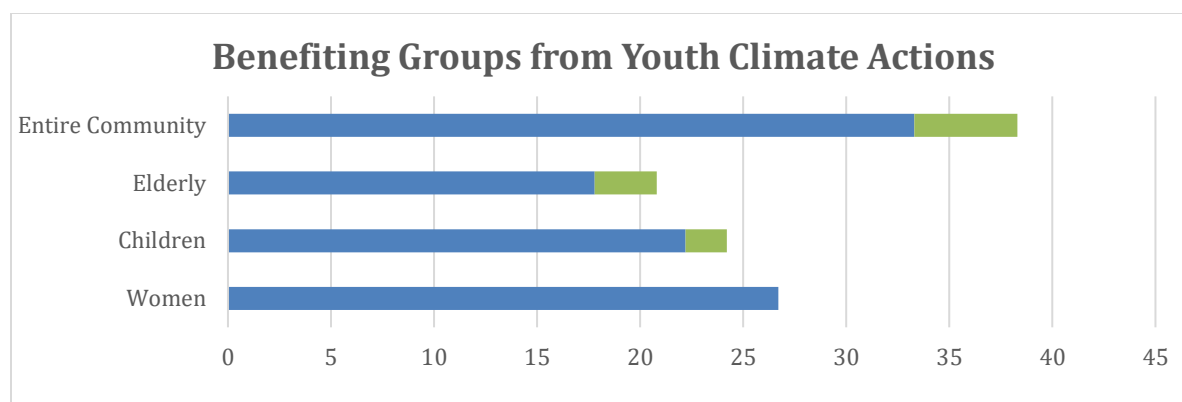


Figure 5: *Benefiting Groups from Youth Climate Actions*

The table highlights which groups have benefited the most from youth-led climate and community activities. Among the 90 respondents, the largest portion (33.3%) reported that the entire community benefits as a whole, indicating that youth initiatives tend to have a broad, inclusive impact rather than focusing on just one segment of the population. Within specific groups, women were identified as the primary beneficiaries (26.7%), followed by children (22.2%) and the elderly (17.8%). These findings show that youth efforts often prioritize vulnerable populations. A lecturer from the University of Dhaka, originally from Maheshkhali in Cox’s Bazar, emphasized that women in their community face serious challenges due to poverty and climate-related risks. However, local youth have taken active steps to support and protect them through various grassroots initiatives. Many key informants also identified women as both the most vulnerable and the most supported group. This distribution underscores that while youth actions are far-reaching, they are particularly impactful for vulnerable groups, showcasing the inclusive and socially conscious nature of youth leadership in climate and community development.

4.4 Changes Noticed Due to Youth Climate Actions

Changes Noticed	Frequency	Percentage (%)
Increased awareness	32	35.6
Better disaster preparation	25	27.8
Support for vulnerable groups	18	20.0

Livelihood support	15	16.7
Total	90	100

Table 8: Changes Noticed from Youth Climate Actions (N=90)

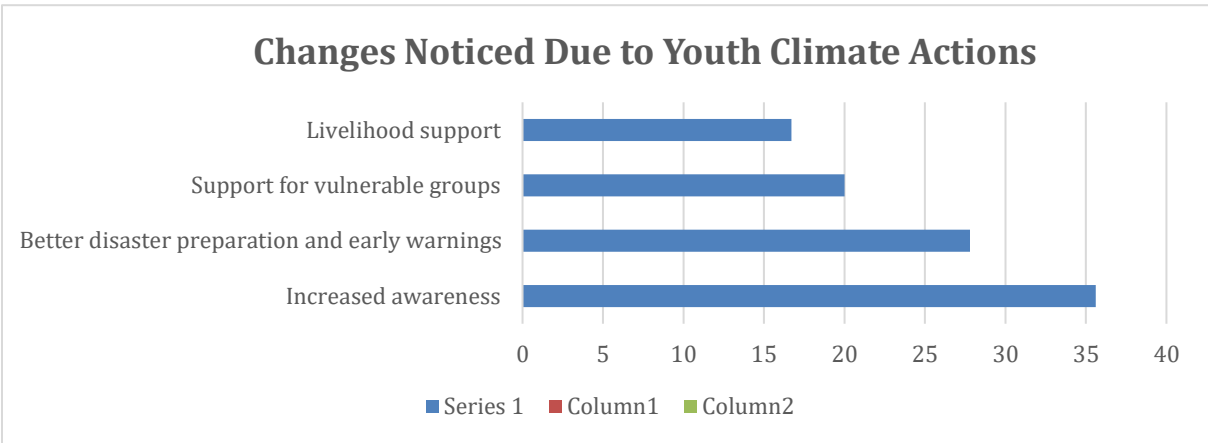


Figure 6: Changes Noticed Due to Youth Climate Actions

The table highlights the most notable changes that have occurred as a result of youth-led climate initiatives. Among the 90 respondents, the most common change observed was an increase in awareness (35.6%), showing that youth efforts are significantly enhancing knowledge and engagement within the community. The next most reported outcome was improved disaster preparedness (27.8%), which underscores the role of youth in boosting the community’s readiness for climate-related hazards. Support for vulnerable groups (20.0%) was also identified as a major outcome, reflecting the inclusive and compassionate nature of youth involvement. A smaller, yet meaningful, number of respondents (16.7%) pointed to livelihood support, suggesting that some youth actions also contribute to economic resilience, though this was noted less frequently. Key informants shared that youth-led efforts have led to clear behavioral and environmental improvements in local areas. These include cleaner environments, greater participation in disaster preparedness, and stronger social cohesion. Youth volunteers have also encouraged eco-friendly habits, like reducing plastic waste and planting mangrove trees in coastal zones. Overall, the findings suggest that youth initiatives are particularly effective in spreading awareness and enhancing disaster readiness, while also providing social and economic support in their communities.

4.5 Challenges Faced by Youth in Climate Leadership

Challenges	Frequency	Percentage (%)
Lack of resources/funding	30	33.3
Lack of knowledge/skills	25	27.8
Limited community support	20	22.2
Political/social barriers	15	16.7
Total	90	100

Table 9: Challenges Faced by Youth in Climate Leadership (N=90)

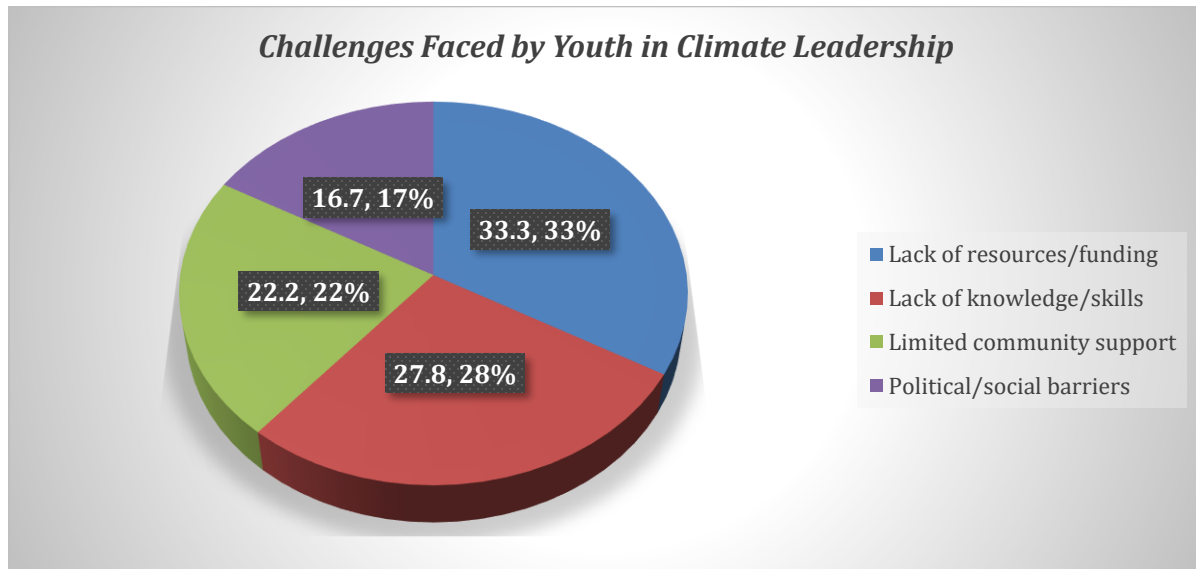


Figure 7: Challenges Faced by Youth in Climate Leadership

The table outlines the key challenges youth face in leading climate and community-based initiatives. Among the 90 participants, the most frequently cited issue was a lack of resources and funding (33.3%), highlighting the financial constraints that limit the reach and sustainability

of youth-led efforts. The next major concern was a lack of knowledge and skills (27.8%), indicating that many young people are eager to contribute but require training and technical support to enhance their impact. Limited community backing (22.2%) was another notable barrier, reflecting a need for greater social acceptance and collaboration. Political and social obstacles (16.7%) were also mentioned, suggesting that broader systemic issues can hinder youth involvement. Respondents also pointed to a lack of leadership training and development programs, particularly in rural and coastal regions. One young participant from Khulna expressed, “We are ready to help, but we need guidance and resources to be more effective.” Cultural and gender-based limitations further restrict participation, especially for young women who may be discouraged from engaging in outdoor or mixed-gender initiatives. Communication gaps between youth groups and local authorities were also flagged as a major barrier to coordination. Taken together, these findings show that youth face both practical and systemic challenges. Addressing these issues, especially financial and capacity-building needs, would better equip young people to drive meaningful changes in their communities.

4.6 Recommendation for Youth Climate Change Actions and Leadership

Recommendation Area	Frequency (f)	Percentage (%)
Training & Education	25	27.78
Financial Support & Funding	20	22.22
Government Programs	30	33.33
NGO & Community Support	15	16.67
Total	90	100

Table 10: Recommendation for Youth Climate Change Actions and Leadership

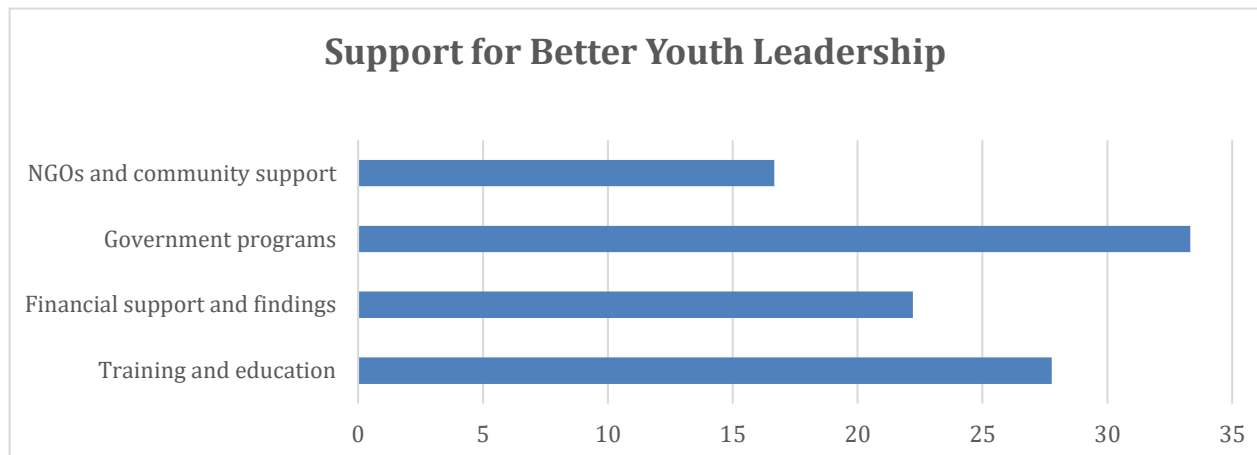


Figure 8: Recommendation for Youth Climate Change Actions and Leadership

The table outlines key areas where respondents believe efforts should be focused to strengthen youth-led climate and community actions. Of the 90 participants, the largest share (33.3%) emphasized the need for government programs, indicating that state policies and institutional support are essential for sustaining youth involvement. Training and education came next (27.8%), underscoring the importance of building youth knowledge, skills, and capacity to respond to climate challenges effectively. Financial support and funding (22.2%) were also highlighted as crucial for scaling up youth initiatives, while 16.7% pointed to the importance of NGO and community backing. Participants and key informants suggested a range of strategies, including official recognition of youth initiatives, enhanced access to training programs, and stronger financial and technical support for grassroots projects. Promoting gender inclusivity and encouraging collaboration between youth groups, local governments, and NGOs were also stressed. A lecturer from Maheshkhali, Cox’s Bazar noted that young people are instrumental in supporting vulnerable elderly populations, but they need better guidance and opportunities. Overall, respondents called for increased awareness, targeted education, and long-term policy commitment to ensure the continued success and sustainability of youth-led climate efforts in Bangladesh’s coastal regions.

5. Recommendations and Conclusions

5.1 Recommendations of the study

This study clearly shows that young people are playing an increasingly important role in addressing climate change, particularly in Bangladesh’s vulnerable coastal areas. Their contributions range from leading awareness campaigns to assisting families during climate-related disasters, demonstrating their ability to create real impact. These efforts often benefit the most at-risk groups—women, children, and the elderly—who are especially vulnerable during

environmental crises. However, several obstacles continue to limit the full potential of youth involvement. These include the lack of formal training opportunities, inadequate financial resources, insufficient institutional recognition, and weak collaboration with NGOs and local communities. In some cases, social and political resistance further hinders their participation. To overcome these challenges, the study offers a range of practical and policy-driven recommendations aimed at strengthening youth engagement in climate action.

1. Training and Education

To become effective climate leaders, young people need the right education and skill-building opportunities. In Bangladesh's coastal regions, this involves more than just basic awareness—it requires hands-on training in disaster preparedness, sustainable agriculture in saline-affected areas, and the use of renewable energy technologies. Educational programs should be practical, easy to understand, and delivered through both classroom instruction and field-based activities. Where possible, digital learning tools should also be included to increase accessibility. Implementing “train-the-trainer” models can help spread this knowledge more broadly, as trained youth leaders and educators share what they've learned with others in their communities. Ongoing evaluations of these programs are also essential to ensure they remain effective, relevant, and adaptable to changing conditions.

2. Financial Support and Funding

A major hurdle for youth-led climate initiatives is the lack of funding to bring their ideas to life. Many promising projects never take off because of this financial gap. Creating a dedicated Youth Climate Fund at the local level could offer small grants and loans, giving young leaders the initial support needed to launch their work. In addition to funding, young people also need training on how to manage resources, develop business plans, and maintain financial sustainability. Programs like startup competitions, mentorships, and incubation centers could give youth the chance to test and grow their ideas. Collaborations with private companies and international donors could also help secure longer-term funding and expand the impact of youth-driven climate efforts.

3. Government Programs

For youth leadership in climate action to grow beyond scattered efforts, strong government backing is essential. Policy frameworks must create space for young people to have a voice in climate planning, especially at the district and upazila levels. Establishing local youth councils can ensure that policies reflect the priorities and ideas of young individuals. Setting aside dedicated budget allocations for youth-led initiatives would further solidify their involvement. Including young leaders in disaster management committees could enhance both readiness and response efforts during emergencies. Additionally, offering government incentives like subsidies or public recognition can inspire more youth to pursue eco-friendly entrepreneurship and become long-term contributors to climate resilience.

4. NGO and Community Collaboration

Collaborating with NGOs, community groups, and youth organizations can significantly boost climate action. NGOs offer training, expertise, and funding, while youth contribute energy and local trust. Clear roles through formal partnerships improve coordination. Starting with pilot projects and involving community leaders like elders and religious figures can enhance acceptance and impact. Blending local knowledge, NGO support, and youth leadership creates more effective and resilient solutions.

5. Recognition and Collaboration

To keep young people motivated, it's important to acknowledge and celebrate their efforts. Public recognition through awards, certificates, or scholarships can spotlight their achievements and encourage others to follow suit. Promoting their success stories in the media and on social platforms can also boost visibility and attract more support. Opportunities for young people to network—locally and globally—through exchange programs, conferences, and study tours can further enhance their experience. Collaborating with universities and private organizations can provide valuable technical skills, while mentorship programs can connect young leaders with experienced professionals for guidance and growth.

6. Removing Social Resistances and Political Barriers

Young people often face challenges like generational skepticism, gender bias, and political interference. Addressing these issues calls for open dialogue with elders and community leaders to build understanding. Ensuring equal opportunities for women and marginalized groups—through safe spaces or childcare support—is essential. Creating non-partisan youth platforms focused on sustainability can help overcome political barriers. Strong protection and ongoing monitoring are needed to safeguard youth voices and adapt to evolving challenges.

5.2 Conclusions

This study underscores the powerful role young people play in strengthening climate resilience in Bangladesh's coastal communities. With creativity, dedication, and a strong sense of responsibility, youth are making meaningful contributions—especially for vulnerable populations. However, without access to training, steady funding, and institutional support, their impact risks being limited and short-lived. The findings emphasize that empowering even a single youth leader can positively influence an entire community. To scale this success, stronger partnerships among government bodies, NGOs, universities, and private organizations are crucial. Long-term financial support and official recognition will help keep young people actively involved. At the same time, dismantling social and political barriers is essential to ensure that youth leadership opportunities are open to everyone, particularly women and marginalized groups. Combining traditional knowledge with modern technology can lead to

practical, lasting solutions. Regular monitoring will ensure that these efforts remain effective and adaptable. Ultimately, the youth of Bangladesh are already stepping into leadership roles. Their energy and innovation need to be supported and celebrated. By following these recommendations, the country can unlock the full potential of its young generation to build a more inclusive, resilient, and sustainable future, while advancing its progress toward the Sustainable Development Goals (SDGs).

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Paper 23

Balancing Tourism and Conservation: Addressing Over-Tourism and Governance Challenges on Saint Martin Island, Bangladesh

Samim Rahman Bhuiyan

Abstract

Saint Martin's Island, Bangladesh's only coral island, is a prime tourism destination, attracting a substantial number of visitors each year. However, the rapid and unregulated growth of tourism has led to significant ecological degradation, threatening the island's biodiversity and natural resources. This study investigates the impacts of over-tourism on Saint Martin's Island, focusing on the challenges of balancing environmental conservation with local livelihoods. Through a literature review and content analysis of policy documents, this research identifies key governance issues, including inadequate infrastructure, lack of policy enforcement, and weak coordination among stakeholders. The findings highlight the detrimental effects of tourism on coral reefs, sea turtles, and other vital marine ecosystems. Furthermore, the study proposes sustainable governance frameworks, such as ecotourism initiatives and the application of adaptive governance strategies, to mitigate tourism's adverse impacts. The results emphasize the need for integrated coastal management that incorporates both ecological preservation and socio-economic development. Ultimately, this research contributes to the growing body of knowledge on sustainable tourism governance in ecologically sensitive coastal areas, offering valuable lessons for managing similar issues globally.

1. Introduction:

Saint Martin's Island is considered a unique coral ecosystem and one of the most appealing spots in the tourism infrastructure of Bangladesh. It is the only coral island in Bangladesh and attracts thousands of tourists, local and foreign, every year (Biswas et al., 2025). However, this emergent tourism has threatened the fragile ecosystem to a great extent. It is a matter of concern that this coral island is under great risk because around 67% corals have been bleached to death due to pollution and uncontrolled tourism (Ara, Alif, & Islam, 2021). The unplanned and unregulated growth of tourism degrades the environment through various issues ecologically vulnerable, including the destruction of coral reefs, pollution, loss of biodiversity, and challenges in confronting sustainable management (Kamruzzaman & Uchinlayen, 2018).

The environmental impacts of over-tourism compromise the viability of these livelihoods in the long run. Poor infrastructure and the absence of regulatory control have exacerbated these problems further, which call for governance to combine conservation goals with socio-economic development (Partelow et al., 2020).

This has called for integrated governance of the coastal system, considering both the ecology and socio-economic dynamics. Adaptive governance frameworks have been called an efficient tool in responding to these complexities. It emphasizes flexibility, stakeholder involvement, and an apt response to a changing environmental and social condition (Partelow et al., 2020). In addition, the principles of interactive governance have been highly inclusive of this interdependency of natural and human systems, hence also more relevant in the context of tourism impact management at ecologically critical areas (Farsari, 2023).

Saint Martin's Island has several governance challenges despite the potentiality to act as a model for sustainable tourism. These include inadequacy in infrastructure, lack of implementation of policies, and less involvement of the community in the decision-making process. Lack of coordination among stakeholders further makes the island less capable of responding to and addressing both the goals of conservation and livelihood development of local people (Kamruzzaman & Uchinlayen, 2018).

This research examines the nexus of conservation and livelihood in Saint Martin's Island and aims to assess governance strategies to reduce over-tourism and offer sustainable development. The results add to the emerging literature on governance of complex coast systems, pointing out lessons that may be identified in this experience to balance ecological preservation with socio-economic development.

2. Research Matrix

Specific Objectives	Research Questions	Methods
To assess the ecological damage caused by unchecked tourism	What are the primary ecological impacts of tourism on Saint Martin's Island?	Literature review
To examine governance challenges in controlling tourism and conserving biodiversity	What governance issues hinder biodiversity conservation on Saint Martin's Island?	content analysis
To propose recommendations for sustainable tourism governance and best practices	What governance frameworks can prevent similar ecological crises?	Comparative analysis, Literature review

3. Literature review:

Numerous studies in the literature consistently highlight the critical challenges posed by over-tourism, including:

Hasan (2009) discusses Saint Martin Island, the only coral island of Bangladesh, regarding the challenges of biodiversity conservation. One major factor contributing to environmental degradation is said to be tourism. Collected activities of live coral, illegal fishing, and construction works have disrupted the fragile ecosystem of the island. On the other hand, the island encompasses 66 species of corals, 240 fish species, and nesting grounds for endangered

sea turtles. However, due to anthropogenic activities, inclusive of unregulated tourism, it is viewed as posing a potential threat to its biodiversity. He calls for integrating biodiversity conservation into tourism management for sustainable development.

Farsari (2023) reviews the underlying challenges of sustainable tourism governance in terms of characteristics of resilience and adaptive governance strategies related to destination management. This work has pointed out, in those areas of environmental and economic sensitivity, the connections that link tourism, governance, and environmental resilience. It questions the conventional top-down approach of governance and, instead, calls for an integrated public-private partnership with community involvement along the road of sustainable development. This paper explores how to apply complexity science in devising adaptive policies by considering the dynamic nature of tourism systems-especially those vulnerable coastal destinations such as Saint Martin Island.

Kamarruzzaman & Uchinlayen (2018) Analyze the factors determining tourists' preference to visit Saint Martin Island. The study, through regression analysis, identified natural beauty, adventure opportunities, and relaxation, along with good services, as motivational factors to travel. Poor infrastructure, hygiene problems, and lack of promotions were identified as important impeding factors to growth. It is recommended that targeted investments in infrastructure, better service standardization, and proper marketing strategies be carried out for sustainable tourism development. In addressing these foregoing factors, Saint Martin Island can further strengthen its competitiveness as a key tourist destination.

Partelow et al., (2020) Review those environmental governance theories applicable to a coastal ecosystem in general, including Saint Martin Island. An urgent need for integrative frameworks of polycentric governance was identified, encouraging multi-level stakeholder collaboration. Various challenges of coastal governance have been discussed in relation to global environmental goals, such as those put forward by the United Nations Sustainable Development Goals. Adaptive governance models were suggested to fit into local practices through international conservation initiatives in order to ensure long-term sustainability for diverse coastal zones.

3.1 Research gaps

The knowledge gap in the existing literature mostly lies in a lack of holistic, updated, location-specific studies that address ecological and socioeconomic impacts of over-tourism, given the biodiversity and economic importance of the islands. Most previous works emphasize general aspects of environmental deterioration and hence miss potential sustainable carrying capacities, mechanisms of governance, and long-term socioeconomic strategies for management. Indeed, data for cumulative impacts related to climate change, tourism, and local practices on island ecosystems are scanty. In this outlook, this work spots the dire need for holistic approaches to be

adopted with more attention to ecotourism involving the communities and implementing necessary policies to ensure conservation of unique biodiversity at the island.

4. Research Methodology

This study aims to explore the relationship between tourism development and its impacts on biodiversity and governance frameworks in coastal ecosystems. Relevant journal articles, reports, and literature focusing on tourism, environmental sustainability, and governance were extensively collected and reviewed. The majority of the resources were contextualized to small islands like Saint Martin Island, with some referencing global case studies and broader trends. Both qualitative and quantitative data were gathered from existing studies using a secondary research approach. Comparative analyses were conducted to highlight key governance challenges and biodiversity impacts. All referenced materials were properly cited to ensure academic integrity and acknowledgment of sources.

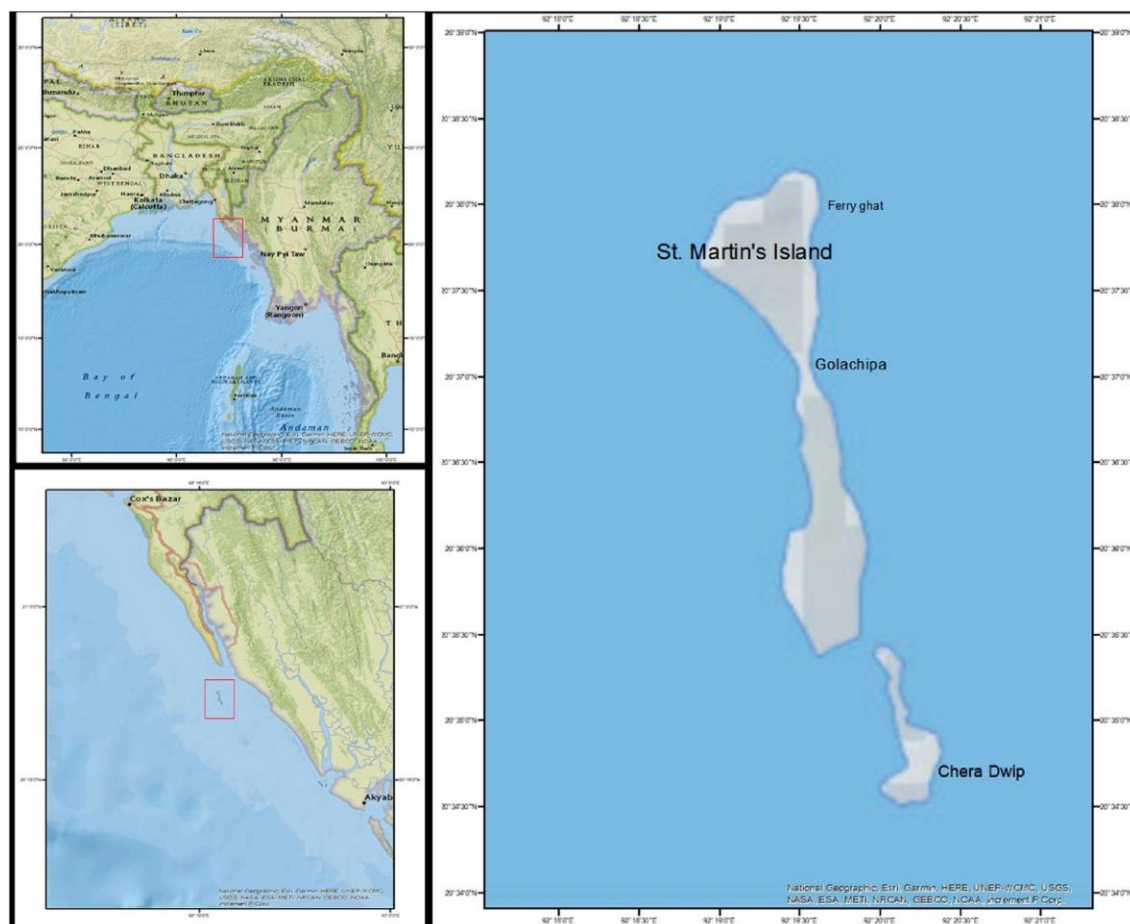


Figure 1: Map of Saint Martin's Island.

5. Findings

Over-tourism refers to the rapid growth of tourism, the overuse of natural resources, damage to cultural attractions, and negative impacts on local communities. It involves excessive tourist numbers, inappropriate behaviors, disturbances for residents, and environmental and social degradation. Protests and resistance to tourism have been reported in affected regions (Wyman et al., 2011).

5.1 Carrying capacity

The principle of tourism carrying capacity (TCC) provides an estimate of the number of visitors that can be welcomed at a location while taking into account the capacities of several elements of the local tourism system, including the physical, environmental, ecological, economic, and sociocultural. Without reducing visitor satisfaction, CCA (Carrying Capacity Assessment) restricts the number of visitors to a level that the general natural, social, economic, and ecological conditions can support. Local communities, as well as their cultural and environmental background, depend on it (Da Silva, 2002).

The Real Carrying Capacity for Saint Martin's Island was calculated as 2,913 visitors/day, based on a series of corrective factors that adjust the physical carrying capacity (PCC). But even this number is not sustainable for the island. There are some factors that must be considered in determining the sustainable carrying capacity of Saint Martin Island (Hassan et al., 2014). However, some factors can reduce the carrying capacity.

5.1.1 Factors for Adjustments:

- Environmental Considerations: Seasonal restrictions account for adverse weather and natural risks like storms.
- Safety and Infrastructure: Unsafe areas and limited facilities reduce feasible capacity.
- Sustainable Practices: Allocating space for local livelihoods ensures tourism does not disrupt essential activities.
- Management Efficiency: The MC reflects the quality of operational and resource management, emphasizing the island's capacity to handle tourists effectively.

The sustainable threshold is 1,835 visitors/day, for balancing tourism with ecological preservation and local well-being (Hassan et al., 2014).

5.2 Reality of tourism (quantified)

Sep	Oct	Nov	Dec	Jan	Feb	March
1000 tourists	2000 tourists	5000 tourists				1000 tourists

Table 1: Number of tourists visiting St. Martin's Island per day in peak season (Hassan et al., 2014)

As per data obtained, approximately 3500 extra tourists came every day from November to February. Total number of overloaded tourists from November to February (for 4 months or 120 days) = $(3500 \times 4 \times 30) = 420,000$ tourists.

6. Discussion

6.1 Impact of over-tourism

6.1.1 Threats to Coral Reefs and Sea Turtles

St. Martin's Island is now a full-fledged tourist destination receiving more than 5,000 tourists every day during peak seasons (November to February) (Hassan et al., 2014). This fragile ecosystem cannot bear the pressure of this many tourists. To accommodate these tourists, hotels, motels, and restaurants are mushrooming as fast as possible, completely disrupting the ecological balance of the island. Corals and sea turtles, the two most important factors, are seriously threatened. Sea turtles nest on the beach between 10:00 p.m. and 2:00 a.m., are being disturbed by the lights and noise from hotels, especially those hotels that use generators late at night (Hasan, 2009). Tourists are collecting corals, shells, starfish, etc., in large numbers, depleting them. The result of the study indicates that coral colonies decreased steadily throughout the study period. A total area of 0.9342 km² of coral colonies disappeared during the study period from 1980 to 2018 (Gazi, Mowsumi, & Ahmed, 2020). Wintering birds migrate during the peak tourist season, and it results in the destruction of the habitat of these birds. Coral reefs are susceptible to human activities because the majority of coral reefs grow in shallow waters which are near to shore where human activities are extensive. Human impacts, such as coral extraction, increased sediment load, population stress, overfishing, oil pollution, waste from hotels and restaurants, use of diesel, uncontrolled tourism, habitat destruction and development along shorelines have dramatic adverse impacts on the coral population (Ahammed et al., 2016).

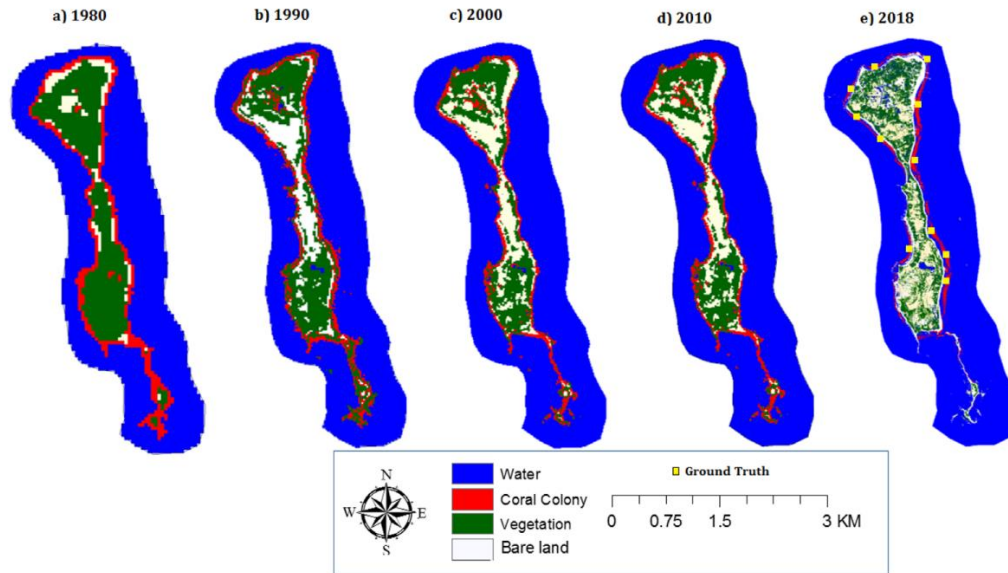


Figure 2: Deterioration of coral colonies between 1980-2018 (Gazi et al., 2020)

6.1.2 Climate Change Impacts

Global climate change seriously threatens the biodiversity of St. Martin's Island. The increase of temperature in the seawater has caused acute mortality to coral reefs, which are crucial to marine ecosystems (Upal, 2015). Corals need symbiotic algae to supplement their nutrient input through photosynthesis. When sea temperature rises above 28 °C, corals expel these symbiotic algae, leading to their starvation (Rahman, 2009). Sea-level rise leads to the erosion of turtle nesting beaches, while increasing sand temperatures disrupt egg incubation and alter hatchling sex ratios (Upal, 2015).

6.1.2 Deforestation and Coastal Erosion

The small islands' sensitive environment is thus particularly exposed to large-scale tourism construction, which is a major cause of seashore erosion, siltation of lagoons and reef damage (Scheyvens & Momsen, 2008). Deforestation on St. Martin's Island has accelerated dramatically over the past few decades. This is primarily driven by factors such as agricultural expansion, harvesting of sand dune vegetation for fodder and fuel, high population density, and natural disasters. Further, the locals cleared vegetation, including mangroves, in order to claim land (Ahmed, 2011). Though coastal erosion is considered a natural process, it has increased due to the removal of vegetation. In addition, the erosion enhanced the turbidity of the water and sedimentation both of which were detrimental to coral ecosystems (Islam & Islam, 2008). Due to reduced vegetation, the habitat of the local as well as migratory birds, including wintering birds such as gulls, terns, plovers, herons and egrets has been reduced (Laitamaki et al., 2016).

6.1.3 Other Negative Environmental Factors

Overpopulation exerts much pressure on natural resources as the local community relies largely on the island for subsistence. Agriculture, being a primary occupation is a source of habitat loss. Rocky land and the lagoons have been cleared for agriculture. Exotic plant species reduce ecosystems (Feeroz, 2009). In the rainy season, agricultural runoff along the coasts carries sediments, nutrients, and pesticides into the coastal waters, which destroy marine life. Sudden cyclones, storm surges, and debilitating fishing and anchoring practices create further vulnerability to biodiversity loss on the island (Upal, 2015).

6.1.4 Alienation of Local Land and Resources

Mainland speculators have bought beachfront property inexpensively in anticipation of tourism-related development. In many cases, this has pushed locals off their land and reduced access to prime beach areas for locals. The path that tourism development has taken in islands has been a very important factor in determining how much the local economy has interacted with the tourism sector. During the early, small-scale phase of tourism development, local employees and local food products could be used. But as the industry expands and larger, more luxurious facilities are built by outside entrepreneurs and international hotel chains, linkage to the local economy is reduced as a consequence (Reis, 2016). In the majority of instances, locals are not suited to higher-skilled jobs, so they were limited to unskilled, poorly paid, seasonal, and part-time work. This has invalidated the promise of the first generation to provide stable income to the island population (Reis, 2016).

6.1.5 Unequal Distribution of Benefits

Tourism also frequently ravages the islands' environments and destabilizes island community life. Where tourism is perceived to be or becomes the principal economic driver, an island community will quickly become ever more reliant on foreign economic and political influences at the expense of its own stability (Weaver, 2017).

6.1.6 Waste management

The government or any other stakeholder in the economy has done little to mitigate the problem of waste management. Sewage and uncollected untreated garbage were either disposed of in open areas or directly piped into the inshore area, which resulted in adverse impacts on the coastal and marine ecosystems (Hossen & Sultana, 2023).

Large volumes of untreated household and commercial trash, including sewage (only 5% of the population has access to sanitary latrines), are also dumped into the nearby coastal water from both locals and visitors. As a result, coastal water quality is steadily declining. (Touhiduzzaman & Rahman, 2017).

6.2 Importance of Saint Martin:

6.2.1 Economic valuation

Saint Martin's Coral Island is an ecologically critical area (ECA) in Bangladesh, significantly contributing to the local economy, generating approximately 33.6 million USD annually through activities such as fishing, tourism, shoreline protection, seaweed cultivation, and shellfish collection (Rani et al., 2020). Tourism and fisheries dominate the economic contributions, with annual values of 19.4 million USD and 13 million USD, respectively. Additionally, implementing an entrance fee for tourists could generate an estimated 1 million USD annually. Over 25-year, the net present value (NPV) of all resources from the island is projected at 545 million USD, assuming a 6.5% discount rate (Rani et al., 2020).

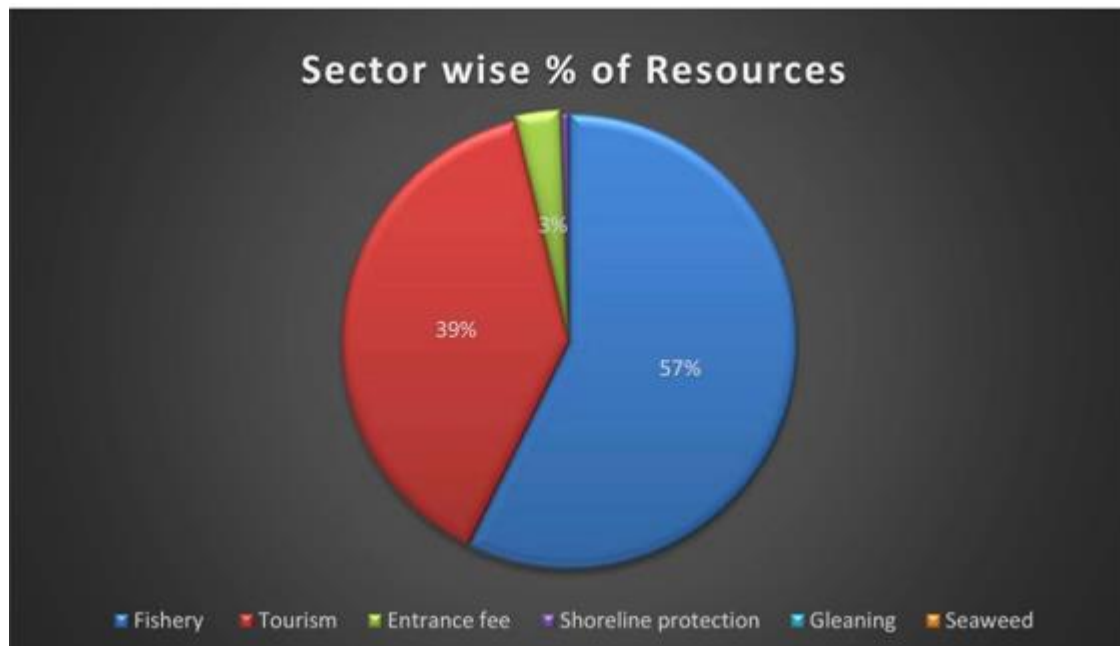


Figure 3: Saint Martin's Island sector contributions (%) (Rani et al., 2020).

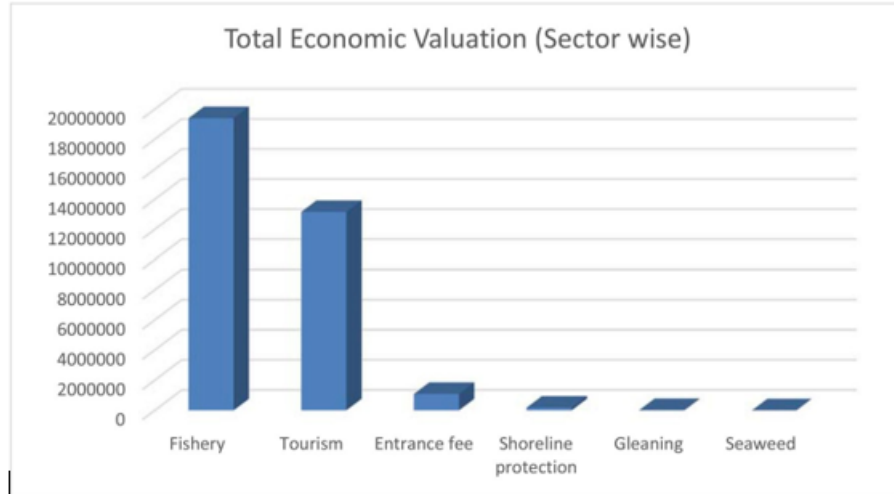


Figure 4: Saint Martin's Island's total economic value (in USD) for each sector (Rani et al., 2020)

6.2.2 Biodiversity Hotspot

The island hosts a diverse range of flora and fauna, including coral reefs, sea turtles, and migratory birds. The coral reef ecosystem is unique in Bangladesh, supporting marine biodiversity and providing habitat for numerous aquatic species (Gazi et al., 2020).

6.2.3 Fisheries and Livelihoods

The surrounding waters of Saint Martin's Island are rich in marine resources, providing livelihoods for local fishing communities. The island supports sustainable fisheries that contribute to food security and income generation for residents (Feeroz, 2009).

6.3 The Governance Challenges

6.3.1 Weak Institutional Coordination

Most small islands have multi-stakeholder arrangements in managing tourism and natural resources, including local governments, environmental agencies, and private tourism businesses. However, these are often plagued by weak institutional coordination and can mean inefficiencies in policy implementations and enforcement. In St. Martin's Island, because of a lack of cohesive coordination among different stakeholders, there has been duplication, miscommunication, and gaps in the conservation policies, hence affecting efficient environmental and tourism management (Biswas, Malaker, & Mollick, 2025).

6.3.2 Lack of Education and Awareness

A major contributory factor to the increasing environmental impact of tourism on St. Martin's Island is a lack of or inefficient awareness and education among tourists, locals, and stakeholders regarding sustainable behavior. Through lack of knowledge about their eventual impact, tourists may well engage in environmentally damaging activities like coral collection, destruction of reefs through water sports activities, and littering. To this end, local communities and businesses may be wholly unaware of the necessity for sustainable use of the resources or the urgency for conservation since unsustainable harvesting of marine resources takes place with other forms of environmental stress (Touhiduzzaman & Rahman, 2017).

6.3.3 Unchecked Development

Construction of tourist accommodation and other related infrastructure happens without proper environmental impact assessment and regulation in many cases. This kind of unchecked development has taken its toll on habitat destruction, poor waste management practices, and depletion of natural resources. Furthermore, hotels, resorts, and other facilities have been built without proper consideration being given to environmental sustainability, increasing the impact on the sensitive ecosystems of the island. (Scheyvens & Momsen, 2008)

6.3.4 Focus on Short-Term Economic Gain

Another reason that aggravates over-tourism is the very short-term focus of many tour operators, investors, and even policymakers. Gains from short-term tourism often blindside long-term sustainability concerns. The pressure for quick profits via mass tourism often creates practices that are harmful to the environment, such as overbuilding or promoting activities that are deleterious to local ecosystems. This myopic practice then makes balancing tourism development and ecological preservation difficult in the long term (Weaver, 2017).

6.3.5 Limited Political Will and Stakeholder Engagement

The final contributing factor is limited government intervention to control the pace at which tourism development occurs on the island. This unhampered expansion of tourism on the island is nurtured by lax government intervention through policies and mechanisms for checking tourist numbers, construction, and environmental safeguards. In the absence of clear and effective regulation of tourism management, the natural resources of the island become subject to overuse and long-term ecological degradation. While setting clear and effective tourism management regulations, the government is an important guarantor that ensures that both the environment and host communities are maintained sustainably (Biswas et al., 2025).

7. Recommendations

7.1 Ecotourism Planning within Marine Protected Areas

Ecotourism, as tourism that is responsible and respectful to the environment, could offer the visitor to enjoy nice sceneries from nature, but at the same time could obtain notions on how to protect it. The main goal of every action always has to be the protection and conservation of the island's natural capital without doing any damage due to tourism (Partelow et al., 2020).

7.2 Identifying Tourism-Related Impacts

Over the course of 14 years, from 2005 to 2019, the built-up area has grown by 175%. Corals have declined by 38%, vegetation covers have expanded by 24%, and a sizable amount of 2.45 acres of vegetation and agricultural land has been converted to built-up space, primarily as a result of increased tourist accommodations.

(Ara et al., 2021). TPI, LST, and built-up regions were found to be positively correlated; beaches near the single jetty have more infrastructure (hotels, resorts, stores, etc.), which puts more strain on these beaches from tourists. Over the past 20 years, St. Martin's island and its distinctive ecology have undergone catastrophic changes, primarily as a result of unchecked tourism growth (Ara et al., 2021). In this respect, proper tourism planning and management are important in lessening these impacts, and activities related to tourism must be weighed against the island's ecological fragility.

7.3 Integrated Coastal Resources Management (ICRM)

This method places a strong emphasis on community participation throughout the whole planning, execution, and monitoring process. With assistance from local councils, government organisations, and academic institutions, the suggested framework centres the management process around local stakeholders. The model imagines a governance framework where government agencies coordinate oversight and policy, scientists offer research-based direction, and locals manage resources daily (Touhiduzzaman & Rahman, 2017).

In order to promote environmental awareness and give communities the tools they need to protect their natural resources, this framework also emphasizes the significance of ongoing education, training, and capacity building. Diversification of livelihoods is a fundamental element of the system. Promoting alternative revenue streams, such as controlled ecotourism, small-scale agro-farming, poultry rearing, and cottage businesses, is advised by the authors because an over-reliance on natural resources contributes to ecological degradation (Touhiduzzaman & Rahman, 2017).

7.4 Impact Assessment and Minimizing Negative Effects

Impact Assessment and Reducing Adverse Effects: The main purpose of an EIA is to notify interested parties about the potential environmental effects of a project and its alternatives. It highlights environmental concerns that should be taken into account while making decisions. The creation and dissemination of impact information has two positive outcomes: it compels a "hard look" at how projects damage the environment and makes it easier for individuals impacted by the proposed project to coordinate. (Ortolano & Shepherd, 1995).

The development of hotels, resorts to serve tourists must go through EIA. These need to be evaluated in terms of the environmental and socio-economic consequences. These will offer better perception to all direct, indirect and induced impacts and suggest feasible alternatives or mitigation strategies.

7.5 Visitor Impact and Management Strategies

Frameworks in the visitor impacts will identify and address environmental impacts brought about by tourism. These frameworks can be crucial in determining biological and social circumstances, baseline information, and the trade-off balance between the maintenance of such environments and recreating chances. (Briguglio & Briguglio, 1996).

7.6 Improving Management Strategies

A sustainable tourism approach would include strategies to protect the island environment and respect the local culture. For instance, the revenues obtained from tourism must be utilized to benefit local communities and the preservation of natural resources. Developing sustainable strategies will have to be done in a manner that secures natural and cultural resources are properly valued and exclude any activities that could threaten or degrade them (Ahammed et al., 2016).

7.7 Standards Setting and Monitoring

Most tourism-related environmental problems are caused due to the lack of standards and inefficient monitoring (Hasan, 2009). Setting of standards based on quality and quantity, for instance, limits on the tourist capacity in any sensitive area and critical threshold of pollution. The environmental protection measures need to be constantly monitored and enforced (Briguglio & Briguglio, 1996).

7.8 Alternative Tourism

Examining other forms of tourism, such as community-based or low-impact tourism, may take some of the pressure off ecologically sensitive areas. Where mass tourism usually involves sun, sea, and sand, the inclusion of alternative forms can help supplement traditional tourism and add

value to the island as a sustainable tourist destination rather than a mass market destination (Habib et al., 2024).

8. Limitations to this study

Data Gaps- Insufficient amounts of historical and reliable secondary data exist on biodiversity, tourism, and environmental impacts

Narrow Scope: Focus on Saint Martin's Island may not generalize to other regions or account for all influencing factors.

Measurement Challenges: Difficulty in isolating tourism impacts from other stressors like climate change or local development.

Seasonal Bias: Data collected during peak tourism may not represent year-round conditions.

Time Constraints: Short study duration may not allow for capturing long-term trends or impacts.

9. Conclusion

Extraterrestrial oceanic and terrestrial resources with high worldwide biodiversity are abundant in St. Martin's Island. Since the island has several rare and endangered species along with various unique ecosystems, its ecological importance is significant (Wyman et al., 2011).

However, due to massive environmental degradation, the place has been listed as one of the environmentally vulnerable areas of Bangladesh. Terrible changes have been observed on this island's distinctive flora and animals over the past 20 years. Little information is presently available about the recent scenario of corals and other associated flora and fauna in St. Martin's. The GoB and other international and nongovernmental groups have taken several steps to protect the island's biodiversity and environment, but those were not adequate as those were not implemented properly (Mousumi et al., 2021). It is not enough to declare the island an ecologically vulnerable area. Proper implementation of the guidelines and policies for safeguarding the rich ecological resources of this important island should be done urgently in the shape of "Ecologically Critical Areas (ECAs)," pollution control, sustainable and controlled tourism, alternative livelihoods for the local people, and more studies. (Rani et al., 2020)

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Paper 24

Climate change in DRR frameworks: Challenges and opportunities for youth-led community mobilization

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Abstract

Bangladesh is one of the most vulnerable countries in world due to climate change. Its coastal areas are severely affected by climate extremes. This paper identifies provisions about involvement of youths in DRR frameworks; and practically measure their challenges & opportunities for community mobilization. Methodologically, an effort is given to find out all youth-related narratives from existing literatures. A total of 100 youth volunteers were interviewed, and six experts of youth-led organizations participated in In-depth Interview (IDI). It was found that policy gaps, coordination difficulties, lack of resource and recognition, non-inclusivity, patriarchal mindset and bureaucratic red tape are major challenges faced by youth volunteers. Noteworthy, Bangladeshi youths have willingness of volunteerism, use of information technology, scope of capacity building, engaging grassroots people; and prospects to strengthening UDMC can contribute for sustainable community-based DRR approach. Respective stakeholders especially state actor, global leaders, forums and funding organizations should take crucial attention for maximizing dividend of youths in this field.

1. Introduction

Youths are significant driving forces for positive changes in the world. A total of 1.2 billion young individuals aged 15 to 24 years, accounting for 16%, live globally (United Nations [UN], 2024). Though youths have myriad contributions to socio-economic and political development, Bhadra (2023) noted that youths are a powerhouse, and they ideally fuel towards growth of the nation if used constructively. Labour Force Survey- 2022 of Bangladesh specified that productive and decent work is the most important means for poverty reduction. Unfortunately, the number of Not in Employment, Education and Training (NEET) youths is 9.65 million (i.e., 22%), whose age is from 15 to 29 years. Youth Policy- 2017 of Bangladesh defined ‘youth’ as an individual aged from 18 to 35 years. In the existing study, the age group of the aforementioned policy has been considered.

Climate change is a global phenomenon. Bangladesh is the seventh most vulnerable country to climate risks in the world (Ministry of Environment, Forest and Climate Change [MoEFCC], 2022). Rashid (2013) specified that Bangladesh is one of the most disaster-prone countries in the world and is constantly facing different kinds of natural and man-made hazards. There are many different types of natural and human-created hazards that pose risk, including floods, flash floods, waterlogging, cyclones, drought, earthquakes, landslides, tidal waves, tornadoes, thunderstorms, riverbank erosion, arsenic contamination of groundwater, salinity intrusion, heatwaves, etc. Impact of climate change, geographical location, land characteristics, numerous rivers, rapid population increase, unplanned urbanization, and industrialization led to the disaster risk. The geographical formation of Bangladesh and the impact of climate change are increasing the number, magnitude, and adverse effects of disasters. Devastating events like the cyclones of 1970 and 1991 washed away many lives and livelihoods of Bangladeshi coastal communities. They also faced a crisis of income during many cyclones, for example, Sidr (in 2007), Nargis (in 2008), Aila (in 2009), Roanu (in 2016), Amphan (in 2020), Yaas (in 2021), Midhili (in 2023), Remal (in 2024), among others.

Pickering et al. (2021) claimed that there are still limited opportunities for youths to learn about disaster management, though their engagement is a powerful engine for operationalizing global and national disaster risk reduction (DRR) policies, including the Sendai Framework. Khatiwada (2022) revealed that climate change is happening. Youths need more grassroots information, knowledge, skills, practices, and groundbreaking ideas to create a sense of ownership and promote mutual learning for minimizing climate-induced disaster risks. Youths' initiated community mobilization on DRR needs to be documented and diffused in a fast-changing world. Based on the above realities, the main aim of this paper is to articulate provisions about youths' engagement in international and national policy frameworks; and challenges & opportunities of youths in practices. Specifically, an effort is taken to identify major issues about youths in disaster-related international and Bangladeshi policies, including NGOs & community-based

approaches, and measure their challenges & opportunities to mobilize coastal communities for DRR.

1.1 International Framework

In 1987, the UN designated the 1990s as the International Decade for Natural Disaster Reduction (IDNDR), in which a resolution was adopted to significantly reduce the damage caused by natural disasters. In 1989, the General Assembly of the United Nations adopted a resolution to establish the International Day for Disaster Reduction, to promote international cooperation in the implementation of disaster prevention measures in countries around the world, and to establish a United Nations Secretariat. During the IDNDR up to 1999, country-level DRR initiatives were developed, and regional DRR cooperation mechanisms were enhanced, including the establishment of the Asian Disaster Reduction Center. Under this international trend, the UN General Assembly adopted the International Strategy for Disaster Reduction in December 1999 and established the United Nations International Strategy for Disaster Reduction (UNISDR). The term 'Disaster Risk Reduction (DRR)' has been used for its mainstreaming since 2000 when UNISDR was launched. In August 2002, *Living with Risk: a global review of disaster reduction initiatives*, the first UN white paper on DRR, was issued in cooperation with Japan, the US, European countries, and the Philippines (Asian Disaster Reduction Center [ADRC], 2015).

The 2nd UN World Conference on Disaster Reduction was held in January 2005 in Kobe City, Hyogo, Japan. The Hyogo Framework for Action 2005-2015 (HFA) was adopted at this conference. UNISDR explains HFA as: Hyogo Framework for Action (HFA) is the first plan to explain, describe, and detail the work that is required from all different sectors and actors to reduce disaster losses. Developing formal and informal channels to reach information among youths, promoting community participation, capacity building of the community, and involving the community in campaigns were major issues, among others (UN, 2005). After that, in March 2015, the 3rd UN World Conference on Disaster Risk Reduction was held in Sendai City, an area affected by the Great East Japan Earthquake. The Sendai Framework for Disaster Risk Reduction 2015-2030 (hereinafter referred to as "Sendai Framework") was adopted at the 3rd World Conference on Disaster Reduction in 2015. It is characterized by significant shifts to proactive disaster risk reduction from the disaster response. It has four priorities. Priority 1: Understanding disaster risk; Priority 2: Strengthening disaster risk governance to manage disaster risk; Priority 3: Investing in disaster risk reduction for resilience; Priority 4: Enhancing disaster preparedness for effective response and to 'Build Back Better (BBB)' in recovery, rehabilitation, and reconstruction. Addressing youths as a key stakeholder, leadership development of youths, space for youths as a change agent in DRR, volunteerism, information dissemination among communities, consultations, technological improvement, developing telecommunication, strengthening community-based organizations, knowledge-hub, campaign & community mobilization, empowering local communities, effective involvement, and initiatives for resilient community are major issues & concerns about youths and local communities (UN, 2015).

Sustainable Development Goals (SDGs), officially known as ‘Transforming our World: The 2030 Agenda for Sustainable Development, the Sustainable Development Goals (SDGs), are a set of 17 aspirational “Global Goals” with 169 targets between them. The SDGs were adopted at the UN Sustainable Development Summit in 2015, USA. The SDGs aim to place countries and the planet on a more sustainable path by 2030. These goals are the foundation of an ambitious new development agenda that seeks to end poverty, help the vulnerable, transform lives and protect the planet. The 17 SDGs are expected to guide policy and funding for 15 years. The SDGs build on the success of the Millennium Development Goals (MDGs). Each of the SDGs relies on reduced disaster impacts to meet its targets. Several goals and targets can contribute to reducing disaster risk and building resilience, even if they are not explicitly stated concerning disaster risk reduction. Reducing disaster risk and building resilience are interrelated thrusts of the 2030 Agenda for Sustainable Development and the Sendai Framework for Disaster Risk Reduction 2015-2030. This convergence offers unprecedented opportunities for building resilience. The framework for the implementation of the 2030 Agenda and its linkages with the Sendai Framework for Disaster Risk Reduction 2015-2030 can help to ensure that disaster risk reduction is mainstreamed across all sectors of sustainable development and climate change adaptation (Mustafa, 2016).

1.2 Bangladesh Context

It is worth noting that, in post-liberation Bangladesh since 1972, two separate ministries were established, namely the Ministry of Relief and Rehabilitation and the Ministry of Food. After some changes, in 2012, the Disaster Management and Relief division was transformed into the Ministry of Disaster Management and Relief. It is envisioned to reduce the risk of people, especially the poor and the disadvantaged, from the effects of natural, environmental and human-induced hazards to a manageable and acceptable humanitarian level and to have in place an efficient emergency response management system (Ministry of Disaster Management and Relief [MoDMR], 2023).

The National Plan for Disaster Management (2021-2025) has strived to enhance the implementation of the Disaster Management Act 2012, Disaster Management (DM) Policy 2015, and Standing Orders on Disaster (SOD)- 2019, which seek to promote safer and more resilient communities. It is a government-wide framework for the effective integration of disaster management planning and programming, focusing on risk reduction and a resilience approach across agencies and sectors. NPDM (2021-2025) takes in a ‘whole of society’ approach to disaster risk management and response initiatives through gender responsiveness and a disability-inclusive approach for resilience (MoDMR, 2020).

National policy instruments, i.e., NPDM, act, policy, and SOD, emphasize local engagement for effective DRR. In this context, youths play a crucial role as agents of change within their

communities. Youth-led initiatives have the potential to bridge the gap between top-down policy frameworks and grassroots action. As members of the most tech-savvy and dynamic segment of the population, youths are particularly well-positioned to leverage new technologies, social media, and community-based networks to enhance DRR efforts. Their ability to engage with local communities and work alongside government & NGOs positions them as key actors in promoting disaster preparedness and resilience. Policy frameworks describe that youths' involvement in community mobilization can also foster greater awareness and proactive behavior toward disaster risks. By participating in disaster preparedness training, early warning systems, and community risk assessments, youths can empower their communities to better understand and mitigate risks. Furthermore, their engagement in local disaster management committees and NGOs allows for more inclusive decision-making processes, ensuring that the voices of vulnerable groups, such as women, children, and the elderly, are heard and addressed. MoEFCC (2022) revealed, in the National Adaption Plan of Bangladesh- 2023-2050, that youths and students are one of the key segments and actors for climate mitigation and adaptation. Youth-led awareness raising, capacity building, rescue, evacuation, nature conservation, watershed, waste management, entrepreneurship, and relevant interventions are necessary for climate adaptation.

1.3 NGOs and Community-based Approach

The NGO's course in Bangladesh underwent a radical upgrade in 1971 when the country became independent. The World Health Organization (WHO) divided operational NGOs into three groups: (a) The community-based organizations (CBOs), which cater to a particular population in a smaller geographical area. The CBOs undertake individual responsibilities compared to other NGOs. (b) National organizations operating in separate developing nations, (c) International organizations pursuing the NGOs' interests in multiple developed countries, while being headquartered in such developed countries. A total of 2,536 Local and National NGOs are working in Bangladesh (Rashid et al., 2020). Some international agencies like U.S. Agency for International Development (USAID), United Nations Development Programme (UNDP), United Kingdom Department for International Development (DFID), European Union (EU), Japan International Cooperation Agency (JICA), Norwegian Agency for Development Cooperation (NADC), Swedish International Development Cooperation Agency (SIDA), Australian Agency for International Development (AusAID), and others actively support in the areas of disaster management of Bangladesh.

Azad et al. (2019) revealed that NGOs have a close connection and reach out to remote localities. They facilitate community members individually and collectively for their socio-economic development, including DRR. Communities identify risks related to disasters, decide on risk reduction and solve disaster risk problems through planning and actions. Communities are entities characterized by a degree of shared norms, values and patterns of reciprocity and are capable of cooperative behavior. Existing coping mechanisms and capacities of the community are important to DRR plans and strategies. It is observed that community-level decision-making

is a negotiated process that is colored by local power struggles and politics as much as by more altruistic values. However, people have learned from adverse experiences and developed ways of responding to disruptive events throughout history for their survival. Ideally, the community manages the implementation of DRR measures in a coordinated way. In this pathway, NGOs play vital roles as a catalyst.

Islam (2013) mentioned that NGOs work as promoters and play a significant role in local-level disaster management in rural Bangladeshi society, where the old institutions and organizational systems had become inadequate to provide external service delivery and govern disasters at all levels. NGOs are contributing efficiently and effectively in all phases of the disaster cycle. Nasreen et al. (2014) indicated that capacity building of the community is a significant part of the process of empowering vulnerable people to cope with and adapt to the impact of disasters, which is needed to move to a world where communities are the first line of defense in facing disasters. This is taken into consideration because the community is the first responder after disastrous situations and is more locally focused. NGOs emphasize supporting a structured learning process of capturing lessons and incorporating best practices into the design and implementation of community-based interventions, including the preparation of a toolkit and guidelines, and visits to adaptation activities in different vulnerable zones.

1.4 Youth-led Community Mobilization

Bangladesh has a coastline of 710 kilometres and an Exclusive Economic Zone (EEZ). There are different views on the delimitation of the coastal areas. The conventional view is that the land that is inundated by the high and low tides is called the coastal belt. Coastal zones refer to areas where land and sea meet. Three indicators have been considered for determining the landward boundaries of the coastal zone of Bangladesh. These are: influence of tidal waters, salinity intrusion, and cyclones/storm surges. A total of 19 districts (Map 1) of the country are being affected directly or indirectly by some of these phenomena (Water Resources Planning Organization [WARPO], 2005). Coastal areas of Bangladesh are faced with several natural hazards like cyclones, storm surges, floods, etc. In addition, there are man-made hazards like arsenic, water-logging and salinity in water & agricultural land. Noteworthy, this zone has diverse ecosystems: mangrove, marine, estuary, islands, coral, sandy beaches, sand dunes and has both 'world heritage sites' and 'ecologically critical areas'.

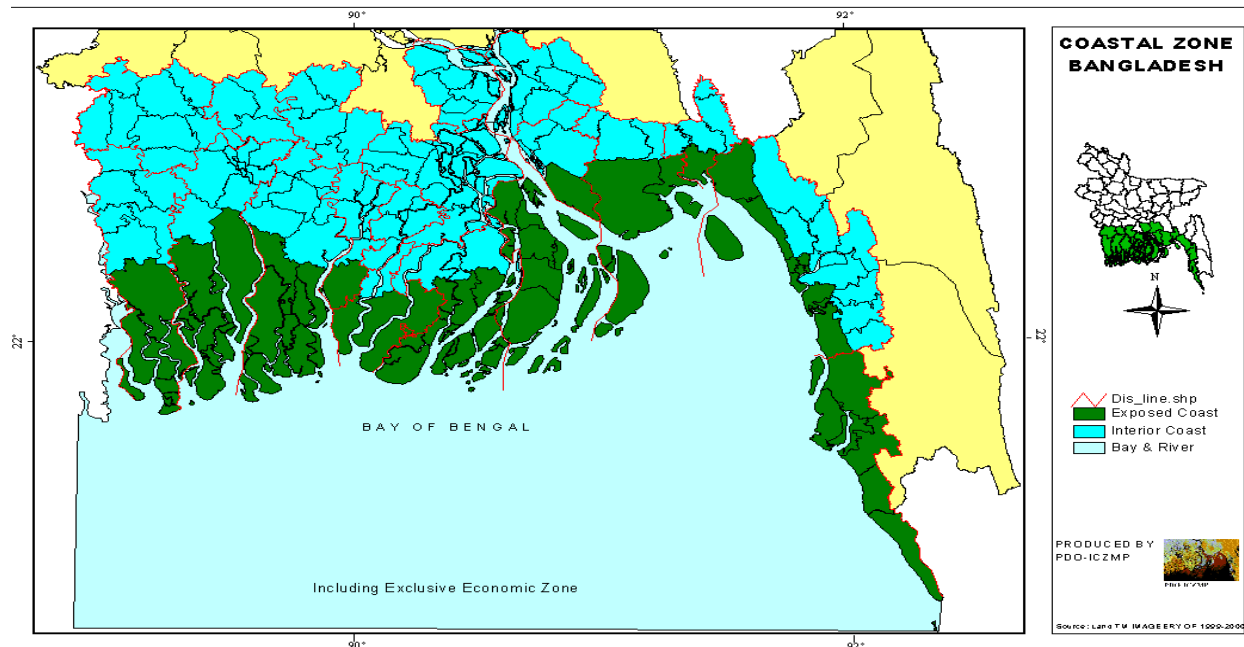


Figure 1: Coastal Zone of Bangladesh. Source: Islam et al. (2006)

Community mobilization in the context of DRR is a critical mechanism that empowers local populations to take active roles in managing risks and responding to disasters. In Bangladesh, especially in disaster-prone coastal areas, mobilizing communities involves fostering collective efforts to plan, prepare, and act in the face of natural hazards. This process builds on the local knowledge, social capital, and collective resources of the community, aiming to create a more resilient and responsive environment to mitigate disaster impacts. This mainly includes organizing community meetings, disaster preparedness training sessions, and capacity-building workshops. Communities are encouraged to actively participate in risk assessment, evacuation drills, and preparation of local disaster management plans through these interventions.

One of the key aspects of successful community mobilization is the involvement of community members at all stages of the disaster management cycle- preparedness, response, recovery, and mitigation. By encouraging active participation, communities can ensure that DRR strategies are locally appropriate and sensitive to their specific needs. This involvement helps to build a sense of ownership over disaster risk management initiatives, ensuring that these measures are more sustainable in the long run. Community mobilization also benefits from the integration of indigenous knowledge with scientific risk assessment methods. Many coastal communities in Bangladesh have developed traditional ways of coping with disasters, such as building cyclone-resistant homes or managing natural resources to prevent erosion. By blending these local practices with modern DRR strategies, such as early warning systems and disaster risk mapping, communities become more resilient and better prepared for future disasters.

Based on the study objective, the authors have depicted a conceptual framework in Figure 2. Issues of DRR frameworks (international and national), particularly relating to youths' engagement, are picked up. Grassroots-level practical challenges and opportunities of youths for community mobilization are addressed to show a real picture in the context of Bangladeshi coastal societies. Youths are considered agents of change within their communities to mobilize people regarding DRR.

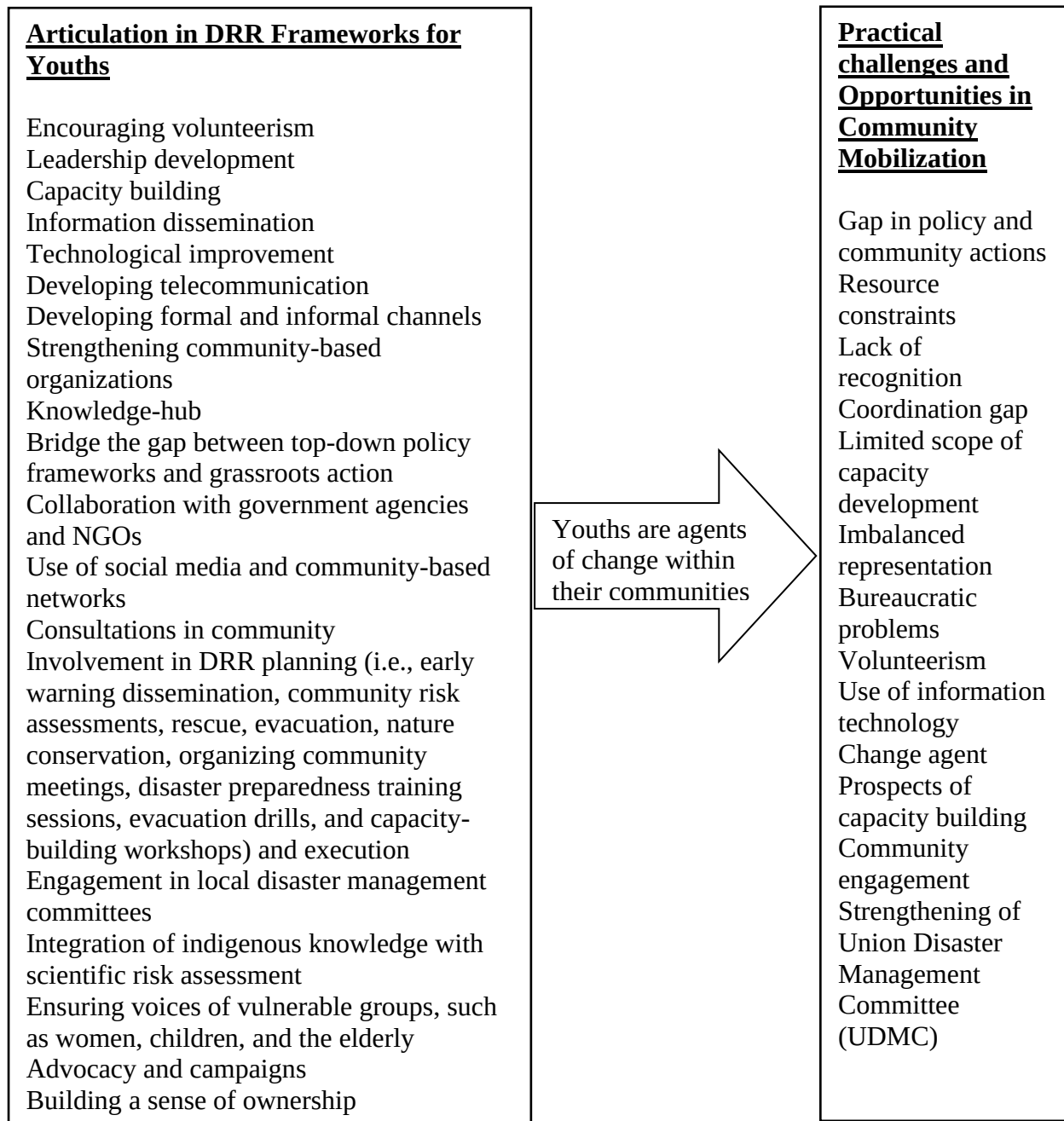


Figure 2: Conceptual Framework

1.6 Data from Grassroots

Barisal district in Bangladesh is considered one of the most climate-vulnerable areas due to its low elevation, coastal location, and exposure to frequent flooding, cyclones, and rising salinity levels, making it highly susceptible to the impacts of climate change (Mukherjee et al., 2020). Thus, the authors collected field data from three sub-districts (e.g., Barisal Sadar, Mehendiganj, Swarupkathi) of Barisal district between November to December 2024. A mixed-methods approach was followed for data collection. A semi-structured questionnaire was used to gather data from 100 youth volunteers (64 males and 36 females) of six youth-based organizations. In addition, six personnel of the same organizations contributed to the in-depth interview (Annex 1). Six local organizations mainly work on disaster management, environment, health, and other social issues. Enthusiastic youth volunteers and small grants from donor agencies and the government are key strengths of these organizations. Engagement in disaster preparedness, relief distribution, rescue, and direct working with community people were major criteria of volunteers to be respondents for the survey questionnaire.

2. Study Findings

2.1 Respondents' Information

Among 100 youth volunteers, 68% were married and 32% unmarried. The majority of them (43%) completed graduation, 23% passed Higher Secondary Certificate (HSC), and 34% completed Secondary School Certificate (SSC). A big portion (79%) of the total respondents are students, and the rest (21%) have just entered professional life.

2.2 Challenges

2.2.1 Gaps between policy and community actions

The community-based DRR approach is still ignored in these realms by policymakers and practitioners. A total of 78% respondents reveal that disaster management policy frameworks often adopt a top-down approach, which may not align with the realities or needs at the grassroots level. Youth volunteers face challenges bridging this gap between policy and community-level action. They also identify that community people are not sufficiently aware of the policies and their impact on what is made for them. In-depth Interviewee 4 raised apprehension in this piece, stating:

“DRR policies are predominantly top-down. We observe that policymakers hear, in few extents, issues and concerns of grassroots people through consultative process; but are not reflected fully in policy frames as expressed by people. Moreover,

described policy issues are not executed in effective ways. There is a big gap of transforming policy decisions into actions.”

2.2.2 Lack of resources and recognition

Budget allocation, necessary equipment, instruments, vehicles, infrastructure, and technical assistance (i.e., preparing contingency plans, conducting simulations, warning messages, distributing humanitarian aids, rescue, evacuation, shelter management, repair, reconstruction, etc.) are part and parcel of DRR. A total of 59% respondents indicate that the lack of sufficient financial and technical resources hinders the implementation of DRR initiatives effectively. In addition to that, 53% respondents perceive that government departments do not formally recognize youth volunteers except members of Cyclone Preparedness Programme (CPP). A government-led intervention. In-depth Interviewee 1 recounted:

“Standing Orders on Disaster, 2019 of Bangladesh recommended for allocation of necessary resources and implementing DRR programs in accordance with the Sendai Framework, SDGs, Delta Plan 2100, Five Five-Year Plan. But general people exposed to disaster vulnerability are deprived, and they never get access to what sort of disaster management programs are being planned and executed by the Upazila (sub-district) and District administrations in Bangladesh. Besides, Upazila administrations are not well supportive to make the Union level Disaster Management Committee (UDMC) effective, as resource allocated for disaster management is usually handled by officers of the government.”

2.2.3 Coordination gap

There is fragmentation of disaster response efforts due to poor coordination among government agencies, NGOs, and community organizations. 39% of total respondents mention that the lack of shared goals and understanding among stakeholders hampers to the execution of unified strategies. Lack of coordination is a major cause of overlap in program interventions. In-depth Interviewee 2 shared:

“Coordination among youth-based organizations, government and NGOs is significantly required for fruitful DRR. But government department sluggishly assists youth-based organizations, even ignoring in coordination process.”

2.2.4 Lack of training and capacity building

Poverty, undernutrition, inadequate human development, unemployment, and youth delinquency are major problems for sustainable community-based DRR in Bangladesh. NGOs have to depend on external funding from donor agencies. Thus, interventions of NGOs are mostly ad hoc-based

rather than mainstreaming on DRR. 76% of total respondents specify that insufficient training and capacity building opportunities by government departments in disaster preparedness, early warning systems, and community mobilization ruin the potential of youths. Moreover, limited access to modern tools, like geospatial mapping or other advanced DRR technologies (e.g., remote sensing, drones, crowdsourcing, cloud storage), hampers youth-led initiatives.

2.2.5 Non-inclusive representation

Women and marginalized groups (e.g., children, the elderly, disabled) are often underrepresented in youth-led and broader disaster management efforts, which limits inclusivity. 67% of total respondents opine that there is very limited access for the above groups in policy discussions. Effective inclusion of women, children, the elderly, and disabled persons in local disaster management forums is very important. In-depth Interviewee 3 specified:

“Utilization of the wisdom and experience of elderly persons is the biggest asset for youths, particularly in community-based DRR. Similarly, the views of children and persons with disabilities are very important for designing and implementing DRR activities. We observe a serious negligence regarding the proper representation of themselves.”

2.2.6 Cultural and bureaucratic hurdles

The traditional societal norms sometimes undervalue the roles of youth in decision-making processes. 57% of total respondents remark that participation of female youths in such voluntary activities is still not encouraged due to stereotyped gender norms and social taboos. A total of 23 female respondents, out of 36, profess that family members permit training, workshops, and meetings on DRR issues rather than humanitarian aid distribution and rescue work because of social insecurity. Bureaucratic hurdles for obtaining permission or funding to take initiatives demotivate youth-based local organizations and their volunteers. In-depth Interviewee 6 briefed:

“The Government of Bangladesh (GoB) do not support unregistered youth-based organizations, and the registration process is also very complicated. The government-led disaster management department is yet to establish a comprehensive knowledge hub for youths. Noteworthy, a specialized agency like the Bangladesh Red Crescent Society provides training for our volunteers on a limited scale.”

2.3 Sense of Volunteerism

Youths of Bangladesh have proactiveness to be involved in voluntary activities particularly for humanitarian response. 98% of total respondents urge that youth force is a valuable asset for mainstreaming of community-based DRR approach. They can promote the collection, analysis, management and use of relevant data and practical information and ensure its dissemination,

considering the needs of different categories of users. Youths have the capacity for baselines and periodically assess disaster risks, vulnerability, exposure, hazard characteristics and their possible sequential effects at the relevant social and spatial scale on ecosystems; and periodically update and disseminate, as appropriate, location-based disaster risk information including risk maps, to decision makers, the general public and communities at risk of exposure to disaster in an appropriate format. In-depth Interviewee 5 explained:

“Intense precipitation in Tripura (a state of India) has caused several rivers to overflow since 22 August 2024. In addition, heavy rainfalls in Bangladesh caused colossal floods mostly in Chattogram (north side), Feni, Cumilla, Noakhali, Lakshmipur, and Brahmanbaria districts. Youths of different districts voluntarily participated in emergency response in flood-affected areas. Their dedication was highly appreciated by all. We should keep up their spirits.”

2.4 Roles as agents of change

Youths, being tech-savvy and dynamic, can leverage social media, technology, and community networks to raise awareness and mobilize grassroots people effectively. 87% of total respondents claim that they are well-positioned to adopt and promote innovative DRR strategies, such as risk & resource mapping and early warning systems. They already developed texts in local dialect and used Short Message Service (SMS), alerts by mobile application, video clips, and an online youth platform, youth networking for information sharing. In-depth Interviewee 1 shared:

“Our youths have vast potentiality and willingness for volunteerism. They can play a role in changing society positively by using updated technology and value-based & lifelong learning. They can also foster our indigenous knowledge in the areas of DRR.”

2.5 Capacity building through NGOs

Few NGOs arrange trainings, workshops, spot visits, and a facilitating platform for youths to lead DRR initiatives, fostering leadership and resilience-building skills. Collaborations with NGOs also offer youth exposure to global best practices in disaster management. 84% of total respondents appeal to increase the exchange program at home and abroad to increase their capacities. In-depth Interviewee 5 suggested taking more initiatives for the capacity development of youth volunteers. According to her:

“Bangladesh is one of the most climate-vulnerable countries in the world. Its coastal zone is severely affected by climate extremes. Our organization arrange capacity building trainings for youth volunteers. Initiatives of the government should be increased in this regard.”

In-depth Interviewee 3 raised his concern about external funding and responsibility of global leaders. According to him:

“Coastal communities are frontline victims of climate change. NGOs' foreign funding declined in Bangladesh due to its transformation to a middle-income economy in 2015. But many remote coastal pockets remain in poverty-stricken and vulnerabilities of climate change. Thus, global leaders should ensure the necessary funds to address DRR issues, among others.”

2.6 Community engagement

Youths are playing a pivotal role in educating their communities about disaster preparedness and risk reduction. 89% of the total respondents acknowledge that it is a great chance for them to work with grassroots people. They urge that if community members directly engage with risk assessments, organizing meetings, training sessions, simulations, early warning dissemination, rescue, shelter management, and rehabilitation, then the results of community-based DRR will be more fruitful. In-depth Interviewee 6 narrated:

“We run one project on DRR, funded by UNICEF. Our youth volunteers have prospects to engage community people effectively.”

2.7 Strengthening UDMC

The Union Disaster Management Committee (UDMC) is an important forum at the grassroots level of Bangladesh. 75% of total respondents believe that community-level youths can raise the voices of people and positively influence decision-making through UDMC. In-depth Interviewee 5 elucidated some examples about the working scope of youths by UDMC. According to her:

“Youths can facilitate to organize UDMC meetings regularly both pre, during and post disaster phases; raise dedicated fund for disaster risk reduction; set up disaster warning station in each Union Parishad office; construct and maintain disaster shelter centers within the Union Parishad; form volunteer teams under each Union Parishad for emergency response; effective training on disaster preparedness and emergency response; enhancing social awareness campaign on disaster management; and ensuring rapid and timely coordination.”

3. Discussion

In this section, the findings of the present study have been critically explained to discover the realms of echo and discordance relating to past studies. The scoping review highlights significant commitments for the involvement of youths in DRR frameworks. This study finds that although Bangladesh has made strides through government initiatives like the National Plan for Disaster

Management (2021-2025) and the Standing Orders on Disaster (SOD-2019), there is still a gap in fully integrating community-level initiatives into these frameworks. The lack of effective partnership and coordination among governmental, non-governmental, and community stakeholders is another significant issue. Similarly, Mallick et al. (2011) claimed that no single group or organization can address every aspect of disaster management. Disaster management thinking sees disasters as complex problems demanding a collective response. Disaster management requires strong vertical and horizontal linkages. Department of Disaster Management (DDM) is responsible for coordinating and making "disaster risk reduction and response activities of all governmental and non-governmental agencies object-oriented and robust". In reality, agencies participating in humanitarian response generally lack a shared understanding of the problem.

Bessaha et al. (2022) identified that formal and informal recognition of youths by the government and civil society organizations increases their willingness to participate in DRR initiatives. However, existing study discovers that government recognition of youth volunteers is comparatively lower. Youth volunteers of this study identify that the representation of marginalized women, children, the elderly, and persons with disabilities is limited in DRR-related policy discussions. Correspondingly, The Daily Star (2019) reported that while two women are included in disaster management committees, i.e., Union Disaster Management Committee (UDMC) but their voices and needs are not always adequately represented. Gender mainstreaming in DRR is one of the major challenges.

Youth volunteers of the present study opine that social taboos and family restrictions actively hamper to engagement of female youths in DRR activities. Equally, Lee et al. (2022) mentioned that stereotyped institutional design, female self-deprecation, household cohorts, social disparagement discourage females to contribute at disaster-resistant communities (DRCs) in Taiwan. Female empowerment should be ensured to increase their involvement in DRR initiatives. Rahman et al. (2020) identified that climate adaptation innovations of Bangladesh face challenges from overwhelming bureaucratic complexities. The fact of the current study is also quite similar, which demoralizes youth volunteers in the community-based DRR approach.

Mafimisebi and Thorne (2017) studied risk perception, behaviors and moral disengagement among youths of Niger. Environmental risks are perceived as more important by youths. Existing study discovers that Bangladeshi youths have a strong sense of volunteerism, especially in humanitarian responses. It has been developed from generational and in-built characteristics. The current study also realizes that youth volunteers will be actual change agents in communities if nurtured properly. They are tech-savvy and dynamic, and have the capacity to develop DRR strategies and execute them properly through community engagement.

The role of NGOs in capacity building and raising disaster awareness at the grassroots level is admirable. Existing study urges increasing NGOs' funding for leadership and capacity development of youths to ensure the sustainability of community-based DRR approaches. Seddiky et al. (2020) also suggested ensuring funding for NGOs for the mainstreaming of DRR, aligning with international principles. Quader et al. (2023) claimed that Union Disaster Management Committees (UDMCs) of Bangladesh face several institutional challenges, like institutional dependency i.e., limited financial and administrative autonomy. The present study mentions that fruitful engagement of youths in UDMC can strengthen its institutional capacity and influence decision-makers for better decentralization.

4. Conclusion

Due to global climate change, DRR frameworks have become more important. Numerous directions and commitments for engagement of youths are highlighted in these international and national frameworks. But its implication is comparatively lower in Bangladesh. It has strong youth forces. Myriad potentialities and contributions of youths in DRR will be systematically ruined due to negligence of respective actors and sectors. Based on the situation, this study urges the state, global leaders, forums and donor agencies to take special and urgent attention to promote the capacity of youths in community-based DRR mainstreaming.

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Paper 25

Critical Assessment of Green Bonds to Finance Climate Action in Indian Cities

Priyal Shethia

Abstract

Indian cities are vulnerable to the impacts of climate change. Coupled with the lack of basic infrastructure, mitigating and adapting to these impacts is financially intensive for city governments. Traditional financing methods are unable to meet the financial gap. To address this, some cities have issued municipal green bonds (MGBs) to finance infrastructure projects. This study critically assesses the role of MGBs as a financing mechanism for climate actions in Indian cities. Through a mixed-methods approach combining policy review, financial analysis, and expert interviews, the research investigates the evolution, implementation, and challenges associated with Indian MGBs. Cities that issued green bonds (Ghaziabad, Indore, Ahmedabad, and Vadodara) form the core of the study, assessed on their fiscal health, bond characteristics, and project alignment with climate goals. The analysis reveals that most issuances are financially incentivized rather than driven by long-term climate financing strategies. MGBs do improve transparency and attract investor interest. However, they remain underutilized due to structural, regulatory, and institutional constraints. Inconsistent transfers, weak non-tax revenues, and absence of robust impact monitoring further limit their effectiveness. Regulatory frameworks exist but require improved standardization in project selection, third-party verification, and impact reporting to safeguard the climate impact. To address these gaps, the study proposes a structured '4 Cee' framework that is built on Creditworthiness, Capital Pipeline, Classification of Greenness, and Compliance Monitoring. This intends to help ULBs prepare, assess, and execute climate-aligned projects suitable for green financing. The framework also highlights the importance of long-term planning, strong institutional frameworks, and reliable post-issuance reporting. Thus, MGBs have strong potential to become a viable instrument for financing climate-resilient infrastructure in Indian cities. However, their scalability depends on capacity building, regulatory clarity, and incentives that reward impact, not just compliance. Institutional strengthening and focused policy support will be essential to mainstream this tool into India's urban landscape.

1. Introduction

Currently, it is estimated that about 36% of the current Indian population resides in cities (Statista, 2025). Concurrently growing, the urban population in Indian is expected to reach 50% by 2050 (Niti Aayog, Asian Development Bank, 2022). About 70% of the global CO₂ emissions are from urban areas, which are also affected by the adverse effects of climate change (IPCC, 2017). The effects of climate change are experienced all over the globe. Extreme weather events such as floods, droughts, and heatwaves are becoming more frequent, causing damage to people, livelihoods, and public assets (XDI, 2023). More than 80% of the Indian population is highly vulnerable to extreme climate events (Mohanty & Wadhawan, 2021). Indian cities already struggle with basic infrastructure systems. Rapid urbanization combined with the increased risk from climate change, puts massive pressure on infrastructure systems, which are already insufficient (Natraj, 2015). To meet the rising infrastructure demand amidst growth and escalating vulnerabilities has created an urgent financing gap for urban areas in India (Srinivasan, Ghoge, Haldar, Bazaz, & Revi, 2023).

In its attempt to strengthen its resolve to develop responsibly, India has also committed for Net Zero Emissions goal by 2070 at the COP26 through its Nationally Determined Contributions under the Paris Agreement. India aims to reduce emissions by 45% by 2030 from 2005 levels (PIB, 2022). This commitment has brought climate action at the forefront of development and paved the way for various policies that prioritize responsible strategies to minimize negative environmental impact. Estimates suggest that India requires an investment of USD 2.5 trillion from 2015 to 2030 (roughly USD 170 billion annually) to meet these NDCs (GIZ, 2025). Another estimate by the International Finance Corporation (2023), suggests that India needs to invest USD 289 billion annually and the actual current investment amounts to USD 44 billion. This brings the gap of annual climate finance to USD 245 billion. Both these estimates suggest the dire need for climate-focused investment in the country.

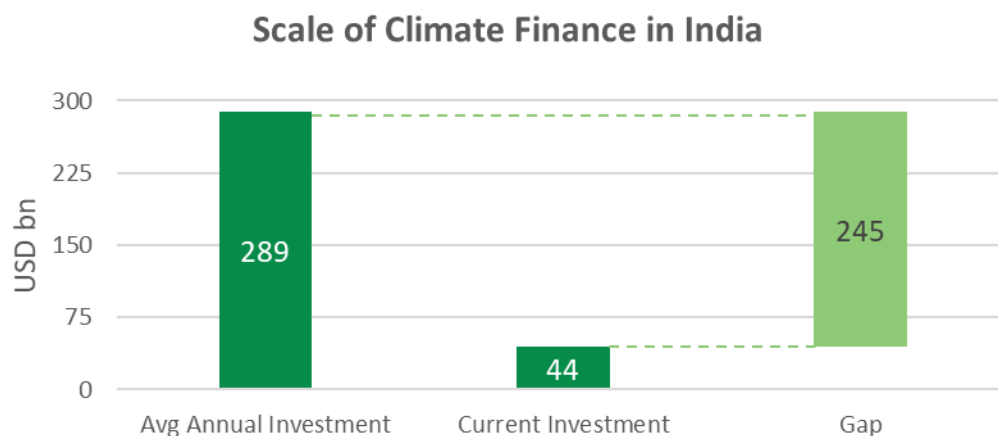


Figure 2: The scale of the Climate Finance Gap in India. (Source: IFC, 2023).

For India to manage emissions in accordance with the NDCs, an average investment amounting to 2.1% of the total GDP would be required (Srinivasan, Ghoge, Haldar, Bazaz, & Revi, 2023). Currently, the total capital expenditure budget for 2025-26 is 3.1% of the GDP of which urban investment amounts to 8.6% (INR 96,777 cr.) (Ministry of Finance, 2022). This shows the large gap in funding that cities need to overcome to tackle the climate crisis. Additionally, climate investments are capital-intensive. However, a large proportion of the municipal budget is utilized for revenue expenditure, and only 40% is used for capital expenditure (International Finance Corporation, 2023). The lack of adequate capital investment slows the execution of projects or activities, which in turn disproportionately increases the burden on the vulnerable.

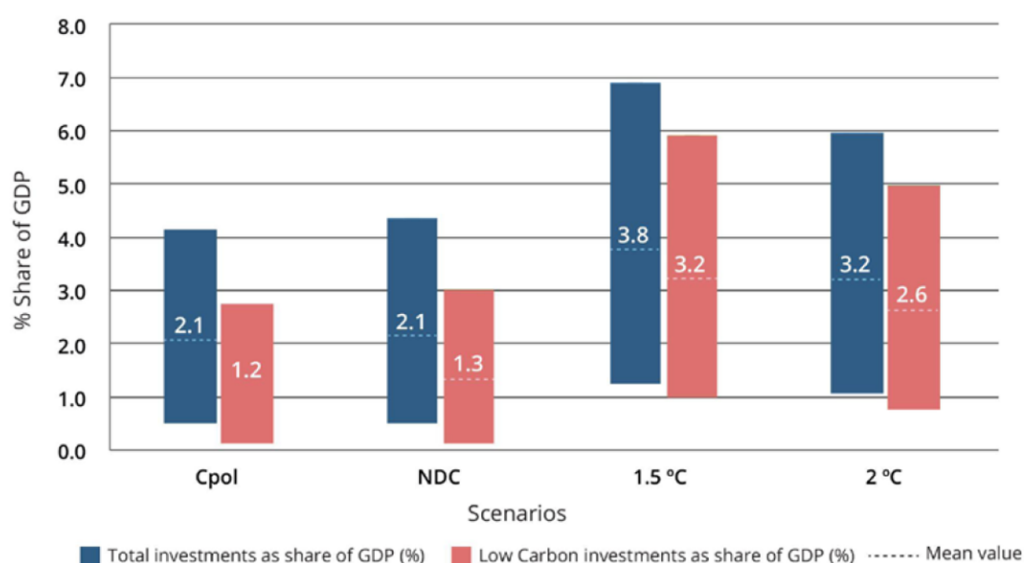


Figure 3: Estimated annual investments as a percentage of GDP in India (2016–50). Source: (Srinivasan, Ghoge, Haldar, Bazaz, & Revi, 2023)

While the need for climate-resilient infrastructure is well recognized, most Urban Local Bodies (ULBs) lack the fiscal space and institutional capacity to mobilize resources at the scale required. As a result, they are dependent on alternate modes of financing through state and central transfers for financing capital projects. These traditional sources, such as transfers, grants, and loans from development finance institutions, are insufficient and unreliable. Moreover, few ULBs have the technical readiness or regulatory autonomy to attract private capital.

The problem is not just financial. Many ULBs rely heavily on intergovernmental transfers, which are not systemic (Praj, 2024). Many states do not provide predictable fiscal support to cities, leaving municipal bodies vulnerable to funding shocks. Even where transfers do exist, they tend to support short-term infrastructure needs rather than long-term climate adaptation or mitigation. Simultaneously, non-tax revenues, although critical for local financial autonomy, continue to be

a small proportion of ULB income due to poor enforcement, outdated valuations, and weak administrative capacity (RBI, 2022).

Yet, the urgency for cities to act on climate is intensifying. India has committed to net-zero emissions by 2070 (PIB, 2022), and cities will play a central role in meeting national climate targets. This requires a dramatic shift in how urban infrastructure is planned, financed, and governed. Indian cities are at a critical juncture. The effects of climate change are already visible, and the infrastructure built today will either lock cities into unsustainable trajectories or lay the foundation for resilience. ULBs need to opt for alternate sources of income that taps into the private capital to finance its infrastructure. Municipal bonds are one such instruments that ULBs can explore to attract private capital. To further the benefits of this instrument, municipal governments can also opt for municipal green bonds (MGBs) to finances projects that contribute to climate action by mitigation or adaptation. The adoption of municipal bonds and particularly green municipal bonds has been largely limited across the country signifying challenges.

This paper critically assesses the municipal green bond ecosystem in India to understand where it stands, what holds it back, and what must change. It argues that without strong institutional frameworks, credible project pipelines, and continuous impact monitoring, green bonds will remain underleveraged. As climate risks intensify, cities cannot afford to delay. The question is no longer whether Indian cities need climate finance but rather how they can build the systems needed to access and utilize it meaningfully.

2. Research Aim

In order to assess the effectiveness of green municipal bonds, the context in which they are being deployed and their evolution from municipal bonds needs to be evaluated, too. The first conceptual tension that arises is whether green municipal bonds vary from municipal bonds. This leads to the study of the evolution of MGBs in India as a tool to finance urban infrastructure. Green municipal bonds are meant as a tool to finance climate action. Cities are encouraged to prepare climate action plans and elevate their efforts to combat climate change through mitigation and adaptation strategies. Although categorized as ‘green,’ the actual environmental impact also needs to be evaluated. This leads to the assessment of the effectiveness of green municipal bonds to finance climate action in Indian cities. The impacts of climate change are across the country; however, the adoption of the tool to finance infrastructure needs to be scaled to achieve large-scale country-wide impacts. With these questions, the research aims to critically assess the role of MGBs and find ways to scale this tool to other cities in cities using a framework that can be readily applied.

3. Methodology

The study adopts a mixed-methods approach combining policy review, financial analysis, and expert interviews. The research investigates the evolution, current implementation, and

challenges associated with green municipal bonds. Ghaziabad, Indore, Ahmedabad, and Vadodara, cities with municipal governments that issued MGBs, form the core of the study, have been assessed for their fiscal health, bond characteristics, and project alignment with climate goals. The findings of the study culminate in a framework that guides the ULBs to improve their capacity to adopt this instrument for financing climate actions in cities.

To study the evolution of municipal bonds, the evolution of the legal and institutional frameworks that gave impetus to municipal bonds and green bonds was conducted. Based on this, the different types of municipal bonds and MGBs that are issued in the market were studied. The development of the municipal bond market in India was then analyzed based on these developments in the legislation and commitments at the national and international levels. This analysis was conducted through a review of the existing Indian legislative frameworks that govern the Indian bond issuances and the international frameworks that guide the development of green finance globally. Bond issuances and their characteristics were reviewed based on secondary literature and desk research, along with stakeholder consultations through semi-structured interviews. To evaluate the role of municipal bonds in financing climate action, a basic overview of the cities that have issued MGBs has been conducted to identify the need for climate action. This has been compared with the financial status of the ULB by analyzing the budget documents and the balance sheets. Documents such as pre-issuance disclosures, detailed project reports and tender documents have been analyzed and studied to assess the alignment of the green principles. Case studies have been conducted through desk research and key informant interviews with national and international experts to understand the scope of the tool beyond its current potential. Based on the assessment of the current frameworks, the effectiveness of MGBs as a financial tool for climate action has been assessed. Based on the challenges identified and the areas for improvement, strategic recommendations have been formulated to scale the instrument. Learnings from case studies and expert opinions have been used to make informed and tactical solutions that can further amplify the tool for climate action in Indian cities.

The scope of the study includes analyzing the evolution of municipal bonds into green instruments, understanding their legal, institutional, and policy frameworks, and assessing their role in enabling climate-resilient infrastructure. The research is concentrated on those cities in India that have issued MGBs until March 2025 (when this research was conducted), namely, Ghaziabad, Indore, Ahmedabad, and Vadodara. However, the study is limited by the availability and accessibility of municipal financial data and post-issuance impact assessments. Additionally, as GNN and IMC issued the bonds before the revised the ILMDS Regulations, there are differences in the compliances that may be applicable to these ULBs as compared to AMC and VMC. Furthermore, some financial aspects such as transfers, are also subject to state legislations, missions, and objectives.

4. Evolution of Municipal Bonds

The development of municipal bonds, both globally and within the Indian context, municipal bonds are issued by public entities for funding public infrastructure projects, with investors receiving fixed interest payments and principal repayment upon maturity. The concept originated in the United States, with the first recorded municipal debt issued by the City of New York in 1812. These instruments gained traction in 1913 due to their tax-exempt status, which boosted investor interest (SEC Historical Society, 2015). There are various types of municipal bonds issued by the government based on various characteristics. There are two broad categories of bonds based on the repayment mechanisms, namely, general obligation bonds and revenue bonds. Indian municipal bonds cannot simply be characterized as general obligation bonds, as they do not receive a sovereign guarantee, nor can they be categorized as revenue bonds, as repayments are not tied to the revenue of the projects financed using the bonds due to low revenue generation. Most bonds have tenors of 3 to 10 years, which is too short a turnaround period for municipal projects. They are instead repaid by escrowing another steady own-source revenue of the municipal body regularly.

In the 1990s, along with economic liberalization and financial decentralization ULBs started borrowing for financing infrastructure projects in cities. Continuous borrowings without adequate repayment strategies were financially unstable for the ULBs (Edanan & Mathur, 1998). The FIRE-D program, supported by USAID, played a key role in encouraging municipal borrowing. High dependency on commercial loans was increasing the borrowing costs for municipal bodies. The municipal bond market thus emerged in India in the 1990s. The first municipal bond was issued in 1997 by Bangalore Municipal Corporation, followed by Ahmedabad Municipal Corporation in 1998 with the first unsecured bond issuance. Over the next decade, several ULBs, including Indore, Nashik, and Nagpur issued bonds, primarily for roads, water supply, and sanitation projects. These bonds had lower coupon rates (13% to 14.75%) as compared to commercial loans that had higher interest rates.

A major turning point was India's move in 1999 to make municipal bonds tax-free, lowering investor risk and borrowing costs. Many smaller ULBs did not have the technical and financial capacity to raise municipal bonds. To combat this, pooled bonds were issued by TNUDF and later Karnataka's WSPF, which further helped smaller ULBs access capital. More than 10 ULBs pooled their resources through the pooled bonds to finance projects in small cities which otherwise would not be able to access these funds.

However, the momentum for municipal bond issuances declined post-2005 due to performance-based grants available to cities under Jawaharlal Nehru National Urban Renewal Mission (JnNURM). This reduced the immediate need for market-based finance as cities had access to a large volume of capital under the mission. Pooled bonds continued to be issued by TNUDF and Karnataka's WSPF; however, such practices were not extended to other states and eventually diminished completely.

After a nearly stagnant period from 2005 to 2016, a key regulatory milestone for the revival of municipal bonds was SEBI's Issue and Listing of Municipal Debt Securities (ILMDS) Regulations, 2015. These regulations set out eligibility, disclosure, and reporting norms, including the establishment of escrow-based repayment mechanisms. Atal Mission for Rejuvenation and Urban Transformation (AMRUT) played a pivotal role in reviving the municipal bond market by offering incentives to cities that raised funds through bonds. They were revised in 2017, 2019, and 2023 to strengthen the regulations and accommodate green municipal bonds. From 2018, ULBs could receive grants on bond issuances under AMRUT, encouraging cities to explore market-based financing. With AMRUT 2.0, an additional incentive was introduced for green municipal bond issuances.

These reforms and incentives were pivotal in the country as 14 cities issued municipal bonds since 2017, starting with Pune Municipal Corporation (refer to Figure 4). The bonds were used to finance water supply and sanitation, and road projects in the cities. Under AMRUT, ULBs were eligible for a grant worth INR 13 crore for every INR 100 crore raised using municipal bonds, with a limit of INR 26 crores. As a result, most bonds were raised with issue sizes up to INR 200 crores based on the capacity and the needs of the ULBs.

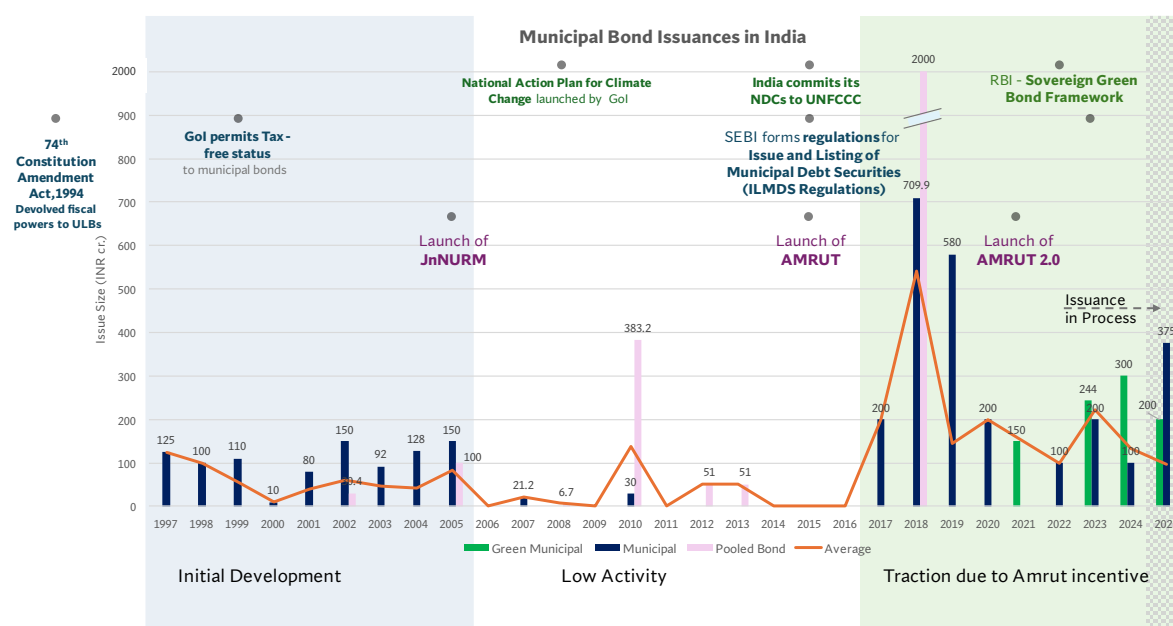


Figure 4: Evolution of municipal bond issuances in India by year. Source: Compiled by author from multiple sources

Note: Municipal bond issuances started in 1997, lost momentum 2006 onwards due to JnNURM and regained traction on 2017 after the launch of AMRUT.

Lastly, state-level regulatory frameworks significantly influence a city's ability to issue bonds. While some states like Maharashtra, Gujarat, and Madhya Pradesh enable ULBs to independently raise funds, many others lack the institutional or legal structures to support this. Although the 74th Constitutional Amendment Act called for fiscal devolution, implementation has been uneven. As a result, even with 164 ULBs having investment-grade ratings by 2022, only a handful have issued bonds. As seen in **Figure 4**:

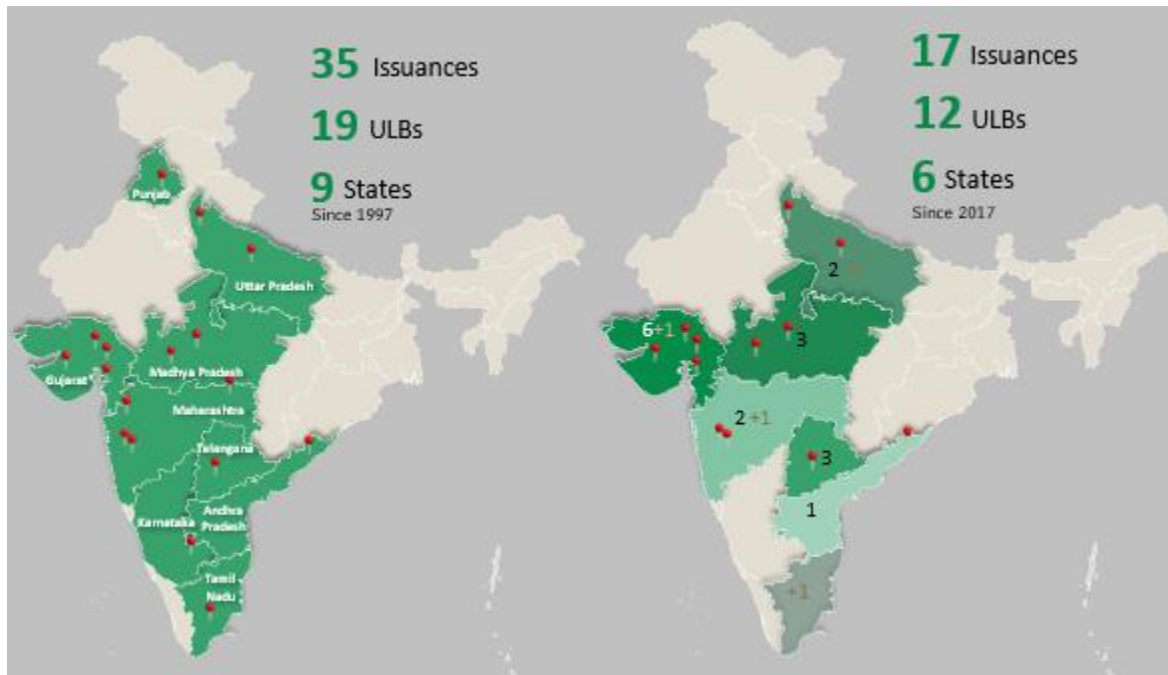


Figure 4: Municipal bond issuances by states since 1997 and 2017

In figures 4 and 5, the bond issuance is concentrated in a few states, and a few cities have repeated bond issuances. Strengthening state-level policies and ensuring reliable fiscal transfers remain critical to scaling up municipal bond use across Indian cities.

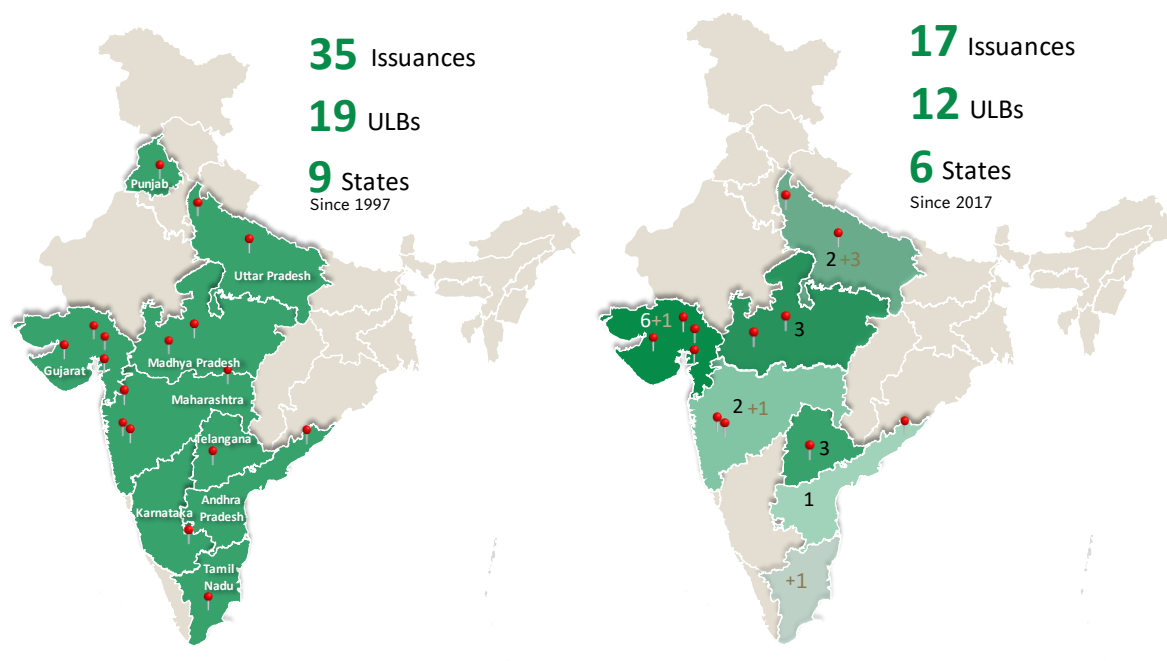


Figure 5: Municipal bond issuances by states since 1997 and 2017. Source: Compiled by the author from multiple sources

Note: A Few states in the country issue bonds due to a lack of financial devolution to the city governments. Even within the states that have cities that issue bonds, only bigger cities tend to issue bonds. After the incentivization due to AMRUT, cities other than capital cities have issued or are in the process of issuing municipal bonds.

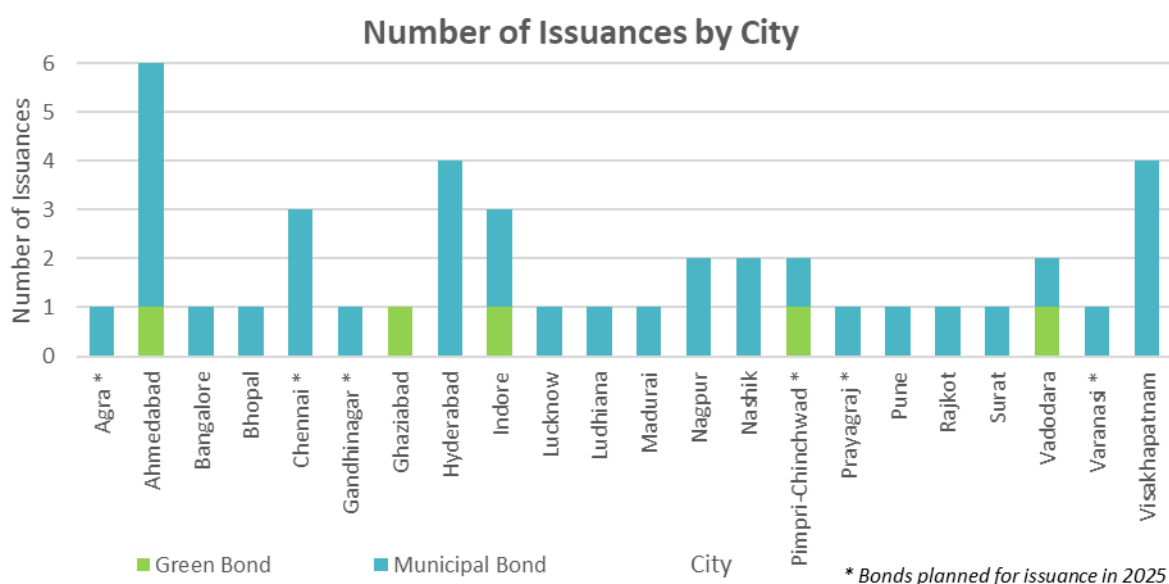


Figure 5: Number of municipal bond issuances by city

Note: Of the 22 cities that have issued or are in the process of issuing municipal bonds, 13 cities have issued it only once (Source: Compiled by author from multiple sources).

While municipal bonds have revived in the last few years due to incentivization under AMRUT, there are many regulatory challenges that are faced by the cities. Their adoption is dependent on the state regulations that govern the fiscal policies for the cities. Furthermore, although municipal bonds have a positive market response, based on discussions with city officials, it was identified that their coupon rates are comparable to the interest rates on commercial loans and loans from development banks (considering the associated expenses of such borrowings). As a result, without an incentive under AMRUT, municipal bonds are simply another form of borrowing with the same cost of capital and more documentation for the ULB, making them unfavorable in the long run.

5. Municipal Green Bonds in the Indian Context

Increased focus on climate action globally and India’s commitment to Net Zero by 2070 led to advances in access to green finance across the country. India is one of the major issuers of green bonds globally. However, municipal and sovereign green bonds constitute a small proportion of the total Indian bond market (CBI, 2023). The regulatory frameworks for corporate green bonds were in place by SEBI; however, the framework for municipal green debt securities was first formulated in 2023 as part of the Issue and Listing of Non-convertible Securities (ILNCS) Regulations, 2021. In 2022, the RBI published the framework for sovereign green bonds (Ministry of Finance, 2022) and India issued its first tranche for SrGBs in 2023 with an issue size of INR 8,000 crores (RBI, 2023). The framework for both SrGBs and MGBs is based on ICMA’s Green Bond Principles (ICMA, 2022). These principles are based on four pillars, as shown in **Error! Reference source not found..** The focus of these principles is to ensure that the proceeds of green bonds are used for projects that have a positive environmental impact and contribute to the adaptation and/or mitigation of climate change by increasing the accountability of the issuer and the transparency of the process.

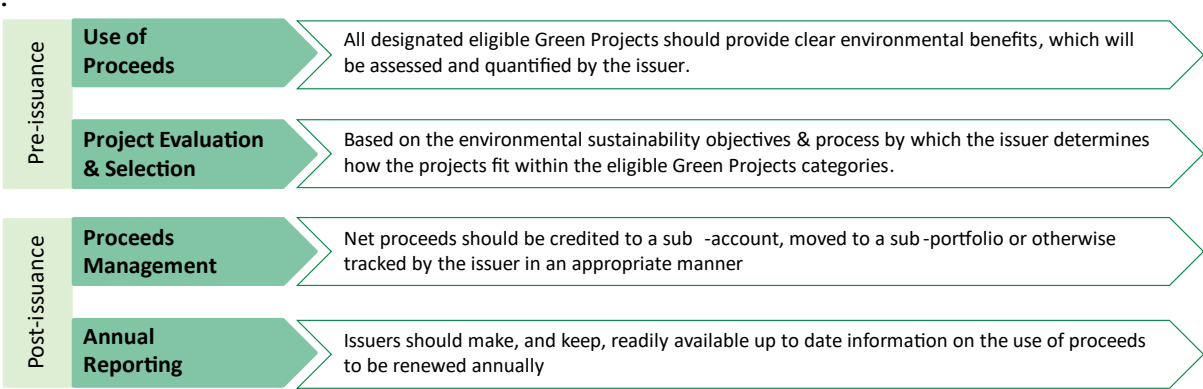


Figure 6: ICMA Green Bond Principles

Note: The four principles of the framework focus on ensuring positive climate impact through the projects financed through green bonds.

According to ILNCS Regulations, the capital raised through municipal bonds should be utilized for financing eligible projects. These eligible projects should fall under the themes specified by the Regulations. These themes have been listed in **Error! Reference source not found..** Most of these themes have projects that are directly or indirectly related to the functions of ULBs and thus, projects that contribute to provision of municipal services in the city can easily qualify for green municipal bonds. ULBs can easily leverage this tool for financing their municipal projects based on the function by ensuring their contribution through climate resilience. Despite this, cities are unable to leverage this instrument highlighting the need to identify the other issues that lead to this inability.

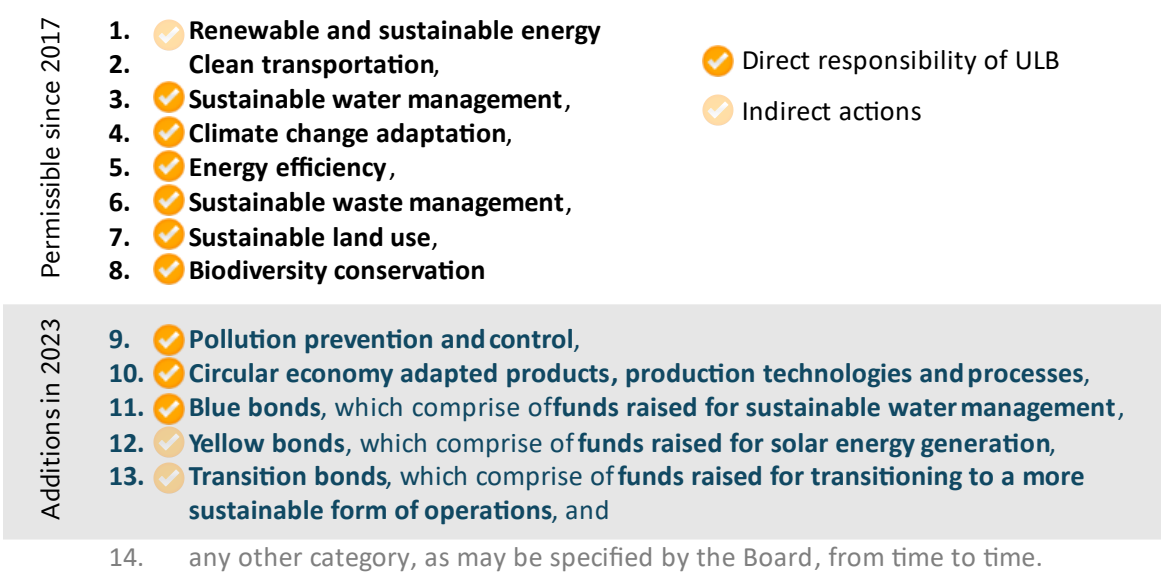


Figure 7: Themes for which projects can be financed through green bonds under the ILNCS Regulations

Note: The themes listed coincide with municipal functions (defined under the 74th Constitution Amendment Act, 1992) directly or indirectly.

Of the 4,852 ULBs in the country, credit rating reports are available only for 223 ULBs of which 95 have investment-grade credit ratings (Cityfinance, 2024). Credit ratings are the first step in identifying the financial capacity of ULBs to access the municipal bond market. The lack of credit ratings highlights the need for major institutional reforms to improve the financial capacity of ULBs. Further, as seen in **Error! Reference source not found.,** tax and non-tax revenue form a smaller component of municipal income than transfers from the centre and state. The financial capacity of ULBs is limited as own-source revenue may not be sufficient for ULBs for repayments, considering long turn-around times for public projects.

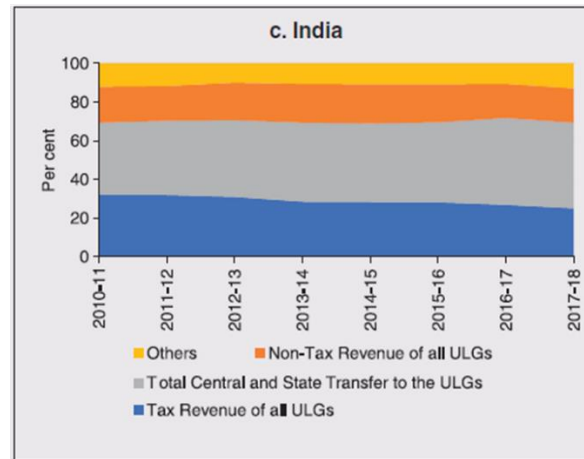


Figure 8: Distribution of income sources for Indian urban local bodies

Note: Central and state transfers form the biggest component of the municipal income, followed by tax revenue (Source: RBI, 2022).

This shows the huge gap in the capacity of city governments to leverage MGBs. Consequently, most green bonds are thus issued by the larger, more powerful municipal corporations that have access to comparatively steady revenue streams and the technical and administrative capacity required to issue municipal bonds. Most ULBs in the country have a long way to go to leverage this tool to generate financing for their municipal projects. The few cities that have thus issued MGBs need to be studied to analyze their financial and institutional capacity in being able to leverage the tool.

6. Financial Status of Cities that Issued Municipal Green Bonds

Four cities have raised municipal green bonds in India. To identify the need for this financing tool, their financial analysis was conducted based on the income expenditure statements for the last seven years (considering the period before municipal bonds were issued). This makes them critical case studies to evaluate the fiscal health, investment strategies, and structural readiness of ULBs to engage with climate-aligned financing tools. Their experiences provide valuable insights into how, and why cities are navigating the shift toward market-based infrastructure finance and the bottlenecks that remain in integrating climate objectives within municipal budgets.

6.1 Ghaziabad Nagar Nigam

From the FY 2015-16 to 2022-23, Ghaziabad Nagar Nigam (GNN), a Tier 2 city, shows increasing income and expenditure but a sharp decline in surplus over time. The city's revenues are heavily dependent on transfers, particularly from the state, which are unsystematic and unreliable. Non-tax revenue remains weak, accounting for a small proportion of total income.

The city's debt exposure is negligible, indicating a conservative financial approach but also reflecting its underutilization of debt instruments for capital investment.

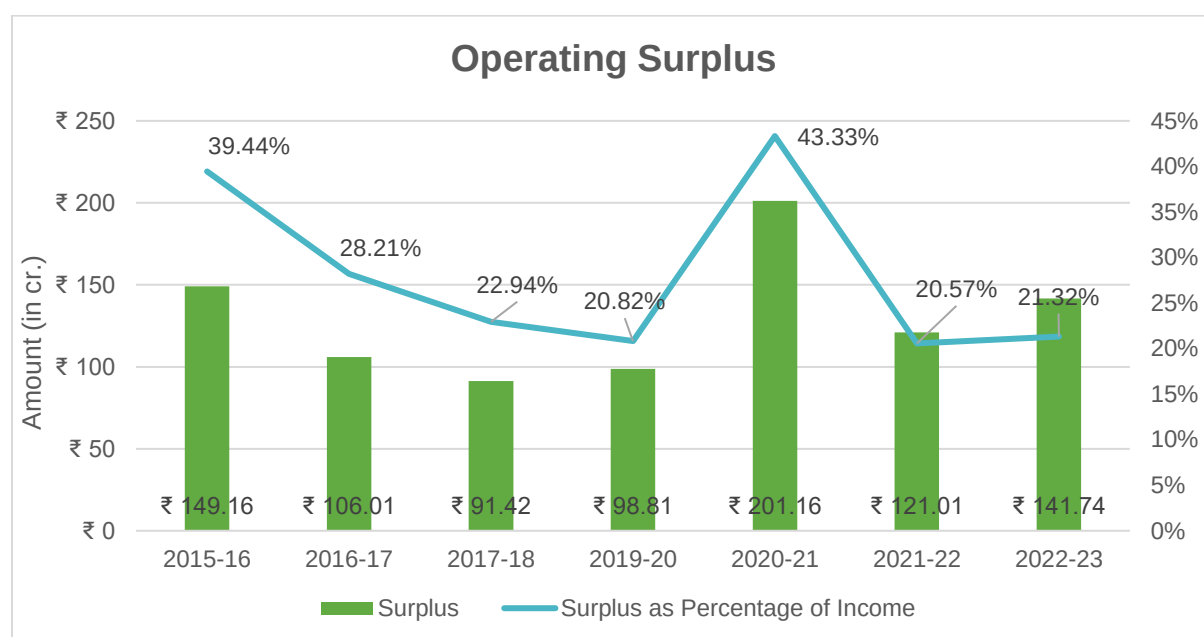


Figure 9: Operating surplus of GNN

Note: Surplus within GNN is a declining component of the income showing higher expenditures despite rising income (Source: Author's analysis based on GNN Income Expenditure Statements).

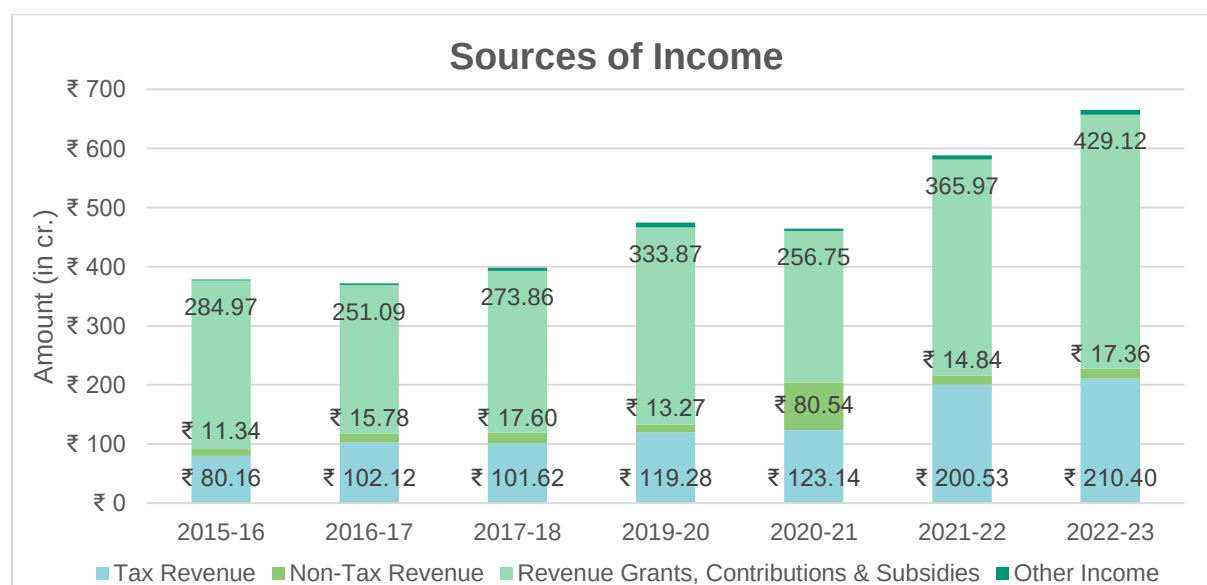


Figure 10: Sources of income for GNN

Note: Revenue from grants forms a major component of income for GNN followed by tax revenue (Source: Author's analysis based on GNN Income Expenditure Statements).

6.2 Indore Municipal Corporation

Indore Municipal Corporation (IMC), another Tier 2 city, exhibits strong growth in non-tax revenues, which form the bulk of its income from FY 2016-17 to 2022-23. While this offers a promising revenue base, increasing administrative and operational costs have begun to erode its surplus (refer to Figure 5). Its financial reliance on user charges is commendable, yet the lack of systemic state transfers places it in a vulnerable position, especially when planning long-term investments.

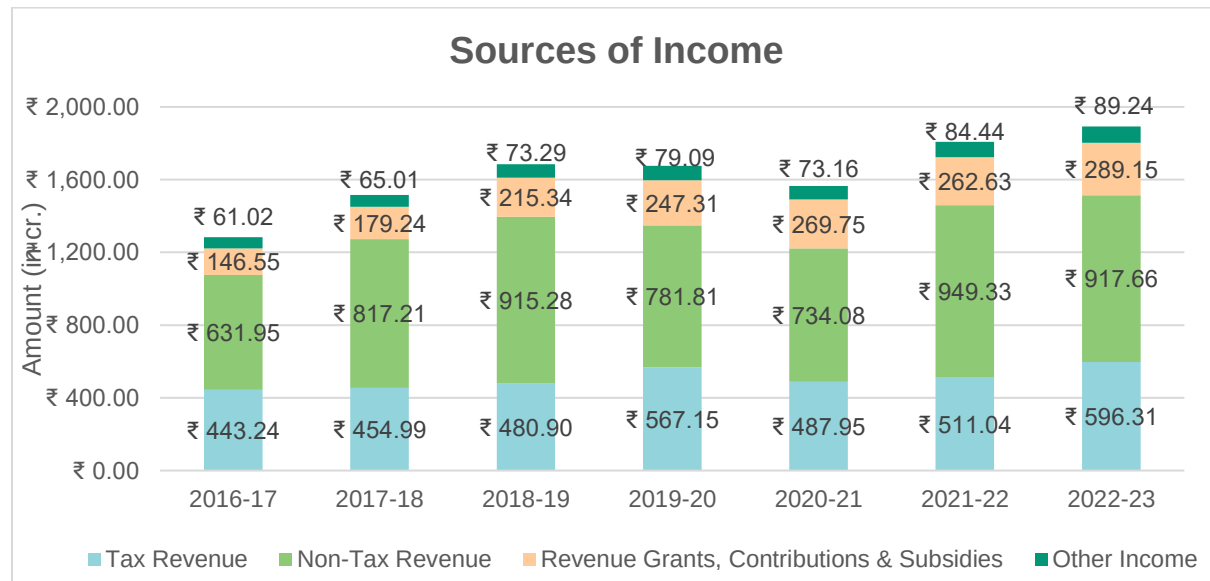


Figure 11: Sources of income for IMC

Note: Non-tax revenue forms a major component of income for IMC followed by tax revenue while grants form a small component of the income showing comparative fiscal stability (Source: Author's analysis based on IMC Income Expenditure Statements).

Figure 5
Operating Surplus of IMC.

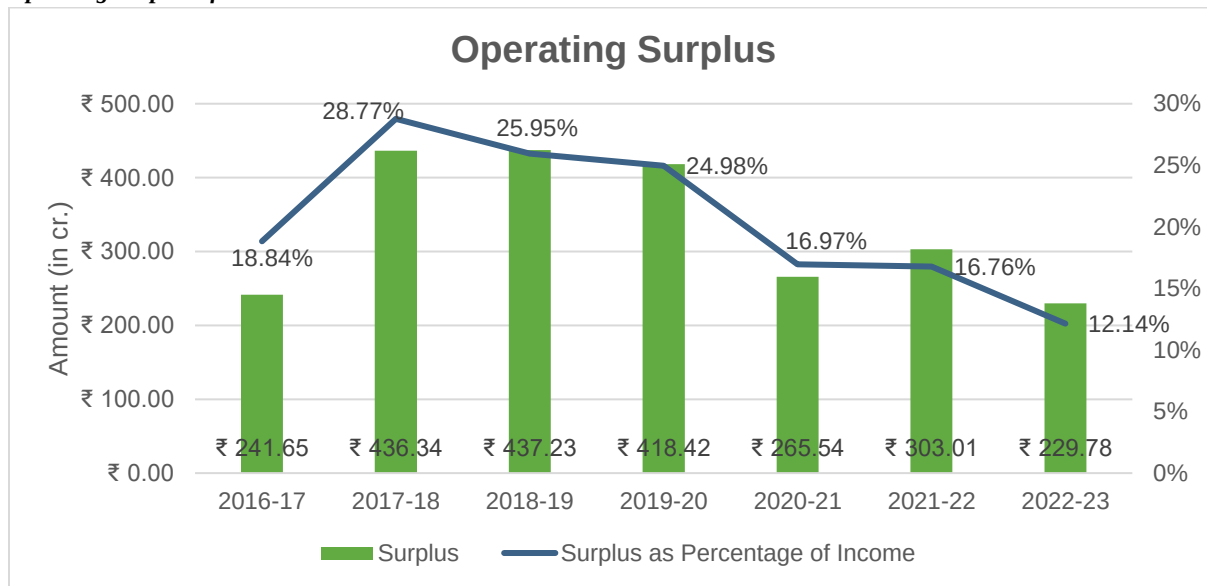


Figure 12: Operating Surplus of IMC

Note: Despite increasing non-tax revenue, surplus is a declining component of the municipal income due to higher expenditures (Source: Author's analysis based on IMC Income Expenditure Statements).

6.3 Ahmedabad Municipal Corporation

Ahmedabad Municipal Corporation (AMC), a Tier 1 city, stands out for its large income base. However, the analysis of AMC's income expenditure statements shows that it also has the highest increase in operating and maintenance costs, alongside fluctuating state and central transfers. Despite moderate debt levels, the growing fixed costs significantly limit its financial flexibility. The surplus has narrowed over the years, underscoring a need for better expenditure control and long-term financial planning.

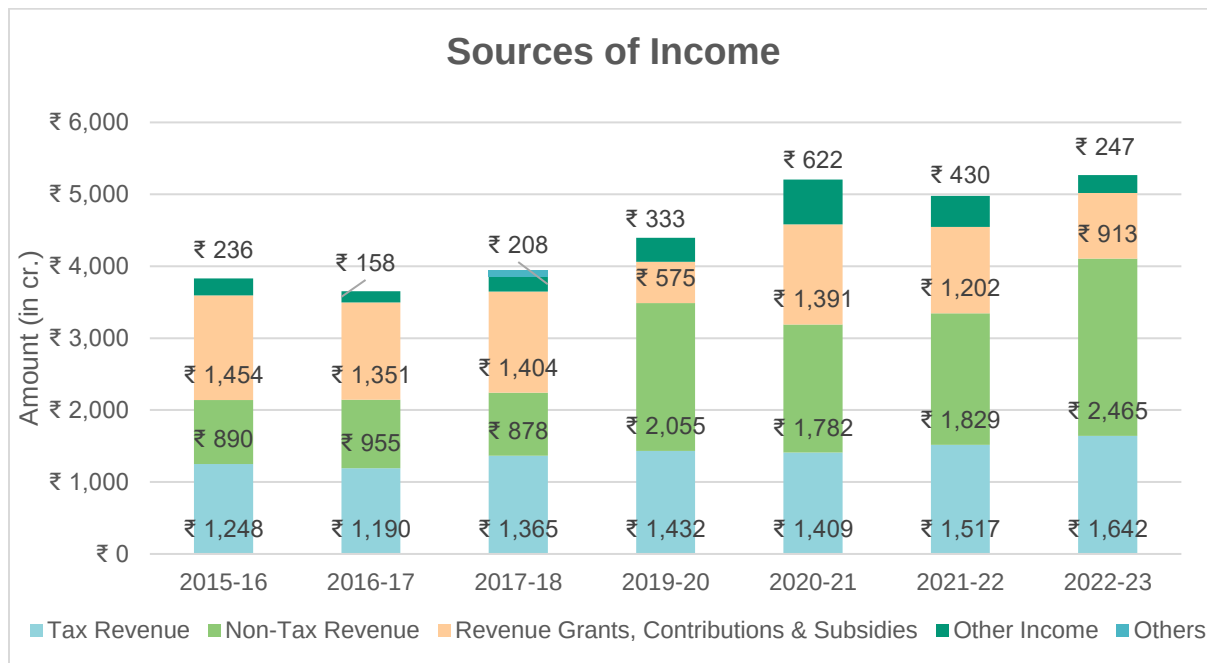


Figure 13: Sources of income for AMC

Note: Despite high income from tax and non-tax revenue, AMC is also heavily dependent on grants (Source: Author's analysis based on AMC Income Expenditure Statements).

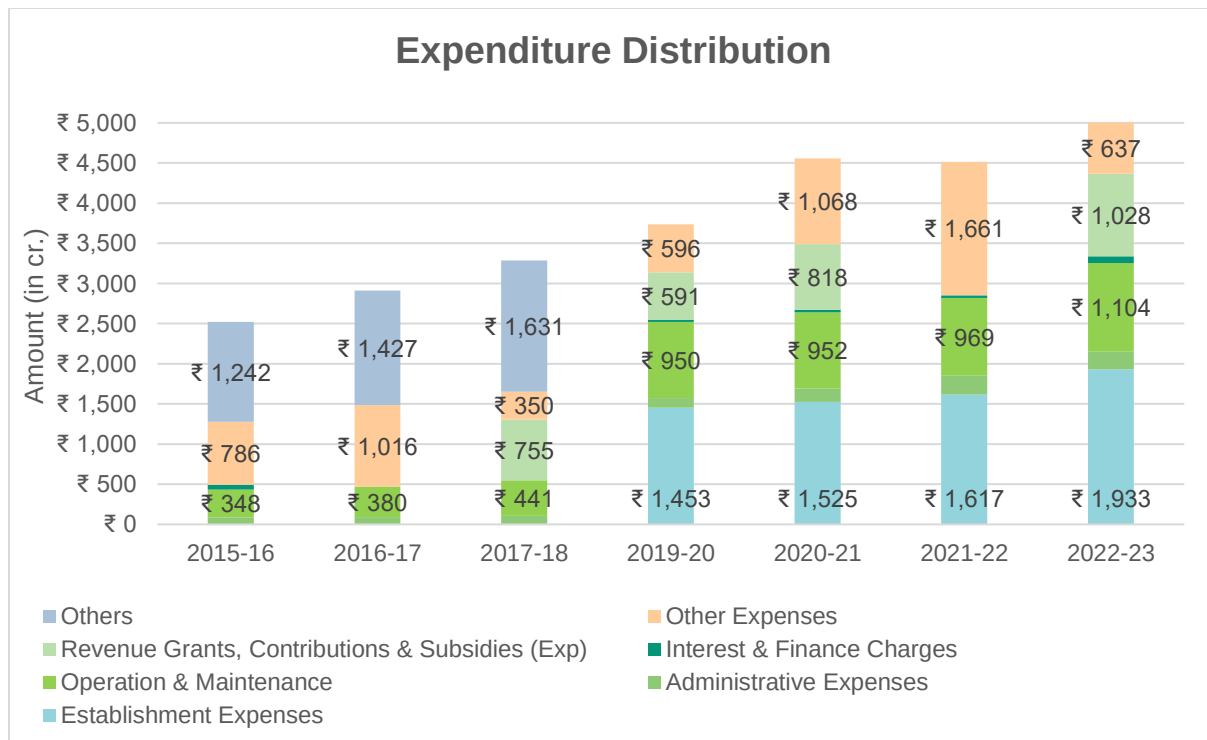


Figure 14: Expenditure distribution of AMC

Note: Increasing expenditures are a challenge for AMC due to high establishment and O&M expenses (Source: Author's analysis based on AMC Income Expenditure Statements).

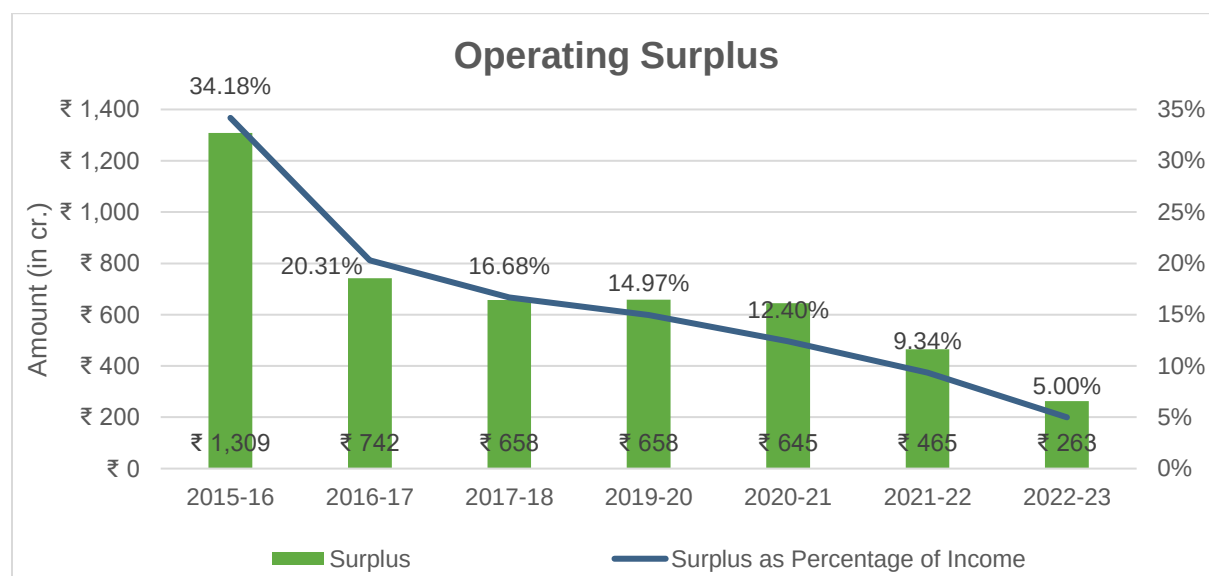


Figure 15: Operating surplus of AMC

Note: There has been a sharp decline in the operating surplus of AMC in the last few years due to increasing O&M costs and fluctuating transfers (Source: Author's analysis based on AMC Income Expenditure Statements).

6.4 Vadodara Municipal Corporation

Vadodara Municipal Corporation (VMC), also a Tier 2 city, shows a modest and fluctuating surplus despite a steadily increasing income. Its budget is heavily reliant on transfers, followed by tax and non-tax revenues. High fixed costs in the form of establishment and other expenditures leave limited fiscal space for capital investments, although its low interest burden indicates room for leveraging debt instruments more strategically.

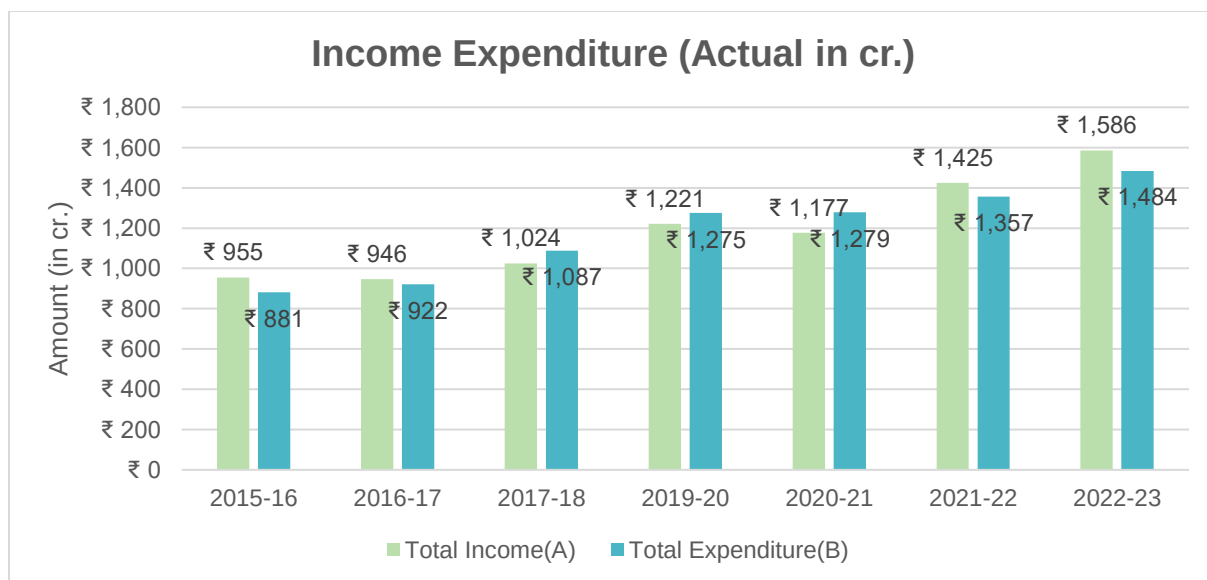


Figure 16: Actual income and expenditure of VMC

Note: VMC shows higher expenditures than the total income in multiple financial years (Source: Author's analysis based on VMC Income Expenditure Statements).

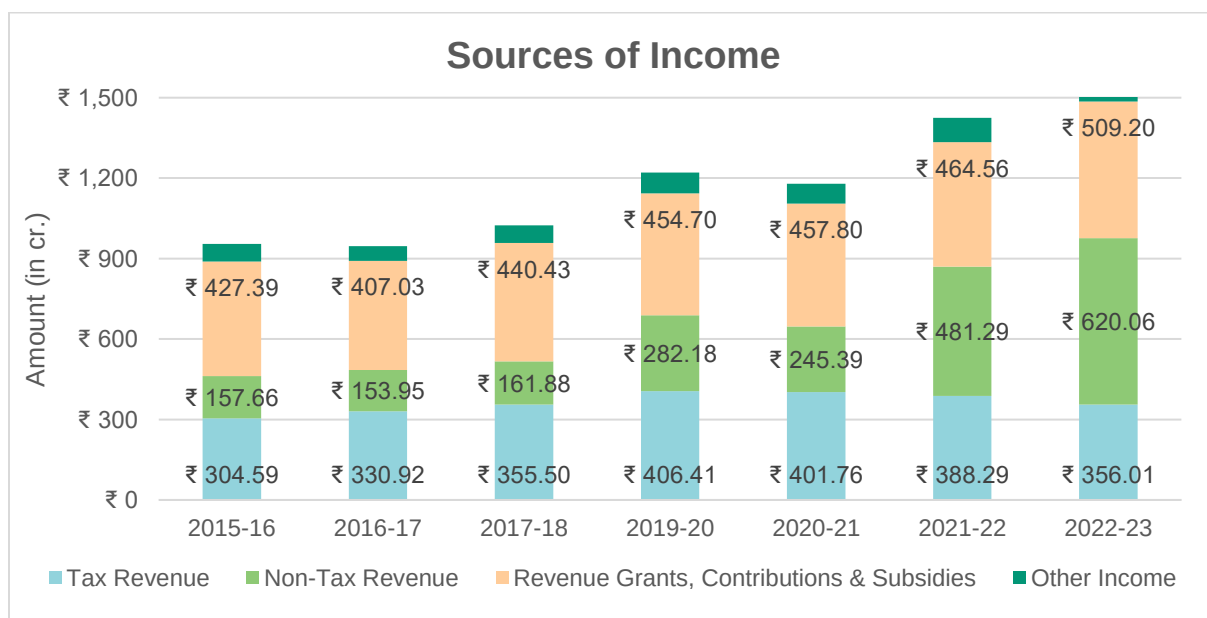


Figure 17: Sources of income for VMC

Note: Grants form a major component of income for VMC, followed by tax and non-tax revenue (Source: Author's analysis based on VMC Income Expenditure Statements).

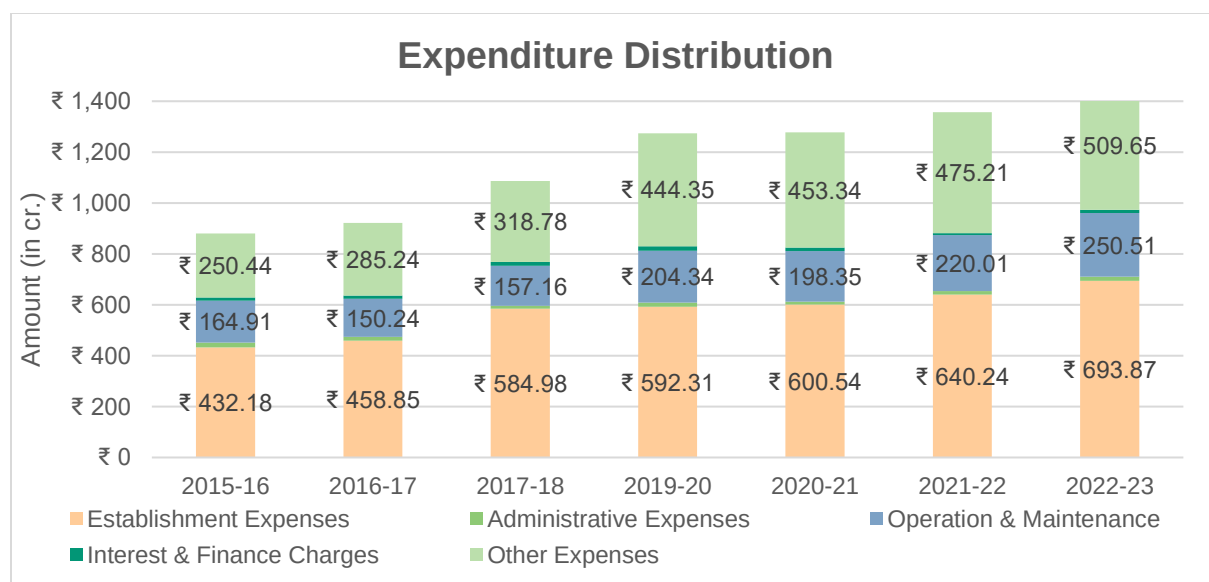


Figure 18: Expenditure distribution of VMC

Note: Establishment and O&M expenses form a significant component of VMC expenditure (Source: Author's analysis based on VMC Income Expenditure Statements).

Thus, the fiscal diagnosis of Ghaziabad, Indore, Ahmedabad, and Vadodara municipal corporations reveals a common pattern. On the one hand, revenues and expenditures have increased across all four cities, but the operating surpluses are either shrinking or volatile. This suggests limited fiscal flexibility and growing expenditure commitments, making it difficult to accommodate new climate-resilient infrastructure projects without external financing. It must also be noted, however, that across all four cities, the use of debt is conservative. While low interest payments suggest fiscal prudence, they also highlight an underuse of available borrowing instruments like bonds. This risk aversion may be due to capacity constraints or the perceived complexity of capital market financing.

Importantly, these financial trends do not necessarily indicate poor financial health or capacity. Rather, they reveal a more nuanced issue, i.e., the absence of strategic financial planning aligned with climate goals. Municipal budgets are not yet structured to support climate-oriented investments, and most cities lack comprehensive pipelines of bankable projects that could qualify for green financing. The gap lies not just in revenue or capacity, but in institutional readiness. None of the cities studied had embedded climate finance strategies within their fiscal planning or investment frameworks. This disconnect limits their ability to design, fund, and implement transformative climate action at scale.

In conclusion, while the balance sheets show cautious financial management, they also underscore a deeper systemic gap. Indian cities are not financially incapable, but they are institutionally unprepared to finance climate resilience through structured mechanisms like green

municipal bonds. Addressing this will require more than improved revenue collection; it demands institutional reforms, better fiscal forecasting, and the development of dedicated capital pipelines for climate action.

7. Analysing the ‘Greenness’ of Municipal Green Bonds

Indian MGBs have generated significant optimism, but a closer examination is needed to identify their effectiveness as a climate instrument. Ghaziabad, Indore, Ahmedabad, and Vadodara became examples by issuing certified MGBs. While the instruments were largely successful in mobilizing capital, as most bonds were oversubscribed and offered competitive coupon rates. However, whether they are truly serving their intended purpose of financing transformative climate action needs to be assessed.

7.1 Project Types and Coupon Rates

The majority of green bonds issued by Indian ULBs have been linked to water supply augmentation, wastewater treatment, and solar energy projects. These are relatively conventional infrastructure categories that meet the eligibility criteria under SEBI’s Green Debt Securities Framework. For instance, Ghaziabad’s ₹150 crore bond was allocated toward tertiary water treatment infrastructure, and Indore’s ₹244 crore issue funded water and solar projects. In each case, the bonds carried credit ratings of AA or higher and attracted considerable investor interest. **Error! Reference source not found.** shows the size of the green bonds issued by the ULBs, their coupon rates, tenure, credit ratings, the projects for which the proceeds were allocated and the certifying agency. The proceeds of the green bonds were used in varying proportions to finance the eligible projects, as seen in **Error! Reference source not found..**

Figure 19: Characteristics of Indian municipal green bond issuances

Note: A brief overview of MGBs issued by GNN, IMC, AMC, and VMC since 2021 (Source: Compiled by Author).

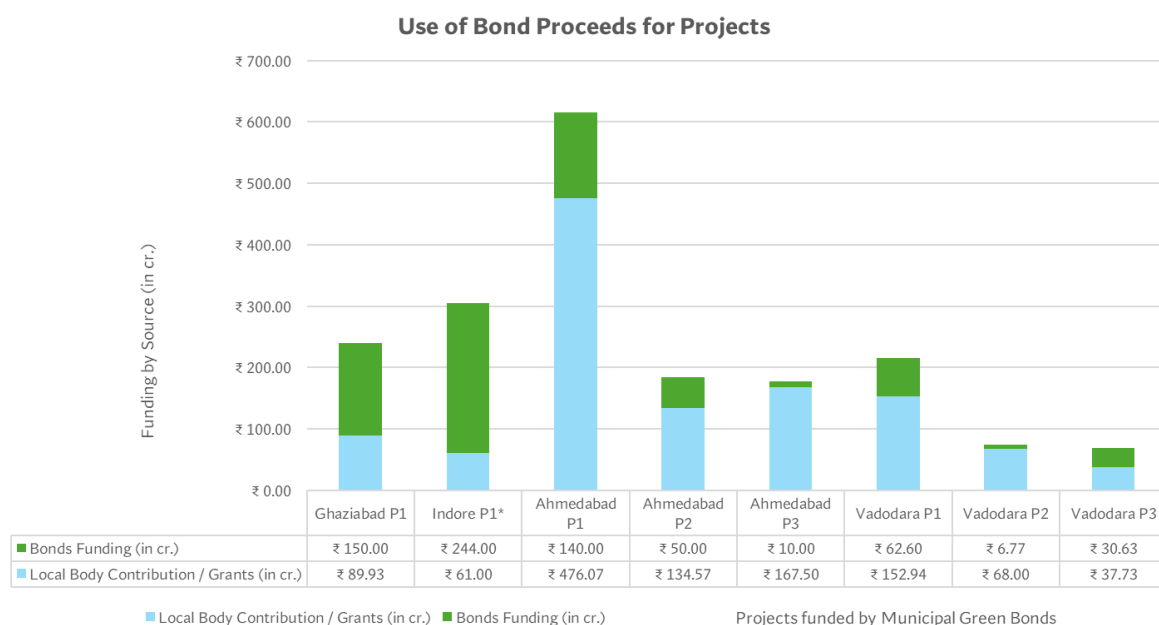


Figure 20: Use of green bond proceeds as a proportion of the project cost

Note: Cities show varying components of bond financing in the projects. It is higher in GNN and IMC and a small portion in AMC and VMC. (P1, P2 and P3 represent the proportion of the bonds in the three projects financed using MGBs by AMC and VMC, each) (Source: Compiled by Author).

As mentioned by several informants, one of the key incentives for cities to issue green bonds was the opportunity to access capital at a lower cost due to low coupon rate compared to commercial loans. Data shows that coupon rates for green municipal bonds were on average 0.56% lower than comparable non-green instruments. The effective cost of capital was even lower due to the grant attached to the issuance under AMRUT.

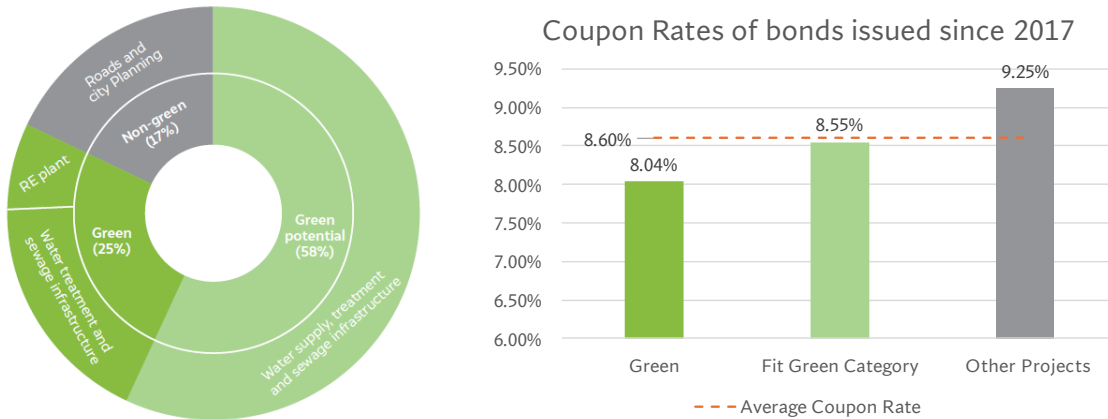


Figure 21: Potential plain municipal bonds that could be green municipal bonds and their coupon rates compared with plain municipal bonds and green municipal bonds

Note: Municipal bond proceeds with possible green outcomes have lower coupon rates than otherwise with MGBs having the lowest average coupon rates (Sources-Left: Bibhudatta & Rathee, 2025, Right: Compiled by Author)

Thus, MGBs do have a direct financial benefit due to their green outcomes as compared to regular municipal bonds. However, they are also associated with notionally higher issuance costs due to more disclosures and certification-related costs.

7.2 ‘Greenness’ of the Green Label

While the certification process lends credibility, the criteria for what qualifies as "green" remain broad and interpretive. Under SEBI’s framework, categories like water management or renewable energy automatically qualify as green, but there is limited emphasis on evaluating emissions reduction potential, lifecycle impacts, or social co-benefits. While the rules focus on the process for the selection of projects financed through green bonds, this process is not clearly laid out, and ULB’s selection criteria are not specified in the placement memoranda. Moreover, the alignment of these projects with a broader climate action strategy, such as a city-level Climate Resilience or Mitigation Plan, is rarely considered. The rating agencies for the MGBs also varies. Additionally, there is no defined criterion for the entity that qualifies to assign the rating to the bond.

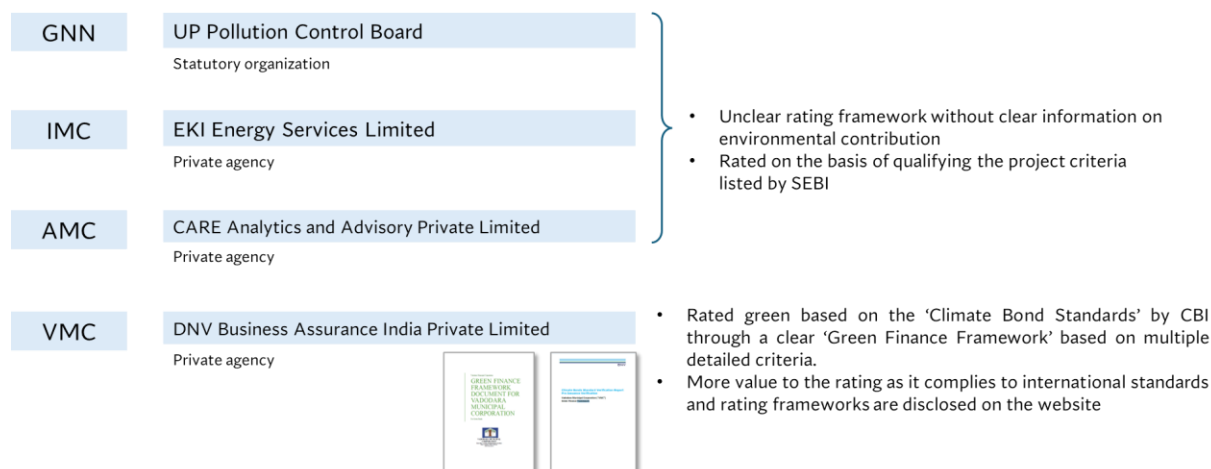


Figure 22: Green certification process for the bonds

Note: The four MGBs have received their green certification from different agencies following undefined frameworks, except in the case of VMC, which follows the Climate Bond Standards. These also do not provide information on the expected environmental impacts in quantifiable terms, making them unaccountable and vague in the long-term.

Thus, while projects may pass the technical checklist, they often lack the ambition, scale, and additionality expected from climate finance. The risk is that green bonds become financing instruments for business-as-usual infrastructure, merely rebranded for market access.

7.3 Impact Monitoring, Third-Party Review, and Long-Term Planning

Although SEBI mandates annual disclosures and impact reports, there are no measurable indicators or third-party audits of the environmental outcomes post issuance and post repayment. The lack of clearly defined Key Performance Indicators and the absence of baseline assessments further limit the scope of monitoring. Cities also lack internal systems for tracking how proceeds are utilized over time. While the project has positive impacts on the environment, this impact is not quantified. Escrow mechanisms exist to safeguard repayments to the investors, but there is minimal scrutiny on whether the financed projects achieve their stated environmental objectives. This puts the environmental credibility of the instrument at risk in the long term. Post-issuance practices remain one of the weakest links in India's municipal green bond framework.

In the absence of rigorous eligibility and reporting criteria, green bonds risk devolving into instruments of greenwashing. While the regulations do mention that greenwashing must be avoided, there are no definite measures that list potential greenwashing actions. The issuance process is driven more by financial necessity and AMRUT-linked incentives than by climate outcomes. This creates a governance blind spot, where the optics of climate action overshadow the substance. Furthermore, there is limited coordination between municipal financial departments and environmental planning wings. As a result, climate considerations are not embedded into project selection or appraisal. This institutional disconnect reduces the efficacy of green bonds as tools for climate transformation.

In summary, while India's MGBs have opened the door to market-based climate finance, their current design and execution fall short of maximizing impact. The framework needs to evolve from a transactional tool to a strategic lever, one that not only raises money but also catalyzes a systemic shift in how cities define, plan, and deliver climate infrastructure.

8. Case Studies: Madrid and San Francisco

Global examples offer useful benchmarks when it comes to MGBs. The cases of Madrid and San Francisco provide actionable insights for Indian cities seeking to improve the credibility, impact, and investor confidence of their green financing initiatives.

Madrid's sustainable finance program stands out for its scale and systemization. The regional government has issued five green and sustainability bonds since 2017, with the 2023 bond raising €600 million at a coupon rate of 3.362%. Oversubscribed by 4.3 times, the bond attracted 111 institutional investors, 57% of whom were international. Madrid's issuance was particularly strong due to the credibility of its project pipeline and its alignment with the EU Taxonomy. It primarily included clean transportation, waste management, and conservation initiatives. Annual impact reports, validated by third-party assessments, detailed measurable benefits such as 249,164 tonnes of CO₂ emissions avoided. Madrid's finance department embedded sustainability into budget codes, ensuring traceable use of funds across fiscal years (Comunidad de Madrid, 2024).

San Francisco's Public Utilities Commission (SFPUC), on the other hand, has institutionalized green bond financing for climate-resilient water infrastructure. With rigorous pre-issuance planning and strong environmental safeguards, San Francisco's approach centers on transparency and public accountability. Bond proceeds fund upgrades to water treatment plants, seawall protection, and emissions reduction through 87 projects. SFPUC's green bond reports publicly disclose project outcomes, budget adherence, and environmental metrics. This has helped establish a long-term relationship with ESG-conscious investors and build trust in the city's governance (San Francisco Public Utilities Commission, 2023).

Both cities reflect that credibility is not just about certification but about systems. The combination of well-defined project pipelines, integration with climate strategies, and commitment to disclosure ensures that green bonds act as instruments of transformation rather than optics.

For Indian ULBs, these examples underscore the importance of embedding green finance within broader fiscal and climate frameworks. However, direct replication is neither feasible nor advisable. The goal should not be to copy these models wholesale, but to adapt their principles. Cities must invest in climate-ready infrastructure planning, establish internal systems for tracking and reporting, and ensure their projects serve not just green labels but real green outcomes.

9. The '4 Cee' Framework for Indian ULBs

As seen above, while India's foray into MGBs has demonstrated appetite and potential, structural deficiencies continue to hinder their effectiveness. To move from isolated issuances to a mainstream, accountable financing tool for climate action, Indian cities need a more comprehensive foundation. The '4 Cee' framework which is based on four pillars, namely, **Creditworthiness**, **Capital Pipeline**, **Classification of Greenness**, and **Compliance Monitoring**, offers a pathway to shift MGBs from simply a tool to finance rebranded infrastructure projects to an accountable tool that focuses on long-term positive environmental impact.



Figure 23: 4Cee Framework based on four pillars

Note: The pillared framework forms the basis for reforms in municipal green bond ecosystem to improve the impact of the instrument in Indian cities.

9.1 The First Pillar: Creditworthiness

A foundational prerequisite for issuing any kind of municipal bond is an investment-grade credit rating. Most cities lack audited balance sheets, use outdated accounting systems, and struggle with inconsistent revenue streams particularly in non-tax revenues. Creditworthiness is often treated as a procedural hurdle rather than a strategic goal. However, building credit capacity is crucial for sustained market engagement. ULBs need structured efforts to improve financial discipline, adopt double-entry accrual accounting, and build multi-year fiscal frameworks. Gujarat's cities, which have relatively stronger accounting practices, demonstrate how administrative readiness translates into investor confidence.

9.2 The Second Pillar: Capital Pipeline

Green municipal bonds in India have lower coupon rates as compared to traditional municipal bonds. Many municipal bonds in India have funded projects that are technically eligible for

attaining positive environmental impacts. However, they did not opt for the green variant of the bond. This is due to the absence of technical capacity and the lack of climate-aligned project pipelines. A strategic capital pipeline should identify high-impact projects based on emission reduction potential, equity outcomes, and vulnerability mitigation.

Cities must integrate climate action plans with investment roadmaps through a City Climate Infrastructure Investment Pipeline. This includes emissions baselining, setting decarbonization goals, and identifying co-benefits (e.g., health, air quality, gender impacts). Bundling smaller projects can help meet the scale needed for bond issuance while reducing transaction and pre-issuance costs. More importantly, planning needs to anticipate the long-term. For example, investments in clean transportation should not only reduce emissions but also increase access and reduce system vulnerability. Strategically planned long-term investments will increase the efficiency of service delivery in the city and minimize ad-hoc and isolated implementation practices that are currently being followed by Indian cities.

9.3 The Third Pillar: Classification of Greenness

The absence of a standardized framework to classify the 'greenness' of projects leads to inconsistencies and potential greenwashing. SEBI's green debt guidelines provide broad categories, but cities often choose projects that are easy to certify instead of those with strategic value. To address this, the use of a "Shades of Green" classification system ranging from light green (incremental sustainability) to dark green (transformative, systemic change) can improve transparency and help align projects with long-term climate goals. Similar frameworks are being adopted globally and can be adapted to India's context. This classification should be complemented by internal screening tools within ULBs that evaluate environmental additionality, resilience impact, and sector-specific alignment with SDG and NDC targets.

9.4 The Fourth Pillar: Compliance Monitoring

Post-issuance impact reporting is perhaps the weakest link in India's green bond ecosystem. SEBI mandates annual disclosures, but enforcement is minimal, and most cities struggle with data collection and analysis. Often, once the bond is issued, the climate agenda takes a back seat. The solution lies in establishing Key Performance Indicators that are embedded during project design itself. These should track both financial (e.g., capital utilization) and environmental metrics (e.g., emission reductions, service coverage). Real-time dashboards, periodic third-party audits, and integration with public information systems can improve accountability. While the mandated escrow mechanism for all municipal bonds shows that financial compliance can be structured well, a similar rigor must be applied to environmental compliance.

The 4 CEE framework isn't a checklist but more a transition model. It shifts the focus from procedural eligibility to measurable impact. When ULBs improve their credit profiles, align

project selection with climate strategy, define greenness transparently, and enforce compliance rigorously, MGBs can evolve from being an opportunistic tool to a long-term financing mechanism for resilient urban development. This transformation will require state-level policy alignment, technical assistance programs, and investor education to mainstream best practices. Only then can India scale MGBs in a way that is both credible and catalytic.

10. Discussion

Municipal green bonds are not the ultimate answer for urban climate finance. Currently, in the Indian context, they are a test of institutional readiness and intent. The few Indian cities that have ventured into this space, Ghaziabad, Indore, Ahmedabad, and Vadodara, have proven that capital can be mobilized when financial and administrative structures are in place. But financing climate action requires more than market access. It requires vision, long-term planning, and the institutional architecture to deliver impact.

Cities that seek to borrow for climate action must also commit to building the governance systems that can guide, implement, and track those investments. This means creating robust project pipelines, defining climate outcomes clearly, and ensuring transparency in fund utilization. The success of a green bond should not be measured solely by its subscription rate or coupon spread, but by whether it helps a city transition toward a more sustainable, inclusive, and resilient future.

Scaling the municipal green bond market responsibly will require not just more capital, but more capacity. ULBs need financial expertise, climate-informed planning processes, and inter-departmental coordination. State governments and regulators must go beyond compliance checklists to provide long-term incentives, technical assistance, and clear frameworks for evaluation.

Ultimately, it is not simply about issuing capital using green bonds but about issuing better ones that focus on outcomes. Bonds that are grounded in evidence, monitored with rigour, and embedded in larger city-level climate strategies. Only then can green bonds move from being a financial instrument to a transformational tool for India's urban future.

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Paper 26

Urban Heat Island Dynamics and Land Cover Transformation in Dhaka: A Statistical Analysis of Climatic Variables (2000–2024)

Luthfunnesa Mim

Abstract

Rapid urbanization in Dhaka has triggered profound land use and land cover (LULC) transformations, contributing to rising urban temperatures and intensified Urban Heat Island (UHI) effects. Understanding the complex interplay between climatic variability and urban expansion is essential for developing effective adaptation and resilience strategies. This empirical study investigates the relationship between key climatic parameters—temperature, sunshine hours, rainfall, and relative humidity—and UHI dynamics in Dhaka over the period 2000–2024. Primary climatic data were obtained from the Bangladesh Meteorological Department (BMD), and secondary data on wetland loss (1990–2020) were used to assess long-term environmental changes. Statistical analyses, including trend analysis, linear regression, and multiple regression, were applied to examine temporal patterns and interrelationships among variables. The findings reveal a consistent warming trend across all seasons, with pre-monsoon temperatures increasing from 27.1°C in 2000 to 29.3°C in 2024, indicating an average annual rise of 0.04°C. Sunshine duration exhibited a steady decline of 0.0555 hours per year, while rainfall and relative humidity showed decreasing but statistically insignificant influences on temperature. The multiple regression model ($R^2 = 0.366$, $p = 0.020$) confirms the overall significance of the relationship, with sunshine having the strongest negative correlation with temperature. Furthermore, wetland areas decreased sharply from 3,448 ha in 1990 to 1,068 ha in 2020, reflecting rapid urban expansion and loss of blue-green spaces. These results emphasize the interconnected nature of climatic and land cover changes shaping Dhaka's urban heat environment. Future research should incorporate additional variables such as air pollution, solar radiation, cloud cover, and wind speed to provide a more comprehensive understanding of UHI dynamics. Strengthening blue-green infrastructure and wetland restoration within Dhaka's urban planning framework is crucial for mitigating heat stress and advancing climate-smart city development.

1. Introduction

1.1 Background of the Study

Rapid global population growth has accelerated urbanization and industrialization, creating both opportunities and challenges for sustainable development (Al Shanto, Zobair, Fahim, & Rabbee, 2025). Over the past five decades, the global urban population has risen dramatically from 34% to 50% (United Nations, 2014), and it is projected to surpass five billion by 2030, exerting immense pressure on land resources and ecosystems (Zhang, Shou, & Dickerson, 2009). According to the *World Urbanization Prospects 2018* report, 55% of the world's population currently resides in urban areas, and this figure is expected to reach 60% by 2050, with Sub-Saharan Africa and Asia experiencing the fastest rates of urban growth (Yu et al., 2020, Nagendra et al., 2018; Song et al., 2018).

This rapid urban expansion, while contributing to economic advancement, simultaneously intensifies environmental stress, natural resource depletion, and ecosystem degradation (Hossain et al., 2023). These challenges are particularly severe in developing nations such as Bangladesh (Hayashi and Rosenberry 2022; Amani et al. 2020). Dhaka city, which is the bustling capital of Bangladesh, is a densely populated urban hub with a staggering population of over 21 million, encompassing an area of 306.38 square kilometres (118.29 sq mi); Positioned at 23° 42' N 90° 22' E in central Bangladesh (Hossain et al., 2023). People from all over the country migrate to this city to earn a livelihood (Imran, Hossain, Islam, Rahman, Bhuiyan, & Alam, 2021), mitigate poverty [(Islam, Abdullah, Ahmed, Islam, Ferdush, & Miah, 2018)], and seek a better life, and all these factors are rapidly increasing the urbanization of the city. This significant population growth of Dhaka is changing its land use and land coverage, which has reduced green and blue spaces. Land is converted for residential, commercial, and industrial use, destroying vegetation and waterways (Hossain et al., 2023). Urbanization has added 7500 hectares of land and lost 6600 hectares of vegetation between 1988 and 2020 (Rahman and Szabó [2021](#)).

These regional land-use changes have been linked to UHI (Urban Heat Island) effect (Seto & Shepherd, 2009; Shahfahad, Naikoo, Islam, Mallick, & Rahman, 2022; Shahfahad, Rihan, Naikoo, Ali, Usmani, & Rahman, 2021). UHI is considered one of the significant problems in the 21st century that human beings are posed with (Rizwan, Dennis, & Liu, 2008). So, when the temperature at the center of the city is found to be higher than its surroundings or the suburban area, this phenomenon is called the Urban Heat Island (UHI) effect (Adinna, Christian, & Okolie, 2009).

Urban heat island (UHI) effects are among such anthropogenic disturbances to influence urban communities (Merckx et al., 2018), as they negatively impact human health, economy, and natural ecosystems (Wang, Harindintwali, Wei, et al., 2023; Perkins-Kirkpatrick & Lewis, 2020; Vogel, Zscheischler, Fischer, et al., 2020; Sahani, Kumar, Debele, et al., 2022). However, in a nation such as Bangladesh, where more than half of urban people live in informal housing (Uddin, 2018), UHI exacerbates the impact of heat waves, disproportionately affecting

vulnerable populations, including informal settlers (Shahrujjaman et al., 2025). One billion people live in informal settlements worldwide, which generally lack secure land tenure and basic services and infrastructure, and are thus vulnerable to multiple impacts of climate change (Satterthwaite et al., 2020), including heat stress. In addition, informal settlements generally comprise low-quality housing, and residents often depend on informal employment in labour-intensive roles for their livelihoods (Ezeh et al., 2017). These inherent characteristics of informal settlements, along with a large existing health burden, mean that residents are highly vulnerable to heat stress and lack adequate refuge and financial security if extreme heat reduces work capacity (Pasquini et al., 2020).

2. Literature Review

Many previous studies have already made significant scientific contributions in this field. Here I organize the findings from different studies in two large thematic areas: 1. Blue-Green Infrastructure and its heat retention capacity, and 2. Urban Heat Island (UHI) and their effect on Informal settlements.

2.1 Blue-Green Infrastructure and Its Heat Retention Capacity

Since the 20th century, when the world population has increased considerably, urbanization-induced land use and land cover change (LULCC) have transformed hydrological landscape and green spaces into impervious surfaces (Chen et al., 2020; Huq, Rahman, & Hasan, 2024; Miah et al., 2024; Razi Sadath et al., 2023)

Abdullah et al., 2024, p.1, argue that, The destruction of wetlands is more prominent in densely populated countries (e.g., China) (Ayon, Shubho, Tanvir, Islam, & Islam, 2020), countries with shortages of water (e.g., Australia) (Naheed et al., 2010), countries with strong agro-industrial systems (e.g., the USA) (Mamun, Mahmood, & Rahman, 2013) and rapidly developing countries (e.g., Bangladesh and India) (Ayon, Shubho, Tanvir, Islam, & Islam, 2020); (Balogun & Ishola, 2017). Through spatiotemporal and remote sensing analysis it is found that, Dhaka representing a significant reduction of 70% of its wetlands (1990- 2020), vegetation cover decreased by 71.82% (1991- 2015), 174.13 km² of urban areas expanded by 249.77%, hot concentration zones increase by 93.73% and the average temperature had increased by 3.26°C (Rayhan et al., 2025; Abdullah et al. 2024; Hussain, Ahmed, & Shumi, 2023).

International Panel on Climate Change (IPCC, 2021) acknowledged that green and blue urban infrastructure elements are particularly effective in reducing air temperatures in cities (Hussain, Ahmed, & Shumi, 2023). Different forms of green infrastructure and Urban water bodies represent both critical ecological and hydrological systems and have been found effective in keeping urban environments cool (Hussain, Ahmed, & Shumi, 2023; Rayhan et al., 2025).

Kumar et al. (2024) argue that urban overheating, driven by the combined effects of rapid urbanization and global warming, can be effectively mitigated through the strategic implementation of urban green-blue-grey infrastructure (GBGI), that balances cooling effectiveness with multifunctional urban ecosystem services.

As water bodies have greater specific heat capacity compared to other physical objects, its warming-up rate is slower than other materials, resulting in the cool island effects during the daytime (Oke, 1987). Different scholars have studied water's heat retention capacity over the years: Cai, Han, & Chen (2018) found water bodies' cooling effects have an obvious influence on the relationship between the LST and urban form factors (e.g., sky view factor and mean building height) in Chongqing, China. Wu and Zhang (2019) observed the "cool edge" effect near water-land interfaces and found that the cooling influence of water bodies can extend up to 800 meters, with a maximum temperature reduction of about 3°C. However, in 2020, Lin et al., found that the ex-situ cooling spillover of water bodies will benefit the surrounding areas within an envelope of 100-m effective cooling distance. Hu et al. (2023) studied Threshold value of efficiency (TVoEs) of 933 waterbodies in 32 major cities across 7 climatic zones in China. The cooling effects of waterbodies varied geographically among climate zones, with tropical and subtropical humid areas showing higher cooling area, cooling efficiency and lower cooling intensity than arid areas.

On the other hand, heat stress can be buffered by urban vegetation, urban green spaces, and urban forests through shading and transpirational cooling (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Armson, Stringer, & Ennos, 2012; Wang, Wang, & Yang, 2018; Pataki, McCarthy, Litvak, & Pincetl, 2011; Konarska, et al., 2016). For example, Tan, Kotamarthi, Wang, et al. (2023) used a regional modeling approach for the Chicago metropolitan area and reported that green roofs reduce the near-surface temperature by 14% compared with solar panel roofs. Likewise, Blanco, Schettini, Vox, 2019 found that green vegetated walls recorded up to 7.7 degrees Celsius lower surface temperature than the uncovered concrete wall during summertime in Valenzano (Bari), Italy. Coutts, White, Tapper, et al. (2016) highlighted that street trees can cool summer daytime air temperatures by up to 1.5 degrees Celsius, yet reported that the cooling effect of trees during extreme heat events was not significant between streets with and without trees. Street trees were also shown to significantly lower surface temperatures in cities across Europe (Schwaab, Meier, Mussetti, et al., 2021).

Although the buffering effect of urban green spaces is influenced by their area (relative to the area of the city) and their spatial configuration (Li, Zhou, Ouyang, Xu, & Zheng, 2012). In 2024, Li et al. used remote sensing data to quantify daytime cooling by urban greenery in the warm seasons across the ~500 largest cities globally. Findings show that this cooling adaptation inequality is due to discrepancies in green space quantity and quality between cities in the Global North and South, shaped by socioeconomic and natural factors.

There are some contrasting studies as well, which argue about the cooling capacity of water heat retention. Jacobs et al. (2020) argue that while small urban water bodies such as ponds and canals are often assumed to provide cooling benefits, their actual thermal impact on the surrounding microclimate is minimal. Using ENVI-met simulations under the REALCOOL project, the study found that temperature reductions from these water bodies are typically less than 1°C and thus negligible for practical urban design purposes. However, complementary features—like tree shading, fountains, and improved ventilation—can enhance the perceived cooling effect. The findings challenge common assumptions about the standalone cooling role of small water bodies and emphasize the need for integrated blue-green design strategies to effectively mitigate urban heat. On the same note, Yu et al. (2020) also argues that while blue-green spaces—such as parks, vegetation, and waterbodies—are widely recognized for their potential to mitigate urban heat island (UHI) effects, there remains significant uncertainty regarding their quantitative and threshold-size-based cooling effectiveness. For water bodies with a depth of at least half a meter, these temperature differences are expected because of the large heat capacity of water in combination with the ability of water to transport heat away from its surface by turbulent mixing (Oke, 1987). However, the latter mechanism also implies that water takes longer to cool down, which may result in water bodies being warmer than the air during the night (Steeneveld et al., 2014).

2.2 Urban Heat Island (UHI) and its effect on informal settlements

UHI is defined as the human-induced urban climate phenomenon characterized by higher temperatures in urban areas than in the surrounding rural areas (Manoli et al., 2019; Oke et al., 2017). The UHI intensity depends on the population, size, surface characteristics, background climate of a city, anthropogenic activities, topography, meteorological conditions, season, and the time of day (Kim and Baik 2002; Liu et al. 2007; Basara et al. 2008; Lee and Baik 2010; Jongtanom et al. 2011; Camilloni and Barrucand 2012; Cui and de Foy 2012; Schatz and Kucharik 2014; Zhao et al. 2014; Tzavali et al. 2015; Du et al. 2016; Wang et al. 2016; Kotharkar et al. 2019; Manoli et al. 2019; Zhang et al. 2022). Air temperatures in the United States' urban and rural areas have risen by 0.24 and 0.16 degrees Celsius per decade (Limaye, Vargo, Harkey, Holloway, & Patz, 2018). Similarly, the temperature of cities in south and east Asian countries, such as China, India, Bangladesh, and Pakistan, has risen by 0.23–0.57 degrees Celsius every decade in recent decades (Shahfahad, Rihan, Naikoo, Ali, Usmani, & Rahman, 2021; Dewan, Kiselev, Botje, Mahmud, Bhuian, & Hassan, 2021; Xiang, Qin, He, Han, & Chen, 2022). Recent records indicate a significant rise in temperature and an increasing frequency of heatwave events across Bangladesh (Shahruijman et al., 2025). Similarly, Kabir and Ryhan (2024) report that Dhaka is nearly 3.9°C warmer than surrounding rural areas, with cyclic temperature fluctuations suggesting a continued warming trend in the coming years.

Worldwide, different scholars have studied the UHI effect on informal settlers: In Makassar, Indonesia, Ramsay et al. (2021) deployed a sensor network across 12 informal settlements by calculating two metrics wet bulb temperature and wet bulb globe temperature. They found that informal settlement residents experience chronic heat stress conditions, Wet bulb temperatures approached the uppermost limits of human survivability, and wet bulb globe temperatures regularly exceeded recommended physical activity thresholds, both indoors and outdoors.

In Bangladesh, informal settlements and their residents are among the most highly exposed and vulnerable to environmental hazards. Abrar et al. (2022) developed a heat vulnerability index (HVI) based on various demographic, socioeconomic, and environmental risk variables in 41 thanas of Dhaka. The analysis revealed strong positive correlations of HVI with exposure (0.62) and sensitivity (0.80), while adaptive capacity had a negative correlation (-0.26), indicating that areas with lower adaptive capacity are more vulnerable to heat stress. Alam et al. (2023) also found that a greater proportion of slum households in Dhaka are located within high to very high vulnerability zones, with approximately 70% of these dwellings being poorly constructed. Shahrujjaman et al. (2025) conducted a study in the Dhaka Metropolitan Area (DMA) to examine the knowledge, attitudes, and preparedness of informal workers regarding heat waves. The findings revealed a significant knowledge gap—although most respondents expressed concern about heat waves, they showed reluctance to change their behavior. Overall preparedness was found to be low, with limited readiness for heat-related emergencies.

Informal residents in Dhaka are among the most exposed to thermal stress, raising critical issues of climate justice. To address these challenges, Bangladesh has implemented several policies, including the National Adaptation Plan (NAP) 2023–2050, which aims to build a climate-resilient nation through effective adaptation strategies that strengthen ecosystems, society, and sustainable economic growth. Goal 3 of the NAP emphasizes developing climate-smart cities through robust urban drainage and water management, expanded green infrastructure, improved human health and WASH systems, and the integration of renewable energy and solid waste management (MoEFCC, 2022, p. 9).

To achieve this goal, urban planning must incorporate UHI mitigation measures and prioritize wetland restoration in the Dhaka Metropolitan Area to revive ecosystem services. Leveraging the heat retention capacity of blue-green infrastructure—including wetlands, ponds, and urban greenery—can complement conventional structural measures, reduce heat exposure, and enhance urban resilience. This approach ensures that the populations least responsible for urban LULC changes or increasing UHI effects are no longer the worst affected, promoting greater climate justice.

3. Theoretical Framework

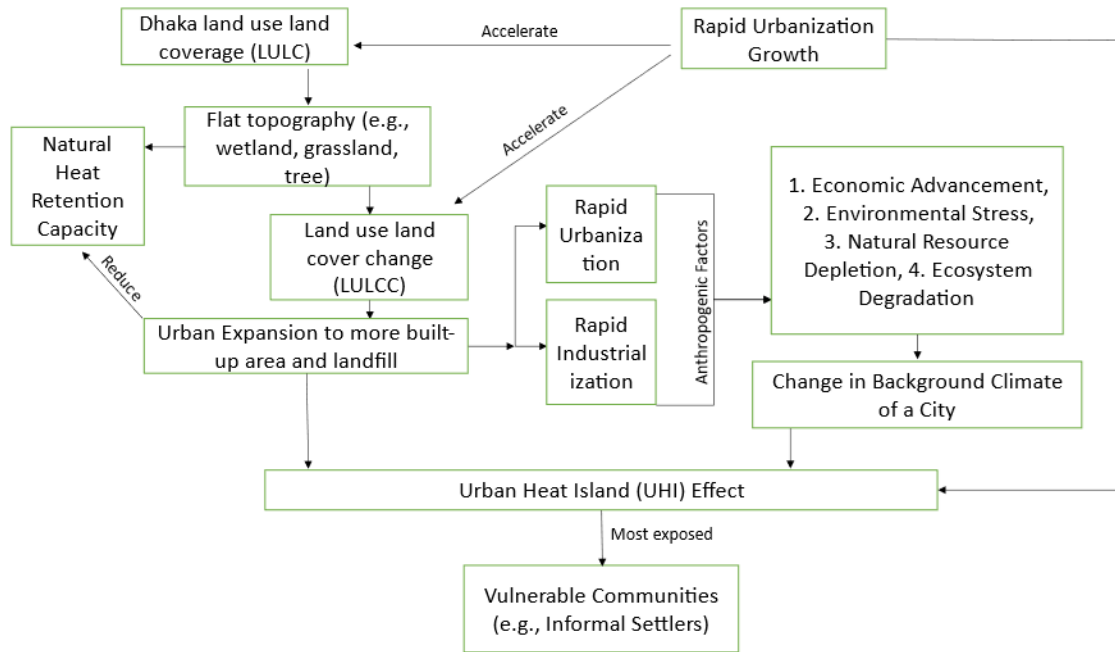


Figure 1: Theoretical Framework Linking Urbanization, Environmental Change, and Heat Vulnerability in Dhaka

Research Gap Identification

The previous studies separately search for either the urban heat island effect and its impact, or water heat retention capacity, LULC change etc. But all these measures are interconnected to each other, and this paper properly highlights the interconnectedness of all these variables/measures.

Research Objective

This Study broadly aims to investigate different climate variables and their relationship with Urban Heat Island (UHI) effect.

1. Different climate variables (e.g., Monthly average Dry-Bulb Temperature in degrees celsius, Monthly average Sunshine hours data, Monthly total rainfall in mm, Monthly average Relative Humidity) trend analysis.
2. Wetland/ Blue infrastructure loss trend analysis.

4. Methodology

This is an empirical-based study that aims to investigate different climate variables and their relationship with the Urban Heat Island (UHI) effect in Dhaka, Bangladesh. A quantitative approach followed by Statistical modelling techniques, including Trend analysis, linear regression and multiple regression, was applied, along with a significance test conducted to find whether the result is statistically significant or not.

Both secondary data (wetland loss over time from 1995-2020) in Dhaka quantified from Landsat imagery, and primary data (Climate variable datasets: e.g., Temperature, Sunshine Hours, Rainfall (mm), Relative Humidity) were used. Primary data were collected from the Bangladesh Meteorological Department (Climate Division) from the period 2000-2024.

Limitation of the Study

This study faces limitations in GIS mapping due to less technical expertise and limited timeframe. Since this study is working with a large dataset for statistical analysis with climate variables for 25 years and GIS mapping for wetland loss for 25 years, it itself needs an individual themed long study period. That is why the secondary dataset of wetland loss (LULC) is used for analysis.

5. Data Analysis

This chapter presents the analysis of climate and environmental data to understand trends and interactions in Dhaka over recent decades. The chapter begins with the seasonal average temperatures (°C) from 2000 to 2024. Subsequently, linear regression analyses were performed for four variables—temperature, sunshine hours, rainfall, and relative humidity—over the 25-year period to identify trends. Finally, a multiple regression analysis was conducted with temperature as the dependent variable and sunshine hours, rainfall, and relative humidity as independent variables to assess their combined effects. The chapter concludes with illustrating the wetland loss in Dhaka from 1990 to 2020, linking environmental degradation with urban heat dynamics and broader climate impacts.

Seasonal temperature average (in °C):

Year	Pre-monsoon (March–May)	Monsoon (June–September)	Post-monsoon (October–November)	Winter (December–February)
2000	27.13333333	28.95	26	19.925
2001	27.8	28.75	26.05	20.15
2002	27.2	28.575	25.7	20.725
2003	27.6	28.9	25.9	19.825
2004	28.43333333	28.475	25.15	20.5
2005	28.16666667	29.05	25.45	21.05
2006	28.36666667	28.975	26.1	21.25
2007	27.83333333	28.675	25.5	19.775
2008	28.36666667	28.725	25.4	20.025
2009	28.73333333	29.225	26.1	20.75
2010	29.43333333	29.35	26.6	20.025
2011	27.6	28.975	26	19.6
2012	28.43333333	29.25	25.7	19.45
2013	28.16666667	29.25	25.5	20.2
2014	29.13333333	29.275	26	19.325
2015	27.96666667	28.975	26.1	20.575
2016	28.73333333	29.325	26.4	21.525
2017	27.7	29.1	26.2	21.45
2018	27.4	29.575	25.75	20.325
2019	28.03333333	29.55	26.25	20.2
2020	27.66666667	29.5	26.75	20.175
2021	29.53333333	29.175	26.4	21.05
2022	28.93333333	29.85	26.85	20.95
2023	28.9	29.95	27.1	21.45
2024	29.33333333	29.85	27	20.65

Table 1: Average seasonal temperatures (°C) for Dhaka, Bangladesh from 2000 to 2024, covering four main climatic seasons: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). The analysis shows an overall warming trend across all seasons, with the most prominent increase during the pre-monsoon period (from 27.1°C in 2000 to 29.3°C in 2024).

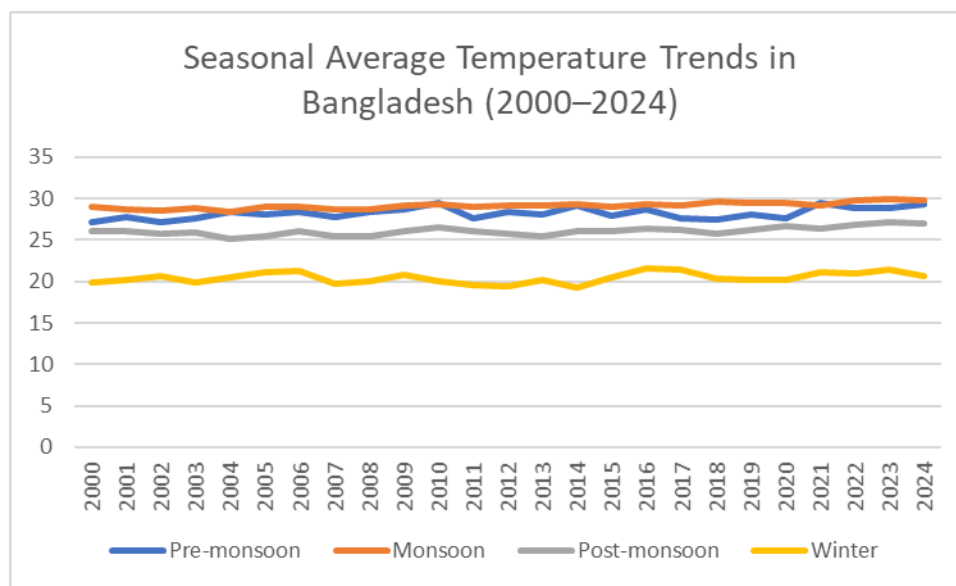


Figure 2: Changes in seasonal average temperatures (°C) in Dhaka, Bangladesh between 2000 and 2024

For Linear regression analysis, the formula used is $Y=a+bX$

Input X range: Independent variable (time)

Input Y range: Dependent Variable (Temperature, Rainfall, Relative humidity, Sunshine)

a = intercept (base value of dependent variable when independent variable = 0)

b= slope → shows how much the dependent variable increases/decreases when the independent variable changes

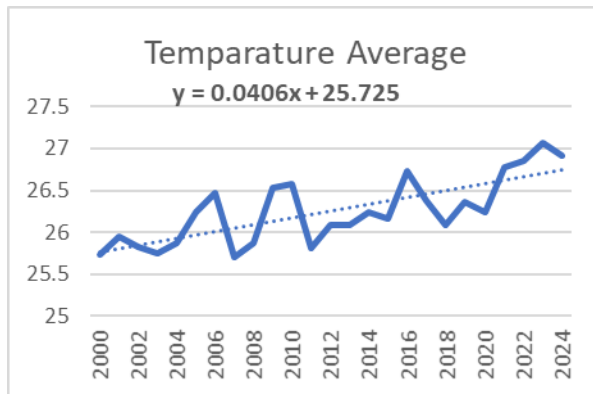


Figure 3: Linear Trend of Temperature Average in Dhaka, Bangladesh (2000–2024)

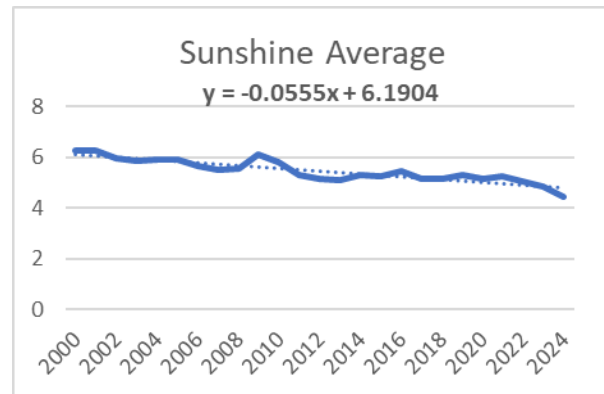


Figure 4: Linear Trend of Sunshine Average in Dhaka, Bangladesh (2000–2024)

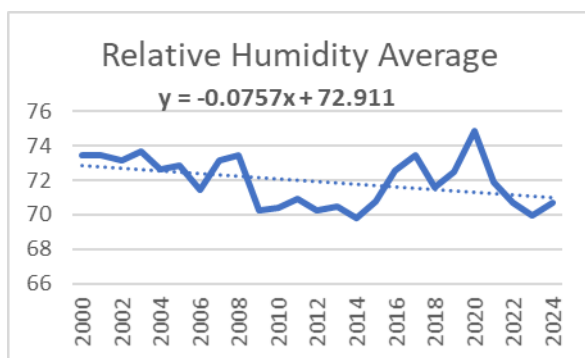


Figure 5: Linear Trend of Relative Humidity Average in Dhaka, Bangladesh (2000–2024)

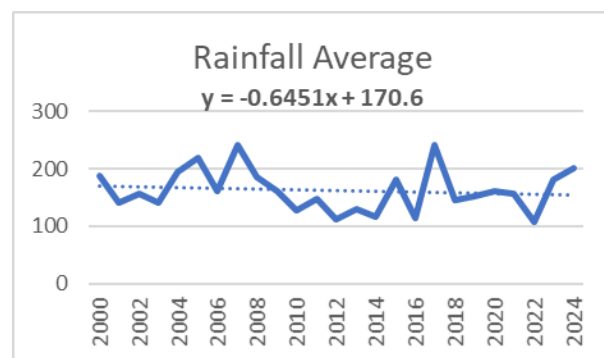


Figure 6: Linear Trend of Average Rainfall in Dhaka, Bangladesh (2000–2024)

Figure 3: Regression Equation:

$$y = 0.0406x + 25.725$$

Where:

- y = Annual Average Temperature ($^{\circ}\text{C}$)
- x = Year (from 2000 to 2024)
- 25.725= Slope (b)
- 0.0406= Intercept (a)

Explanation: Linear regression analysis of annual mean temperature data from 2000–2024 shows a statistically consistent warming trend in Dhaka ($y = 0.0406x + 25.725$). The positive slope indicates an average increase of 0.04°C per year ($\approx 0.4^{\circ}\text{C}$ per decade).

Figure 4: Regression Equation:

$$y = -0.0555x + 6.1904$$

Where:

- y = Average sunshine hours
- x = Year (from 2000 to 2024)
- -0.0555 = *Slope (b)*
- 6.1904 = *Intercept (a)*

Explanation: From 2000 to 2024, the average daily sunshine duration has been steadily declining by about 0.0555 hours (3.3 minutes) each year, starting from roughly 6.2 hours/day in 2000 to about 4.8 hours/day in 2024.

Figure 5: Regression equation:

$$y = -0.0757x + 72.911$$

Where:

- y = Average Relative Humidity (%)
- x = Year (from 2000 to 2024)
- -0.0757 = *Slope (b)*
- 72.911 = *Intercept (a)*

Explanation: Regression analysis indicates a declining trend in Dhaka's average relative humidity over the period 2000–2024 ($y = -0.0757x + 72.911$). The negative slope suggests an annual decrease of approximately 0.08%, consistent.

Figure 6: Regression equation:

$$y = -0.6451x + 170.6$$

Where:

- y = Average annual rainfall (mm)
- x = Year (from 2000 to 2024)

- $-0.6451 = \text{Slope } (b)$
- $170.6 = \text{Intercept } (a)$

Explanation: Regression analysis of rainfall data (2000–2024) reveals a declining trend ($y = -0.6451x + 170.6$), indicating an average reduction of 0.65 mm per year.

For multiple regression analysis the formula used: $T_{avg} = \alpha + \beta_1(\text{Rainfall}) + \beta_2(\text{Humidity}) + \beta_3(\text{Sunshine}) + \epsilon$

$\beta_1, \beta_2, \beta_3 \rightarrow$ show how each independent variable affects temperature when the others are held constant.

$\epsilon =$ error term (unexplained variation)

Regression Equation:

Temperature Average $= 34.43 - 0.3495(\text{Sunshine}) - 0.0866(\text{Humidity}) - 0.00025(\text{Rainfall})$

Multiple linear regression output,

where:

Dependent variable (Y) = Temperature Average

Independent variables (X) = Sunshine Average, Relative Humidity Average, Rainfall Average

Intercept (34.43)

Sunshine (-0.3495)

Relative Humidity (-0.0866)

Rainfall (-0.00025)

Explanation:

The overall regression analysis indicates that the combined effects of sunshine, relative humidity, and rainfall significantly predict temperature changes [dependent variable]. Between 2000–2024, the average temperature tends to increase when sunshine duration decreases. However, humidity and rainfall did not show statistically significant effects. Rainfall and humidity play smaller roles in temperature variation.

<i>Regression Statistics</i>	
Multiple R	0.605306848
R Square	0.36639638
Adjusted R Square	0.275881577
Standard Error	0.342054006
Observations	25

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	1.420830202	0.473610067	4.047916678	0.020362956
Residual	21	2.457019798	0.117000943		
Total	24	3.87785			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>
Intercept	34.43410229	3.774849788	9.121979477	9.44296E-09
Sunshine Average	-0.349500251	0.169868699	-2.057472943	0.052270223
Relative Humidity Average	-0.086616089	0.05867311	-1.476248475	0.154715888
Rainfall Average	-0.000248001	0.002042911	-0.121395782	0.904531669

- $R^2 = 0.366 \rightarrow$ The model explains 36.6% of the variation in the dependent variable.
- Adjusted $R^2 = 0.276 \rightarrow$ After adjusting for 3 predictors, 27.6% of variance is explained.
- $F(3, 21) = 4.05, p = 0.020 \rightarrow$ The regression model is statistically significant overall.

So,

- The overall regression model is significant.
- Among the variables, Sunshine has the strongest (near-significant) relationship with temperature.
- Humidity and Rainfall have weaker and statistically insignificant relationships.

Land type	1990		1995		2000		2004		2010		2015		2020	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Wetland	3448	11.28	3145	10.28	2947	9.64	2348	7.68	1972	6.45	1838	6.01	1068	3.5
Grassland	23193	75.88	20891	68.35	19935	65.22	19683	64.39	18541	60.66	14987	49.03	8699	28.46
Built-up	2448	8	4666	15.26	5408	17.69	6647	21.74	7091	23.2	11695	38.26	14327	46.87
Tree	1028	3.36	1253	4.09	1591	5.2	1313	4.29	1060	3.46	1126	3.68	5636	18.44
Landfill	447	1.46	609	1.99	683	2.23	573	1.87	1900	6.21	918	3	834	2.73

Table 2: Summary of Land Use Land Cover Classification Statistics between 1990 and 2020. Note. Adapted from [Development at the cost of unsustainable degradation of wetlands: Unraveling the dynamics (historic and future) of wetlands in the megacity Dhaka] by Abdullah et al., 2024, p. 3.

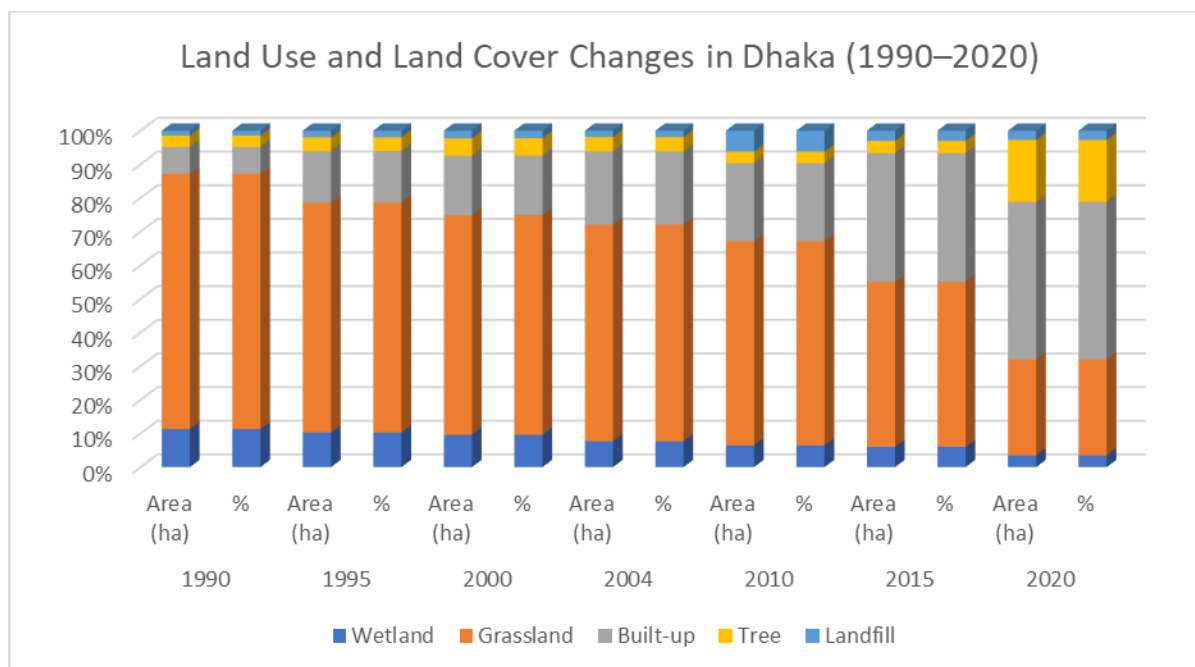


Figure 7: Land use and land cover changes in Dhaka between 1990 and 2020

Figure 7 illustrates land use and land cover (LULC) changes in Dhaka from 1990 to 2020. During this period, wetlands and grasslands declined sharply, while built-up areas expanded rapidly, reflecting intense urbanization. Tree cover increased moderately, particularly by 2020, possibly due to urban greening initiatives, and landfill areas showed minor fluctuations. Overall,

these changes highlight significant ecosystem transformation and mounting environmental pressures from urban expansion in Dhaka.

6. Findings and Discussion

The analysis reveals significant trends and interrelationships between key variables. The seasonal temperature averages demonstrate a consistent warming trend across all four climatic seasons, with the most notable increase occurring during the pre-monsoon period, rising from 27.1°C in 2000 to 29.3°C in 2024. Linear regression analysis confirms this pattern ($y = 0.0406x + 25.725$), indicating an annual temperature increase of approximately 0.04°C per year (0.4°C per decade).

Analysis of sunshine duration shows a gradual decline of about 0.0555 hours per year, suggesting reduced daily sunlight exposure, while relative humidity and rainfall also exhibit declining trends over the 25 years. Multiple regression analysis, where temperature served as the dependent variable and sunshine, relative humidity, and rainfall as independent predictors, yielded an overall significant model ($F(3,21) = 4.05$, $p = 0.020$). The model explains 36.6% of the temperature variation ($R^2 = 0.366$). Among the predictors, sunshine duration showed the strongest near-significant negative relationship with temperature, whereas humidity and rainfall had weaker, statistically insignificant effects.

The analysis does not explain the exact causes of the negative correlations observed among the variables. The limited interrelationship between temperature, rainfall, sunshine, and humidity suggests that other climatic and atmospheric factors not included in this model—such as air pollution, wind speed, solar radiation, or cloud cover—may play substantial roles in influencing Dhaka's local temperature dynamics and its interrelationship with UHI effect. This limited explanatory power reflects complex atmospheric interactions, consistent with Yu et al. (2020) and Jacobs et al. (2020), who emphasize that limited parameters alone cannot fully capture the dynamics of urban thermal environments.

The wetland loss and land use land cover change (LULCC) data further highlight a strong environmental linkage: as wetlands and green spaces declined, built-up areas expanded rapidly, corresponding with an increase in surface temperatures. This relationship aligns with the characteristics of the Urban Heat Island (UHI) effect, where loss of blue-green infrastructure exacerbates heat accumulation in urban environments. These changes strongly correlate with rising surface temperatures, echoing Rayhan et al. (2025) and Abdullah et al. (2024), who found that Dhaka lost nearly 70% of its wetlands alongside a 3°C temperature increase over recent decades. The loss of blue-green infrastructure undermines natural cooling processes, as recognized by the IPCC (2021) and Hussain, Ahmed, & Shumi (2023), who identify wetlands and urban greenery as vital in regulating heat through evapotranspiration and shading.

7. Conclusion

This study highlights the strong link between Dhaka's rapid urbanization, land cover transformation, and rising temperatures over recent decades. The consistent warming trend and sharp wetland loss underscore the city's growing vulnerability to Urban Heat Island effects. To guide future research and interventions, it is essential to expand analyses beyond temperature, sunshine, rainfall, and humidity to include additional climate variables such as air pollution levels, cloud cover, solar radiation, and wind speed. Incorporating these factors can provide a more comprehensive understanding of the drivers of UHI and thermal stress in rapidly urbanizing regions. Moreover, integrating wetland restoration, blue-green infrastructure planning, and sustainable urban design into Dhaka's climate adaptation strategies can help mitigate UHI impacts and enhance climate resilience. These findings offer empirical support for developing data-driven urban policies which emphasizes climate-smart city development.

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Paper 27

How Media Frame Climate-Induced Migration from Bangladesh: A Comparative Analysis of National and International Media Coverage

Md. Azharul Islam

Abstract

Climate-induced migration is not a new phenomenon in Bangladesh. Now, it is one of the most pressing socio-environmental challenges of the 21st century, particularly for Bangladesh. There are many reasons, such as salinity incursion in the southern part of Bangladesh, floods, rising sea level, and riverbank erosion, which are mainly responsible for climate-induced migration. Although the national and international media play an important role in representing climate-vulnerable issues, the representation of climate migration issues in Bangladesh remains inconsistent. This research investigates how both the national and international media cover climate-induced migration issues. Researchers by using framing theory and an asymmetrical comparative content analysis method due to a lack of sufficient international media coverage, examined climate-induced migration framing. The study took a purposive sampling technique and analyzed 80 news articles published between January 2022 and June 2024; 60 from two of the leading Bangladeshi newspapers (Prothom Alo & The Daily Star) and 20 from major international news outlets (Al Jazeera, BBC). The content analysis of national and international media results shows that most of the outlets of Bangladeshi media primarily frame climate migration as a humanitarian cause, showing struggles, displacement, and resilience instead of addressing the global problem, while the international media frames the problem as a global crisis, connecting it to geopolitical issues, climate justice debates, and regional imbalance. The results also show that the tone of the national outlets is mainly negative, mentioning crisis and loss. In contrast, international media demonstrate visual content as alarming, and national media use emotion-evoking images. The study promotes a more analytical framing of climate-induced migration in national media as well as balanced framing in the international media.

1. Introduction

Climate change is not only a distant environmental concern but also an urgent and crucial global concern. This concern directly threatens human lives, security, and well-being (IPCC, 2022). For a developing country like Bangladesh, this impact is so acute. As Bangladesh is a riverine country surrounded by the Ganges, Brahmaputra, Meghna, and Jamuna rivers, and has a direct link with the Bay of Bengal, it is highly vulnerable to sea-level rise, the problem of salinity, and riverbank erosion (Islam, 2020). These environmental issues are responsible for the displacement of millions of people, which is known as climate-induced migration. It is a forced movement of people due to climate issues. Bangladesh is known as the “ground zero” of climate change impacts, as it is at high risk of climate change (Penning-Rowsell et al., 2013). Recent projections suggest that one in every seven people in the country may be displaced due to climate change by 2050 (World Bank, 2025). Though this problem has received significant attention in scientific and humanitarian dimensions from climate researchers and development agencies, how it is portrayed in the media has received comparatively less scholarly focus.

The media has a soft power and can play a critical role in shaping public perception, creating a policy discourse among the policy makers, and framing the urgency of climate migration and its effects (Entman, 1993; McCombs & Shaw, 1972). In Bangladesh, national media work as the primary source of information for both policymakers and the public. On the other hand, international media coverage has the power to place the issue on the global stage and create policy discourse all over the world. However, there are lots of disparities in coverage between national and international media. These kinds of disparities in media coverage and framing may influence how climate-induced migration from Bangladesh is understood both nationally and internationally. This study uses framing theory to investigate the framing of climate-induced migration and conduct a comparative content analysis of national and international media. It aims to answer the following two research questions:

1. How do national and international media usually frame climate-induced migration from Bangladesh?
2. To what extent do the frequency and framing of coverage differ between the two contexts?

Focusing on the two questions, the study enhances the growing field of climate communication, and it demonstrates how the framing of media may influence climate policy advocacy and global awareness, both nationally and internationally, on climate-induced migration from Bangladesh.

2. Literature Review

2.1 Climate-Induced Migration: Global and Bangladeshi Context

Climate-induced migration, also called environmental displacement, refers to the forced movement of individuals or communities due to environmental change factors, such as rising sea

levels, droughts, river erosion, salinity, and extreme weather events (No, 2008). More than 30 million people worldwide were displaced in 2022 alone by climate-related disasters (IDMC, 2023). The Intergovernmental Panel on Climate Change (IPCC, 2022) warned that this situation could worsen, especially in low-lying and densely populated regions where adaptation capacity is limited. Bangladesh is among the most vulnerable nations globally, as it is situated in a climate danger zone with overpopulation and reliance on climate-sensitive livelihoods (IPCC, 2022; (G. M. M. Alam et al., 2017). Projections indicate that by 2050, sea levels may rise, potentially displacing 13 million people (Jenny, 2017). Studies show that displacement in Bangladesh is directly connected to climate impacts such as loss of agricultural land, salinity, coastal intrusion, and repeated cyclone damage (M. R. Islam & Shamsuddoha, 2017). Consequently, migration to Dhaka and Khulna is increasing, causing overcrowding and heightened socio-economic pressures (Ferdous, n.d.). Several studies also reveal that climate migration in Bangladesh has significant socio-economic impacts, including loss of livelihoods, urban overcrowding, and increased poverty (Ferdous, n.d.). However, while humanitarian aspects have been extensively studied, the media's role in shaping the narrative of climate justice and how the media tries to frame the climate migration issue remains relatively less examined.

2.2 Media Framing of Climate Change and Migration

According to Entman (1993), the way issues are presented through selection, emphasis, and exclusion shapes audience perceptions and policy debates. In the issue of climate change, media frames often emphasize scientific certainty or uncertainty, human impacts, related economic aspects, or political conflict (Boykoff, 2013). Similarly, media coverage about climate-migration can also be framed in various ways, like humanitarian empathy, security concerns, or development opportunities (Benson, 2013). Scholars highlight striking differences between national and international media in how they frame climate-induced migration. Studies have shown that international media often highlight climate-migrants' issues from the Global South through a humanitarian and victimhood lens (Farbotko, 2010). In contrast, national media may emphasize adaptation measures, local resilience, or political accountability (Rhaman, n.d.); (Miah et al., 2011). Similarly, development-oriented frames may open discourses on resilience, innovation, and adaptation funding, but put at risk the human suffering. This is how framing choices can influence the level of urgency conveyed to policymakers and the public, as well as how people perceive climate migration.

2.3 Climate Change Communication in Bangladesh

Bangladeshi media have been seen to play a significant role in disaster communication, especially in reporting on extreme weather events such as cyclones, floods, and river erosion (Raza et al., 2025; E. Alam & Collins, 2010). During the national emergency, the media were found to have functioned as crucial sources of information, for example, warning the people about the bad weather and disaster preparedness campaigns disseminated. However, when it is an issue of climate change, Bangladeshi media are seen to provide coverage largely event-driven

rather than sustained (Nurunnabi, 2016). Most of the reports are seen during the visible disasters, such as cyclones or floods, while the long-term structural dimensions of climate vulnerability, for example, riverbank erosion, gradual salinity intrusion, and climate-induced migration (M. R. Islam & Shamsuddoha, 2017). This can be called an episodic reporting style that tends to create a cycle of heightened awareness during crises by prolonged neglect in public discourse (Eide & Kunelius, n.d.). As a result, many important issues of climate disasters, such as infrastructure deficits, transitions of livelihood, or the socio-political implications of large-scale displacement, remain underrepresented.

Bangladeshi media often portrays the climate issue as loss and damage, focusing on poverty, livelihood, and devastated lives (Eide & Kunelius, n.d.). As a result, coverage on migration as a survival strategy receives comparatively less focus despite its significance in shaping the response to climate risk among the public (Martin et al., 2014). Similarly, language choices in media coverage can play a significant role in shaping public perceptions. Media use emotive adjectives such as ‘helpless, powerless, or suffering’ that can prolong the sense of urgency and overlook structural causes and political responsibility (Martin et al., 2014). This is how such rhetorical strategies may overshadow demands for climate justice and equitable responsibility-sharing. In contrast, international media covered Bangladeshi climate migration in sensationalist framings. Media of the Global North sometimes emphasize vulnerability, framing Bangladesh as ‘Ground Zero’ of climate change (Boykoff, 2013). This framing may focus narrowly on spectacle and tragedy rather than inquiring into the structural drivers of climate change, including climate-induced migration (Carvalho, 2007). So, the overall framing of the climate issue in Bangladesh is mainly characterized by episodic crisis reporting and the need for sustained structural engagement. Framing the humanitarian issue is the main subject of Bangladeshi news media, which creates framing gaps, and these gaps have profound implications for climate policy (Paprocki, 2022). A comparative analysis of the national and international media highlights that national outlets integrate climate migration into broader socio-economic contexts, and international outlets present the issue as a humanitarian crisis (Cottle, 2009). This framing gap can affect whether migration is seen as a temporary disruption or a systemic, long-term adaptation challenge.

To sum up, while the existing literature emphasized climate migration and its socio-economic implications, few studies have conducted a comparative content analysis of national and international media framing. The study addresses the gap and examines how the issue is constructed for domestic versus global audiences, as well as how such framing may influence climate justice advocacy.

3. Theoretical Framework

The study uses the framing theory of Entman (1993), which explains how the selection and emphasis of certain aspects of issues influence public perception and create policy debates. In the context of climate migration, frames can emphasize human suffering, security threats, resilience,

and adaptation or increase the awareness of climate justice (Benson, 2013). Framing theory in media is frequently used in environmental communication. Climate issues are framed can either mobilize collective action or reinforce apathy towards victims (Boykoff, 2013). Similarly, according to Nisbet (2009), frames can be used as an interpretative package to guide public understanding of scientific and political debates on climate communication. Climate change and its effects in Bangladesh are a lived reality. That's why the humanitarian frame often dominates media coverage, showing crisis, loss, and damage.

Moreover, Bangladeshi journalists have the tendency to show human-centered crises when framing climate-related issues, emphasizing personal suffering, community resilience, and local adaptation (Islam & Hasan, 2020). However, in the context of international media, security is dominantly framed. Previous research also highlights that in the context of climate migrants, countries in the Global South are often framed as victims (Farbotko & Lazrus, 2012), whereas national media outlets tend to focus on resilience, adaptation, and political accountability (Riaz & Rahman, 2016). Framing theory is also interconnected with agenda-setting theory. McComb and Shaw (1972) argue that the media may influence what people think about. This is how the media directs the public and policymakers' attention toward specific issues designed by the media. In climate communication, Bangladeshi media seek to raise awareness of human suffering (Rahman, 2020), while international media are concerned with migration flows, security, and geopolitical risks (Benson, 2014). However, Entman's (1993) framing theory helps to explain how Bangladeshi and international media construct narratives differently.

4. Methodology

The study adopts an asymmetrical comparative content analysis method to examine climate-induced migration framing. It uses an asymmetrical approach due to a lack of sufficient international media coverage on climate migration from Bangladesh. The study used a purposive sampling technique where a sample (n=80) of articles was taken from the leading two Bangladeshi newspapers and from two international media outlets serving as a comparative subset. Articles were collected from *Prothom Alo* and *The Daily Star*, the most widely read newspapers in Bangladesh, and from *BBC* and *Al Jazeera* as representatives of international media. The sampling period covered January 2021 to June 2024. These media were selected because, after examining all print media websites, we found that *Prothom Alo* and *The Daily Star* have the most comprehensive collection of climate-induced migration news, and *BBC* and *Al Jazeera* are among the most influential global news outlets providing extensive coverage of climate-related issues in South Asia.

Searching keywords such as “climate migration”, “climate refugees”, “flood displacement”, “river erosion migration”, “climate-induced migration in Bangladesh”, the study collected 60 relevant articles that were purposively selected from Bangladeshi newspapers and 20 articles from international media due to limited coverage on climate-induced migration. For data analysis, a detailed codebook was developed, informed by previous studies (Entman, 1993;

Benson, 2014; Boykoff, 2011) on media framing of climate issues. The study includes key variables and categories coding. First, Frame type: *Humanitarian, Resilience/Adaptation, Security Threat, Policy and Governance*. Second, Tone: *Positive, Negative, and Neutral*. Finally, Source Diversity: *Migrants, Government officials, NGOs and civil society, Climate experts, international organizations*. To ensure the reliability of data, two independent coders were trained on the coding scheme and coded a random subset of 15% of the articles. The coding procedure found a value ranging from 0.79 to 0.85, which indicates that there is a substantial agreement. The study avoids collecting similar content published in selected newspapers.

4. Findings

4.1 Dominant Media Frames

The findings demonstrate a huge difference in media coverage between national and international media in how they frame the issue of climate-induced migration. The dominant frame of Bangladeshi media is humanitarian (60%), portraying migration mainly in terms of displacement, loss, and damage, and the urgent need for financial aid. On the other hand, international media adopt this frame less frequently (35%), and the difference between the two media is statistically significant ($P < 0.05$) (Figure 1). International media emphasized the security threats frame (40%), while Bangladeshi media used this frame comparatively less (10%), connecting migration to risks of instability and conflict ($P < 0.01$). However, framing like resilience/adaptation and policy/governance appear in both contexts, where national media covered policy/governance 7%, and international media covered 15%. Similarly, in the contexts of resilience or adaptation, the framing between the two media is almost the same. Bangladeshi media covered 23% while international media covered 10%. These two differences are not statistically significant ($P > 0.05$), ($P > 0.05$) indicating no strong divergence in how these factors are covered.

4.2 Distribution of Media Frames by Media Type

FRAME TYPE	BANGLADESHI MEDIA (N=60)	INTERNATIONAL MEDIA (N=20)	MEDIA X ² (df = 3)	P-VALUE
HUMANITARIAN	36 (60%)	7 (35%)	5.12	0.023*
RESILIENCE/ADAPTATION	14 (23%)	2 (10%)	2.20	0.138
SECURITY THREAT	6 (10%)	8 (40%)	9.60	0.002**
POLICY/GOVERNANCE	4 (7%)	3 (15%)	1.14	0.285

Table 1: Framing-distribution table

4.3 Tone of Coverage

In the context of tone in media coverage, the result reveals a striking similarity between national and international media outlets. In both media, the climate migration issue is portrayed negatively (73% Bangladesh and 75 % in international media), emphasizing crisis, loss, and vulnerability. Similarly, the framing of neutral and positive tones appears only occasionally. Neutral reporting is relatively uncommon, where Bangladeshi media frame 20% negativity, and in international media 15 %. Similarly, the national media frames 7%, while the international media frames 10% as positive framing. So, no statistically significant differences are observed between the two groups ($P>0.05$) (Figure 2). In both media, climate migration is framed through a pessimistic lens, highlighting risk and suffering rather than opportunities. However, in terms of neutral framing, it is also quite similar between the two media (20% vs 15%).

TONE	BANGLADESHI MEDIA (N=60)	INTERNATIONAL MEDIA (N=20)	MEDIA χ^2 (df=2)	P- VALUE
NEGATIVE	44 (73%)	15 (75%)	0.03	0.862
NEUTRAL	12 (20%)	3 (15%)	0.29	0.589
POSITIVE	4 (7%)	2 (10%)	0.16	0.690

Table 2: Tone of Articles by Media Type

4.2 Source Diversity

The result of the sources analysis demonstrates a significant difference between national and international media in how climate migration is reported. The majority of the outlets of Bangladeshi media heavily rely on the voice of migrants and displacement persons (40% vs 10%, $P<0.05$), while international media cite NGOs, climate experts, and international agencies far more frequently ($p<0.05$), where Bangladeshi media cites NGOs as sources only 30%, on the other hand international media cite 65%. International media mainly highlight institutional perspectives and global expertise. However, both media cite government officials as sources, but the difference between them is not statistically significant. The overall chi-square test ($\chi^2 = 15.10$, $df = 4$, $p = 0.0045$) (Figure 3) reveals a strong connection between source type and media origin, suggesting that Bangladeshi media depend on local voices while international media focus on experts and organizations. However, while the use of the government as a source was slightly higher in national media, it was not statistically significant ($P>0.05$). Bangladeshi media uses government officials as sources for 50%, and international media uses 35%. Note: The percentages show the share of articles that quoted each source type. Because one article may include more than one source, the totals are higher than 100%.

SOURCE TYPE	BANGLADESHI MEDIA (N=60)	INTERNATIONAL MEDIA (N=20)	MEDIA X ² (df=4)	P-VALUE
MIGRANTS/DISPLACED	24 (40%)	2 (10%)	5.36	0.0206*
GOVERNMENT OFFICIALS	30 (50%)	7 (35%)	1.10	0.2952
NGOS/CIVIL SOCIETY	18 (30%)	13 (65%)	5.97	0.0146*
CLIMATE EXPERTS	12 (20%)	11 (55%)	6.55	0.0105*
INTERNATIONAL AGENCIES	10 (17%)	12 (60%)	10.04	0.0015**
OVERALL (5×2)	—	—	15.10	0.0045

Table 3: Sources Quoted by Media Type

4.3 Visual Representation

Visual representation can play a significant role in shaping public perception of climate-induced migration. Visual representation in media outlets highlights a clear difference in how national and international media portray climate-induced migration. The majority of visuals (70%) in Bangladeshi outlets consist of empathetic portraits displaying vulnerable families, children, and community gatherings. The result shows that Bangladeshi media tends to emphasize human suffering and resilience. These visuals create an emotional connection with the local audiences by showing the lived realities of climate victims. This kind of human-centered representation aligns with local journalistic tendencies to highlight the social humanitarian dimensions of climate change. Conversely, international media mainly focus on environmental destruction imagery, for instance, flooded landscapes, eroded coastlines, and maps illustrating sea-level rise, which cover 65% of total imagery. These images represent the migration as an environmental issue instead of a community-centered crisis. This framing makes the audience feel more distant from the people who are actually suffering. This visualization portrays a geographical problem rather than a human-centered one.

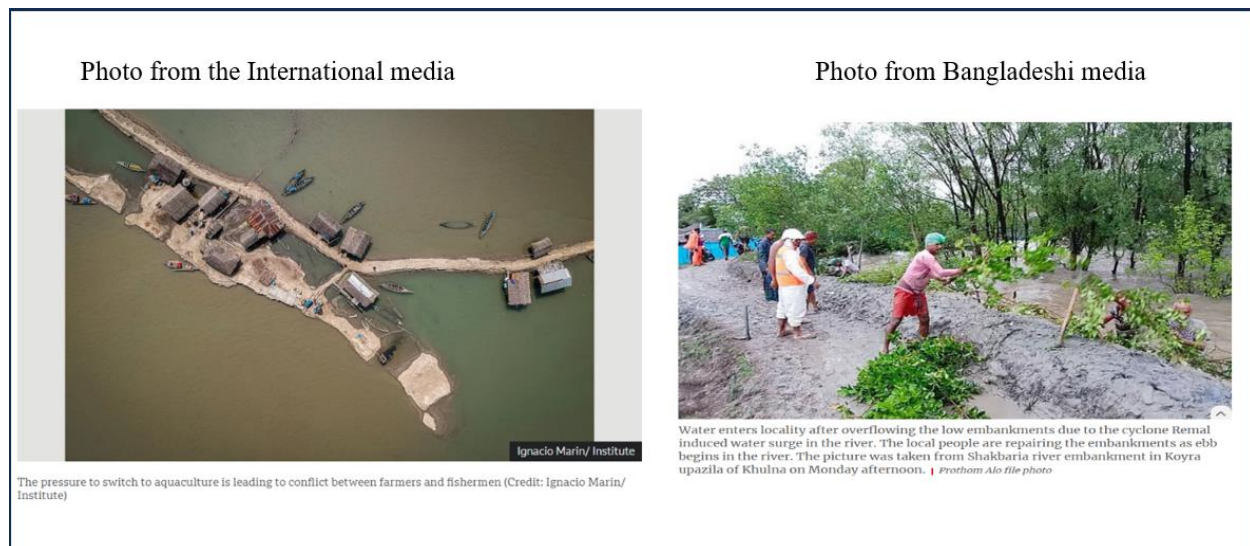


Figure 1: Sample of photos used in the national and international media

5. Discussion

This study examined how climate-induced migration from Bangladesh is framed in national and international media, demonstrating notable differences in framing patterns, source diversity, and visual representations. The results suggest that Bangladeshi media usually implement a humanitarian frame (60%) in climate stories as a dominant frame, portraying migration mainly in terms of displacement, loss, and damage, and the urgent need for financial support. This emotive frame expresses a localized concern, showing the experience of vulnerable populations, consistent with the agenda of emphasizing attention to immediate human suffering. However, this dominance frame in Bangladeshi media aligns with previous research that highlights the local media's role in shaping lived experiences, vulnerability, and resilience (Rahman, 2020; Haque & Grafakos, 2021).

Conversely, international media adopt security threats more frequently (40%) in their content as a dominant frame, focusing on migration to risks, instability, and conflict. The difference in framing between national and international media shows that the audience and global politics can shape media coverage. While Bangladeshi media try to raise awareness inside the country, international media are more concerned about global security. However, Entman's (1993) idea supports the findings that the media frames explain problems and provide solutions based on cultural and political perspectives.

Similarly, the analysis finds a huge difference in using sources between national and international media. The majority of the outlets of Bangladeshi media heavily rely on the voice of migrants and displacement persons, offering a narrative grounded in direct experience, covering 40% local sources. In contrast, while international media cite NGOs, climate experts, and international agencies far more frequently. This result is relatable to the previous researches,

which highlight the dependency on local voices by local media, while international media try to cite experts or official sources to make the story more credible (Eberl et al., 2018 & Howarth, 2016).

However, both national and international media tend to use a negative tone in climate migration reports, where Bangladeshi media portray 73% negativity, and international media portray 75% of the overall tone. This negative framing of the climate migration issue demonstrates that climate-induced migration is mostly highlighted as a problem that can enhance the idea of weakness instead of resilience and solving problems (Nisbet, n.d.). In this type of climate communication, researchers argue that the media generally try to use fear-based or negative stories instead of emphasizing problem-solving matters (O'Neill et al., 2015); (Boyce & Lewis, 2009). This is how the media is creating the “climate victim” stereotype. This stereotype is hiding people’s ability to adapt and policy solutions.

The difference between the two types of media is observed in the case of visual representation. Bangladeshi outlets try to depict a human crisis imagery through visualizations. This happens in the national media as these media follow the event-based news where daily crises erupt through the human-centred picture (Islam & Hasan, 2020). However, international media emphasize the geopolitical and environmental problems in visualization, showing a flooded landscape, eroded coastline, and vulnerable areas on the map rather than highlighting a human one. This visual semiotics highlights that images serve as powerful framing that can reinforce or challenge textual narratives (Dancygier, 2023). This is how different visuals can shape perceptions of who and what is most affected by climate change. On the whole, the media are an important factor in shaping how climate-induced migration is understood in Bangladesh. The study finds some coverage gaps both for the national and international media in the framing of climate-induced migration from Bangladesh. The framing of media coverage differs between the two contexts because of geopolitical interests, as national media are always concerned about internal problems, and international media show concern over migration that could cross the international border.

6. Limitations

This study has some limitations that should be acknowledged. First, the sample size is relatively small, with only 50 articles from both national and international media, which may limit the generalizability of findings. A large sample could capture a wider variety of frames. Second, the study was conducted through a manual coding system, which may introduce the possibility of subject bias in the examination frame. The study did not follow the formal intercoder reliability measures like Cohen’s Kappa, but further research should employ this formal coding system to ensure the reliability of findings. Third, a limitation of the study is to get easy access to some international media outlets. Archived items of BBC reports were limited during the research period. As a result, there may be a possibility to collect comparable high-reach content, which may affect the comparability of international farming across all important outlets. Another

limitation of the study is the collection of articles by using keywords. The selected keywords may not capture all related articles on climate-induced migration. And finally, the short timeframe (2021-2025) of the study may not provide deeper insight into evolving framing strategies. Despite the presence of some limitations, the study provides a meaningful comparative analysis of national and international media on climate-induced migration.

7. Conclusion and Recommendations

The study provides a comparative analysis to investigate how both the national and international media cover climate-induced migration issues from Bangladesh. It offers insights into how framing, sourcing selection, tone, and visual representation shape the discourse. The study finds differences between the two media in how they frame the climate migration problem. The main difference between the two media is that Bangladeshi media emphasize humanitarian narratives using local voices as main sources, while international media privilege security threats, citing experts and international organizations. However, both contexts overwhelmingly portray climate migration through a negative lens, focusing on crisis rather than opportunities. The findings underscore that media framing is very significant in understanding media discourse on climate change and migration. Media framing not only informs the audience but also can create policy debates and create perceptions among the people (Entman, 1993). The findings also underscore those framing choices can create different consequences. Humanitarian frames may create human sympathy and mobilize financial support, but may make migrants seem helpless. Similarly, security framing by international media may bring international attention, but may highlight the migrant people as threats rather than showing people with rights (Ibrahim & Yasmin, n.d.). So, balanced framing should come from both types of media. For future study, researchers could study further to look at a longer period and include more regional and global media to examine whether these patterns continue or change in different political contexts.

Based on the findings, the study provides some recommendations. First, the national and international media should ensure the balanced framing of climate migration. Second, media houses could provide special training to journalists to cover climate communication reports. Finally, Policy actors and NGOs should collaborate with the media to ensure constructive representation that may influence global attention in favor of climate migrants.

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Paper 28

A Multistage Machine Learning Framework for Survival Prediction in CKD: Evidence from Savar Enam Medical College

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Abstract

The aim of this research is to develop a reliable decision-support system for survival classification of chronic kidney disease (CKD) patients by utilizing biomedical records and laboratory test results. In middle-income households, a CKD diagnosis often leads to considerable emotional and financial hardship, highlighting the need for effective identification of risk factors for the disease.

We want to implement various algorithms of multistage machine learning with the intent of evaluating and comparing their accuracies and other performance parameters in the process of detection of chronic kidney disease.

The chronic kidney disease dataset of 200 patients from Enam Medical College, sourced from the UCI Machine Learning Repository, was used to develop six supervised machine learning models in Python for disease detection. Although chronic kidney disease has been widely studied, there is limited research focusing on multistage classification for predicting patient survival. To fill this research gap, we employed predictive modeling to examine relationships between patient characteristics and CKD survival outcomes.

Using supervised machine learning, six classifiers were evaluated for predictive accuracy. Notably, the Random Forest algorithm achieved the highest test accuracy (90%), Mean Cross Validation Accuracy (95.4%) and exhibited strong generalization capabilities, offering balanced metrics in terms of precision, recall, and F1 scores across all six classes. This makes it a suitable choice for real world applications involving complex, multi-class CKD datasets.

In conclusion, advancements in machine learning, coupled with predictive modeling, offer compelling methods for enhancing CKD survival prediction. These findings underscore the potential of machine learning models to provide new, reliable solutions for multistage CKD classification, paving the way for further application and validation in CKD prognosis and other chronic conditions.

1. Introduction

Chronic kidney disease (CKD) is a global health issue which affects approximately 10% of the population across the world (1). The incidence of CKD is also not uniform, and it ranges between 22.48% in the world and up to 26% in urban dwellers in Dhaka over 30 years of age, as compared to 13% in other urban populations (2). Bangladesh has one-third of rural residents who are suffering the risk of CKD, which usually goes undiagnosed (3). Variations in prevalence may be due to study design, sample size and urban-rural distribution. The prevalence of CKD in Bangladesh is on the rise, and the prevalence in the world was estimated to be 14, with Bangladesh added (4).

Older adults, women, racial minorities, and individuals with diabetes mellitus or hypertension are prone to CKD (5). It leads to slow kidney damage that leads to poor filtration of blood, leading to waste build-up (6). The symptoms involve fever, pain in the back, vomiting, nosebleed, diarrhea, and rash (7). The primary causes are diabetes and hypertension, which implies that the prevention of CKD can be done by managing the prior two conditions(8). Because of the asymptomatic course of progression of the disease in many cases, people are not aware of CKD until its advanced stage (9).

Clinical prognosis makes use of albuminuria, glomerular filtration rate (GFR), and a lowered GFR is associated with a higher mortality rate due to cardiovascular and renal deaths (8,10). CKD may result in end-stage renal disease (ESRD) that necessitates dialysis or transplantation, and a 5-year survival rate of transplantation is approximately 80% CKD is also implicated with immune, hematological, endocrine, neurological and electrolyte imbalances (8,10,11).

CKD has an estimated prevalence of more than 850 million individuals, and it is the third highest death-causing illness across the entire world (12). Nonetheless, in low and middle-income nations with low rates of healthcare access, about 90 percent of adults with the disease go undiagnosed (13).

The trend of CKD is important to estimate its effect on the planning of the health of the population (3). Among the preventive measures, weight loss, dietary changes, physical exercise, quitting smoking, early referral to nephrologists, and the use of appropriate medications are lifestyle changes, creating dialysis units and training medical personnel (4).

The costs of CKD are high both to the economies of the world and in the high-income countries, CKD costs 2-3% of annual healthcare expenditure(14). Kidney failure has heavy effects on the families of the middle classes (15). Machine learning has been automated to help in diagnosis and early intervention, and provides cost-effective, fast, and accurate recognition to help clinicians and patients (16).

1.1 CKD Staging by eGFR

GFR, or blood filtration volume per minute per 1.73 m^2 , is used to measure renal performance (17). Chronic Kidney Disease (CKD) can be divided into five stages according to the estimated Glomerular Filtration Rate (eGFR) which is used to determine the kidney condition. Stage 1, eGFR of $90 \text{ mL/min/1.73 m}^2$ or more, is an indication of normal kidney functioning. Mild CKD is characterized by an eGFR ranging between 60 and 89, indicating stage 2. Stage 3 is defined as moderate CKD with a range of eGFR of 30 to 59. Stage 4 has an eGFR of 15-29, which is a sign of severe CKD. Lastly, the last stage of CKD is Stage 5, the end one, which is characterized by a less than 15 eGFR in which kidney functions are severely impaired(18–20).

It is not easy to diagnose at early stages because there are no symptoms; doctors pay attention to systemic treatment and prevention of disease progression(17,21).CKD affected more than 843.6 million people in the world in 2017 (5). In Bangladesh in 2012-13, chronic glomerulonephritis (25.5%), diabetic nephropathy (41), and hypertensive renal disease (33) are the main causes of CKD stage 5 among hemodialysis patients (22). There is a restriction in the health system with 0.36 physicians and 0.6 hospital beds per 1000 people (23).

The prediction of patient survival in CKD is difficult to accurately predict because of the multistage nature of the disease and resulting in poor outcomes and interventions occurring later (24).

The purpose of this study is to use more advanced machine learning methods to enhance better survival predictions by building a multistage categorization system to enhance clinical decision-making and patient care. The goal of this paper is to enhance clinical decision making and personalized treatment plan development by developing and testing a multistage classification model that uses state-of-the-art machine learning algorithms to determine the survival of the patient in chronic kidney disease. The study aims to reveal the major risk factors that influence the demand for chronic kidney disease in Bangladesh and solve the issue of classification using advanced machine learning algorithms, such as random forest, gradient boosting, extreme gradient boosting, and Naive Bayes. Moreover, the research will attempt to compare the predictive capacity of these models on various stages of CKD in order to identify the best method by which disease can be staged and its prognosis can be achieved. Finally, the idea is to determine the most efficient machine learning model in order to improve the early diagnosis and optimize the patient management strategies.

2. Literature Review

Chronic kidney disease (CKD) is a significant issue of public health concern in the world because of an increase in its prevalence and high morbidity and mortality rates (21). Predicting patient survival in CKD is a crucial factor that can response to clinical decisions and patient outcomes(12). The development of the machine learning has also allowed researchers to create more advanced models to predict the outcome of CKD patients, which serves as a potentially

effective tool in the medical community (13). Details of related studies on CKD prediction using machine learning are shown in Table 2.

Reference	Model	Data Set	Output	Limitations
Qin et al., 2020c	NN, NB, SVM, RF, LR, KNN	The data set contains 400 samples.	With a 99.75% performance rate, RF outperformed the other machine learning models	The limitations of the conditions, the available data samples are relatively small, including only 400 samples.
Islam et al., 2023b	Ada, XG, Cat Boost, DT, ET, RF, NB, KNN, LGBM, SVM, GB, SGB, Hybrid	The data set contains 400 samples.	XGBoost accuracy of 0.983, precision of 0.98, recall of 0.98, and F1-score of 0.98.	The limitations of the conditions, the available data samples are relatively small, including only 400
Nishat et al., 2021b	LR, KNN, SVM, RF, DT, NB, MLP, QDA	The data set contains 400 samples.	Among the models, Random Forest displayed the highest accuracy of 99.75%.	The limitations of the conditions, the available data samples are relatively small, including only 400
Ifraz et al., 2021b	DT, KNN, LR	The data set contains 400 samples.	Logistic Regression classification approach was shown to be the most accurate (97%) in this capacity.	The limitations of the conditions, the available data samples are relatively small, including only 400
Saha et al., 2019b	RF, NB, MP, LR, Adam – DNN	The data set contains 13,000 samples.	Adam-Deep learning beats all other methods with a prediction accuracy of 97.34%	The choice of features (age, appetite, test results) might not capture all relevant aspects of chronic kidney disease.
Abd & Abdullah, 2021	NB	The data set contains 400 samples.	Naive Bayes algorithm is among the top algorithms for identifying diseases with a high accuracy of 99.24%	The limitations of the conditions, the available data samples are relatively small, including only 400
Dritsas & Trigka, 2022b	NB, BN, LR, MLP, KNN, J48, LMT, RF,	The data set contains	Accuracy of 99.2%, the Rotation Forest (RotF) emerged as the dominant	The limitations of the conditions, the available data samples are

	RT, REPT, RoF, ABM1, EL	400 samples.	model in the comparison.	relatively small, including only 400
Senan et al., 2021	RF, DT, KNN, SVM	The data set contains 400 samples.	The random forest algorithm achieved 100% accuracy, precision, recall, and F1-score, outperforming all other applicable techniques.	The limitations of the conditions, the available data samples are relatively small, including only 400

Table 1: Overview of Machine Learning Models Applied in Previous Chronic Kidney Disease Prediction Studies

Although in some studies, the single-stage survival prediction or binary classification models have been employed to research chronic kidney disease (CKD), they are not often sufficient to comprehensively capture the disease course across various stages(15,25,26). Two possible machine learning methods that have shown the potential to be useful in modeling non-linear relationships that are complex in healthcare data are random forest and gradient boosting(17,22). The application of their use in multistage categorization models in predicting CKD survival is scarcely studied, however(7).To bridge this gap and enhance survival predictions and serve in clinical decision-making, the model employed by this study is a multistage classification model incorporating a variety of machine learning methods(12,22).

3. Methodologies

3.1 Data Overview

The data is available on the UC Irvine Machine Learning Repository, and it consists of 200 medical records of patients who were acquired at Enam Medical College in Savar, Dhaka, Bangladesh. This multivariate data is in the domain of Health and Medicine and has 28 features. Currently, the dataset exists in its raw form. There are no gaps in the data set. This data is under the Creative Commons Attribution 4.0 International License (CC BY 4.0) (27,28).

This data includes actual patient data of the Bangladeshi Enam Medical College, Savar, Dhaka. It is raw; it requires pre-processing to implement machine learning. In the research applied ordinal encoding 15 categorical ordered variables transformed into numerical form to improve model performance and accuracy (10,13).

3.2 Data Partitioning and Train-Test Split

Train-Test Split is a fundamental machine learning method which is applied to assess the generalization of a model by splitting data into training and testing sets(29). The model is trained on the training set and tested on the test set to determine whether there is overfitting. In this study, different proportions of the train-test split were used in each of the models, where the

better performance SVM, Multinomial Logistic Regression, Extreme Gradient Boosting, and Multinomial Naive Bayes all used a train-test split of 65%-35% whereas the Random Forest and Gradient Boosting models used a 70-30 split. This custom strategy is useful to maximize model training and assessment on a per-algorithm basis (29,30).

3.3 Feature Scaling and Standardization Techniques

Feature scaling normalizes the feature scales so that they all have the same level of influence in the modelling process, thereby enhancing convergence and interpretability (31). In a feature, standardization (Z-score scaling) makes features have zero mean, unit variance, most often used with scale-sensitive algorithms, e.g. logistic regression, linear regression, and SVMs (32). This improves the stability of the models and comparative analysis of coefficients (33).

3.4 Outcome Variable

The outcome variable in the study is a newly developed variable of class that is the stage of chronic kidney disease (CKD). It proposes six categories of the original binary CKD status and the disease progression stages to 0 (no CKD) to 5 (Stage 5 CKD). The variable will help the model to categorize the patients in different stages of CKD to be able to have a more detailed prediction and analysis.

3.5 Explanatory variable

The explanatory variables of this dataset are a combination of demographic, clinical and laboratory characteristics of chronic kidney disease (CKD). These variables include blood pressure, blood, and urine values, biochemical indicators, health disorders, and patient features. They are mostly categorical or integer variables and have some of the most important predictors of patients like blood pressure, blood urea, serum creatinine, hemoglobin, diabetes, hypertension, and patient age. Table 3 shows that all the variables are fully filled with no missing data to give a comprehensive picture of identifying and forecasting CKD progression.

Variable Name	Actual Name of Variable	Type	Missing Values
bp (Diastolic)	Blood Pressure	Integer	No
bp limit	Blood Pressure Limit	Integer	No
Sg	Sugar	Categorical	No

Al	Albumin	Categorical	No
class	Class	Binary	No
Rbc	Red Blood Cell	Integer	No
Su	Sugar	Categorical	No
Pc	Pus Cell	Integer	No
Pcc	Pus Cell Clumps	Integer	No
Ba	Bacteria	Integer	No
Bgr	Blood Glucose Random	Categorical	No
Bu	Blood Urea	Categorical	No
Sod	Sodium	Categorical	No
Sc	Serum Creatinine	Categorical	No
Pot	Potassium	Categorical	No
hemo	Hemoglobin	Categorical	No
Pcv	Packed Cell Volume	Categorical	No
Rbcc	Red Blood Cell Count	Categorical	No
wbcc	White Blood Cell Count	Categorical	No
Htn	Hypertension	Integer	No
Dm	Diabetes Mellitus	Integer	No

Cad	Coronary Artery Disease	Integer	No
appet	Appetite	Integer	No
Pe	Pedal Edema	Integer	No
Ane	Anemia	Integer	No
Grf	eGFR	Categorical	No
stage	Stage	Categorical	No
affected	Affected Patients	Integer	No
Age	Age (Range)	Categorical	No

Table 3: In-depth descriptions of each feature in the main CKD dataset

3.5 Statistical analysis

The Python environment was used to conduct Exploratory data analysis (EDA) which is based on the Jupyter notebook that provides the interactive and reproducible data cleaning, visualization and model-building environment.

Multicollinearity : Multicollinearity can be explained as the presence of two or more predictor variables in a sample that are highly correlated, i.e. have redundant information about one another (34). This complicates the isolation of the effect of each predictor on the dependent variable (35). Multicollinearity in parametric models such as linear regression and logistic regression, among many others, may cause a number of problems such as Unstable Coefficient Estimates, Difficulty in Interpreting Coefficients, Increased Standard errors. This can cause bad performance when applied to new information (overfitting) due to multicollinearity (36).

Class imbalance and SMOTE: SMOTE (Synthetic Minority Over-sampling Technique) is a technique that is employed to deal with class imbalance by generating artificial samples on the minority group. The principle of it is to find the k-nearest neighbors of each minority case and create artificial points along the line segments between the given instance and the neighbors. The process is effective in balancing the classes, which makes the model better learn boundaries of decisions and leads to high classification. SMOTE is also more diverse than traditional oversampling, and it minimizes the chances of overfitting. Nonetheless, SMOTE is not to be used blindly, and it can cause overfitting when synthetic examples are too similar to existing points and weak in high-dimensional spaces where distance measures become irrelevant (37).

Modeling approach: In order to provide sufficient comparison, we have trained six machine learning models they represented both parametric and non-parametric models: Multinomial Logistic Regression, Support Vector Machine (SVM), Random Forest, Gradient Boosting, Extreme Gradient Boosting (XGBoost) and Naive Bayes. An analysis of headmap and correlation analysis was used to remove redundant features before training parametric models or turning them into another feature. All model selection, hyperparameter optimization, and performance evaluation were done via stratified k-fold cross-validation of the training set, and the eventual performance was reported on a held-out test set (38,39).

Evaluation metrics: In the multiclass prediction task which we report, accuracy, recall, and F1-score of each one of the classes, and macro-averaged metrics to reflect the overall performance. Further analysis of the class-specific behavior was taken through confusion matrices as well as class-wise cross validation (40,41).

3.6 MODELING

Two general models are parametric and nonparametric model, which are applied in statistical analysis and machine learning, with the key difference that they all make different assumptions about the nature of data and provide varying degrees of flexibility.

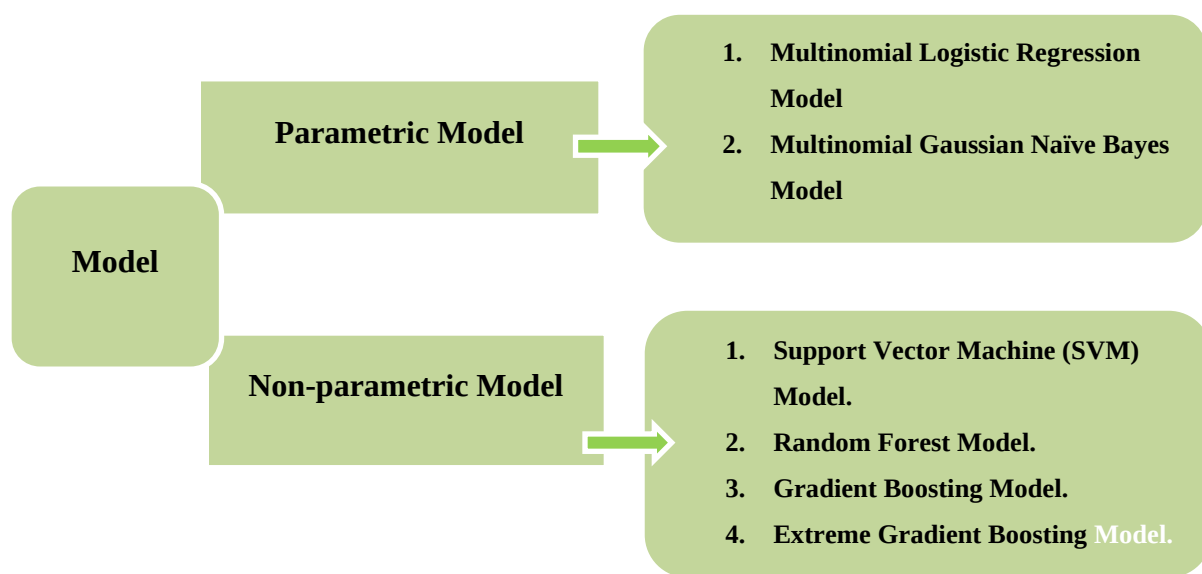


Figure 1: Flowchart Illustrating the Machine Learning Model Development and Prediction Process

Fig. 1 is a flowchart that lists machine learning models in the chronic kidney disease (CKD) development and prediction process. The flowchart breaks the models into two main categories; parametric and non-parametric models. The parametric models are multinomial logistic

regression and multinomial Gaussian naive Bayes, whereas non-parametric models are a support vector machine (SVM), random forest, gradient boosting, and extreme gradient boosting models. This visualization gives a systematized representation of the standard machine learning methods used in CKD prediction research works (42–44).

Parametric Models: Parametric models suppose that the data has a certain form, and its number of parameters is fixed (e.g., linear regression). They are effective and interpretable but can fail to capture complex patterns because of their weakness in flexibility(45,46).

Nonparametric Models: Nonparametric models do not have many assumptions about the data structure, and this feature allows more complex relationships (e.g., decision trees). Their application to extensive data is good, but they can overfit, and computations are usually time-intensive(46).

Multinomial Logistic Regression Model: Statistical categorization model is known as logistic regression which calculates the probability of an event falling in a category. Logistic regression is a binary classifier that is based on the concept of regression, despite the word regression being contained within the name(8).

Naive Bayes Classifier: Naive Bayes classifier is a supervised learning algorithm which is founded on the Bayes' Theorem on the premise that all features are conditionally independent given the class and it predicts the class by estimating the probability of each class given the values of the features. Although it is simple, it works well particularly when dealing with high dimensional data such as text classification(47,48).

Support Vector Machine (SVM): Support Vector Machine (SVM) is a classification/regression supervised learning algorithm, and it identifies an optimal hyperplane that segregates various classes and the approach maximizes the distance between classes(49,50).

Random Forest Model: Random Forest algorithm is a supervised learning algorithm, which constructs several decision trees on various data subsets. It summarizes the performance of these trees through averaging to enhance accuracy of prediction. This group methodology assists in addressing macro scale issues and can be flexible to many tasks through decreasing overfit and enhancing strength(51,52).

Gradient Boosting (GB): Gradient Boosting (GB) is a machine learning method that is an ensemble, which means it consists of several weak models (usually decision trees) to form a strong predictive model. It constructs models in a sequential manner by which a new model tries to minimize the errors of the collective past models by optimizing the gradient of the loss with respect to predictions. This is done by a continuous process of refining prediction by addressing errors of earlier models(53–55).

Extreme Gradient Boosting (GB): The popular and highly successful machine learning technique is tree boosting. XGBoost is an end-to-end, scalable tree boosting system popular among data scientists to deliver state-of-the-art performance on numerous tasks(56–58). It is an efficient version of gradient boosting that includes such functions as parallelization, regularization, and support of large-scale data.

4. Results

Fig. 2 is a correlation heatmap applied to evaluate visual assessment of multicollinearity between features through the visual representation of the correlation matrix. The graphical display helps to easily detect the presence of high correlation coefficients between pairs of features, which is an indication of multicollinearity. In particular, the variables of packed cell volume, blood pressure limit, and serum creatinine were referred to as candidates that showed multicollinearity. Multicollinearity, which is a high level of correlation between predictor variables, brings in redundancy that makes the model harder to explain, the model has more variability in coefficient estimates and it is less robust.

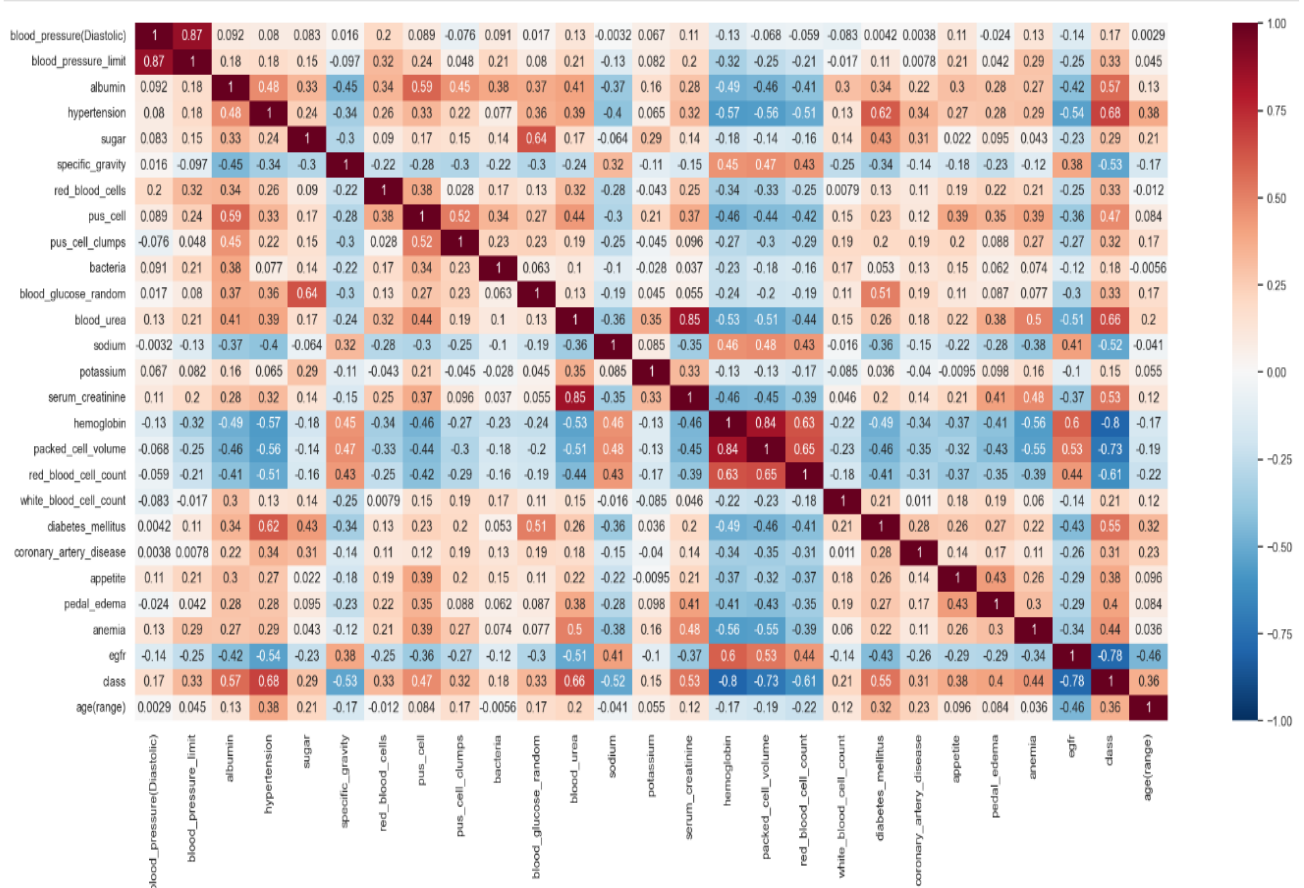


Figure 2: The Heatmap of Data with Correlations Profile

Logistic regression and Naive Bayes are parametric models that are vulnerable to multicollinearity as they rely on accurate estimation of the parameters, in which inflated estimates may reduce the interpretation and prediction. Non-parametric models such as the Support Vector Machines (SVM), the Random Forest, the Gradient Boosting and the Extreme Gradient Boosting are less so since they do not rely on explicit parameter estimates and are thus less susceptible to redundancy. A feature removal process was, therefore, used to reduce multicollinearity, which improved the performance of the parametric models. There were six diverse machine learning models that were used to guarantee rigorous analysis and strength of results.

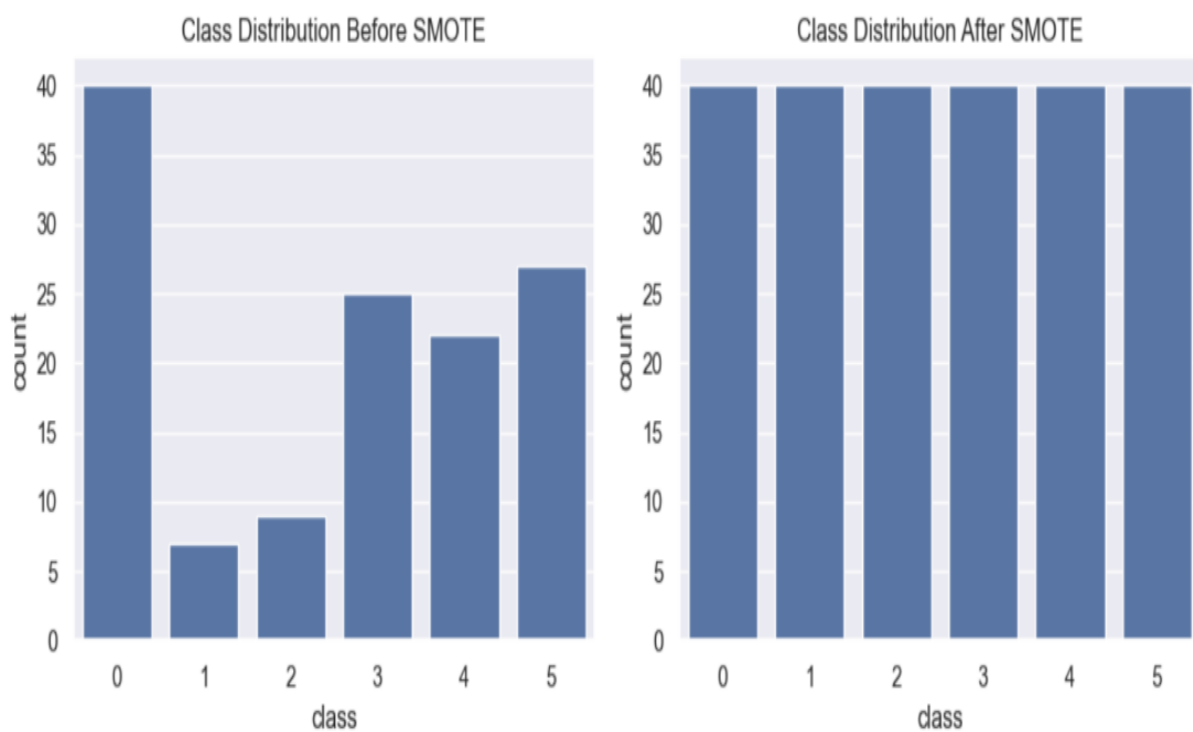


Figure 3: Comparison of Class Distributions Before and After Applying the SMOTE Technique for Data Balancing

Fig. 3 depicts how SMOTE technique affects the distribution of classes by demonstrating that all the classes are represented equally after resampling. Precision is the count of hits made which is significant when false positives are expensive. Recall measures are used to find out the number of true positives, which are important when it is dangerous to miss a positive. F1 score combines precision and recall in a single measure and is particularly helpful in imbalanced data, which

offers a more accurate view of performance as compared to accuracy alone(59,60). This brief overview indicates the essence of every measure in classification analysis. Table 4 to Table 7 have provided that the Random Forest is the best of the models considered based on a few reasons. To begin with, it attained a test accuracy of 90 percent and the cross-validation score of 95.4 percent which means that it can cross-validate well across data splits. This is reflected in its consistency in the cross-validation folds; this is evidence of reliability and robustness. Secondly, the performance of Random Forest is balanced between classes, and there is high precision, recall, and F1-scores, especially those classes that have a greater number of samples, like Class 0, Class 4, and Class 5. This balance means that the model successfully models the patterns of classes in a way that does not overfit or underfit certain specific classes(61,62). Also, its high recall rates and accuracy, particularly on critical classes imply that it performs better at reducing false positives as well as false negatives, which is important in the application where false classification can be disastrous.

Further, the data in the model are well-established, which implies that the tests are more accurate, and there is less chance of overfitting, which is often a major advantage of Random Forest because of bootstrapping and decision-tree aggregation. Lastly, Random Forest is also interpretable, with the feature importance measurement, which can enable practitioners to have knowledge of which features have the greatest impact on classification. Its consistency in the performance within different subsets of data also increases its usability in the real-world conditions where the data can be different. Altogether, accuracy, generalization, balanced measures with classes, and interpretability enable Random Forest to become a very appropriate model to be used in practice, especially when dealing with multiclass complex data.

Classes	Support Vector Machine	Multinomial Logistic Regression	Random Forest Model	Gradient Boosting	Extreme Gradient Boosting	Naive Bayes Classifier
0	1.00	0.94	0.97	0.96	0.94	0.94
1	0.67	1.00	1.00	1.00	0.67	1.00
2	0.50	0.50	0.67	0.40	0.67	0.43
3	0.57	0.57	0.71	0.62	0.50	0.60
4	0.85	0.90	1.00	1.00	0.92	0.78
5	0.78	0.58	0.78	0.78	0.78	0.50

Table 4: Class-Wise Precision of Machine Learning Models for Chronic Kidney Disease (CKD) Prediction

Classes	Support Vector Machine	Multinomial Logistic Regression	Random Forest Model	Gradient Boosting	Extreme Gradient Boosting	Naïve Bayes Classifier
0	1.00	1.00	1.00	0.93	0.97	1.00
1	1.00	0.50	1.00	1.00	1.00	0.50
2	1.00	1.00	1.00	1.00	0.67	1.00
3	0.67	0.67	0.83	0.83	0.83	0.50
4	0.58	0.47	0.67	0.60	0.58	0.37
5	0.88	0.88	1.00	1.00	0.88	0.88

Table 5: Class-Wise Recall of Machine Learning Models for Chronic Kidney Disease (CKD) Prediction

Classes	Support Vector Machine	Multinomial Logistic Regression	Random Forest Model	Gradient Boosting	Extreme Gradient Boosting	Naive Bayes Classifier
0	1.00	0.97	0.98	0.95	0.95	0.97
1	0.80	0.67	1.00	1.00	0.80	0.67
2	0.67	0.67	0.80	0.57	0.67	0.60
3	0.62	0.62	0.77	0.71	0.62	0.55
4	0.69	0.62	0.80	0.75	0.71	0.50
5	0.82	0.70	0.88	0.88	0.82	0.64

Table 6: Class-Wise F1-Scores of Machine Learning Models for Chronic Kidney Disease (CKD) Prediction

Model	Test Accuracy	Mean Cross-Validation Accuracy
Random Forest Classifier	90.00%	0.954
Gradient Booster Classifier	85.00%	0.934

Support Vector Machine	84.29%	0.795
Extreme Gradient Booster Classifier	82.85%	0.954
Multinomial Logistic Regression	80.00%	0.812
Multinomial Naïve Bayes Classifier	75.71%	0.566

Table 7: Test Accuracy and Mean Cross-Validation Accuracy of all Models

5. Discussion

Comparing the current research on CKD classification with the existing research, such crucial points are identified as the limitation of the data sets, model effectiveness, and the methodologies used. This study and the earlier ones point out the serious limitation in the sample sizes which are too small; this research involved 200 patient records whereas other studies tend to report around 400(15,63). These limits may put model faithful and generalizability to test(22,23).

Random Forest scored 90 percent in the test. Class 0 was very accurate in terms of precision (0.97) and recall (1.00), but Class 4 was accurate with a recall of 0.67. These findings are consistent with literature in which Random Forest had been shown to be the most effective(6,8,11), but differences in metrics could be due to differences in feature selection, sample size and optimization (21).

One benefit of the methodology is that the SMOTE was used to deal with the class imbalance, which resulted in a higher accuracy in predicting the minority classes along with the issues that have not previously been adequately studied, and consequently, the minority classes showed a lower performance in all other cases(13,25).

Besides, the given study also recognizes hyperparameter tuning as one of the key areas of future improvement, as well as data augmentation and further feature engineering to improve robustness(7,17,65). Although the test accuracy was 90 percent, the comparative analysis highlights the existing issues in CKD classification especially the limitation of the data set, imbalance of different classes, and the general necessity to optimize the process thoroughly to achieve better clinical outcomes in CKD patients((9,22,63).

6. Limitations and Future Work

This paper admits the existence of some limitations that could influence the interpretation and generalization of CKD classification model. To begin with, the sample size of 200 patient records is small enough to reduce statistical power and encourage overfitting, and consequently, limits the applicability of the model to large CKD population groups. Second, there does not seem to be representativeness in different demographic groups, comorbidities, and recording sites, which may bias model results when used in different clinical environments. Even though the use of SMOTE resulted in improved class imbalance, the accuracy and recall of minority

classes were still inferior compared to that of the majority classes, which meant that sensitivity differences were still present in the underrepresented CKD stages. Third, feature selection and engineering limitations, as well as possible differences in feature availability in different datasets, can be barriers to reproducibility and the discovery of universally predictive biomarkers. Fourth, the analysis was limited to test-accuracy and-class based measures without any clinical oriented evaluations like calibration, decision-curve or external validity. Finally, hyperparameter optimization was not done with exhaustiveness, that is, without systematic optimization or automated search, the model may not reach its full potential under different data conditions.

The future work must overcome these constraints in order to enhance robustness and clinical relevance. Generalizability would be improved by increasing the sample size by using larger and more heterogeneous cohorts across multiple centers and would permit external validation. The extensive optimization of hyperparameters (e.g., grid search, random search, Bayesian optimization) and the analysis of other/hybrid models (e.g., gradient boosting, XGBoost, or stacking ensembles) may provide beneficial improvements in performance. Exploring new, more sophisticated approaches to imbalanced data, e.g. focal loss, cost-sensitive learning, or region-specific resampling can further lessen the instances of minority-class misclassification. Extended feature engineering, such as access to new biomarkers, longitudinal features, and interactions terms, and more stringent feature selection, can determine variables with increased predictive and clinical value. Prospective studies and decision-analytic measurements, such as calibration measures, are required to determine the clinical usefulness and effect of the model on patient outcomes. Lastly, by making it fully reproducible by reporting all preprocessing steps in detail, by providing a list of features, and by providing code, it will be easy to reproduce it and compare it to other datasets.

7. Conclusion

One of the multi-class classification problems we solved using the Chronic Kidney Disease Dataset was the prediction of CKD risk depending on the age and test results. We ensured that our data analysis by exploration did not produce any missing values, and ordinal encoding was applied to categorical features. The graphics showed that the Random Forest model was the best-fitting model, which was accurate, balanced, and interpretable hence suitable to multi-class, complex data. Shortcomings were that the dataset size (200 records) was very few to generalize and that there was high class imbalance that influenced prediction of minority classes. To solve this, SMOTE has been used to equalize the class-distributions and enhance accuracy. Hyperparameter tuning can provide additional refinements, and future research can make it more robust by data augmentation, class balancing and better optimization to assist reliable CKD classification and prediction.

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Selected Abstracts

Developing Waterlogging-Resistant Crops and Ensuring Food Safety in Flood-Prone Regions of Noakhali, Bangladesh: A Case Study

Farjana Nur Naly

Bangladesh, a country highly vulnerable to climate-related calamities, faces significant challenges in guaranteeing food security, particularly in areas such as Noakhali that are increasingly prone to flooding. The frequent waterlogging disrupts agricultural production, putting many livelihoods at risk. Using a mixed-method approach that includes farmer questionnaires, field experiments, and water quality assessments, the study demonstrates how resilient rice varieties can maintain high yields when submerged for extended periods of time. To improve resilience among populations threatened by flooding, this project investigates the creation and uptake of waterlogging-resistant rice varieties, such as BRRI dhan79 and BRRI dhan91, in conjunction with coordinated food safety measures. In comparison to traditional rice, field tests showed these cultivars sustain greater longevity and production in flooded environments, providing a workable option for climate-adaptive agriculture. Furthermore, after floods, considerable contamination risks were found in both food and water safety assessments, better sanitary facilities and disaster recovery strategies. This study advances the goal of a resilient and sustainable Bangladesh by fusing food safety programs with agricultural technology breakthroughs.

Assessment of legacy nitrogen in the Gumai Beel agricultural land use area, Rangunia, Chattogram

Shumaia Haque Shuvra, Dr. Shyamal Karmakar, and Mohammad Ashraful Amin Emon

Legacy nitrogen is known as residual nitrogen that is accumulated in the soil due to long-term fertiliser application. This study investigates nitrogen (N) and phosphorus (P) variation in agricultural fields across the top layer (0-10 cm), middle layer (10-20 cm), and bottom layer (20-30 cm) during three agricultural seasons (Growing season, post-growing season, and new season). A total of 66 soil samples were collected from GIS-generated random sampling points, and each sample consists of 5 sub-samples.

Through soil sampling, laboratory analysis, and statistical analysis (ANOVA, one-way, Tukey's HSD test), variations in soil properties were assessed across different soil depths during the growing and post-growing seasons. Findings reveal significant seasonal variation in nitrogen concentration for all soil layers, the bottom layer ($F=19.4$, $p<0.001$) showing the most evident changes due to leaching and the mobility of legacy nitrogen. On the other hand, phosphorus

showed significant variation only in the middle and bottom layers, due to its low mobility in soil. A questionnaire survey was conducted with approximately 30 farmers to understand the types and amounts of fertilisers used during the summer and rainy seasons. These results emphasise the importance of seasonal monitoring and soil profile-based assessment for sustainable nutrient management practices.

BRRI Auto Seed Sower: A Climate-Smart Solution for Sustainable Rice Farming

Fariha Akhter, Dr. Md Kamruzzaman, Morsheda Akter Maliha, and Hodaya Bin Akter

Agriculture in Bangladesh, a flood-prone country, faces significant challenges due to climate variability, labour shortages, and rising costs of traditional farming methods. In flood-affected areas, the manual seedbed preparation, which typically takes 30-45 days before transplanting, is vulnerable to destruction during flooding. Climate-smart mechanisation, particularly the BRRI Auto Seed Sower, offers a solution to these challenges by improving seed placement precision and accelerating seedbed preparation. This low-cost, user-friendly machine distributes 140–160 grams of sprouted seeds per tray at a rate of one tray per second, with adjustable settings to accommodate various rice varieties. In flood-prone areas, this technology allows for quicker recovery of seedbeds, even after floods, by significantly reducing the time required for seed sowing. Unlike traditional methods, which require 25-30 days during the Aus and Aman seasons and 30-45 days during the Boro season, the BRRI auto seed sower reduces seedbed preparation time to only 12-15 days for the Aus and Aman seasons and 25-30 days for the Boro season, allowing for faster transplanting. This time-saving advantage becomes especially crucial in areas prone to flood damage. The machine also complements rice transplanter technology, helping to reduce transplanting time and ensuring more efficient crop management. Beyond enhancing productivity, the BRRI Auto Seed Sower promotes gender inclusion and rural entrepreneurship in the seedling business, as it creates opportunities for women farmers and entrepreneurs to actively participate in agriculture. By reducing reliance on manual labour and improving recovery time after floods, this technology contributes to Bangladesh's goals of food security, environmental resilience, and climate-smart agriculture, offering a model for other flood-prone countries worldwide.

Keywords: Seedlings, Mechanisation, Transplanting, Flood-prone, Sustainable

Integrating AI and Remote Sensing in Community-Led Climate-Smart Agriculture in Coastal Bangladesh

Mafruha Somya

Bangladesh's coastal zones are constantly threatened by salinity intrusion, cyclones, and changing weather patterns are challenging to smallholder agriculture and food security. For tackling climate change, Climate Smart Agriculture (CSA) is a suggested approach for improving food security. Different practices of CSA have been promoted by the Department of Agriculture Extension since 2010, but the spatial effectiveness and scaling potential under different climatic stress conditions of those approaches remained unexplored.

This study integrates Artificial Intelligence (AI) into predictive analytics and crop modelling, while combining Remote Sensing and Geographic Information Systems to provide real-time and large-scale monitoring of lands, crops, and climate variables for the effectiveness of Climate-Smart Agriculture practices across the coastal regions of Bangladesh. Time-series analysis by Landsat (2000-2025) and Sentinel-2 (2017-2025) imagery is processed to analyse vegetation indices (NDVI, EVI) for crop vigour, (NDMI, LSWI) for soil-water stress detection, and also map crop classifications, change detection, and cropping intensity. SAR data support flood and waterlogging analysis. Climate datasets (CHIRPS, rainfall) and (MODIS, LST) are integrated for Rainfall-Runoff modelling and Drought mapping. Community and NGO records provide the location of CSA practices and AI-powered Machine Learning Models, including Support Vector Machines (accounting for more than 20%), and Random Forests are trained to classify cropping patterns, predict yields under different IPCC climate scenarios by 2040.

The result delivered a predictive CSA suitability map of different practices under near-term climatic stressors (drought, floods, salinity) and an explainable feature-importance analysis to surface what drives CSA success. It also identified resilient agriculture practices, highlighted hotspot zones for intervention. Yield Prediction Models indicate that community precision agriculture can reduce climate-induced crop losses compared to conventional practices.

This study recommends a scalable spatial and temporal framework, combining smart technologies with community engagements to enhance the adaptive capacity for sustainable and climate-resilient agriculture.

Assessing the Impacts of Land Use Change on Soil Organic Carbon and Vegetation in Sylhet Wetland Ecosystems

Antara Fairuz and Anomita Faiz

Wetlands are valuable natural resources that provide us with numerous ecosystem services, including the maintenance of groundwater quality, protection from natural hazards, storage of organic carbon, and habitat for a diverse set of flora and fauna. The Sylhet basin in Bangladesh comprises numerous wetland ecosystems. Rapid urbanisation over the last forty years has likely altered the land use and land cover (LULC) pattern, which in turn affects soil organic carbon (SOC) levels and hydrological equilibrium. This study assessed nine wetland sites using field

data and remote sensing indices (NDVI, NDWI, BUI), showing that despite seasonal fluctuations, SOC levels remained stable, highlighting wetlands as significant carbon reservoirs. Soil properties such as SOC, pH, bulk density, cation exchange capacity, total nitrogen, etc., were used to estimate the carbon storage potential. Principal component analysis (PCA) indicated that urban growth, soil pH, organic carbon, etc., were the key factors explaining over 65% of the variance. Clustering methods were used to group the soils according to their health status into healthier versus degraded, revealing that agriculture, urban expansion, and loss of water bodies are strongly linked to soil carbon decline, threatening ecosystem resilience. The use of such multivariate statistics, along with geospatial indices, can be used to monitor long-term changes in land use patterns and their effect on soil health. Wetlands are important carbon sinks; according to our analysis of SOC and hydrological equilibrium of these areas, agriculture and urbanisation are on the brink of hampering the integrity of these valuable resources and making them potential carbon sources. An area-specific policy approach is required to preserve the soil organic carbon levels in order to protect and conserve our wetlands.

Navigating Environmental Sustainability in Tanguar Haor: Awareness, Practices, and Challenges of Tourists and Majhi (Boatmen)

Hossain Mahmud and Shawan Akanda

Tanguar Haor, one of Bangladesh's Ramsar Sites, represents a critical wetland ecosystem with rich biodiversity. In recent years, its growing popularity as a tourist destination has led to increased environmental pressures. Despite its ecological importance, limited research has examined how key stakeholders perceive and address the challenges of tourism-related waste management. This qualitative study examined the awareness, practices, and challenges faced by tourists and Majhi (boatmen) in promoting environmental sustainability in the Haor. Using purposive sampling, in-depth interviews were conducted with 15 tourists and 5 Majhi to capture their perspectives. The findings reveal that both tourists and boatmen are aware of environmental issues, yet their practices often fail to reflect this awareness. Tourists frequently cook on boats and dispose of food waste, plastics, and cooking utensils directly into the water. The absence of portable washroom facilities means that all ships discharge human waste directly into the Haor, further polluting the water. Boatmen rely on diesel engines and, in some cases, large generators to run air conditioners, contributing to air and noise pollution. Although boatmen possess practical knowledge of environmental changes, their ability to adopt sustainable practices is limited by inadequate facilities and a lack of formal education. Tourists also face insufficient disposal options and weak enforcement of environmental regulations, preventing them from translating awareness into practice. The study recommends developing proper waste disposal and sanitation facilities on all boats, regulating motorised boat entry, and implementing targeted environmental education campaigns using offline (signage, workshops, guided tours) and online (social media, travel blogs, videos) strategies to influence both tourists and boatmen. These

measures, combined with more vigorous enforcement of environmental regulations and collaboration among government agencies, NGOs, and local communities, are essential to ensure the long-term conservation of Tanguar Haor and its biodiversity.

Dynamics of Vegetation Cover and Water Body Changes in Taguar Haor Region

Jahid Hasan Sagora and Bedatraye Chanda

Tanguar Haor, located in the Sunamganj district of northeastern Bangladesh, is a unique wetland ecosystem that supports rich biodiversity and sustains the livelihood of thousands through agriculture and fisheries. This study investigates the spatio-temporal dynamics of vegetation cover and water body changes in the Tanguar Haor region using multi-temporal Landsat imagery over the period of 2010 to 2025. Vegetation and water extents were mapped through the application of the Normalised Difference Vegetation Index (NDVI) and Normalised Difference Water Index (NDWI). For image preparation, cloud masking and composition are performed for data accuracy. To analyse the change detection, the Mann–Kendall test is used to get annual and seasonal variations, which highlights the trade-offs between expanded water coverage during the monsoon and reduced vegetation. This trend analysis and change detection revealed the long-term patterns of vegetation loss in persistently inundated zones and the expansion of vegetation in drying areas. The results show a strong positive correlation between water body fluctuations and vegetation dynamics, where seasonal restoration is supported by rising water, whereas vegetation development is hampered by rising or extended inundation. These findings provide critical insights into the eco-hydrological balance of Tanguar Haor and underscore the need for integrated wetland management strategies in the face of climate variability and anthropogenic pressures.

Keyword: Tanguar Haor, NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), Dynamics"

Climate Change and the Proliferation of Water Hyacinth in Bangladesh: Ecological Drivers, Impacts, and Future Scenarios

Rabila Tarannum Chowdhury and Abdur Rahim Mahin

Water hyacinth (*Eichhornia crassipes*) is recognised as one of the world's most invasive aquatic plants, exerting severe ecological, economic, and social pressures on freshwater systems. In Bangladesh, its rapid proliferation is increasingly shaped by climate change stressors such as rising temperatures, altered rainfall regimes, eutrophication, and hydrological variability. This study synthesises existing scientific literature and recent case studies to examine the relationship between climate variability and the expansion of water hyacinth in tropical riverine ecosystems.

Evidence indicates that even modest increases in temperature (25–30 °C) and nutrient enrichment can drastically accelerate biomass accumulation, doubling growth in less than two weeks under optimal conditions. Projected warming trends and enhanced nutrient runoff suggest further intensification of hyacinth invasions in Bangladesh, particularly in the Ganges–Brahmaputra–Meghna delta. The ecological consequences include biodiversity loss, reduced dissolved oxygen, disruption of fisheries, and navigation blockages, with cascading socioeconomic costs for river-dependent communities and industries. Scenario analyses indicate that, under mid- to high-emission climate trajectories, the extent and frequency of water hyacinth outbreaks will significantly increase by mid-century. By consolidating secondary data, this review highlights the urgent need for integrated scientific research on the ecological thresholds and climate sensitivities of invasive macrophytes in South Asia. Such understanding is critical for advancing predictive modelling and for informing sustainable water governance in the context of climate change.

Innovating Climate Resilience through Microinsurance and Embedded Finance: Lessons from Bangladesh's Aquaculture Sector

Yeasir Arafat, Tahmeed Rifa and Monisha Das

"As climate-induced disasters intensify in Bangladesh, aquaculture-dependent communities face growing financial risks due to recurring flash floods, cyclones, and salinity intrusion. This is especially critical for smallholder fish farmers in low-lying flood-prone areas like Mymensingh and coastal districts such as Satkhira, Khulna, and Bagerhat, where traditional coping mechanisms are inadequate. The Bangladesh Microinsurance Market Development Programme (BMMDP) piloted an innovative climate resilience solution combining microinsurance with embedded finance models, offering both risk protection and accessible financing.

This initiative bundled climate-indexed aquaculture insurance with inventory credit and digital service delivery through platforms like the Matsha Bondhu app. The model enabled smallholders to access pre-financed inputs and receive timely payouts for fish mortality linked to climatic shocks, reducing liquidity stress and promoting continuity in production. It also promoted biodiversity-sensitive aquaculture practices and reached marginalised groups, including women and youth, who are typically excluded from formal financial systems.

Drawing from field evidence and stakeholder consultations, this paper explores how such integrated financial tools can serve as green investment models while contributing to climate justice and equity. The findings highlight practical challenges around data infrastructure, actuarial modelling under climate uncertainty, and regulatory readiness, offering pathways for policy innovation and scalable replication. This case underscores the potential of localised, tech-enabled financial instruments in building resilient livelihoods and advancing inclusive adaptation strategies in Bangladesh's most vulnerable aquaculture zones."

Agent-Based Modelling of Plastic Circularity under Constraints: Recycling Supply Chain Dynamics in Delaware, USA

Idowu Kunlere, Oluwadare Badejo, Marianthi Ierapetrinou, and Kalim Shah

Efforts to advance circular plastic economies often prioritise technological solutions while underestimating material degradation and actors' behavioural complexity. Yet such simplifications risk overstating long-term gains in recycled material uptake and emissions reduction. Existing studies, typically based on static optimisation or linear diffusion assumptions, rarely account for heterogeneous actors, feedback loops, or the diminishing returns of reuse. This study addresses that gap by employing an agent-based model to simulate the recycled plastic supply chain in the US State of Delaware, incorporating behavioural decision rules, policy influence, and a cap on mechanical recycling cycles. The model analyses three scenarios: deterministic, yield-stochastic, and yield-demand stochastic, each tested with and without recycling degradation dynamics. Results show that while degradation constraints limit ultimate system performance, they also stabilise emissions and uptake, mitigating volatility under uncertain conditions. Systems lacking such constraints demonstrate exaggerated growth and instability due to unrealistic material flow assumptions. These findings underscore the importance of embedding material feedback and behavioural adaptation into circular economy models. For policymakers, the results highlight recycling infrastructural investment while shaping expectations through demand aggregation, information transparency, and quality standards. More realistic modelling of circularity systems can improve intervention design, reduce transition risks, and align ambition with operational constraints.

Machine Learning-Based Predictive Model for Measuring Employment Growth and Socio-economic Impacts of Green Finance in Bangladesh

Nayeem Shahriar

Climate finance has emerged as a pivotal mechanism for fostering sustainable development, yet its socio-economic impacts—particularly in terms of employment generation and youth entrepreneurship—remain underexplored in the Global South. Bangladesh, one of the world's most climate-vulnerable nations, faces the dual challenge of mitigating climate risks while creating inclusive economic opportunities for its growing youth population. This study proposes a Machine Learning-based predictive model to assess the employment growth and socio-economic outcomes of green finance initiatives in Bangladesh.

The research will integrate datasets on climate finance disbursements, green microcredit programs, and entrepreneurial ventures with socio-economic indicators such as job creation,

income diversification, and community resilience. Using supervised learning algorithms, including Random Forest, Gradient Boosting, and Neural Networks, the model will predict short- and medium-term employment outcomes of green finance allocation. Feature importance and SHAP (Shapley Additive Explanations) analysis will be employed to enhance interpretability, ensuring that policymakers can identify the financial and demographic variables most strongly associated with positive socio-economic impacts.

The results will assess if targeted allocation of green finance to youth-led enterprises in renewable energy, waste management, and sustainable agriculture has the potential to generate significant employment multipliers and enhance household-level climate resilience. The model will demonstrate that predictive analytics can inform more equitable and efficient financing strategies by identifying sectors and regions where youth entrepreneurs are most likely to drive sustainable growth.

This research will contribute to both the Machine Learning and Climate Governance literature by offering an evidence-based framework to measure the socio-economic returns of climate finance. For Bangladesh, it can provide actionable insights for aligning national climate strategies with employment and development objectives, highlighting the role of data-driven decision-making in advancing sustainable urban and rural transitions.

Climate Finance Effectiveness in Agriculture: Lessons from Global Adaptation Projects

Bushra Anjum, Nafia Saddaf, and Laura Kuhl

Defining and measuring adaptation effectiveness is of significant scholarly and practical interest, but the literature remains theoretical, and evidence of what works remains based primarily on individual case studies. Questions remain about the long-term effectiveness and sustainability of adaptation projects, particularly after external funding is no longer available. International climate funds, including the Adaptation Fund, the Global Environment Facility's Least Developed Countries Fund and Special Climate Change Fund, the Green Climate Fund, and the Pilot Program for Climate Resilience, have supported adaptation initiatives across developing countries for almost two decades, providing a rich evidence base to systematically examine adaptation effectiveness. We conducted a comparative analysis of completed projects across diverse regions, with a focus on agricultural projects. Through a systematic analysis of more than 50 completed agricultural projects with independent evaluations or project completion reports, we identify recurring challenges, document lessons learned, and synthesise recommendations for future programming. Particular attention is given to the strategies employed to ensure sustainability, including institutional strengthening, capacity building, community ownership, and financial mechanisms. We highlight patterns of success and failure, providing insights into why certain approaches were effective and others were not, and how future investments can maximise long-term impact.

The Economics of Loss and Damage: Who Pays for Climate Injustice?

Dr. Md. Hasan Ali

The escalating impacts of climate change: rising sea levels, intensified extreme weather events, and slow-onset environmental degradation, are inflicting irreversible losses and damages, particularly in vulnerable countries with minimal historical responsibility for greenhouse gas emissions. This paper examines the economics of loss and damage through the lens of distributive justice, focusing on the critical question: Who pays for climate injustice? Drawing on empirical evidence, climate finance mechanisms, and international policy debates, the study analyses the economic dimensions of loss and damage, distinguishing it from adaptation and mitigation finance. It explores the disproportionate economic burdens faced by Least Developed Countries (LDCs) and Small Island Developing States (SIDS), where climate-induced shocks erode GDP, undermine livelihoods, and exacerbate poverty traps. The analysis critically evaluates the emerging Loss and Damage Fund agreed upon under the UNFCCC framework, assessing its potential to operationalise the "polluter pays" principle, address financing gaps, and ensure timely and equitable compensation. The paper also interrogates the political economy of climate negotiations, highlighting the tension between historical emitters and climate-vulnerable states and the challenges of assigning liability in a fragmented international legal landscape. By integrating perspectives from climate economics, international law, and development studies, the research argues that sustainable and just financing requires binding commitments from high-emission nations, innovative funding mechanisms such as climate taxes and debt swaps, and the recognition of loss and damage as a standalone pillar of climate action. Ultimately, the study contends that resolving the "who pays" question is not only an economic necessity but also a moral imperative to rectify deep-rooted climate inequities.

Keywords: Loss and Damage, Climate Justice, Climate Finance, Polluter Pays Principle, Vulnerable Countries, UNFCCC

Rethinking Bangladesh's Approach to Climate-Induced Internal Displacement: Shifting from Disaster-Centric Frameworks to Rights-Based Legal Frameworks

Md. Harisur Rohoman

The adverse impact of climate change has already been a leading cause of internal displacement in highly vulnerable countries such as Bangladesh, where millions of people are displaced due to sea level rise, riverbank erosion, and extreme weather events. Despite these growing issues, climate-induced internally displaced persons (IDPs) remain unprotected under domestic laws and policies in Bangladesh, which are mainly focused on disaster management, such as emergency

response and short-term relief distribution, without adequately addressing the rights of IDPs. This approach creates a protection gap for IDPs, for which the government often fails to address the specific vulnerabilities of these individuals.

The objective of the study is to critically assess the current policy and legal framework of Bangladesh and to explore ways of shifting from a disaster-oriented framework to rights-based legal frameworks for the comprehensive protection of IDPs. Through a doctrinal research methodology, it evaluates existing domestic policies, laws, and institutional frameworks alongside international environmental, human rights, and disaster reduction frameworks to identify existing gaps and inconsistencies and the areas of reform.

Although Bangladesh has adopted national policies addressing displacement, such as the National Strategy on Internal Displacement Management, however, these policies are not comprehensive. Moreover, as no legislation or constitutional provision directly recognises the IDPs, a rights-based approach to the legal framework has not yet been developed. Adopting a rights-based legal framework is required for bridging the protection gap, and it would ensure enforceable rights, improve coordination among stakeholders, and provide sustainable solutions for IDPs. Moreover, this approach can also offer a model for other highly vulnerable countries to address the rights-based approach to IDP issues. Keywords: Displacement, IDPs, Policy, and Legal Framework

In the Land of Bonbibi: Environmental Injustice, "Sticking by" and Cross-border Mobilities of Sundarban's Women

Mrittika Bhattacharya

Sundarban - the largest mangrove forest in the world, sharing borders between India and Bangladesh is susceptible to environmental stressors like floods, cyclones, sea-level rise, irregular rainfall, and drought- ranked in order of the severity of impacts by the women participants of my ten-month-long feminist participatory research in the villages of Jharkhali and Goranbose in Indian Sundarban. Among the host of different factors that have led to cross-border mobilities in the post-independence period, environmental stressors have increasingly become primary drivers in the face of climate change. Additionally, these women are disproportionately impacted owing to gendered hierarchies and their interrelations with environmental resources for income generation and performing household chores. They identify three types of mobilities - crossing borders for moving to Kolkata because "Kolkata is closer than Dhaka", the male family members moving further to the cities in Eastern and Southern parts of India, while the women stay behind in Sundarban's villages and move temporarily to safer locations like "Aila centres" in disaster scenarios. When it comes to the second type of mobility, the women also share stories of moving to the cities along with their husbands and children for precarious, low-paid jobs or travelling on a daily basis to Kolkata for domestic work and working on construction sites.

However, the women look at the cross-border mobilities and then move to the cities as a disjuncture in their journey of adaptation since they move away from environmental resources and their traditional sources of livelihoods, and their stay in the cities is mired with insecurities. Rather, they define adaptation as “sticking by” on an everyday basis. It involves “sticking with” the environment and “sticking together” as a transnational community beyond political borders. They emphasised the women-led everyday coping strategies, like developing organic farming to floating gardens, to building hand-made river banks for preventing the flood waters from entering the agricultural lands. My ongoing doctoral research, thus, accounts for the primarily environment-induced mobilities practiced by these women, questions the approaches of migration-as-adaptation, and complexifies how the international mobilities become localised while also highlighting the self-perceptions of adaptation as expressed by the women.

Climate Justice on Screen: Equity and Resilience in Bangladeshi Cinema

Muhammad Mustafizur Rahman

Bangladesh contributes just 0.3% of global greenhouse gas emissions but is among the most climate-vulnerable countries in the world. Climate justice and equity are therefore urgent, lived realities, particularly for coastal communities, the rural poor, women, and children who face disproportionate risks. This paper explores how Bangladeshi cinema frames these issues through qualitative content and visual analysis of selected films. The analysis centres on three fictional features: *Dukhai* (1997), *Haldaa* (2017), and *Nonajoler Kabbo* (*The Salt in Our Waters*, 2020). Each dramatises climate impacts within distinct social and ecological settings. *Dukhai* humanises the relentless cycle of cyclone loss and rebuilding in coastal villages. *Haldaa* portrays the twin exploitation of river ecosystems and women, linking environmental degradation to patriarchal oppression. *Nonajoler Kabbo* depicts the clash of superstition and science in a fishing community grappling with livelihood loss and climate uncertainty. For comparison, the docudrama *Are You Listening!* (2012) and animated short *Tomorrow* (2019) illustrate real-life displacement and youth-centred climate advocacy. Across these films, key themes of vulnerability, displacement, inequity, resistance, resilience, and global-local connections emerge. Collectively, they show how Bangladeshi filmmakers reframe climate change as an ethical crisis that intersects with class, gender, and cultural identity. By turning abstract statistics into human-centred stories, cinema becomes both a cultural witness and a tool of advocacy. These works highlight resilience and agency while calling for equitable climate action that places justice, dignity, and community voices at its centre.

Keywords: Climate justice, resilience, equity, Bangladeshi cinema"

Climate-Induced Sedentarisation Impacts on the Intangible Cultural Heritage of Nomadic Communities in Southeastern Morocco

Said Skounti

Climate change is one of the major challenges of our time, having significant impacts on the economy, society, people, and their cultural heritage. In this paper, I explore the profound impacts of climate-induced sedentarisation, particularly driven by severe droughts, on the cultural heritage of nomadic communities in southeastern Morocco. I focus on the intangible cultural heritage, which is deeply impacted by climate change, due to its inherent dependence on the environment where people live. Using a qualitative approach with in-depth interviews with both sedentary and practicing nomads, the research reveals how the scarcity of natural resources has forced these communities toward sedentarisation, leading to significant cultural losses. Traditional practices, such as multi-day wedding celebrations and the use of Tamazight language as their mother tongue language, are eroding as families shift to urban centers. The findings highlight how these changes threaten the transmission of elements of the intangible cultural heritage of nomads to the future generations.

Keywords: climate change, nomadic communities, sedentarization, intangible cultural heritage, Amazighs."

Addressing Systemic Inequalities in Climate Adaptation: Empowering Women, Youth, and Indigenous Peoples for Climate Justice

Farhat Maisha Arpa, Lieutenant Tahmidul Muttaqin

Gaps in adaptation governance disproportionately affect women, youth, and Indigenous peoples, communities deeply vulnerable to climate impacts, but often sidelined in the legal and policy architecture, due to systemic inequalities of power and privilege. Addressing such inequalities is crucial for implementing the Paris Agreement and the Sustainable Development Goals. This work employs a comprehensive legal-analytical approach coupled with a scoping review of 316 interdisciplinary files following PRISMA-ScR standards that integrate the distributive, procedural, and recognition aspects of climate justice. Moreover, quantitative displacement data together with qualitative case studies clarify the converging vulnerabilities that these groups face.

This study employs a legal-analytical framework and a scoping review of 316 interdisciplinary sources, incorporating international environmental and human rights law. Data synthesis covers distributive, procedural, and recognition justice aspects. Quantitative climate displacement statistics and qualitative case studies further contextualize vulnerabilities and adaptive capacity.

Research shows women represent nearly 70% of climate-induced displacements globally, yet their involvement with adaptation policymaking remains disproportionately low. Customary landholding Indigenous people face legal disenfranchisement and ongoing tenure insecurity, despite their custodian role to critical traditional knowledge systems necessary for efficient nature-based adaptation. Analogously, there is intergenerational inequity because youth participation is subject to administrative processes that exclude governance. The results highlight critical deficiencies in existing frameworks of adaptation that tend to reproduce maladaptive outcomes due to insufficient recognition and inclusion of disadvantaged populations.

The study recommends integrating strong legal tools that operationalize substantive equality, inclusive participation, and legal recognition of vulnerable groups into climate adaptation governance in order to address these injustices. It becomes clear that institutions must be strengthened in order to protect land rights, support capacity-building, and take into account a variety of epistemologies. Furthermore, in order to guarantee accountability and transformative resilience, legally binding commitments centered on climate justice principles must be developed.

In conclusion, in order to achieve equitable, sustainable climate adaptation, advance human rights, and enable resilient futures for marginalized populations under increasing climate risks, it is critical to address systemic inequalities through intersectional legal approaches.

Keywords: Climate Justice; Systemic Inequality; Adaptation Governance; Indigenous Peoples; Women and Youth

Non-Linear Modeling of Land Surface Temperature Using Environmental Indices: A Comprehensive Machine Learning Approach with 24-Year Landsat Time Series Data

Al Tahsin Mahamud Khan and Tanjina Rahman Chuti

Land Surface Temperature (LST) prediction from satellite-derived environmental indices remains challenging due to complex non-linear relationships and temporal variability. While traditional linear approaches show limited success, the potential of advanced machine learning methods for capturing intricate environmental interactions requires systematic investigation.

We analyzed 24 years (2000-2024) of Landsat 7,8,9 monthly statistics encompassing 236 observations across four key environmental indices: Normalized Difference Vegetation Index (NDVI), Modified Normalized Difference Water Index (MNDWI), Normalized Difference Built-up Index (NDBI), and LST. Following rigorous data preprocessing and outlier treatment, we implemented comprehensive feature engineering including polynomial expansions, interaction terms, and ratio features. Six machine learning algorithms were systematically evaluated: Random Forest (RF), Gradient Boosting (GB), Extra Trees (ET), Support Vector Regression

(SVR), Multi-Layer Perceptron Neural Networks (MLP), and Ridge Regression. Hyperparameter optimization employed grid search with time series cross-validation, while model performance was assessed using chronological data splitting (2000-2019 training, 2020-2024 testing).

Random Forest achieved superior performance with Test $R^2 = 0.1226$ (RMSE = 4.52°C), representing a 472% improvement over baseline linear approaches. Tree-based algorithms consistently outperformed other methods, with Gradient Boosting ($R^2 = 0.1012$) and Extra Trees ($R^2 = 0.0887$) following. Feature importance analysis revealed NDBI as the most predictive index (38% importance), despite weak linear correlation with LST ($r = -0.035$). Neural networks demonstrated convergence instability, while ensemble methods provided stable but not superior performance ($R^2 = 0.1019$). Cross-validation revealed temporal performance decline ($R^2 = 0.215$ to 0.028 across folds), indicating evolving environmental relationships.

This study establishes that tree-based machine learning algorithms effectively capture non-linear relationships between environmental indices and LST, with interaction effects proving more predictive than individual measurements. The moderate prediction accuracy ($\pm 8.9^\circ\text{C}$ prediction interval) supports applications in regional climate monitoring and comparative studies while highlighting the need for additional meteorological variables for higher precision applications.

Assessing Flood Resilience Strategies in Two Vulnerable Riverine Chars: A Comparative Index-Based Approach to Nature-Based and Structural Methods

Md Sabbir Ahmed, Dr. Abu Reza, and Md Towfiqul Islam

Flood-affected char areas are most vulnerable to climate change and climatic hazards worldwide. However, most earlier studies have focused on two flood-prone areas in the Teesta and Brahmaputra River systems, facing the ongoing threat of seasonal inundations and riverbank erosion, jeopardizing lives, livelihoods, and infrastructure. Although decades of structural responses have been deployed to these communities, many chars remain at an extremely high risk of residual flooding due to poverty and the hydrological variability exacerbated by climate change. To address the gap, this research aims to develop an index-based approach to measuring household readiness for flood adaptation planning in these rural riverine char areas. Using structured questionnaires, the research engaged 600 households from selected hazard-proximal unions to measure perceptions across three adaptation dimensions (behavioral, structural, and ecological) and three adaptation components (awareness, willingness, and self-efficacy). The Dimension-based Adaptation Planning Index (D-API) and Component-based Adaptation Planning Index (C-API) then revealed that ecological adaptation measures such as community forestry through embankment bio-shields were perceived as being more effective and socially mobilizing as compared to behavioral forms of readiness, such as early evacuation or raised storage sources. The lack of readily available risk communications and the deeply ingrained social dependence on livelihoods explained the lagging effectiveness of behavioral readiness.

Regression analysis finds that the education level of household heads and the extent of prior flood damage were positive predictors of adaptation readiness. In contrast, age, larger household size, and the proportion of older people were negative predictors. The results highlight the importance of community-specific, participatory flood adaptation strategies that combine nature-based solutions with behavior change communication and community-localized infrastructure planning. These findings can help inform union- and district-level disaster management plans in Rangpur and Kurigram and contribute to building resilience for some of Bangladesh's most vulnerable rural populations.

Assessing the Impact of Economic Development on Flood Dynamics: A GIS-Based Basin Analysis of the Feni River, Bangladesh

Shoaib Md. Shice and Md. Aminur Rahman Sarker

The increasing frequency and severity of flooding in the Feni District of Bangladesh necessitate a rigorous investigation into its underlying causes, particularly the role of rapid infrastructural development. This study employs Geographic Information Systems (GIS) and remote sensing techniques to conduct a comprehensive water basin analysis of the Feni River, aiming to determine the impact of the Mirsarai Economic Zone development on altering natural hydrological patterns and exacerbating flood events.

The methodology involved a multi-temporal analysis using satellite imagery to map land-use and land-cover (LULC) changes between 2010 and 2023. GIS-based hydrological modeling was used to analyze changes in surface runoff, water flow paths, and basin morphometry. Key metrics included the Normalized Difference Vegetation Index (NDVI) to track loss of permeable surfaces and the calculation of impervious surface area within the watershed.

Preliminary findings indicate a significant correlation between the MEZ's construction and increased flood vulnerability downstream in Feni municipality. Satellite imagery confirms the alteration and constriction of natural drainage channels and floodplains to accommodate infrastructure, funnelling water more rapidly towards downstream areas.

The study concludes that the large-scale land conversion for the economic zone has materially disrupted the natural water balance of the Feni River basin, acting as a critical amplifier of recent flood events. We propose three policy recommendations:

- 1. Mandatory Cumulative Impact Assessments:** Enforce rigorous pre-development hydrological impact studies for all major infrastructure projects within the basin.
- 2. Implement Compensatory Storage:** Mandate the construction of retention ponds and artificial wetlands within the MEZ to mitigate increased runoff.

3. Revise Zoning Regulations: Develop and enforce watershed-specific zoning laws that protect critical drainage channels, floodplains, and natural water retention areas from future encroachment.

This research provides a data-driven framework for integrating basin-level hydrological planning into economic development strategies to foster sustainable and resilient growth.

The Role of Media and Public Awareness in Strengthening Waste Management Systems for a Sustainable Environment

Md. Enayet Hossain, Md. Matiur Rahman

Waste Management systems remain one of the most pressing environmental challenges of the 21st century, which is immediately linked to urbanisation, consumerism, and unsustainable practices. This study examines the role of media and public awareness in strengthening waste management systems to achieve a sustainable environment.

The objective of this study is to explore how different forms of media-traditional (Print and Electronic) and digital (social media), along with community-level awareness initiatives, contribute to waste reduction, proper segregation, and responsible disposal practices.

A mixed-method approach was adopted in this paper, combining a content analysis of environmental media campaigns with surveys conducted among urban and rural residents to assess awareness levels, behavioural changes, and participation in proper waste management initiatives.

Key findings indicate that media campaigns significantly enhance public awareness and participation in waste management, while awareness programs foster long-term behavioural change necessary for sustainable practices. However, the effectiveness of these efforts is influenced by socio-economic factors, policy support, and accessibility of waste management infrastructure.

The paper concludes that a cooperation between media advocacy, educational outreach, and strong institutional support is essential for building resilient waste management systems aligned with Sustainable Development Goals (SDG), especially Goals 11, 12, and 13.

Keywords: Waste Management, Media, Public Awareness, Behavioural Change, Environmental Sustainability, SDGs

The Power of Visual Media: How Documentaries Influence Bangladeshi University Students' Attitudes Towards Environmental Pollution

Md. Sipon Mia

Documentaries show true events, problems, and situations using stories and faithful analysis. They bring audiences new knowledge and understanding of challenges related to the environment, culture, and society through pictures. Through evocative pictures and vivid stories, documentaries educate people and change the way they think about various important matters. They educate students by telling stories and giving them explanations, which helps them grasp hard-to-understand environmental matters such as air and waste pollution. Even though studies have highlighted the benefit of multimedia resources to environmental literacy, there is very little research on how Bangladeshi students' views regarding pollution are shaped by watching documentaries. Yet, how students react to the film depends on their background, knowledge beforehand, and their experience with it. The main purpose of the study was to measure shifts in students' knowledge of environmental issues before and after watching documentaries. Evidence points out that watching documentaries can greatly increase students' grasp of environmental topics by breaking down hard-to-understand details and showing real examples of pollution through engaging stories. Although certain students start practising sustainability and appreciate its value, others insist on creative, engaging, and visual approaches as they remain unchanged. The results of this study prove how documentaries can support environmental education and influence people to work together against the challenge of pollution in Bangladesh.

Keywords: Pollution, Visual Media, Behavioural Change, Documentary

Media-Enabled Climate Education: An Observational Case Study across Five Mohara Schools

Md Nahidul Islam

The high vulnerability of Bangladesh to climate change requires pragmatic, school-based programs that link theory to everyday activities in riverine communities. This observational case study asked if low-cost media and school “publication” outputs, such as animated films, posters, and student art, could stimulate climate awareness and pro-environmental engagement by school-age children in Mohara (Karnaphuli riverside), Chattogram.

Under BANGLALEADS (formerly Stark Bangladesh's) Aware With Us initiative, activities included a screening of the animated short Tomorrow plus a quiz (n=80), poster campaigns on plastic pollution/deforestation (n=330), a dialogue-based workshop for older students (n=70), and a sketching activity on “healthy vs. unhealthy Earth” (n=80) with students in Grades 1–10 (N=560). Data included observations, field notes, facilitator debriefings, and informal student/teacher comments, which were compiled for descriptive purposes.

By level: Primary 87.5% (490/560); secondary 12.5% (70/560). By modality: posters 58.9% (330/560); film quiz 14.3% (80/560); workshop 12.5% (70/560); drawing 14.3% (80/560). Observed effects were early climate-positive behaviour (even the change of throwing waste into an overnight pot instead of down the river where the dolphins live), visible teacher–student pairs (posters ever reminding about the entire process), interest in plant care, and student prompts for follow-on actions (a drawing competition), spotlighting a long-standing engagement.

Media and school-based publication outputs (film, posters, student artwork) are pragmatic levers for situating the climate as relevant to learning by rendering abstract topics concrete and behaviour-related. For scaling up, delivery of the activities by teachers and simple measurement (e.g., short pre/post checks) can be used to evidence learning, additionally extending these activities to the wider community in response to local environmental problems."

Greening or Grinding: Unpacking the Environmental Impact of Globalisation in Eurasia

Sonia Hassan and Dr. Muhammad Haris

This study investigates the impact of globalisation (GL), ecological footprint (EFP), natural resources (NR), and total reserves (TR) on environmental crisis (EC), examining 84 Eurasian nations from 1991 to 2021 through a comprehensive index integrating CO₂ and GHG emissions metrics and leveraging dependency theory. Employing a robust methodological approach combining parametric and non-parametric methods, the analysis reveals that GL and NR negatively correlate with EC, while EFP and TR positively correlate with EC. The effects of globalisation dimensions encompassing economic globalisation, political globalisation, and social globalisation on EC vary across developed and developing economies. Introducing an innovative environmental crisis index, the research uncovers complex relationships between globalisation and environmental sustainability, offering guidance for policymakers to reduce EC through resource-independent, low-carbon pathways. While the findings are limited to Eurasian nations, future studies could extend this analysis for broader applicability. The study provides practical insights for fostering sustainable economies and mitigating EC, supporting global initiatives to decrease CO₂ and GHG emissions, and promoting healthier environments and sustainable living conditions worldwide.

The Political Economy of Climate Agreements: A Systematic Review of Economic Impacts and Governance

Mashuil Basher, Farzana Afrose, Tasfiah Akter Tanjel

International climate agreements have shaped global responses to climate change for nearly three decades. The Kyoto Protocol (1997) introduced binding emission targets for developed

countries, while the Paris Agreement (2015) shifted to a pledge-and-review model based on nationally determined contributions (NDCs). More recent mechanisms, including the Global Stocktake (GST) and the EU Carbon Border Adjustment Mechanism (CBAM), aim to enhance ambition and reduce carbon leakage. Yet, evidence on how these agreements influence economies and how political dynamics shape their outcomes remains fragmented. This paper provides a systematic review of the political economy of climate agreements, focusing on economic outcomes such as growth, trade, competitiveness, carbon pricing, and climate finance. Following PRISMA 2020 guidelines, studies published between 2000-2025 are reviewed across economics, law, and policy. Peer-reviewed research and institutional reports are included where they link climate agreements to economic and political dimensions. Evidence shows that carbon taxes and emissions trading systems, inspired by Kyoto and expanded after Paris, reduce emissions with limited effects on GDP and jobs while encouraging low-carbon innovation. Competitiveness impacts are modest, though energy-intensive sectors face challenges. CBAM is emerging as a tool against leakage, though fairness and WTO compatibility remain contested. Clean energy investment is rising, but financing gaps persist in developing regions. Few studies connect economic outcomes with political analysis. Limited evidence exists on CBAM's effects on developing countries, the alignment of finance with Article 2.1(c), and the feasibility of climate agreements. This study is significant for stringent policy implications since the effectiveness of Kyoto, Paris, and other future agreements depends on strong political institutions, fair burden-sharing, and credible finance mechanisms.

Keywords: Kyoto Protocol; Paris Agreement; Political Economy; Climate governance; Climate finance; Climate agreements.

Climate Governance and Environmental Policy - Bangladesh's Delta Plan 2100: A Policy Review of Progress and Implementation Challenges

Ryiana Mubashira

Bangladesh, one of the most climate-vulnerable deltaic nations in the world, adopted the Bangladesh Delta Plan 2100 (BDP2100) in 2018 as a long-term adaptive strategy to promote sustainable development and strengthen resilience against climate change through the end of the century. This policy review, based on Baseline Studies, Volume 06: Governance and Institutional Development, focuses on the early phase of BDP2100 by analysing institutional reforms, sectoral progress, and systemic barriers. Notable Institutional advances include the creation of the National Delta Governance Council (NDGC), chaired by the Prime Minister, which provides top-level political oversight, and the establishment of a Delta Wing in the Planning Commission to coordinate cross-ministerial activities, with delta objectives now integrated into more than 15 ministries. Sectoral achievements are visible in disaster preparedness, coastal protection, and agriculture, notably the rehabilitation of over 400

kilometers of embankments, construction of approximately 1,000 cyclone shelters, expansion of early-warning systems to cover 95% of coastal populations, release of more than 20 salt-tolerant rice varieties, and pilot adaptive aquaculture projects over 50,000 hectares, all of which enhance resilience in vulnerable regions. However, critical gaps persist that the proposals by Bangladesh Delta Authority (BDA) and Delta Fund have not been operationalised, centralised coordination remains incomplete, and financing falls short, with allocations averaging only 1.2% of GDP against a projected need of USD 37 billion by 2030. Access to international climate finance is weak, with less than USD 500 million secured from the Green Climate Fund, while monitoring systems remain output-focused, with limited digital integration and weak accountability. These shortcomings highlight a growing mismatch between BDP2100's ambitious aspirations of achieving upper-middle income status by 2030 and long-term climate resilience by 2100, and the realities of implementation. Strengthening adaptive governance, legislating a Delta Act, operationalising the Delta Fund, empowering local governments, and fostering inclusive participation are essential if BDP2100 is to move from vision to effective policy and serve as a global model of climate governance and delta management.

Introducing Green Port Policy for Sustainable Development: Policy Recommendations for Bangladesh

Sheikh Mehbuba Moitree and Mahir Ibne Mahfuz

The Green Port Policy (GPP) is an initiative involving environmental and eco-friendly practices in port operations. The policy is essential not only for mitigating the negative impacts of the port area, i.e., climate change, but also for improving the sustainability of steady port operations. The policy also emphasises community engagement, environmental regulations, and continuous monitoring and reporting of performance. This paper examines the impacts of implementing a GPP in Bangladesh under a sustainable development legal system. The port activities contribute to air pollution, water contamination, and habitat destruction. In Bangladesh, there is no addressing of the GPP in legal frameworks. This paper, therefore, delves into the intersection of environmental sustainability and the environmental legal frameworks, as well as how the GPP can be mainstreamed with the already existing national and international laws and regulations in the promotion of environmental stewardship, economic growth, and social well-being. This study explores areas of prospective advantages in green ports, extending to the reduction of carbon emissions, improvement in energy efficiency, and better waste management, besides focusing on the challenges and barriers that are encountered with implementation. Therefore, the paper, through lessons from case studies of some green port initiatives worldwide, tries to draw inferences for Bangladesh to cull out actionable recommendations for policymakers, stakeholders, and the maritime industry. Therefore, these findings contribute towards the broad dialogue on sustainable development and provide insights towards the formulation of robust

legal and regulatory frameworks that are well-aligned to international best practices and the unique socio-economic environment of Bangladesh.

Climate's Youngest Victims: Governance of Street Children amidst Climate Change in Bangladesh

Yazdi Zaman

The United Nations estimates that there are up to 150 million street children in the world, and the number of street children has started to increase globally, particularly in developing countries. This paper aims to investigate the impact of climate change on street children in Bangladesh and further understand the causes of failure in policy implementation and child laws to assist street children. In line with the objectives, the research adopted a mixed methodology involving both quantitative and qualitative approaches. The research was conducted through secondary sources, and data were collected from newspapers, journals, articles, and development organisations and NGOs working on the issue, such as the CCRI of UNICEF, Save the Children, BBS, Plan International, and others, which analysed the case of street children. This paper aims to explore the effects of climate change on street children in Bangladesh, particularly in Dhaka, where most street children in the country reside. Additionally, this study will contribute to facilitating knowledge regarding the present status of climate's youngest victims (street children) and investigate their coping mechanisms, survival skills, and future in the streets amidst exacerbating threats of climate change. The paper will conclude with a call for action and best practices from around the world to protect street children in an era of mounting climate change impacts.

Keywords: climate change, street children, policies, child laws

Trapped by design: An integrative typology of critiques, failures, and fixes of the voluntary carbon market for corporate decarbonization

Idowu Kunlere

Despite persistent criticisms, several organisations have continued to employ the voluntary carbon market (VCM) as part of their corporate decarbonization strategy. In explaining the VCM's durability amid such sustained scrutiny, existing analyses often isolate individual concerns, such as justice deficits, gaming practices, and financialization, but rarely show how these elements combine to sustain what many now call an "integrity gap." Drawing on forty-nine key texts spanning political economy, behavioural science, and degrowth advocacy, this paper constructs a nine-part typology that ranges from the mechanics of structural lock-in, integrity shortfall, regulatory capture, and speculative finance to the moral outrage of commodification ethics and degrowth advocacy. We trace critique patterns across peer-reviewed articles, NGO

reports, and litigation filings from 1994 to 2024 using inductive coding, emblematic text synthesis, and network and temporal mapping. We identify a recurrent feedback loop, lock-in → financialization → capture → legitimacy crisis (followed by narrative repair), that both generates controversy and forestalls reform. Integrity scandals provoke new legitimacy narratives (for example, “high-integrity credits”), which in turn renew demand and deepen institutional entrenchment. The paper’s contribution lies in integrating fragmented literatures into a coherent causal framework, revealing how VCMs absorb critique without structural change. We propose “stress-test” criteria for policy and corporate actors to assess whether market reforms disrupt or merely rebrand low-integrity practices. Without such checks, voluntary credits risk perpetuating reputational cycles rather than delivering real climate outcomes.

The New Climate Colonialism: How the Renewable Energy Revolution Perpetuates Global Injustice

Fawje Ferdous Millat Ramisa and Bibi Julekha

The global transition to renewable energy is a crucial climate change requirement. However, the current model of this transition risks perpetuating a form of climate colonialism, where the externalities of “green” solutions are unjustly burdened by the world’s most vulnerable communities. This research investigates the significant justice and governance gaps within renewable energy supply chains, arguing that without integrated, binding governance, the green energy revolution will replicate the degradation of the fossil fuel era.

The study employs a mixed methodology analysis of international law and policy gaps, paired with case studies of lithium and cobalt extraction for batteries and examination of end-of-life waste streams for solar panels and wind turbines. Findings reveal that voluntary corporate sustainability policies fail to prevent land degradation and labour exploitation in mining regions. Also, global recycling infrastructure is critically underdeveloped because less than 10% of solar panels are recycled, which creates a plethora of toxic electronic waste. The research also establishes a direct correlation between mineral extraction activities and heightened social conflict in mining regions, highlighting the limitations of an extraction-based transition model.

In conclusion, the narrow focus on carbon reduction is creating harmful environmental consequences. The pursuit of minerals for batteries and decommissioned solar panels and turbine blades, which contain hazardous and non-recyclable materials, creates a new waste crisis. Therefore, a fundamental shift is required not merely through a transition in energy sources, but a transformation in governance. We conclude that binding international laws and rights-based policies are essential to mitigate these social, economic, and environmental damages and to ensure a transition that is truly just and sustainable. Otherwise, in our desperate bid to escape one form of ecological colonisation, we risk inaugurating another, creating the cycle of injustice we seek to end.

Keywords: Climate colonialism; energy justice; green supply chains.

Indigenous Knowledge and Nature-Based Climate Solutions: Insights from the Khumi Community in Bandarban, Bangladesh

Sheikh Mehzabin Chitra, Chayan Chakma, Shakil Mia, and Mst Emi Begum

The indigenous knowledge and the climate adaptation and the solutions approach in terms of nature-based are the lifecycle journeys of survival in its archetypal nature, but what is special is the environmental practices of Khumi indigenous community. The study undertakes the investigation of this gap in providing an answer to the question in regard to sustainable resource management and the ecological knowledge strategy of the Khumi people in Rowangcchari, Bandarban district of Bangladesh. The research design employed was that of qualitative research because 12 interviews (10 IDIs and 2 KIIs) were conducted together with 2 case studies of community farmers, local leaders, and elders, and supplemented with field data. Findings of this work explored multifaceted forestry, conventional management of water, and the jhum method of shifting cultivation that produced ecosystem resilience and biodiversity at the local level. These solutions and adaptive responses to environmental and climatic stressors, which were provided by the Khumi community, are reinforcing in nature and based on their financial status, the socio-cultural values, and the way that they were used to do things. The outward demands also described in this study are: The policy ignorance, deforestation, and the introduction of tourism, which are threatening to disrupt both the inter-generational and ecological balance in the knowledge of Khumi community. The paper argues for the rational use of the local Khumi traditional practices in the national climate adaptation policies, since it is locally-driven, inclusive, and even culturally-based to address the growing problems of climate change.

Perspectives on the environment and environmental policies: Local beliefs and experiences of informal hillside settlements slum areas of Jalalia, Sylhet, Bangladesh

Md Syful Islam and Saifur Rahiman Himon

In the 21st century, global climate change and the implementation of climate policy have become pressing challenges. Large populations worldwide, including in Bangladesh, live in informal slum settlements and often perceive environmental change differently due to distinct local knowledge, experiences, and beliefs. This qualitative study examines how residents of hillside slums in Jalalia, Sylhet, Bangladesh, perceive their natural environment, its changes, and relevant policies through the lens of their local beliefs and lived experiences.

This study used a multi-method qualitative research design, collecting data through seven in-depth interviews, two focus-group discussions, five key-informant interviews, participatory rural

appraisal (PRA) exercises, and narrative case studies. Participants were selected through purposive and thematic analysis, with member checking was used to triangulate insights and identify core themes.

Results indicate that residents have limited formal environmental and environmental policy knowledge, and they interpret environmental issues through the lens of survival and local belief systems. They create various myths or narrative frameworks to explain, while natural hazards (e.g., floods, droughts, landslides) were explained using religious or folktale etiologies, and policies and interventions (e.g., eviction, infrastructure, hill modifications) were interpreted in political-economic terms. Environmental degradation (e.g., tree-cutting or building on unstable slopes) is often normalised as a survival strategy, and environmental policies are ignored or perceived as oppression.

The analysis, informed by cognitive ecological anthropology, reveals that most residents frame the environment primarily as a struggle for subsistence and often view policy as a threat. Interviews and PRA showed that a significant mismatch exists between formal environmental policies and community worldviews, reflecting broader global variations in climate attitudes. Bridging this policy–practice gap in peripheral urban areas requires aligning environmental policies with local worldviews."

Assessing the people's perception of Climate Change projects: A case study on Kakchira Union community under Barguna District

Md. Fahad Rabid, Bushra Monowar Duti, Dr. Abdul Khaleque

Bangladesh, a climate-vulnerable nation, has invested heavily in climate change interventions, particularly in adaptation and resilience. However, there is a lack of understanding about how local communities perceive these initiatives and whether they effectively address their needs and reduce vulnerability. This study aims to assess the perceptions of local community people towards the impacts of climate change projects in meeting their demands in the Kakchira union of Barguna district. Using a mixed methodology, it intersects quantitative surveys and qualitative key-informant interviews to investigate community involvement and participation, and project impact on the ground.

The research findings indicate a significant disconnect and discrepancy between these project objectives and the actual needs of the community. Although important programs like the CCRIP and LoGIC have been rolled out, 92% of respondents had not heard about these projects, suggesting poor articulation and engagement. Furthermore, of all the survey respondents, only 5.6% of people had participated in decision-making, while 90% felt their risk of disasters had not decreased. The study raises concerns regarding a lack of community ownership, insufficient awareness, and the absence of inclusive participation. Although NGOs have played a critical role

in raising awareness about climate change, government-led initiatives seem to have limited reach at the grassroots level.

This study found lessons where climate projects have failed to increase local resilience/adaptation, despite claims of participatory planning, based on their non-inclusivity and mismatch with the local needs. It calls for a new way of implementation; from a top-down to a bottom-up approach that reinforces the local dimension of decision-making and planning, also providing increased transparency in climate funding, the tailoring of adaptation, and the strengthening of capacity-building. Developing and enhancing participation and inclusivity will be critical to ensure that projects on climate change realise substantial and long-term benefits for disadvantaged groups in Bangladesh."

Agency-led Adaptation and translating vulnerability to viability: Evidence from Sundarban Coastal Communities of Bangladesh

Rukhser Ahmed, C. Emdad Haque, and M. Abul Kalam Azad

Despite growing recognition of local adaptation actions contributing to enhancing community resilience in the disaster context, relatively little attention has been directed at how disaster-affected communities exercise their agency to shape these adaptive pathways. In this context, the present study investigates how small-scale fishing communities in the Sundarbans coastal region of Bangladesh mobilise individual and collective agency to craft locally-grounded adaptation responses in the face of recurring climatic, environmental, and socio-political stressors. The study also identifies and analyses those factors that act as barriers and opportunities in building adaptive capacity of these fishing communities. A case-study approach is adopted using qualitative research methods for analysing empirical data. Primary data were collected from nine key informant interviews and six focus group discussions, as well as from participant observations. The findings reveal that human agency attributes in connection with existing socio-institutional settings are deeply embedded within local adaptation actions that directly contribute to enhancing the adaptive capacity of the fishing communities. These strategies are not merely reactive but reflective of intentional responses shaped by accumulated lived experiences. These responses vary according to households' socio-economic traits and adaptive outlooks across livelihood dimensions. However, various structural barriers constrain the translation of agency attributes towards viability. Based on our findings, we argue for integration of agency-driven perspectives in adaptation planning and disaster policy frameworks, and for more attention to how social, political, and institutional enablers or barriers shape these community-led adaptation pathways.

Integrating Indigenous Knowledge and GIS-Based Remote Sensing for Community-Led Climate Adaptation and Riverine Sustainability in Bhairab, Bangladesh

Mofassir Azad and Mozakkir Azad

This study explores the integration of Indigenous Knowledge (IK) with Geographic Information Systems (GIS) and remote sensing technologies to promote community-led climate adaptation and strengthen riverine sustainability in Bhairab, Bangladesh. Leveraging traditional ecological knowledge, which has been passed down over centuries, this research combines local insights with advanced geospatial tools to better understand and address climate vulnerabilities. In 2023, through participatory mapping, local knowledge was incorporated into GIS-based models to monitor environmental changes, including riverbank erosion, flood patterns, and biodiversity degradation. The study revealed that the incorporation of IK significantly improved the accuracy of flood prediction models by 20%, while also enhancing community awareness and resilience against climate impacts. The findings highlight the potential for blending Indigenous wisdom with modern scientific methods to foster sustainable climate adaptation strategies and improve environmental management practices in riverine areas.

Keywords: Indigenous Knowledge, GIS, Remote Sensing, Climate Adaptation, Riverine Sustainability"

Struggling in Rising Waters: An Exploration of Mental Health among Adolescent Girls during Floods in Gwainghat, Sylhet

Faria Azmee and Laila Akhter Lovely

More than a billion children worldwide are impacted by the more frequent and severe weather events brought on by climate change. Severe flooding, particularly through the Gowainghat area, frequently destroys lives, homes, and livelihoods in Bangladesh's Sylhet district. Families are forced into filthy, overcrowded shelters by floodwaters, which causes emotional distress. Because of their age, gender norms, and social constraints, teenage girls are especially at risk during such crises. However, planning for disaster response still mostly ignores their mental health requirements.

This study seeks to: (1) explore the mental health experiences of teenage girls during and after flooding in Sylhet; (2) examine the impact of social, familial, and gender-based factors on their mental well-being; and (3) identify culturally appropriate strategies to support resilience and psychosocial care. Method: A qualitative research design was used to understand the lived experiences of adolescent girls affected by flooding. Researchers conducted 15 in-depth interviews, 8 key informant interviews, and two focus group discussions (FGDs), each with 6–8

teenage girls. These methods helped capture the complex emotional and social challenges the girls face within their cultural and environmental context.

The findings show that teenage girls frequently experience anxiety, fear, helplessness, and emotional instability during and after floods. Gender-based vulnerabilities, family disruptions, and a lack of access to mental health resources worsen their psychological distress. However, support from families, schools, and community networks significantly helps in coping and recovery. Conclusion: Adolescent mental health in flood-prone regions like Sylhet must be understood through a socio-cultural lens. Disaster preparedness and response plans must include adolescent mental health services. Culturally sensitive, school-based interventions and trained local community workers are essential to building psychosocial resilience. This research offers valuable insights for academics, policymakers, and humanitarian organisations working in climate-affected regions.

Environmental Recovery and Urban Stagnation: A Spatial-Social Study of Hazaribagh After Tannery Relocation (2015–2025) and its Sustainability Outcomes

Hasmi Al Kabir Zarif

The relocation of Bangladesh's toxic leather tanneries from Hazaribagh to Savar in 2017 was hailed as a major step toward urban sustainability and environmental justice. However, nearly a decade later, the question is, did Hazaribagh actually move towards healing, or has the population been left to languish in a post-industrial limbo?

This study investigates the socio-environmental impacts of the relocation of tanneries by combining spatial imagery analysis with micro-scale perceptions. By tracking the land use and environmental change through GIS Mapping in three key years—2015 (pre-relocation), 2020 (mid-term), and 2025 (current)—conclusive inferences are suggested in the form of separating landscape change, discernible reduction in pollution, and fixed points. To complement this, short interviews with residents and employees yield qualitative insights regarding perceived environmental quality, reuse of the land, and economic transformation.

This research suggests the necessity for inclusive, long-term urban planning beyond industrial relocations. Inadequate rehabilitation policies, minimal investment, and widespread residual waste areas are signs of a short-term and half-done process. Thus, the study calls for post-industrial land use planning on a long-range basis and requires collaborative strategies in sustainable redevelopment for industry-affected urban cities. The Hazaribagh example urges policymakers to reimagine post-toxic spaces not as vacant lands, but as dynamic components of equitable, sustainable cities."

Exploring the Role of Artificial Intelligence in Enhancing Public Transit Accessibility to Airports for Low-Carbon Urban Mobility

Arnav Prakash

Airports are vital parts of cities, connecting people, goods, and ideas across the globe. But getting to and from airports often relies heavily on private vehicles, contributing to traffic congestion and carbon emissions. As cities look for ways to become more climate-friendly, improving public transit access to airports is a practical and necessary step. This research explores how artificial intelligence (AI) has been used in recent years to help cities understand and improve these connections.

Using only secondary data—such as satellite imagery, transit maps, and publicly available planning documents—this study reviews how AI tools have supported better decision-making in urban mobility. These tools include smart routing systems, real-time transit tracking, and models that help planners identify which neighbourhoods lack reliable airport access. By analysing case studies from cities around the world, the research highlights how AI has helped reduce car dependency, improve transit efficiency, and support more inclusive access to airports.

Visual maps and diagrams are used to show how well-connected airports are in different urban settings, and where improvements are most needed. This work responds directly to ECC25's theme of “Global Strategies and Local Actions” by showing how global advances in AI can inform local climate solutions. It encourages planners, policymakers, and researchers to learn from existing examples and consider how AI-informed insights can guide future transit improvements.

Ultimately, this research underscores the transformative potential of data-driven insights in shaping equitable and climate-resilient mobility systems. By examining how artificial intelligence has supported more inclusive and low-emission access to airports, the study offers a practical framework for cities seeking to align transportation planning with broader environmental goals—advancing a future where mobility not only connects people, but also contributes meaningfully to planetary well-being.

Urban Environmental Sustainability Assessment of Dhaka Metropolitan City Using a Geospatial-statistical Approach with Remote Sensing Indices

Md. Shohel Khan, Sajid Ibne Jamalfaisal, Tahsinur Rahman, Sayed Abu Johany and Md. Sabit Mia

Rapid urbanisation and land use transformation have increasingly degraded urban environmental sustainability (UES), threatening ecological balance and human well-being in Dhaka Metropolitan City areas. Understanding the spatial distribution of UES is essential for

sustainable urban management in these regions. This study aimed to assess the UES of the highly urbanised areas of Dhaka Metropolitan City based on five remote sensing-based indices, such as land surface temperature (LST), normalised difference vegetation index (NDVI), water index (NDWI), built-up index (NDBI), and bareness index (NDBaI), and analysed through principal component analysis (PCA). In addition, a weighted linear combination (WLC) was used to classify the area into five categories (very poor to very high). Landsat 8 satellite imagery was used to extract all of these indices by using Google Earth Engine and further analysed by Python 3.13 and ArcMap 10.8 software. PCA results revealed that the first two components, PC1 (eigenvalue = 3.11) and PC2 (eigenvalue = 1.32), explained 87.72% of the variance, with LST (29.06%) and NDBI (26.30%) being the dominant contributors to UES, followed by NDVI (16.59%), NDBaI (15.48%), and NDWI (12.57%), respectively. The correlation analysis indicated a strong negative association between NDVI: NDWI ($r = -0.97$) and NDVI: NDBI ($r = -0.83$), while NDBI showed strong positive correlations with NDWI ($r = 0.74$) and LST ($r = 0.68$). The WLC showed that 42.36% and 40.29% of the study area were categorised under “low” and “moderate” UES, respectively. Only 16.41% of the area exhibited “high” sustainability, while “very high” and “very low” categories accounted for 0.10% and 0.84%, respectively. This study provides a comprehensive spatial understanding of UES in Dhaka City, which can guide policymakers and urban planners in formulating sustainable urban development strategies and may suggest an evidence-based spatial framework to identify vulnerable zones for city areas. Keywords: Build-up index; Principal component analysis; Spatial framework; Sustainable strategies; Weighted linear combination.

Urban Heatwave Resilience: An Analytical Study of Adaptation Strategies and Approaches

Sabrina Jahan, Sunzida Kazi Lisa

Urban areas worldwide are increasingly experiencing intensified heat stress due to climate change and rapid urbanisation, posing significant challenges to public health, infrastructure, and overall urban resilience. This study systematically examines adaptation strategies aimed at mitigating urban heat vulnerability, enhancing urban resilience with a focus on urban greening, sustainable infrastructure, heatwave early warning systems, and community-based adaptation initiatives. Using content analysis, a comprehensive review of 88 studies from databases including Web of Science, Scopus, and Google Scholar was conducted.

As urban heatwaves intensify due to climate change and rapid urbanisation, cities like Dhaka face growing challenges in managing heat-related risks. This study systematically reviews effective adaptation strategies of a diverse range of novel ideas and practical measures while exploring public perception through primary survey data that improve urban resilience and mitigate vulnerability to heat stress. However, the effectiveness and applicability of these strategies vary across different urban landscapes and socio-economic contexts. The findings

reveal that strategies such as urban greening, wetland restoration, cool roofing, and early warning systems are effective in theory, but their success is often hindered by barriers like limited funding, weak policy enforcement, and lack of public awareness. Notably, the same challenges identified in global literature were echoed by respondents in Dhaka, highlighting a critical alignment between academic insight and on-ground experience. By integrating both secondary and primary research, the study emphasises the need for context-specific, interdisciplinary, and inclusive approaches to enhance urban heatwave resilience. The report concludes that coordinated planning, policy reforms, and community engagement are essential to ensure that adaptation strategies are not only well-designed but also effectively implemented in practice. The study underscores the need for multidimensional, context-specific strategies to address the unique challenges faced by different urban regions, particularly marginalised communities.

This research provides a holistic framework for policymakers, urban planners, and stakeholders, offering practical insights to enhance urban heat resilience and reduce vulnerability, particularly in the context of Bangladesh. Effectively implementing adaptation strategies is critical to mitigating the long-term impacts of urban heat and ensuring sustainable urban development.

Rooftop Farming as a Climate Adaptation and Its Legal Framework for Sustainable Urban Living in Bangladesh

Ashraful Hassan

The most significant cities in Bangladesh are heating very fast. It is not only because of climate change, but also because of a phenomenon called the “Urban Heat Island” effect. It refers to where concrete buildings and roads trap heat, which creates massive problems. It makes people sick and drives up electricity bills from using more AC and other cooling electronics. Moreover, it creates hardship for people to work, especially the poor, who cannot afford cooling. While everyone is discussing big-picture climate solutions, there is a simple and effective solution called rooftop farming. This method involves transforming flat rooftops into small gardens with soil and plants, which is a great way to fight the heat. Significant research indicates that plants and soil absorb heat, which reduces the local temperature by a few degrees and may even help mitigate the effects of air pollution. On top of that, these rooftop gardens are contributing to our food security by providing fresh vegetables for families. Unfortunately, not many people are doing this yet. To fix this, we need to make it easier for people to get started. Although the National Agriculture Policy has recognised it, significant policy gaps and legal lacunae still remain. So, the government is yet to take the initiative to raise awareness among people, which leaves them blind folded. By following the qualitative method, this research emphasises that there is a need for government initiatives through legislation and policy to encourage rooftop farming and make urban areas more livable and sustainable.

Keywords: Urban Heat Island (UHI), Rooftop Farming, Climate Change, Sustainable Urban Living.

Green Infrastructure for Climate-Resilient Urban Growth in Bangladesh: A Conceptual Framework for Policy and Practice

Md. Safiuz Zaman and Most. Ayesha

Rapid urbanisation in Bangladesh's major cities, particularly Dhaka and Chattogram, is intensifying climate risks such as recurrent flooding, heat stress, ecological degradation, and the loss of green spaces. Conventional grey infrastructure has proven insufficient, while retrofitting existing neighbourhoods is costly and disruptive. A focused literature review was conducted, drawing on international experience with multifunctional Green Infrastructure (GI) such as rooftop gardens, pocket parks, constructed wetlands, and vegetated buffers. Design principles and governance lessons were analysed and synthesised to develop a Bangladesh-specific conceptual framework for new urban developments. The proposed framework integrates GI as core site elements in urban projects and couples them with enabling mechanisms, including policy integration in building approvals, developer incentives, clear performance metrics, and locally led participation in design, stewardship, and monitoring. This approach positions GI as a planning requirement rather than a supplementary option, offering co-benefits such as flood mitigation, urban cooling, biodiversity support, improved water quality, and enhanced food/amenity provision. The framework provides policymakers, planners, and developers with an actionable pathway to scale climate-resilient, livable urban growth in Bangladesh, aligning with locally led adaptation and sustainable governance priorities.

Keywords: Green infrastructure; climate resilience; urban planning; Bangladesh; policy framework

Urban Heat Islands and Social Inequality: A Study of Climate Vulnerability of Sylhet Region

Jahid Hasan Sagor, Israt Jahan Epti, and Nishamoni Sinha

Urban heat islands (UHIs) are the phenomenon in which cities face higher temperatures than rural settings in their proximity, which are being recognised as a climate stressor that impacts disadvantaged populations disproportionately. It is rational because it uniquely integrates GIS-based UHI mapping with qualitative research on how vulnerability to extreme heat in Sylhet results from the overlapping of physical environments and social inequities, an approach that is largely absent in Bangladesh's climate studies. This study examines the relationship between

urban heat island effects and social inequality by showing how environmental processes of inequalities interact to shape different experiences of heat.

Methodologically, satellite imagery (Landsat 8/9) was used to analyse Land Use Land Cover (LULC), Land Surface Temperature (LST), Normalised Difference Vegetation Index (NDVI), and Normalised Difference Built-Up Index (NDBI). GIS-based spatial statistics (Local Moran's I) identified clusters of high heat intensity. To capture lived experiences of inequality, qualitative methods including In-Depth Interviews (IDI), Key Informant Interviews (KII), Focus Group Discussions (FGD), and observation were conducted in vulnerable neighbourhoods.

Findings reveal that heat intensity is highest in densely built-up areas with minimal vegetation, especially in rapidly urbanising zones of Sylhet Sadar. Spatial statistical (Local Moran's I) analysis confirmed significant hotspots where the LST overlaps with low vegetation and high built-up density. These hotspots coincide with low-income settlements lacking electricity, cooling options, and adequate housing. Qualitative data highlight persistent indoor heat, poor nighttime cooling, fatigue, and greater vulnerability for women, children, the elderly, and outdoor labourers. As well as the correlations analysis also shows a positive correlation ($r=0.7$) between LST and social inequalities.

Overall, the study shows that urban heat stress in Sylhet is not evenly distributed but concentrated in socially marginalised spaces, underscoring the need for equitable climate adaptation and inclusive urban planning.

Mapping and Predicting Groundwater Potential and Depletion in DWASA MODS Zone-4: GIS and Machine Learning Approaches for Sustainable Groundwater Recharge

Md. Mashrur Abdullah Raiyaan, Marzan Muntaha, and Lt. Col. Md. Shafiul Azam

Groundwater depletion is a pressing concern in rapidly urbanising regions like Dhaka, Bangladesh, where escalating water demand and limited recharge threaten aquifer sustainability. This study focuses on mapping and predicting groundwater potential and depletion in the Dhaka Water Supply and Sewerage Authority (DWASA) MODS Zone-4, a densely populated urban area heavily reliant on groundwater resources. Employing Geographic Information Systems (GIS) and remote sensing, thematic layers including land use/land cover (LULC), soil, geology, slope, rainfall, and drainage density were integrated through weighted overlay analysis to delineate groundwater potential zones (GWPZs) for 2017, 2019, and 2021. Results indicate that moderate potential zones dominate, covering 10.29–11.06 km², with high and very high potential zones concentrated in the western and northern areas due to favourable aquifer conditions and higher infiltration rates. Machine learning models, specifically Random Forest (RF) and XGBoost, were utilised to predict future static water levels (SWL) up to 2050, incorporating historical SWL and house connection data as proxies for extraction pressure. The models project

a significant decline in SWL, reaching approximately 400–440 feet by 2050, aligning with Dhaka's reported depletion rates of 6.6–9.8 feet/year. However, model performance was constrained by moderate errors (MAE: ~36 feet, RMSE: ~43 feet), indicating limitations due to insufficient input parameters and potential data inconsistencies. The analysis highlights how urbanisation, characterised by impermeable surfaces like roads and buildings, severely restricts groundwater recharge, exacerbating depletion. Mitigation strategies such as Managed Aquifer Recharge (MAR) and the use of permeable concrete are proposed to enhance infiltration in urban settings. Recommendations for future research include incorporating advanced machine-learning techniques, high-resolution multi-temporal data, and real-time monitoring systems to improve prediction accuracy and support dynamic groundwater management. Results provide critical insights for sustainable water resource planning, offering a scalable framework for other urban aquifers facing similar challenges due to rapid urban growth and over-extraction.

Water Scarcity Mitigation: A Site-Specific Analysis for Sustainable Rainwater Harvesting

Anasua Pramanik and H. M. Rasel

Global water constraints have significant implications for socio-economic development, agricultural productivity, and environmental sustainability. Bangladesh, particularly its agriculturally dependent region like Rajshahi, faces acute seasonal water scarcity issues due to fluctuating rainfall patterns, increased water demand, limited groundwater recharge, and over-extraction of groundwater. Since climate variability continues to intensify, rainwater harvesting (RWH) has emerged as a promising solution. It presents a viable and sustainable strategy to capture and store excess rainfall, thereby reducing dependence on over-extracted and unreliable groundwater sources. This study aims to identify suitable sites for implementing RWH systems in Rajshahi, integrating geographic information systems (GIS), remote sensing (RS), and analytical hierarchy process (AHP). Several factors, such as rainfall, runoff, soil texture, soil permeability, land use/land cover, slope, and drainage density, are to be evaluated to assess the suitability of different locations for rainwater harvesting structures. Integration of hydrological and spatial data provides a comprehensive understanding of the region's water management potential. The proposed framework offers a valuable insight to promote climate-resilient water management across other drought-prone regions of Bangladesh and beyond.

Women-led homestead gardening for salinity resilience in coastal Bangladesh: lab evidence and local knowledge from Hatia Island

Angshita Das and Samim Rahman Bhuiyan

Coastal Bangladesh faces rising soil and water salinity, cyclone losses, and food insecurity. Women manage most homestead gardens and household water, yet their knowledge is often ignored in formal plans and decision-making. This study links simple lab tests on ash gourd (*Benincasa hispida*), which is a common, nutrient-rich vegetable, with the community design of low-cost adaptation in Hatia Island. Objectives are: (1) identify salinity thresholds for seed germination and early growth, and (2) co-create a practical “garden bundle” with women farmers that improves yields under saline stress. Methods include a 30-day lab experiment (0–1 ppt salinity; weekly destructive sampling of stem length, leaf water content, chlorophyll, and Na/K/Ca/Mg/P) and field work (60 household surveys, 12 key-informant interviews, and 3 small co-design workshops). We also run a simple cost-benefit analysis and a feasibility score (acceptability, affordability, maintenance). Expected results show declining growth with increasing salinity, but better survival rates were seen using locally tested practices such as raised beds, compost/biochar, mulching, and small rainwater tanks. The garden bundle is expected to increase dietary diversity, reduce water use, and strengthen women’s decision-making. The work offers an evidence-based, locally led, nature-based pathway that unions, extension services, and youth groups can scale with micro-grants and climate finance.

Assessing Disaster Preparedness Among Women in Dhaka’s Slum: A Comparative Study of Working and Non-Working Groups in the Context of Climate Change Adaptation

Md Abdullah Al Sabid

The largest informal community in Dhaka, Korail, is especially vulnerable to the effects of climate change, including heat waves, waterlogging, and many biological hazards. Due to socioeconomic and gender-based vulnerabilities, women in these locations are disproportionately vulnerable. However, based on their social positions, their preparedness levels for disasters can differ greatly, especially between those who work and those who stay at home. This study attempts to compare the preparation of working and non-working women in ten different slums throughout the city for disasters in the context of threats brought on by climate change. A mixed-methods approach was adopted to ensure both breadth and depth of analysis. Quantitative data were collected using a simple random sampling technique across 100 households, evenly divided between working (garments and households) and non-working women. Qualitative insights were gathered through Key Informant Interviews (KIIs) with local NGO representatives and urban planners, and Focus Group Discussions (FGDs) with community women.

The study looks at risk awareness, emergency preparation, evacuation procedures, early warning system accessibility, and adaptive behaviours. Their adaptation methods for climate-induced hazards are also highlighted based on gender and social status. According to preliminary research, working women have better access to knowledge and outside networks, but their time and mobility constraints limit their ability to be prepared at the family level. On the other hand,

women who do not work frequently rely on their connections in the community but do not receive official training or exposure to preparedness.

In addition to providing policy insights for inclusive, community-based disaster preparedness measures catered to the unique experiences of women, this research adds to the conversation on gendered resilience in urban informal settlements.

Eco-Engineered Biochar from Wood Waste for Efficient Chromium(VI) Removal: A Circular Remediation Strategy

Sumaya Binta Ashraf

Heavy metal pollution, particularly from hexavalent chromium [Cr(VI)], poses a significant threat to aquatic ecosystems and public health. This study presents an eco-friendly and cost-effective method for Cr(VI) remediation using biochar synthesized from waste *Acacia auriculiformis* wood through slow pyrolysis at 600°C under a nitrogen atmosphere. The resulting biochar exhibited a high surface area (144.899 m²/g) and porous morphology, confirmed through BET, SEM, EDAX, and FTIR analyses.

Batch adsorption experiments demonstrated a maximum Cr(VI) removal efficiency of 96.89% at an adsorbent dosage of 1.5 g/L, with equilibrium reached within 45 minutes. Adsorption behavior followed both Langmuir and Freundlich isotherms, while kinetic modeling indicated pseudo-first-order dynamics. The presence of oxygen-containing functional groups and a honeycomb-like structure enhanced the biochar's affinity for chromium ions.

This research highlights the potential of waste biomass valorization for heavy metal remediation, contributing to circular economy principles and climate-resilient water management. The findings support scalable applications of biochar in local and regional water treatment systems, aligning with global strategies for environmental sustainability and pollution control.

From Vulnerability to Resilience: Youth Innovation Hubs for Climate-Smart Futures

Md. Aminur Rahman

Kurigram, in northern Bangladesh, is one of the world's climate frontlines. Communities here face three flash floods annually, scorching heatwaves in summer, and life-threatening cold spells in winter. Agriculture, the backbone of livelihoods, is increasingly fragile while climate-smart agriculture (CSA) is yet to take root. Without urgent action, food security and rural resilience remain at grave risk. Empowering youth as catalysts of innovation and grassroots leadership offers a transformative pathway forward.

I propose establishing a Youth Innovation Hub in a local high school as a pioneering model for climate adaptation and leadership development. The hub will function as an interactive learning and experimentation space, decorated with climate knowledge walls, digital learning corners, and innovation boards that showcase student-led ideas. A linked demonstration plot will display CSA practices—flood-tolerant crops, water-efficient irrigation, sack and organic farming, and agroforestry systems—allowing students to learn by doing and to transfer skills to their communities. The space will be designed as both inspiring and practical, with climate science murals and resource libraries that encourage creativity, collaboration, and ownership.

The initiative directly advances global commitments: SDG 13 (Climate Action) by strengthening adaptive capacity, SDG 2 (Zero Hunger) by promoting resilient food systems, and SDG 4 (Quality Education) by embedding climate literacy into school learning. More than a classroom, the hub will be a platform for peer learning, intergenerational knowledge exchange and youth-led outreach to farmers—bridging science, practice, and community action.

Media, Education, and the Making of Climate-Conscious Citizens

In this study, the role of media and education in the formation of the population understanding of climate change and the advancement of environment-friendly behavior is considered. With the growing pressure on the environmental situation, clear and understandable communication becomes an essential tool to have citizens comprehend the research, recognize stakes, and feel inspired to act. Schooling institutions provide the necessary knowledge; however, learning in the classroom is in some cases not sufficient. Traditional and digital media have strong persuading and/or negating effects on climate communication, impacts the opinion of citizens, and affects norms. These two aspects together may have a positive outcome and create increased awareness and involvement or create a mixed disappointment and apathy. This paper examines how schools, colleges, journalists and internet sites liaise to develop literate and critical-minded citizens. Misinformation, political division, and media bias, problems that impede understanding among the population, are also handled. On the basis of recent researches, case studies, and global schemes, the paper highlights best approaches in integrating climate education into the curriculum and strengthening climate reporting. Finally, it argues that the cooperation between educators and media workers is the key to the development of the society being able to understand climate change and wanting to address it. In complementing these connections, we can close that gap between info and action, thereby, empowering citizens to participate more actively in climate solutions.

Impact of Youth Climate Change Actions and Leadership on Coastal Communities in Bangladesh

Mst. Sadia Islam and Shaon Munshi

Bangladesh is one of the most climate-vulnerable countries in the world, with coastal areas facing frequent climate challenges. These challenges hamper livelihoods, destroy infrastructure, and have unwanted impacts on vulnerable groups like women, children, and the elderly. In this context, youth play a significant role as active agents of change through leadership and engagement in contributing to climate change actions. This study investigated the impact of youth climate change actions and leadership on coastal communities in Bangladesh with highlighted their contributions and barriers they encountered in promoting resilience. And provided evidence-based recommendations to strengthen youth engagement and participation in improving climate resilience in Bangladesh. This study adopted a mixed-methods research design with both qualitative and quantitative methods. Participants were purposefully selected to represent different age groups and social roles within the coastal communities. Data were collected through observation, surveys, and interviews. The survey results were analysed statistically, while the interview responses were examined thematically to bring out the challenges faced and strategies used. The results showed that youth climate initiatives and leadership have a positive impact on the lives of coastal community people, especially on women, children, and the elderly. Survey results emphasised noticeable improvements, and awareness increased by 80%, while interviews revealed challenges like limited resources and social resistance. The findings suggest that broad, youth-centred programs can enhance local community actions in coastal areas of Bangladesh. This study recommends supporting youth through training, collaboration with GOs and NGOs, and recognition of their work for better, sustainable global strategies and local actions. This study contributes to bridging the gap between youth participation and community development. The study not only fills academic gaps for further research but also guides policies, inspires community practices, and amplifies youth voices in climate resilience.

The Role of Grassroots Youth Leadership in Ecosystem Adaptation: A Study on Sylhet Sadar Upazila

Rashedul Islam Sagor, Sanjida Jahan Sania, and Mouari Devnath

Ecosystem adaptation has become a crucial priority in Sylhet, where pollution, climate change and rapid urbanisation are intensifying environmental vulnerabilities. This qualitative research aims to understand how youths at the grassroots level help their communities to become more resilient and foster adaptive practices. Data was collected from purposive sampling consisting of 15 young leaders, volunteers, activists, and 3 Focus Group Discussions (FGD) with respondents, who were ready to provide the corresponding insights about their involvement in environmental

issues in their vicinity. This analyses the role of youth leaders in raising awareness, advocating for change, and promoting sustainable behaviour, ecosystem adaptation, and change. According to studies, tree plantation, waste management, recycling, as well as pre-flooding activities, in particular, have improved as a direct result of the youth's contribution to the activities undertaken. The situation has been improved, but some factors in the form of inadequate allocation of resources, absence of recognition, support in the form of policies, and institutional framing have turned out to be the main obstructs towards the impeded success of such initiatives. Regardless of the existence of such initiatives, the study proves the innovation, determination, and flexibility of the grassroots youth. It further predicts that, with a more solid institutional support, focused training, and more clearly integrating them into the policy process, these youth leaders would become central forces of action for promoting a sustainable urban ecosystem in Bangladesh. Together, the findings highlight the imperative for identifying and uplifting youth voices in environmental governance, and position grassroots youth leadership as a critical force for adaptive and transformational ecological change in the near and long term.

Keywords: Grassroots youth, Ecosystem, Climate change, Urbanisation

Resources Recovery from Electronic Waste for Climate Resilience and Mitigating the Carbon Footprint of Digital Waste

Saborni Sikder Rama, Md. Ismail Hossen, Nowshin Alam, Aniruddha Das, Likhon Bonik Mridul, Syed Shadid Nasif

The increasing amount of electronic waste poses a significant environmental threat, and its improper management ultimately causes greenhouse gas emissions and eventually increases the carbon footprint. This study considered the Printed Circuit Board (PCB) for the heavy metal extraction and quantified the potential climate benefits of establishing a formal e-waste recycling framework in Bangladesh, a region with rapidly growing e-waste generation. In this country, there is not a single large-scale heavy metal recovery plant, and this land has only some local scrap businesses to separate metals from e-waste. The proposed plant consisted of two major segments: mechanical separation and chemical separation processes. The mechanical separation process had six units: those were the jaw crusher, grinding, screening, cyclone separator, magnetic separator, and lastly the electrostatic separator. Then, the grinded metal mixture was fed into the adiabatic reactor along with the natural gas and air stream. Thus, the chemical separation started. Additionally, we considered copper, aluminium, gold, silver, and tin in the metal mixture as these were the major compositions in the PCB board. From the reactions in the reactor, the copper, tin, and aluminium formed smaller amounts of oxides (<1%). The carbon footprint of two scenarios (1) the existing unofficial dumping and dismantling methods, and (2) a suggested model of formalised collection and resource recovery for 3.2 metric tons of e-waste was compared using a life cycle assessment (LCA). From these units, we recovered 614.49 kg

Cu/day, 131.22 kg Sn/day, 0.95 kg Au/day, and 1.40 kg Ag/day, respectively. By implementing this plant in Bangladesh, the net reduction of carbon emissions will help prevent the situation from getting worse.

Learning and Living with Climate Change: The Role of Education and Media in Shaping Everyday Awareness in Tangail and Comilla, Bangladesh

Israt Jahan, Israt Jahan Tithy

Bangladesh is highly vulnerable to climate-related hazards such as floods, cyclones, and river erosion. This study explores how climate education and media shape public awareness, perceptions, and adaptation strategies in climate-affected areas including Tangail (Basail Upazila) and Comilla (Daudkandi Upazila). This research applied quantitative and qualitative mixed method approach, combining survey data from 150 respondents local residents, farmers, students, and teachers selected through stratified random sampling with focus group discussions involving students, teachers, and community leaders. Television and social media are the main sources of climate information, though coverage is often incomplete, fragmented, or misleading. While most respondents expressed deep concern about climate change, their knowledge of practical adaptation strategies remained limited. Climate education in schools was found to be inadequate and poorly connected to local experiences. The study highlights the need for integrating climate literacy into school curricula, strengthening teacher training, and ensuring climate-sensitive media reporting. Community-based awareness campaigns are also crucial to link global climate knowledge with local realities. Overall, a combination of education reform and responsible media engagement can play a vital role in enhancing climate resilience in Bangladesh.

Grassroots Innovation as a Pathway to Equitable Climate Solutions

Fahad Rahul, Md. Ismail Hossain, Suneha Safayet Audrika, Sumaia Akter Lamisa

The number of people between 15 and 24 years old makes up around 16 percent of the world population, whereas in Bangladesh, more than 30 percent of the population is below 25, representing a demographic dividend with untapped potential of leading climate. Despite the high rate of over 70 percent of the world climate adaptation funds being channelled through top-down channels, lower-level youth-based programs are often more cost-effective and inclusive, particularly in grassroots locations where climate effects are experienced most. The theme Youth Led Climate Justice and Grassroots Innovation explores how young leaders and grassroots innovators are changing how the climate is responded to by combining justice frameworks with community-based technologies and social solutions. The use of youth-led grassroots initiatives

has been proven to achieve a level of engagement of the community up to 40 percent higher than externally imposed interventions, which is why case studies are important in fostering climate equality and resilience. More importantly, young climate start-ups in South Asia have already attracted more than USD 150 million in green investments in 2020 alone, which has also demonstrated their ability to combine social entrepreneurship with environmental justice. The following track will critically examine measures of inclusion, participation, financial flows, and quantifiable results of adaptation to examine how youth leadership can promote equitable climate transitions, promote cost-effective innovations, and reshape justice in climate governance. The discussion aims to come up with scalable strategies that embrace grassroots innovation and youth involvement in an effort to deliver effective and justice-oriented climate solutions.