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Effect of Climate Variability on Rice Production in Liberia

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Abstract

Climate variability poses major challenges to agriculture worldwide amid an increasing world population and growing food demand. This study evaluates the impact of climate variability on rice production in Liberia. Rice yields and production data (1990–2023) were attained from the Food and Agriculture Organization Statistics (FAOSTAT), while temperature and precipitation were sourced from ERA5 Agrometeorological Indicators and the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS). Trends and relationships were analyzed using Mann–Kendall, Sen's slope tests, and Spearman's rank correlation. Multiple linear regression estimates climate variables' impact on rice productivity. The results show that mean, minimum, and maximum temperatures increased by 0.57 °C, 0.55 °C, and 0.55 °C, respectively, with precipitation variability at 180.31 mm. Climate variables showed diverse correlations with rice production. Regression results revealed a significant negative impact of minimum temperature (p-value = 0.015) on production and a positive effect of precipitation on yields (p-value = 0.036). Farmers in Liberia recognized climate impacts and adopted adaptation strategies, but resilience is hindered by limited credit access, low technology adoption, reliance on traditional practices, and inadequate extension services. Overall, the findings highlight the sensitivity of rice production in Liberia to climate variability and underscore the need for guided adaptation and institutional support to augment farmer resilience.

Keywords: rainfall variability; climate variability; food insecurity; agriculture; farmer adaptation strategies; rice production; temperature trends; climate change; Liberia

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1. Introduction

Climate variability, including alterations in climate variables such as rainfall and temperature, have significant implications, particularly on climate-sensitive sectors such as agriculture [1–4]. Rice is one of the most important crops and a staple food in many regions worldwide. Its production is highly sensitive to climate change, as it is heavily dependent on climatic factors such as temperature and precipitation for growth and development [5,6]. A study conducted by Algarni et al. [7] utilizes a qualitative descriptive research technique, focusing on analyzing the impact of climate change on rice production and developing effective strategies to enhance efficiency, sustainability, and global food security. The findings show a strong correlation between climate variability and declining rice yields, particularly in rainfed regions, due to water scarcity, soil degradation, and increased pest infestations. Past studies [8–10] have revealed that temperature increases during the reproductive stage of rice, especially during panicle initiation, flowering, and fertilization, may severely reduce yield and grain quality. Also, Song et al. [10] indicated that an increase of 1 °C in temperature above the optimum threshold reduced the yield by 8%. Another study revealed that grain yield declined by 10% for each 1 °C increase in the growing-season minimum temperature in the dry season, whereas the effect of maximum temperature on crop yield was insignificant [11]. On the other hand, recent studies found that for every 100 mm increase in precipitation above the optimal thresholds, rice yield decreased by 6.4 kg in India [12]. Similarly, Gumel et al. [13] employed the Decision Support System for Agrotechnology Transfer (DSSAT) Model to examine the impacts of rainfall on rice yield, and they found that an increase in daily mean rainfall of +1 mm to +2 mm above the threshold led to a decreased yield of −4.0% to −51.5% in Malaysia.

These impacts of climate change threaten food security and diet quality, thereby exposing vulnerable populations across continents to multiple forms of malnutrition, thus contributing to mortality and morbidity [14]. Furthermore, a recent scientific report employed a threshold regression approach to identify and estimate critical temperature change thresholds, while linear mixed-effects models were used to evaluate the impacts of climate change on crop yields under varying levels of temperature increase. The findings revealed that rising temperatures negatively affect crop yields across countries, with the adverse effects intensifying once temperature increases surpass specific threshold levels. For example, in the case of wheat, a 1 °C increase in temperature results in a 6.1% reduction in yield when the temperature rise remains below 2.38 °C; however, yield losses increase to 8.2% per 1 °C warming once the threshold of 2.38 °C is exceeded. Similarly, rice yield losses per 1 °C increase in temperature rise from 1.1% to 7.1% when warming surpasses the 3.13 °C threshold. In contrast, no threshold effect was detected for maize; instead, temperature increases lead to an average yield reduction of 4.03% per 1 °C [15].

Research on rice production is crucial due to its importance for global food security, rural livelihoods, and its sensitivity to climate change [16]. Rice is the primary cereal food for over 60% of the global population; it is produced in many countries, with Asia accounting for more than 90% of its production and consumption worldwide [17]. In Africa, rice is one of the major sources of calories [6,18] and is gradually becoming a staple food and income source in many sub-Saharan African (SSA) countries [6]. In SSA, the annual rice consumption between 2009 and 2019 was 27.4 million metric tons, while average production was estimated at 15.4 million metric tons [19]. The demand for rice is continuously rising in the region due to population increase and urbanization, but production remains low to meet the demands of the consumers [20,21].

In Liberia, rice is produced by approximately 69% of all farmers and accounts for about 50% of adult caloric intake; the annual per capita consumption is estimated at around 133 kg [18]. This makes rice one of the most important crops for food security and economic livelihood in the country; however, domestic rice production is inadequate to satisfy its national demands [22]. For instance, referring to past years, production reduced by 20.55% (from 257,995 metric tons in 2018 to 170,000 metric tons in 2021), which led to substantial imports (560,000 metric tons in 2021). These imports cost over USD 100 million and accounted for approximately 65% of the total consumption [22], an enormous amount for less-developed countries such as Liberia. These reductions may be attributed to several factors [23,24].

Over the past three decades, Liberia has experienced shifts in climate patterns, including rising temperatures, irregular rainfall, and increased frequency of extreme weather events such as floods and droughts [25,26]. Given that Liberia depends solely on rainfed agriculture, these changes, as mentioned previously, have direct and indirect impacts on crop productivity, particularly rice, which has specific climatic requirements for optimal growth. This situation is compounded by the fact that about 70% of the Liberian population depends on agriculture and forestry for their livelihoods and the overall significant contribution of agriculture to the country's economy [24,27]. It is within this context that the present study looks at the interplay between climate variability and rice production and productivity in Liberia. Hence, it is essential to assess how climate variability affects rice production to understand the issue and suggest strategies to improve resilience and food security in the country. For instance, Dorbor-soko [28] conducted a study on the assessment of the impacts of climate variability and change on rice production in Bong County, and Wuokolo [29] worked on assessing the perception of climate change and barriers to strategic adaptation for smallholder farming in Todee District in Liberia. Similarly, another work, Sarnoh [30], assessed climate risks in central and northern Liberia. The studies mentioned above examined smaller geographic areas within the country, but there has been no comprehensive study on the relationship between climate variability and rice yield in the entire country. Another study, Allen Jr. and Diallo [24], conducted a systematic review, but their focus was on assessing the impact of climate change on Liberia's agricultural sector and strategic adaptation approaches. Given the limited research on this topic, the connections between climate variability and rice production across the entire country have not been extensively explored. Most studies have concentrated on specific regions. Therefore, this study aims to evaluate the effects of climate variability on rice production in Liberia using country-specific data from 1990 to 2023.

Specifically, this study aims to determine trends in rice production and yield in Liberia from 1990 to 2023, examine patterns and changes in key climate variables (precipitation and temperature), and assess the association and statistical relationship between climate variables and rice productivity. Furthermore, the study incorporates future climate projections under the RCP8.5 scenario to determine whether the increasing trends and variability observed during the historical period are likely to persist in the coming decades. The findings are intended to support the formulation of climate-resilient agricultural policies, strengthen adaptive capacity, and guide extension services. Accordingly, this study provides novel, Liberia-specific evidence that enhances understanding of how climate variability influences agricultural productivity, contributing to the broader literature on climate impacts in Liberia and across sub-Saharan Africa.

2. Materials and Methods

2.1. Description of the Study Area

Liberia is bordered by Sierra Leone on the west, Guinea to the north, Côte d'Ivoire (Ivory Coast) to the east, and the Atlantic Ocean to the south (Figure 1). It covers a total area of 111,350 km^2 and has a total population of 5.3 million inhabitants [31]. Liberia lies at latitudes 4°20′ to 8°30′ north and longitudes 7°18′ to 11°30′ west [32]. The study area has a tropical climate, characterized by a rainy season that runs from May to November and a dry season from December to April. The average annual precipitation ranges from 2500 mm to 5000 mm per year [32], while temperatures fall between 23 °C and 33 °C [33]. Relative humidity reaches 90–100% during the rainy season and 60–90% during the dry season [34]. Under the considerable study period of 1990–2023, seasonal mean precipitation for the major rice production periods (April to September) in Liberia ranges from 1170 mm to 3017 mm, while seasonal mean temperature was 23.2 °C to 25.8 °C as presented in the Supplementary Materials (Figure S1). The climatic conditions appeared to be more favorable for rice production despite differences among the classes. Using the Köppen–

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Geiger climate classification, there are three major climate types or classifications in Liberia, namely: the tropical monsoon, tropical rainforest, and tropical savannah. Most of Liberia's climate is tropical monsoon (76%), followed by tropical rainforest (15%), with the remaining 9% classified as tropical savannah [35]; see also Supplementary Materials (Figure S2).

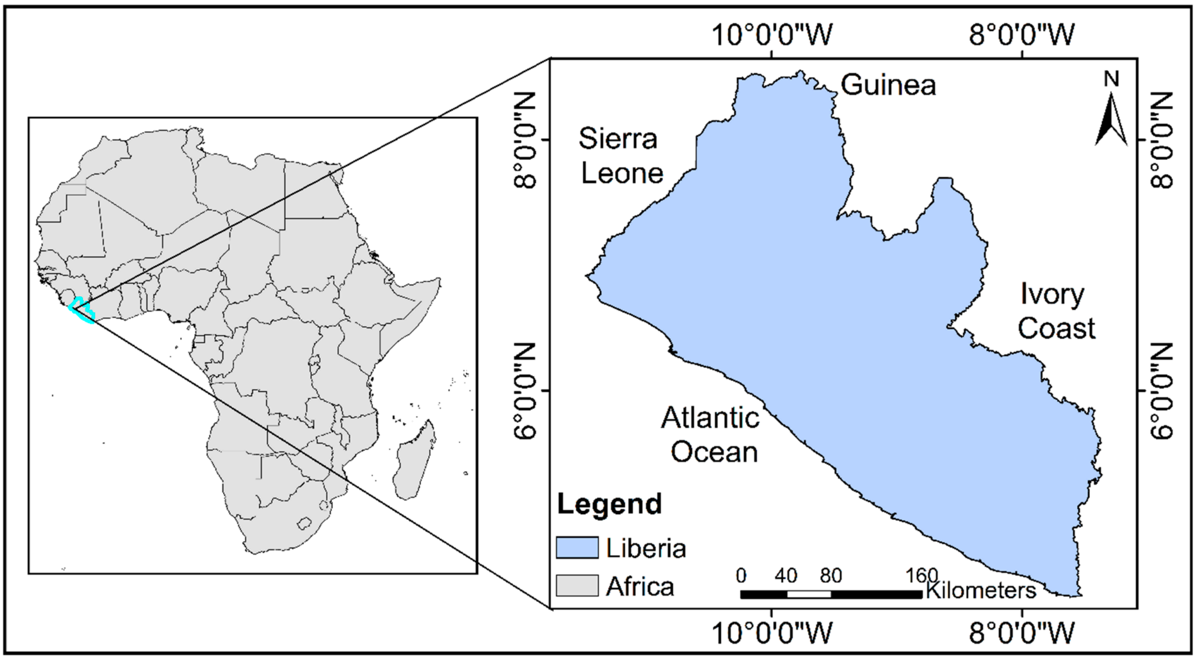

Figure 1. Location of the study area.

Agriculture is the major source of livelihood for the country's population and remains a major contributor to Liberia's economic development. However, rice is one of the most cultivated crops, and its production in the study area is predominantly practiced by subsistence farmers under rainfed conditions. The average rice yields of the country scaled at approximately 1.2 t/ha with notable production in Nimba, Bong, and Lofa counties, respectively, which account for 56% of the country's rice production [36,37], whereas relatively lower production occurs in Margibi, Montserrado, and Grand Bassa counties, respectively (see Figure S1 available in the Supplementary Materials).

2.2. Study Design and Data Collection

This study adopts an integrated quantitative, spatial–temporal, and correlational research design to examine the effects of climate variability on rice production in Liberia over the period 1990–2023. The study uses a secondary data approach. It is based on datasets sourced from three major websites, namely the Food and Agriculture Organization Statistics (FAOSTAT) database, the ERA5 Agrometeorological Indicators covering a period from 1990 to 2023 [38], and the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) database referring to the same period [25]. The research design is appropriate because it integrates time-series trend analysis, geospatial data processing, and econometric modeling using multiple linear regression to examine temporal changes and the relationship between climate variability and rice yield (Figure 2). In addition, scenario-based climate projections and a structured literature synthesis were incorporated to provide broader contextual insight into potential future climate conditions and their implications for rice production. The analytical framework consists of three main components: (i) detection of historical trends in rice production and climate variables, (ii) statistical evaluation of the influence of climate variables on rice productivity, and (iii) spatial analysis combined with climate projections to assess variability and potential future changes. Given that this study relies primarily on secondary and model-based data, it cannot fully establish causal relationships. Incorporating field-based measurements and primary data collection in future research would strengthen validation and improve causal inference. Details on the data follow below.

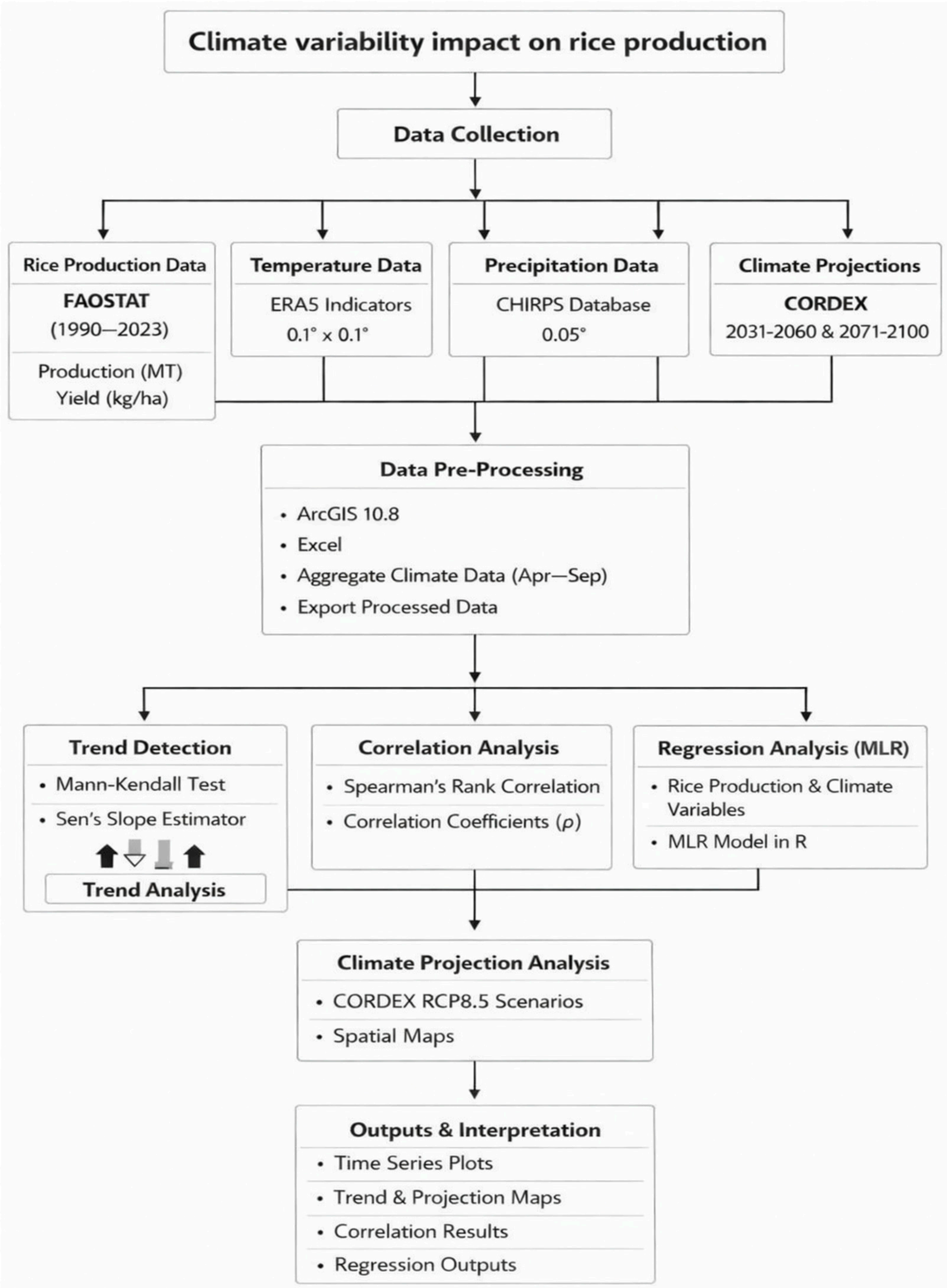

Figure 2. Conceptual flowchart of the study data and methods.

2.2.1. Rice Production Data

Data for rice productivity (paddy) (kilogram/hectare–kg/ha) and production (in Metric ton—MT) from 1990 to 2023 (34 years) were collected from FAOSTAT open data https://www.fao.org/faostat/en/#data/QCL (accessed on 11 March 2025). This data was sorted and prepared on an Excel sheet and then analyzed against climate datasets.

2.2.2. Climate Variables (Temperature and Precipitation)

Temperature data (°C) from 1990 to 2023 was obtained from ERA5 Agrometeorological Indicators, available online at https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels (accessed on 13 March 2025). Its horizontal resolution is 0.1° × 0.1°. Precipitation data (mm) covering the period of 1990–2023 was sourced from the CHIRPS store https://data.chc.ucsb.edu/products/CHIRPS-2.0/ (accessed on 11 March 2025). CHIRPS integrates the Climate Hazards Precipitation Climatology (CHPclim) and in situ station data to create gridded rainfall time series with 0.05° resolution for trend analysis and seasonal drought monitoring [39,40]. Projection data on temperature and precipitation were sourced from the CORDEX (Coordinated Regional Climate Downscaling Experiment), available at https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels?tab=download (accessed on 20 April 2025). The dataset contains a spatial resolution of 0.22° × 0.22° (~25 km). Both projection datasets (temperature and precipitation) were based on two different time periods (RCP8.5, 2031–2060, and RCP8.5, 2071–2100), were accessed in NetCDF format, and then processed in the ArcGIS 10.8 environment. All climate datasets, including temperature and precipitation, were considered based on a national-level, six-month seasonal timescale (April to September), while taking into account the key considerable period for rice production in the study area. In this study, we reviewed the current literature to collect information on farmers' perceptions of climate change impacts and the coping mechanisms they employ.

2.2.3. Data Processing and Quality Control

In this study, before the statistical analysis, the rice production and climate datasets underwent comprehensive preprocessing and quality control checks to ensure data accuracy and consistency. The datasets were examined for missing values, inconsistencies, and potential outliers using descriptive statistics and graphical methods, including time-series plots and boxplots [41,42]. A cross-validation of anomalous values against the original data sources was employed to confirm their validity [42]. Furthermore, temporal alignment of climate and production datasets was considered. Spatial climate datasets were clipped to the Liberia boundary and aggregated using zonal statistics to derive national-level averages. The processed datasets were then exported for statistical analysis. The validated or cleaned dataset was subsequently used for trend analysis, correlation analysis, and multiple linear regression. These procedures enhance the reproducibility, transparency, and robustness of the study's statistical findings [42].

2.3. Data Analysis

Data analysis followed a stepwise approach (Figure 2). Firstly, we preprocessed the raster dataset of the climate factors (temperature and precipitation) from ERA5 and CHIRPS, obtained as gridded raster data and processed in ArcGIS 10.8 environment to extract seasonal average values for Liberia. The raster datasets were spatially aggregated by clipping them to the study area boundary, and the mean, minimum, and maximum temperatures and precipitation values over the study area to represent national-scale climatic conditions were obtained. From the generated spatial outputs, numerical values were then inputted in an Excel spreadsheet. These data were used to plot variables including precipitation and temperatures and production and yield in order to compute various analyses such as trends, correlation, and regression analysis. Climate projection data was processed to produce a spatial map to depict the change in each variable under the considerable time periods. In addition, long-term spatial maps of precipitation and temperature were generated to illustrate the spatial variability of climatic conditions across the country as presented in Figure S1 of the Supplementary Materials. Furthermore, a comprehensive review of the existing literature, institutional reports, and reliable research findings addressing climate–agriculture interactions in Liberia and the broader sub-Saharan African region, with a focus on West Africa, was conducted to access information on farmers' perceptions of climate risks and the coping strategies they employ to address climate change [43].

2.3.1. Detection of Trends

The non-parametric Mann–Kendall test (Mk test) and Sen's slope estimator were applied to identify the trend in various parameters, including production, yield, and precipitation and temperature [44]. The Mann–Kendall test is more favored for identifying monotonic trends in variables, as it remains unaffected by outliers [44,45]. Apart from being robust to outliers, the MK test, and its non-parametric nature, also means that it does not depend on regularly distributed data [46]. It compares all pairs of observations in the dataset, assesses the direction of the trend (increase or decrease), and then tests its statistical significance.

In order to test whether or not to reject the null hypothesis, the MK test was used, where we apply Equations (1) and (2):

H_0. *This considers no monotonic trend present in the series.*

H_a. *This suggests the presence of a monotonic trend in the series.*

At a 5% significance, a p-value of less than 0.05 results in the acceptance of the alternative hypothesis, indicating a trend exists in the data. Conversely, if the p-value is greater than 0.05, the null hypothesis (H_0) is accepted, suggesting the non-existence of a trend in the data [47]. The test statistic, S, was subsequently computed as the sum of the integers:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(Xj - Xi) \quad (1)$$

where n indicates the number of years, x_j and x_i are the annual values in the years j and k, respectively. The function sign($x_j - x_i$) provides an indicator function that takes the value 1, 0, or −1 according to the sign of the difference ($x_j - x_i$) where $j > i$:

$$sign(Xj - Xi) = \begin{Bmatrix} -1\ for\ (Xj - Xi) < 0 \\ 0\ for\ (Xj - Xi) = 0 \\ +1\ for\ (Xj - Xi) > 0 \end{Bmatrix} \quad (2)$$

A positive value shows an upward (increasing) trend in the time series, while a negative value indicates a downward (decreasing) trend.

However, Sen's slope was computed, a non-parametric technique for estimating the overall slope or trend in a dataset over time. It is mostly suitable when analyzing time-series data [48]. It is a method that is more robust in trend estimation, and it is especially advantageous for data that do not assume normality or that contain outliers [45,48]. The slope estimator or N pairs is computed as follows:

$$Q_i = \frac{x_j - x_k}{j - k}, \quad if\ j > k \quad (3)$$

where x_j and x_k denote the annual values throughout the years j and k, respectively. Sen's slope estimator of slope is calculated as the median of the pairwise slope values (Q). The median of the N slope estimates was obtained by simple averaging. N values of Qi were ranked from smallest to largest, and Sen's estimator was computed as follows:

$$\left\{ \begin{array}{c} Q\left[\frac{N+1}{2}\right] \; if \; N \; was \; odd \\ \frac{1}{2}\left(Q\frac{N}{2} + Q[(N+2)/2)\,/2]\right) \; if \; N \; was \; even \end{array} \right\} \tag{4}$$

In this study, we considered the trend to be statistically significant when the p-value was less than 0.05. Time-series analysis was employed to evaluate the trend in rice production, yield, mean seasonal rainfall, and temperatures (mean, minimum, and maximum temperatures) for the period 1990 to 2023. Several time-series plots were generated using Microsoft Excel based on the following variables: rice production, yield, precipitation, mean temperature, minimum temperature, and maximum temperature, respectively. Additionally, future climate projections under the RCP8.5 scenario were analyzed to provide context for the historical climate trend analysis and to assess whether the observed temperature and precipitation patterns may continue in the future.

2.3.2. Correlation Test

Spearman's rank correlation test was applied for estimating the monotonic relationship between production statistics (production and yield) and climate parameters, which in this case are mean temperature, minimum temperature, maximum temperature, and precipitation, respectively. The correlation analysis was conducted at two levels. First, we computed a general correlation test to find the relationship of rice production and yield with climatic variables from 1990 to 2023 (34 years period). Second, a particular time interval correlation test was carried out to identify the association of production and yield statistics with climatic variables corresponding to the period where rice production and yield trends displayed a significant reduction in the time series. The formula used in determining Spearman's correlation is shown below:

$$\rho = 1 - \frac{6\Sigma\, d_i^2}{n(n^2-1)} \tag{5}$$

where d_i represents the differences in paired ranks; that is, $i = R_{xi} - R_{yi}$, and n is the total number of observations, which is 34 observations for the study area. The value of ρ lies between -1 and 1, and direct associations were indicated by positive values, whereas inverse associations were indicated by negative values.

2.3.3. Regression Analysis

Following the correlation analysis, multiple linear regression (MLR) was utilized to evaluate the combined relationship or impact of climate parameters and rice productivity [49]. The MLR model is defined by Equation (6).

$$Y_t = \beta_0 + \beta_1 P_{rec} + \beta_2 T_{min} + \beta_3 T_{max} + \varepsilon_t \tag{6}$$

where

Y_t: Dependent variable (rice production in t/ha, or yield in kg/ha).
P_{rec}: Mean precipitation (mm).
T_{min}: Mean minimum temperature (°C).
T_{max}: Mean maximum temperature (°C).
β_0: Intercept baseline (rice yield when all predictors are 0).
β_1, β_2, β_3: Regression coefficients (effect of each predictor on rice production and yield).
ε: Error term (unexplained variability).

Mean temperature was excluded from the regression analysis based on its correlation with minimum temperature and maximum temperature. Model diagnostics were conducted to ensure the validity of regression assumptions, including assessment of multicollinearity using the Variance Inflation Factor (VIF), evaluation of residuals for normality and homoscedasticity, and testing for autocorrelation with the Durbin–Watson test. The R Software (Version 4.3.1) was used to perform all statistical and regression analysis, with a significance level set at $p < 0.05$.

3. Results

3.1. Annual Rice Production Trend

Rice production in Liberia has shown a significant increase over the past 34 years (1990–2023). The Mann–Kendall test shows that this upward trend is statistically significant (p-value < 0.001) (Table 1). Total production increased from 180,000 tons in 1990 to 256,200 tons in 2023, representing a gain of 76,200 tons over the period. The Mann–Kendall Coefficient ($\tau = 0.510$) showed a moderate to strong positive trend of rice production over time (Table 1, Figure 3). This is further supported by the MK statistics ($Z = 4.212$), indicating the existence of a monotonically increasing trend. Sen's slope estimates of 6515 also confirm a substantial annual rate of increase in rice production across the study period. Despite the general positive trend, rice production exhibited notable inter-annual fluctuations during some periods (Figure 3). For instance, between 1990 and 1995, production declined noticeably, followed by an increase from 1995 to 1998. A decreasing phase occurred between 1998 and 2003, after which production recovered sharply from 2006 to 2008. From 2008 to 2012, production remained relatively stable, showing only minor fluctuations. A consistent growth phase was observed from 2014 to 2016, followed by a short-term decrease between 2016 and 2017, while 2017 to 2023 remained relatively stable (Figure 3).

Table 1. Mann–Kendall and Sens's slope test results for rice production and yield.

Factors	Kendall Tau	MK-Stat (S)	p-Value	Trend	Sen's Slope
Production	0.510	4.212	p-value < 0.001 ***	Yes	6515
Yield	−0.0036	−0.0148	0.9882	No	0

Significant levels: $p < 0.001$ (***).

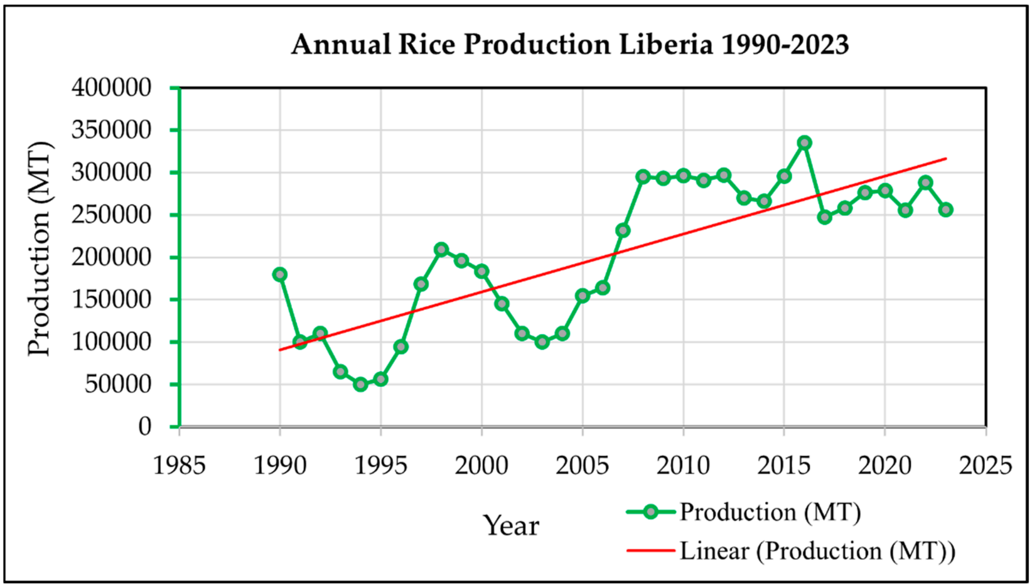

Figure 3. Annual variability of total rice production in Liberia from 1990 to 2023.

3.2. Annual Rice Yield Trends

Overall, between 1990 and 2023, rice yields have remained relatively stable, showing no statistically significant increase over time. The Mann–Kendall Tau coefficient ($\tau = -0.0036$) depicts an extremely negative weak decrease (Table 1). However, the corresponding p-value (p-value = 0.9882) confirms that this correlation is not statistically significant. Similarly, the MK statistics ($Z = -0.0148$) support the absence of a monotonic trend in rice yields. Sen's slope estimates of zero further support the lack of any significant change in yield during the study period (Table 1).

Despite the overall stability, rice yields exhibited fluctuations across different sub-periods (Figure 4). Between 1990 and 1991, yield slightly decreased from approximately 1030 kg/ha to 900 kg/ha. From 1992 to 2000, yields moderately increased from 900 kg/ha to 1250 kg/ha. This was followed by a sharp decline between 2000 and 2003, when yields dropped to approximately 800 kg/ha. A strong recovery occurred from 2003 to 2008, with yields rising to 1550 kg/ha. However, a sudden drop to 1200 kg/ha was observed in 2009. From 2012 to 2017, yields experienced a gradual decline, decreasing from 1280 kg/ha to 1050 kg/ha while from 2017 to 2023, rice yield remained relatively stable (Figure 4).

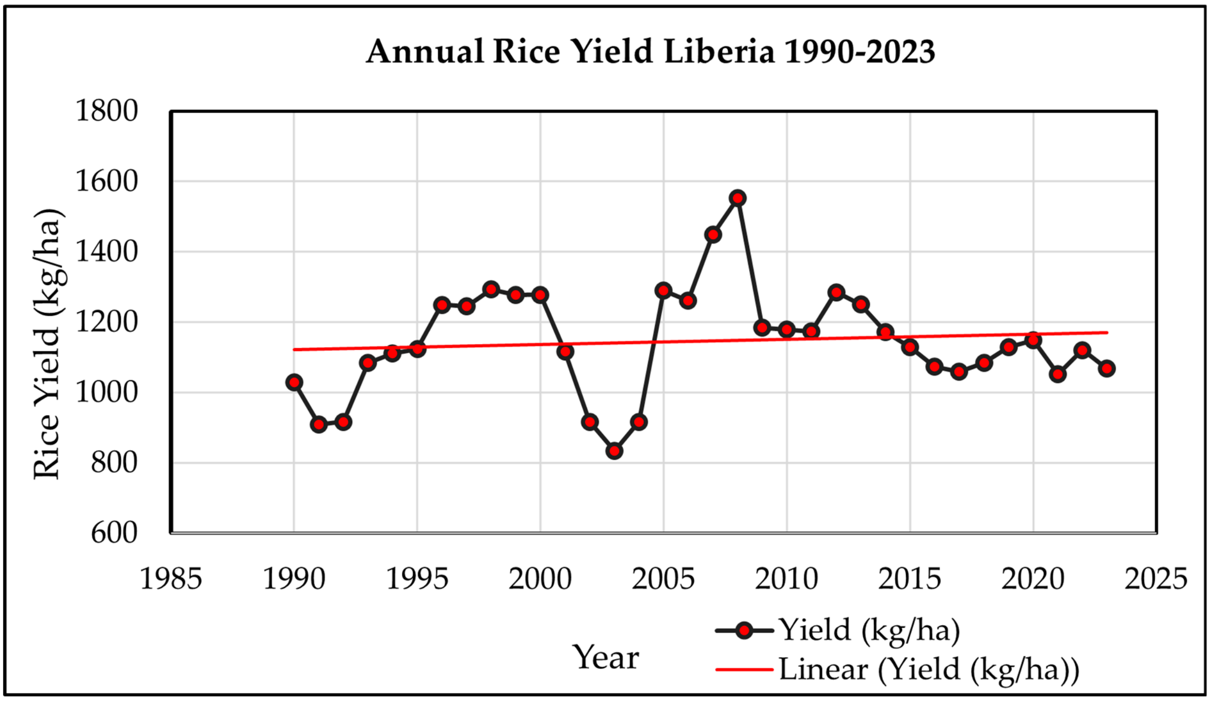

Figure 4. Annual variability of total rice yield in Liberia from 1990 to 2023.

3.3. Patterns of Climatic Variables

3.3.1. Seasonal Precipitation Trends During the Study Period

Between 1990 and 2023, annual precipitation exhibited a slight but statistically non-significant increasing trend (p-value = 0.464). Over the study period, total annual rainfall increased from 3160.66 to 3340.97 (with a slight increase of 180.31 mm, p-value = 0.464). Despite this modest upward tendency, the data reveal substantial inter-annual variability. In particular, the periods between 1994 and 1996, 2005 to 2006, and 2009 to 2010 were characterized by pronounced fluctuations, including years with both exceptionally high and low rainfall anomalies (Table 2, Figure 5). During the periods of 2003 to 2005, 2011 to 2012, and 2019 to 2022, there was a slight decrease in precipitation, and with a prominent decrease from 2008 to 2009 (Figure 5). Overall, the Mann–Kendall Tau coefficient ($\tau = 0.102$) indicates a very weak positive association between annual precipitation and time; values fluctuate randomly. This observation is supported by the MK statistic (Z = 0.830) and Sen's slope estimates of 5.144, which suggests a slight upward trend. The non-significant p-value (p-value = 0.464) confirms that no major long-term trend in precipitation occurred between 1990 and 2023.

Table 2. Mann–Kendall and Sen's slope test for precipitation and temperature.

Factors	Kendall Tau (τ)	MK-Stat (Z)	p-Value	Sig.	Sen's Slope
Precipitation	0.102	0.8301	0.464	No	5.144
Mean Temperature	0.511	4.1759	<0.001 ***	Yes	0.119
Minimum Temperature	0.509	4.1985	<0.001 ***	Yes	0.0125
Maximum Temperature	0.277	2.2704	0.023 *	Yes	0.0075

Significant levels: $p < 0.001$ (***), $p < 0.05$ (*).

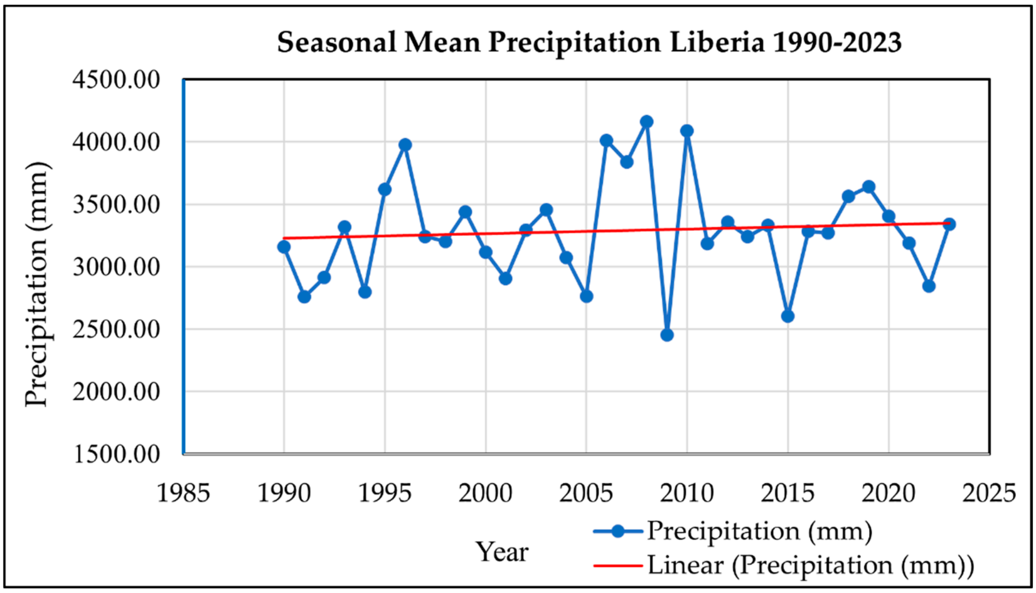

Figure 5. Seasonal mean precipitation variability in Liberia from 1990 to 2023.

Figure S1 in the Supplementary Materials depicts projected precipitation for the mid-century (2031–2060) with that of the end-century (2071–2100). These projection results of precipitation, for instance, RCP8.5 2031–2060, revealed a variability with a lower value of 937.51 mm and a highest of 4072.29 mm (see Figure S3a, Supplementary Materials), while RCP8.5 2071–2100 demonstrated a variation from 843.98 mm to a highest value of 3801.95 mm, respectively, as shown in the Supplementary Materials (Figure S3b). The long-term average variability in seasonal precipitation from mid-century to the end of the century is expected to range from −93.56 mm to −240.34 mm, as depicted in the Supplementary Materials (Figure S3a,b).

3.3.2. Temperature Trends

From 1990 to 2023, mean, minimum, and maximum seasonal temperatures all showed an overall increasing trend. The mean temperature rose from 25.73 °C to 26.30 °C, representing an increase of 0.57 °C (p-value < 0.001) (Figure 6a). Similarly, the minimum temperature increased from 24.76 °C to 25.31 °C (an increase of 0.55 °C, p-value is <0.001) (Figure 6b), while the maximum temperature rose from 29.19 °C to 29.76 °C (an increase of 0.55 °C, p-value = 0.023) (Figure 6c). The Mann–Kendall Tau coefficients for mean, minimum, and maximum temperatures were 0.511, 0.509, and 0.277, respectively, indicating weak to strong increasing trends over the study period. These findings suggest that the upward trend was more pronounced in the mean and minimum temperatures, followed by the maximum temperatures. Although the increases were relatively small in absolute terms, Sen's slope estimates of these variables are as follows: mean temperature (0.119), minimum temperature (0.0125), and maximum temperature (0.0075). This further confirms the presence of gradual warming across all temperature indicators during the study period (Figure 6a–c).

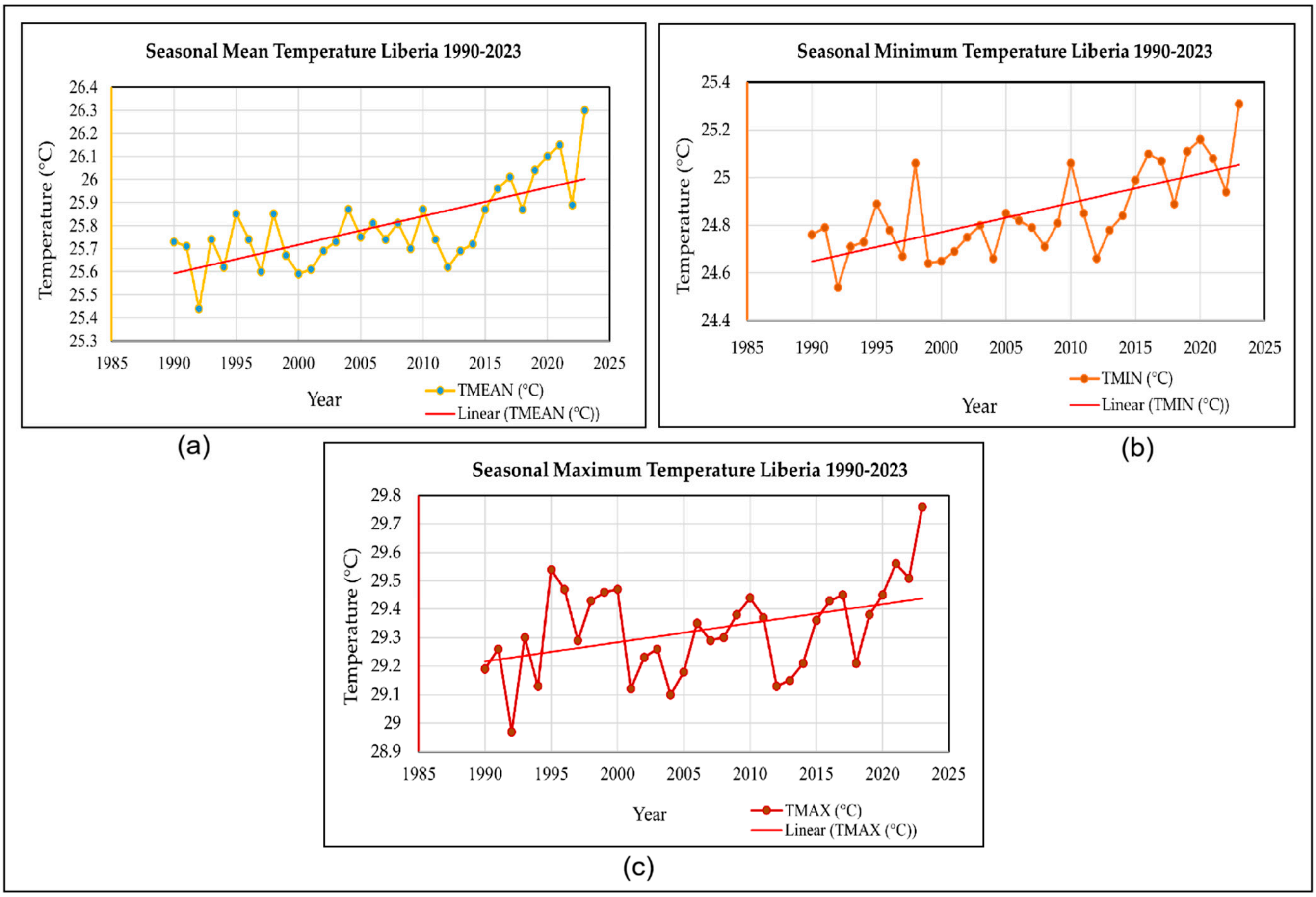

Figure 6. Seasonal mean temperatures: (**a**) mean, (**b**) minimum, and (**c**) maximum temperature variability in Liberia from 1990 to 2023.

Figure S4 within the Supplementary Materials shows projection results of temperature for the mid-century (2031–2060) and end-century (2071–2100). Results of the RCP8.5 for temperature during 2031–2060 revealed significant increasing changes ranging from 24.20 °C to 27.25 °C at the middle of the century, with an estimated increase of 3.03 °C (Figure S4a of the Supplementary Materials), and Figure S4b of the Supplementary Materials demonstrates that the 2071–2100 RCP8.5 interpolation demonstrated a change from 25.95 °C to 28.74 °C in temperature, indicating an absolute increase of 2.7 °C during the time period. This means that the combined projected change in temperature from 2031 to 2100 is expected to reach 4.54 °C as shown in the Supplementary Materials (Figure S4a,b).

3.4. Seasonal Temperature and Precipitation Impact on Rice Productivity

3.4.1. Correlation Between Climate Variables and Rice Productivity

Correlation analysis for 1990 to 2023 suggests that climate variables in Liberia (precipitation and mean, minimum, and maximum temperatures) did not significantly affect rice production, as p-values were 0.956, 0.082, 0.531, and 0.908, respectively. However, there may be some inter-variability or minor impacts under various time periods. Precipitation shows a non-statistically significant negative relationship with production and a positive association with yields (Table 3).

Table 3. Correlation (r) between rice production (MT), yield (ton/ha), and climate variables—precipitation (mm), mean, minimum, and maximum temperatures (°C) ($p < 0.05$, $n = 34$)—during the period of 1990–2023.

Rice	Precipitation		Temperature					
			Mean		Minimum		Maximum	
	Correlation	*p*-Value	Correlation	*p*-Value	Correlation	*p*-Value	Correlation	*p*-Value
Production	−0.010	0.956	−0.303	0.082	−0.111	0.531	0.021	0.908
Yield	0.259	0.139	−0.284	0.104	−0.205	0.246	0.112	0.527

Similarly, rice yield (tons/hectare) also shows no statistically significant associations with climatic factors (*p*-value > 0.05). Although there is an observed weak positive correlation with precipitation (r = 0.259), this may signify that higher rainfall tends to slightly favor rice yield, even though not strongly enough to be statistically significant. Rice yield also shows a negative correlation with mean and minimum temperatures (Table 3), suggesting that higher temperatures may negatively affect yield in the study region, even though the association is not statistically significant, as the *p*-value is greater than 0.05.

Considering the correlation results across different timescales for both rice production and yield revealed that most climate parameters exhibited a statistically non-significant relationship with rice productivity over the various periods analyzed. An exception was observed for the minimum and maximum temperatures during the 1998–2003 period, which showed a highly significant correlation with production (*p*-value < 0.001) (Table 4). For rice yield, significant associations were identified for mean and minimum temperatures during 2000–2003 and for precipitation during 2003–2005, with *p*-value less than 5%. Additionally, during the period 2012 to 2023, mean temperature (*p*-value = 0.004), minimum temperature (*p*-value = 0.036), and maximum temperature (*p*-value = 0.002) exhibited significant correlations with rice yield (Table 4).

Table 4. Correlation (r) results between rice production (MT), yield (ton/ha), and climate variables—precipitation (mm), mean, minimum, and maximum temperatures (°C)—under different time intervals ($p < 0.05$).

	Precipitation		Temperature					
			Mean		Minimum		Maximum	
Factors per Time Interval	Correlation	*p*-Value	Correlation	*p*-Value	Correlation	*p*-Value	Correlation	*p*-Value
TI-I. Production								
1990–1995	−0.314	0.544	−0.429	0.397	−0.371	0.469	−0.543	0.266
1995–1998	−0.8	0.2	−0.105	0.895	0.2	0.8	−0.8	0.2
1998–2003	−0.314	0.544	0.2	0.704	1	<0.001 ***	1	<0.001 ***
2003–2008	0.383	0.309	−0.100	0.797	−0.233	0.546	0.533	0.139
TI-II. Yield								
2000–2003	−0.80	0.20	−10	<0.001 ***	−10	<0.001 ***	0.20	0.80
2003–2005	−10	<0.001 ***	0.50	0.667	0.50	0.667	−0.5	0.633
2012–2023	0.154	0.633	−0.760	0.004 **	−0.608	0.036 *	−0.796	0.002 **

TI-I, production, and TI-II, yield, under different time intervals; significant levels: $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*).

3.4.2. Regression Results of Climate Variables Impact on Rice Production

The regression model relating rice production and climate variables indicated that climate variables influence rice production in Liberia, explaining 26.16% of the total variation (R^2 = 0.2616, *p*-value = 0.026). Among the climatic variables analyzed, minimum temperature was the only factor that showed a statistically significant negative effect on rice production (β = 2.676; *p*-value = 0.015), indicating that higher minimum temperatures are associated with a reduction in rice production in Liberia (Table 5).

Table 5. Regression results of climate variables—precipitation (mm), mean minimum temperature, mean maximum temperature (°C), and rice production (MT), ($p < 0.05$, n = 34).

Predictor	Coefficient	Std. Error	t-Stat	*p*-Value
Intercept	−5.077	2.462	−2.062	0.048 *
Precipitation	9.335	33.31	0.280	0.781
Mean TMini	−2.676	1.031	2.593	0.015 *
Mean TMax	−4.767	1.164	−0.410	0.685

$p < 0.05$ (*), R^2 = 0.2616.

On the other hand, the regression results of rice yield against climate parameters revealed a positive relationship between the observed and predicted values (R^2 = 0.231) (Table 6). Approximately 15.4% of the variation in rice yield was explained by the independent variables, as indicated by the adjusted R^2 of 0.154 and a model *p*-value of 0.046, which is less than 0.05, thus confirming the statistical significance of the model. Considering the various climatic variables evaluated, the analysis revealed that only precipitation displayed a statistically significant positive effect on rice yield (*p*-value = 0.036), as shown in Table 6, suggesting that higher rainfall contributes to increased rice productivity in Liberia.

Table 6. Regression results of climate variables—precipitation (mm), mean, minimum, and maximum temperatures (°C), and rice yield (ton/ha) ($p < 0.05$, n = 34).

Predictor	Coefficient	Std. Error	t-Stat	*p*-Value
Intercept	−37.482	4485.479	−0.084	0.934
Precipitation	0.134	0.061	2.201	0.036 *
Mean TMini	−327.594	189.915	−1.743	0.092
Mean TMax	275.450	211.997	1.299	0.204

$p < 0.05$ (*), R^2 = 0.231.

4. Discussion

4.1. Trends in Annual Rice Production

The Mann–Kendall and Sen's slope test results demonstrate that rice production has shown a significant increasing trend over the study period (1990–2023) despite the variation in production across different time intervals. This noticeable increase in production in the study area aligns with regional agricultural reports and studies that have documented a gradual increase in rice output in West Africa due to the expansion of cultivation and government programs promoting rice self-sufficiency [50,51]. Likewise, refs. [19,21] indicated that the increase in production in the SSA region is largely driven by the expansion of rice-harvested areas and not referring to as yield. For instance, between 2000 and 2020, the harvested area rose from 6.9 million ha to 16.6 million ha, while the increase in rice yield was relatively low, increasing from 1.7 to 2.1 t ha^{-1} [21], supporting the fact that the increase in rice productivity is dissimilar to the increased actual yield. The observed fluctuations in rice production in Liberia cannot be attributed solely to changes in cultivated area, but rather to the interaction between multiple biophysical and socio-economic factors.

Extreme climatic events, including droughts and seasonal flooding, periodically constrain production in both upland and lowland predominantly rainfed systems, leading to substantial year-to-year variability [52]. In addition, policy changes affecting the distribution of improved seeds, agricultural extension services, and input subsidy programs may influence production in specific periods [28,53]. Variations in rice cultivation areas, driven by land availability, labor constraints, and broader socio-economic conditions, further contribute to inter-annual fluctuations [53]. Together, these interacting factors provide important context for understanding the pronounced increases or declines observed in certain years, despite the overall upward trend in rice production.

4.2. Analysis of Trends in Annual Rice Yield

Despite increases in total rice production in Liberia, rice yields have remained stagnant, indicating no significant trend. This implies that the observed rise in total rice production is predominantly driven by land expansion rather than improvements in productivity per unit area [21]. Recent studies noted that Liberia's average national rice yield has remained low in recent decades, at around 1.2 metric tons per hectare, which is considerably lower than yield reported in several other West African countries, including 3.0 t/ha in Côte d'Ivoire, 2.7 t/ha in Ghana, 3.4 t/ha in Mali, and 4 t/ha in Benin, respectively [37,54]. Several interacting biophysical, structural and agronomic factors contribute to the persistent stagnation in yields. These include climate variability and the predominance of traditional rainfed farming, limited adoption of improved rice varieties, and the low use of modern agricultural inputs such as improved seed, fertilizers, mechanization, and irrigation. In addition, limited access to farm credit agricultural support services constrain farmers' ability to adopt productivity-enhancing technologies [18,24,37]. Fertilizer application in Liberia averages less than 5 kg per hectare, which is significantly below the sub-Saharan African average of approximately 20 kg per hectare [55,56]. Low fertilizer input limits soil nutrient availability, preventing rice crops from achieving their yield potential. In addition, baseline surveys indicate that only about 19–20% of farmers cultivate improved rice varieties, while fertilizer use among smallholders is reported at less than 5% [55,57]. Recent studies have also revealed the limited used of improved seed (about <5%) and a low level of access to extension services (<10%) by farmers in the country [58]. These low adoption rates are attributed to restricted access to quality seeds, limited extension services, and lack of awareness of the benefits of modern technologies [57]. Reports from the World Bank, ref. [59], and the World Food Programme (WFP), ref. [60], indicate that improvements in rice yield in Liberia and other West African countries have been constrained by several challenges, including limited access to improved rice varieties, irrigation technologies, inadequate use of fertilizers, and inadequate extension services. Farmers often rely on traditional practices and local seed varieties, which are less responsive to modern yield-enhancing technologies, thus limiting productivity growth per hectare [21,61]. Furthermore, climate variability—particularly irregular rainfall and temperature extremes—affects critical rice growth stages, limiting yield potential even under favorable climatic conditions [62,63]. Overall, the stagnation in rice yields reflects a combination of biophysical, socio-economic, and institutional constraints, highlighting that increases in total rice production have not translated into proportional improvements in yield per hectare.

4.3. Trends in Climatic Variables

4.3.1. Analysis of Trends in Precipitation

The results of the Mann–Kendall test showed a non-significant upward trend in precipitation during the study period, reflecting high variability in rainfall patterns. Although rainfall during the growing season showed a slight increase, this change was not statistically significant. However, the absence of a statistically significant trend in seasonal rainfall totals does not necessarily imply stability or reliability in rainfall distribution. For example, intra-seasonal variability, including delayed onset of rains, mid-season dry spells, and early cessation, remains a critical constraint on planting date decisions and ensuring stable crop development [64]. Such irregularities are often masked by long-term trend analysis but exert significant influence on productivity outcomes [65]. This finding aligns with previous studies' results, which indicate that rural agricultural communities' increasing understanding of changes in local climate conditions, particularly regarding rainfall onset, duration, and distribution, as well as changes in temperature patterns, directly affect rice planting and harvesting dates [28,33]. Studies across West Africa [64] have shown that intra-seasonal rainfall variability has greater implications for yield stability than annual rainfall totals. Moreover, interpolated projection of precipitation under different scenarios of RCP8.5 2031–2060 and RCP8.5 2060–2100 revealed a strong variability in precipitation, indicating an average projected decrease in precipitation by −93.56 mm to −240.34 mm as shown in the Supplementary Materials (Figure S3a,b). These variabilities would hinder farmers' production practices, including changes in planting calendar, crop type, and management practices, which may result in low productivity [66]. Thus, while current rainfall levels in Liberia remain relatively stable, their temporal distribution may be posing significant risks for food production. This study, therefore, underscores the temporal variability of key climatic variables, including precipitation and temperature.

4.3.2. Analysis of Temperature Trends over the Study Period

Results from the Mann–Kendall test revealed an overall statistically significant increasing trend in temperature, which may hold critical implications for rice production. Kendall's Tau coefficient suggests a general tendency for temperature to increase over time and is highly steady. Continued increases in temperature could have adverse impacts on rice production in the country, a trend that has also been perceived by local farmers in northern Liberia [28,29]. These findings in rising temperatures are consistent with the Liberia National Adaptation Plan document [67], which highlighted that Liberia's mean air temperature will increase by 0.4 °C to 1.3 °C from 2010 to 2050, based on Regional Climate Models (RCMs). Similarly, the Sixth Assessment Report (AR6) of the United Nations Intergovernmental Panel on Climate Change (IPCC) documented that the global surface temperature has increased by 1.1 °C during the past decades (2011–2020) compared to 1850–1900, with further increases of 1.5 °C expected by 2021–2040 [1]. Additionally, temperature projections for Liberia under RCP8.5 suggest a continued increase in mean air temperature over two future periods, 2031–2060 and 2071–2100, highlighting the potential for escalating thermal stress on rice production if current trends persist. These projected changes in temperature varied in both time series, including the periods 2031 to 2060 and 2071 to 2100. The projected changes from 2031 to 2060 are expected to reach 3.03 °C, as highlighted in the Supplementary Materials (Figure S4a), and 2.7 °C during the period 2071 to 2100 (see Figure S4b in the Supplementary Materials), whereas the overall increase from 2031 to 2100 is expected to reach 4.54 °C as shown in the Supplementary Materials (Figure S4a,b). The estimated increase in temperature and variability in precipitation under the RCP8.5 scenario suggests that the climatic trends observed during the historical period may exist, which could influence future rice production conditions in Liberia. These findings support the broader evidence that temperatures are rising globally and regionally, which may hold critical implications for Libera's predominant rainfed rice production system in the future.

However, referring to previous years, existing studies have revealed that this increasing trend has been perceived by farmers across the study area, and they have further employed various adaptive strategies, including the use of short-duration varieties, adjusting planting schedules, diversifying crops, and basic soil-water management [29,30]. Furthermore, this finding aligns with similar studies underlining the conspicuous increasing trends in temperatures across various regions worldwide [44,68]. For instance, Asfaw et al. [69] reported inter-annual variability in rainfall, with mean and minimum temperatures showing significant increasing trends over time, whereas the maximum temperature trend was not significant. They recommend that agricultural sector strategies be designed to account for the declining and erratic rainfall patterns and the increasing temperature trends.

Regional studies support these findings, indicating an increase in production. In Moyamba District, southern Sierra Leone, Yila et al. [70] found that temperature exhibited a noticeable increasing trend over the study period, negatively affecting crop production. Similarly, research across West Africa indicated that rising mean temperatures would likely affect rice productivity by accelerating rice phenology, shortening the grain-filling period, and increasing evapotranspiration, thereby heightening the vulnerability of Liberia's largely rainfed rice systems [8,71]. Moreover, the increase in minimum and maximum temperatures beyond the normal threshold may pose a risk to crop performance. For example, high temperatures are particularly harmful, as they increase plant respiration, limit carbohydrate availability for grain filling, and reduce spikelet fertility, ultimately lowering yield potential [72]. Specifically, temperatures above 35°C at the flowering stage have been shown to cause spikelet sterility and severe yield reduction in rice [9]. However, countries are already facing considerable economic impacts, which are likely to worsen as global warming increases the frequency of extreme events [66].

Given Liberia's dependence on rainfed production systems, such exposure may increase the likelihood of crop failure. Overall, the findings indicate that although temperature did not show a statistically significant impact on rice production during the study period (1990–2023), the observed warming trend suggests that continued increases in temperature may pose potential risks to rice production in Liberia in the future. Therefore, it is essential to implement various adaptation measures such as adjusting planting date, use of short-duration local rice varieties, crop diversification, soil and water conservation, and adopting heat-tolerant varieties in order to boost productivity [71,73–75]. Such strategies align with adaptation behaviors observed in other West African countries, notably Nigeria, Ghana, and Sierra Leone, where smallholder farmers modify agricultural practices to cope with rainfall variability and temperature extremes [70,76,77].

4.4. Impact of Seasonal Temperature and Precipitation on Rice Productivity

4.4.1. Discussion of the Relationship Between Climate Variables and Rice Productivity

The study findings indicate that, over the 34 years, no statistically significant relationships were identified between rice production and the accessed climate variables. Nonetheless, production exhibited moderate negative correlations with precipitation, as well as with the mean and minimum temperatures. By contrast, rice yield displayed moderate and more consistent associations with temperature-related variables. These patterns suggest that overall production and productivity are likely influenced more strongly by non-climatic factors such as land expansion, soil quality, access to quality seed, agronomic practices, and policy interventions rather than by climate conditions alone. Supporting this interpretation, ref. [19,21] reported that low yields in rainfed environments constitute a major constraint, such as sub-optimal natural resource and crop management practices commonly adopted by smallholder farmers. These include inadequate water management and limited use of fertilizers, herbicides, and machineries for rice production, noting that rainfed production systems account for approximately 70% of the global harvested rice area. Gül et al. [78] demonstrated that non-climatic factors such as area under rice cultivation, fertilizer use, labor force, and water resources affect rice production and have substantial impact on yield. Furthermore, a study conducted by [79] identified key barriers such as low adoption of improved varieties and irrigation technologies, limited access to climate information, low access to extension services, inadequate access to finance and inputs, and overreliance on traditional knowledge that hinder a farmer's adaptation and can result in low productivity levels.

Analysis across multiple timescales revealed fluctuating relationships between climate variables (temperatures and precipitation) and rice yields. Rice yield displayed a strong and negative correlation with precipitation during specific periods, for instance, from 1998 to 2003 for production, and from 2003 to 2005 for yield, suggesting that excessive rainfall and flooding likely constrained rice growth and productivity during these intervals. These results are pertinent, especially the case where rice production in Liberia is mainly based on upland and lowland systems, both of which are largely rainfed and highly sensitive to climate variability. Upland rice, which dominates cultivation, relies heavily on seasonal rainfall, while lowland rice grown in valley bottoms and floodplains also depends on precipitation for water availability. Adequate rainfall is essential during key growth stages—such as germination, tillering, panicle initiation, and grain filling—to maintain soil moisture and support crop development [80]. Insufficient rainfall during these stages can cause water stress and reduced yields, whereas adequate precipitation enhances plant growth and grain formation, explaining the positive relationship between precipitation and rice yields observed in this study. These patterns align with findings reported for other regions of West Africa [21]. The statistically significant negative relationship between precipitation and yield during 2003–2005 further indicates that excessive and insufficient rainfall can contribute to yield reduction [12,81]. However, significant negative correlations were observed for minimum and maximum temperatures within 1998 to 2003 for production, and for mean, minimum, and maximum temperatures within 2000–2003 and 2012–2023 for yield. These results underscore the adverse effects of temperature extremes during these periods, which are consistent with evidence presented in the AR6 Synthesis Report [1]. The report highlights that climate variables, particularly temperature and precipitation, have varying and significant associations with agricultural production and productivity globally and across regions. Previous studies have similarly demonstrated that climate variables, particularly temperature and precipitation, exert major influences on crop productivity, including rice [6,9,49]. Similar findings have been reported in other West African countries. In Côte d'Ivoire, rainfall variability has been shown to significantly influence rice farming performance and farmers' economic outcomes [82]. Also, studies conducted in Ghana indicate that variations in rainfall patterns and temperature significantly affect agricultural productivity and contribute to yield fluctuations across seasons [9]. Regional studies covering Sierra Leone and Guinea also report substantial variability in rice yields across climatic zones, driven by interactions between climatic conditions and farm management practices [83]. At the broader regional scale, climate change has already contributed to measurable reductions in crop productivity in West Africa, highlighting the increasing influence of temperature and rainfall variability on agricultural systems [84].

In this study, the findings show that temperature and precipitation exhibited significantly different associations with rice production and yield across diffident timescales, compared with the entire study period (1990–2023), during which no significant relationship was observed. In tropical rice-growing environments such as Liberia, where baseline temperatures are already relatively high, further increases in nighttime temperature may intensify respiration losses and reduce grain-filling efficiency, thereby negatively affecting rice productivity. To mitigate these constraints, it is crucial to effectively deploy a diverse set of technologies such as water preservation technologies in rainfed and irrigated lowland rice, site-specific nutrient management practices, tools to support decision-making (crop growth simulation models), and labor-saving technologies developed in recent decades [21,85].

4.4.2. Regression of Climate Variables Against Rice Production and Yield

Based on the regression results for production, minimum temperature emerged as the only climate variable that significantly influenced rice production in Liberia during the study period. Minimum temperature exhibited a significant negative effect, indicating that a 1 °C increase in minimum temperature is associated with a 2.676 MT decrease in rice production. This suggests that elevated minimum temperature (nighttime temperatures) may impair crop performance, possibly due to increased respiration rates that lead to energy loss, disruption of physiological recovery processes, and heightened stress during sensitive growth stages such as flowering and grain filling [86,87]. This finding is particularly critical in the context of climate change, as minimum temperatures are increasing at a faster rate than maximum temperatures [75,88]. Another study revealed that elevated temperatures pose serious risks to crop production and productivity [86]. Similarly, refs. [64,89] noted that increased temperatures adversely impact the growth and development of rice plants, particularly during processes such as germination, tillering, flowering, and grain filling stages.

Overall, the findings suggest that temperature-related stresses, especially those associated with minimum temperature, play a more critical role in determining rice production outcomes than precipitation [81,90]. This highlights the crop's sensitivity during flowering and grain-filling stages [91]. Similar patterns have been reported across western and southern regions of Africa, where temporal fluctuations in temperature account for a substantial proportion of yield variability [92,93]. The regression analysis further revealed that, although climate variables collectively exert a moderately significant influence on rice yield in Liberia, the R^2 value of 15.4% indicates that the majority of yield variation is likely driven by non-climatic factors. These may include soil fertility, production systems and management practices, pest pressure, technological adoption, and broader socio-economic conditions. The regression analysis identified precipitation as the only climatic factor that significantly influenced rice yield during the full study period, when accounting for other climatic and soil variables, even though the simple bivariate correlation was not statistically significant. This finding aligns with [28,30], who, in their studies, emphasized the direct and indirect implications of rainfall on Liberia's rice production system. The positive association underscores the central role of rainfall in Liberia's predominantly rainfed rice production systems [30,89]. This positive relationship between precipitation and rice yield observed in this study is therefore consistent with the ecological characteristics of rainfed agricultural systems, where crop performance strongly depends on rainfall distribution and seasonal water availability. In tropical environments such as Liberia, rainfall variability can significantly influence yield outcomes by affecting water availability during critical growth stages and supporting physiological processes such as photosynthesis, nutrient transport, and panicle development [1,86]. Similarly, research across West Africa and other tropical regions is closely linked to the variability and distribution of seasonal rainfall [84].

These findings provide valuable insights for formulating appropriate agricultural policies and practices that enhance adaptive capacity, inform extension services, support climate-resilient agricultural development, and guide policy frameworks addressing climate hazards to enhance food security.

5. Conclusions and Policy Recommendations

This study examined the effects of climate variability on rice production in Liberia over the period 1990 to 2023. The results indicate a consistent increasing trend in temperature variables (mean, minimum, and maximum), alongside pronounced rainfall variability. These patterns align with farmers' perceptions of delayed rainfall onset and irregular distribution. The findings further reveal that the relationships between climate variables and rice production and yield vary across different timescales, suggesting that climate factors exert context-specific influences depending on the timing and magnitude of temperature and precipitation changes.

Although climate variability contributes to fluctuations in rice output, regression results show that climate variables explain only a modest proportion of the observed variation (26.16% for total production and 15.4% for yield). Minimum temperature was found to have a statistically significant negative effect on rice production, while precipitation positively and significantly influences yield. Spatial analysis further demonstrates changes in seasonal temperature and precipitation patterns across the study area, indicating uneven exposure to climate risks. Future projections under RCP8.5 suggest continued increases in temperature and substantial variability in precipitation during both mid-century (2031–2060) and end-century (2071–2100) periods, with important implications for future rice productivity.

Despite an overall increase in total rice production, yields have remained essentially stagnant over the study period. This indicates that non-climatic factors, such as limited access to improved seed varieties, irrigation infrastructure, fertilizers, credit, and low extension services, may be constraining productivity. Therefore, climate variability alone does not fully explain the persistently low rice yields in Liberia; rather, a combination of climatic, agronomic, and socio-economic factors drives the productivity gap and continued reliance on imports.

In response or to reduce future substantial losses due to the consistent variation in climate factors, farmers in Liberia should consistently adopt adaptation practices even though evidence from the existence literature indicates that farmers have adopted several adaptation strategies, including adjusting planting dates, using short-duration varieties, crop diversification, and basic soil and water conservation practices. However, these responses are still rudimentary and largely informal, which are constrained by limited institutional and financial support, increasing farmers' vulnerability to climate variability.

To enhance resilience and ensure sustainable rice production, several policy measures are recommended. First, strengthening localized climate information systems is essential to provide timely and accessible forecasts, alongside improving the capacity of national meteorological services to disseminate user-friendly climate information. Second, investment in agricultural research and development should prioritize the dissemination of short-duration, drought-tolerant, and flood-resistant rice varieties suited to diverse agroecological zones. Third, improving access to agricultural inputs through targeted subsidies, microfinance schemes, and farmer cooperatives is necessary to reduce production constraints. Fourth, extension services should be strengthened to support the scaling and refinement of existing farmer-led adaptation practices through technical guidance and institutional backing from government agencies and non-governmental organizations.

Finally, policy interventions should incorporate socio-economic dimensions of farmer resilience, including gender, education, and market access, to ensure that adaptation strategies are inclusive and context-specific. By integrating these approaches, Liberia can transition from reactive coping mechanisms to a more proactive, climate-resilient rice production system capable of enhancing food security and reducing import dependence.

Limitations of the Study and Future Directions

This study offers a comprehensive assessment of rice production trends and climatic influences in Liberia; however, it was constrained by various limitations, including firstly, the absence of a field-based or ground-truth dataset, which makes it limited to correlation.

Thus, in the absence of causation, conclusions are based on assumptions. This justifies the need for future research on the physiological and morphological response of rice crops to precipitation and temperature. Secondly, although the study analyzes production and climate at a national level, it does not include other important extreme climate events such as floods, prolonged droughts, and cyclones, which can induce abrupt fluctuations in rice yields. Additionally, due to the national geographical extent, the study did not take into consideration the socio-demographics and geographical differences between regions. Hence, future research can build on these findings by integrating high-resolution data on climate extremes to assess their direct impacts on rice productivity, incorporate field-based data to investigate the physical impact of temperature and precipitation on productivity, while also incorporating socio-demographic factors and the geographical extent or subdivisions. Addressing these aspects will enable more precise, context-specific insights to inform climate-resilient rice production strategies and targeted policy interventions in Liberia.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli14040084/s1, Figure S1: Spatial variability of precipitation and temperature with major and minor rice production areas; Figure S2: Liberia climate classes based on Köppen classification; Figure S3: Climate projection of precipitation; Figure S4: Climate projection of temperature. All other information and materials supporting the findings of this study are provided within the text of the article.

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Abbreviations

CHIRPS	Climate Hazards Group InfraRed Precipitation with Station
CORDEX	Coordinated Regional Climate Downscaling Experiment
DSSAT	Decision Support System for Agrotechnology Transfer
EPA	Environmental Protection Agencies
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
GDP	Gross Domestic Product

IPCC	Intergovernmental Panel on Climate Change
Mk	Mann–Kendall
NAP	National Adaptation Plan
MLR	Multiple Linear Regression
RCMs	Regional Climate Models
SSA	Sub-Saharan Africa
WFP	World Food Programme

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