frontiers in Climate

TYPE Original Research
PUBLISHED 16 June 2026
DOI 10.3389/fclim.2026.1846364

Check for updates

OPEN ACCESS

EDITED BY
Rajiv Kumar Srivastava,
Texas A and M University, United States

REVIEWED BY
Lan Tran,
Lincoln University, United States
Chintakindi Saikiran,
National Institute of Agricultural
Extension Management (MANAGE), India

*CORRESPONDENCE
Calvince Andele Ogutu
✉ eogutu39@gmail.com

RECEIVED 02 April 2026
REVISED 19 May 2026
ACCEPTED 22 May 2026
PUBLISHED 16 June 2026

CITATION
Ogutu CA and Cavane E (2026) Farmer awareness, knowledge and understanding: a multi-level assessment of adoption of climate-smart agricultural practices among smallholder farmers. *Front. Clim.* 8:1846364.
doi: 10.3389/fclim.2026.1846364

Farmer awareness, knowledge and understanding: a multi-level assessment of adoption of climate-smart agricultural practices among smallholder farmers

Calvince Andele Ogutu[1,2]* and Eunice Cavane[1]

[1]Department of Economics and Agrarian Development, Faculty of Agronomy and Forestry Engineering, Eduardo Mondlane University, Maputo, Mozambique, [2]Center of Excellence in Agri-food Systems and Nutrition (CE-AFSN), Eduardo Mondlane University, Maputo, Mozambique

Climate-Smart Agriculture (CSA) offers potential solutions for enhancing productivity, building resilience, and mitigating climate change, yet, successful implementation depends on farmer's understanding of CSA practices across multiple levels. This study assessed smallholder farmer's levels of awareness, knowledge and understanding of principles of 13 CSA practices, examining variations by gender and education. A cross-sectional survey of 400 smallholder farmers collected data on three levels per practice: awareness (heard of practice), knowledge (know how to implement), and understanding of principles (comprehend underlying concepts). Descriptive statistics, t-test, ANOVA, chi-square tests, correlation analyses, and progression analysis supported with non-parametric alternatives and robustness checks confirmed results. Awareness ranged from 47% (improved varieties) to 100% (intercropping). Knowledge levels were generally lower with least gap for rainwater harvesting (81.0% aware vs. 39% knowledge). Three distinct patterns emerged: (1) awareness exceeding knowledge (superficial awareness) for rainwater harvesting, agroforestry, and bio-fertilizers; (2) knowledge exceeding awareness (terminology mismatch) for improved varieties and soil fertility management; and (3) aligned awareness and knowledge for remaining practices. Women showed significantly higher awareness, knowledge, and understanding of principles than men (Cohen's d > 0.9). Education strongly associated with awareness and knowledge (η^2 = 0.65, 0.70) respectively but weakly with principles (η^2 = 0.03). Secondary education was a critical threshold; less-educated farmers had 0% awareness of four practices (conservation tillage, cover cropping, soil fertility management and water-efficient irrigation). Composite measures addressing terminology mismatches showed true familiarity with improved varieties at 82.5% versus 47.0% awareness. Farmer population showed polarization: 54.2% had high awareness (10–13 practices) whereas 15.0% had very low awareness (0–3 practices). From the finding, we conclude that effective CSA promotion requires targeted awareness campaigns for low-awareness technologies, gender responsive approaches that recognize women's high awareness, and education sensitive extension that builds on the strong education gradient while reaching currently excluded farmers.

KEYWORDS
awareness, climate-smart agriculture, knowledge, smallholder farmers, understanding of principles

1 Introduction

1.1 Background

Climate change poses unprecedented challenge to global agriculture systems, threatening food security and livelihoods, particularly among smallholder farmers in developing countries (Lipper et al., 2014; Tilman et al., 2011). The increasing frequency of drought, erratic rainfall patterns, and extreme weather events has intensified the vulnerability of agricultural systems, especially in sub-Saharan Africa where rain-fed agriculture predominates (Harvey et al., 2014). In response to these challenges, climate-smart agriculture (CSA) has emerged as an integral approach to addressing the triple goals of sustainably increasing agricultural productivity, enhancing resilience to climate shocks, and reducing greenhouse gas emissions where possible (FAO, 2013).

The CSA framework encompasses a diverse range of practices, including agroforestry, conservation tillage, improved crop varieties, integrated pest management, rainwater harvesting, and soil fertility management (Chandra et al., 2017). These practices are designed to work synergistically, building the adaptive capacity of farming systems and the mitigation potential of agriculture (Campbell et al., 2014). Despite the recognized potential of CSA, adoption rates remain suboptimal in many smallholder-farming contexts across Africa (Branca et al., 2021; Zougmoré et al., 2016). A systematic review by Finizola e Silva et al. (2024) identified over 40 factors influencing CSA adoption, categorized as personal, farm-related, financial, environmental and informational factors.

1.2 The challenge of technology adoption

Research has consistently demonstrated that adoption of agricultural technologies is a complex process influenced by multiple interacting factors (Feder et al., 1985; Rogers, 2003). Among the most cited barriers to adoption are limited access to information, credit, inputs, and markets (Ogada et al., 2021). However, a growing body of literature emphasizes that farmers' lack of awareness and knowledge about CSA practices is a primary constant (Teklewold et al., 2013; Kassie et al., 2015). The systematic review by Mulungu et al. (2025) reveals that 76% of studies reported increased adoption of good agricultural practices following information interventions, while 60% demonstrated improved awareness highlighting the critical role of information availability and access in technology uptake.

The relationship between information and adoption is not straightforward, however, recent research by Miehe et al. (2025) challenged the prevailing wisdom that "information leads to adoption," demonstrating that correcting inflated expectations about improved seed performance actually reduced short-term adoption but led to more realistic decision-making. This finding underscores the importance of understanding farmers' mental models and expectations when designing extension interventions.

1.3 Conceptual framework: levels of understanding

Understanding farmers' cognition regarding agricultural innovations is complex and multi-dimensional. Drawing on educational psychology Krathwohl (2002) and diffusion of innovation theory Rogers (1983) and Rogers (2003), we conceptualize farmers' understanding as operating at three distinct levels: (1) awareness level – in this dimension, a farmer has heard of the CSA practice and knows of its existence, this represents declarative knowledge at its most basic level (Leslie, 2016). Awareness is necessary but not sufficient for adoption. In CSA context, a farmer may know that mulching helps crops because they have seen or heard about it from extension services but cannot explain how it works, Ogunyiola et al. (2022) emphasize that awareness alone does not guarantee adoption as farmers' local knowledge systems may interact with introduced practice in complex ways. (2) Knowledge level where a farmer understands how to implement the practice. This is procedural knowledge, which is the ability to perform the practice (Ryle, 1949). In CSA context, a farmer knows that mulching involves covering soil with residues, understands when to apply it, and recognizes that it helps retain soil moisture and reduce erosion. Farmers at this level can potentially apply the practice on their farms, though they may face resource, structural or institutional hurdles. (3) Understanding of principles – the level at which a farmer comprehends the underlying scientific principles and concepts. This represents conceptual knowledge – understanding why the practice works (Krathwohl, 2002). In CSA context, a farmer understands that mulching reduces evaporation, moderates soil temperature, improves soil organic matter, and enhances water-use efficiency under drought conditions. Farmers at this level can adapt practices to their specific context and troubleshoot problems independently, which is critical for sustained adoption and innovation (Glendenning et al., 2010). These three–level framework aligns with Bloom's revised taxonomy Wilson (2016) and provides a more nuanced assessment of farmer cognition than simple binary measures of awareness or adoption commonly used in agricultural research (Udry et al., 2024; Evenson and Gollin, 2003) (Figure 1).

2 Conceptual framework

2.1 Previous research on awareness and knowledge

Previous studies have documented varying evidence on farmer awareness of agricultural technologies. Marenya and Barrett (2007) found that intercropping and crop rotation were deeply embedded in smallholder farming systems in western Kenya, suggesting indigenous knowledge transmitted across generations. Partey et al. (2018) reported that 95% of farmers in Ghana were aware of CSA concepts, with agroforestry and water management practices among

---

Abbreviations: ANOVA, Analysis of Variance; CI, Confidence Interval; SE, Standard error; CSA, Climate-Smart Agriculture; IPCC, International Panel on Climate Convention; FAO, Food and Agricultural Organization; IPM, Integrated Pest Management; OR, Odds Ratio; SD, Standard Deviation; SPSS, Statistical Package for the Social Sciences; HSD, Honestly Significant Difference; SMS, Short Message Service; ICT, Information Communication Technology; CE-AFSN, Center of Excellence in Agri-Food Systems and Nutrition; DNA, Deoxyribonucleic Acid; CARE, Cooperative for Assistance and Relief Everywhere; CGIAR, Consultative Group on International Agricultural Research; SDAE, Serviço Distrital de Actividades Económicas.

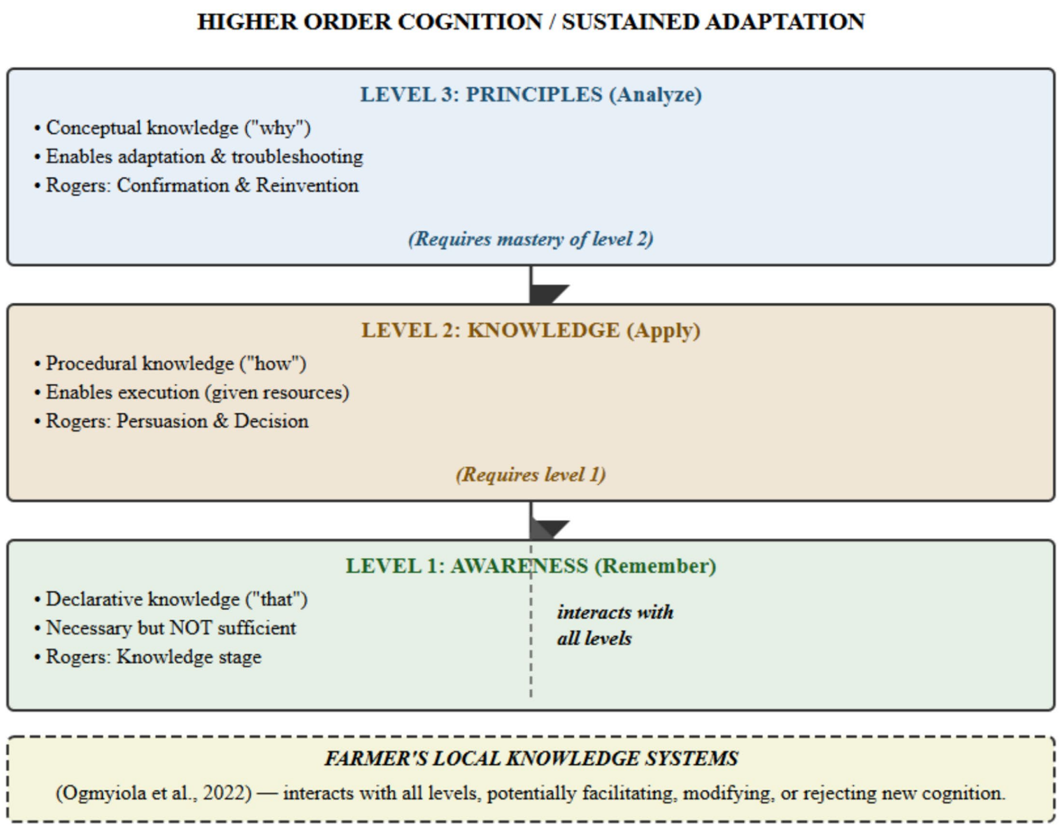

FIGURE 1
Conceptual framework for CSA adoption.

the most widely recognized. The role of information and communication technologies (ICTs) has received increased attention. The systematic review by Mulungu et al. (2025) documented that ICT interventions including mobile apps, SMS, educational videos and voice-calling services have demonstrated positive impacts on awareness, adoption, yield and income. However, the success of these interventions depends on well designed messaging, adequate user training, and integration with complementary interventions.

The study by Okori et al. (2022), Makapela et al. (2025), and Kangogo et al. (2024) show that farmer-to-farmer learning and community-based training approaches significantly improve agricultural productivity and technology adoption. For instance, farmer-led extension and training initiatives have increased crop yields by 30–40% and improved farm income among smallholder farmers in sub-Saharan Africa. Evidence on agricultural knowledge and gender differences show mixed results. A recent study in Tanzania by Manono et al. (2025) noted male domination in climate-adoption decisions at the household levels due to ownership and control of land and access to agricultural support services. However, Nchanji et al. (2025) in Eastern Uganda and Bogweh et al. (2025) in Tanzania reported that women had higher access to and sustained use of improved common bean varieties, indicating that gender dynamics are context specific and may be shifting with target interventions. Gulati et al. (2026) using data from India, found that women's agricultural networks are approximately 26% larger than men's, but these networks rarely overlap, meaning extension targeting only men reaches only part of the household's learning space. A systematic review by Finizola e Silva et al. (2024), Awoke et al. (2024), and Boudalia et al. (2024) highlighted gender as one of several personal factors influencing CSA adoption, though its effects are often mediated by other variables. Mutenje et al. (2019) provide additional evidence on gender perspectives in CSA adoption.

Across multiple studies, education has stood out as a strong predictor of agricultural knowledge and adoption. Goni et al. (2025) found that level of education was significant ($p < 0.05$) in influencing adoption of CSA practices in Ethiopia, Ghana and Nigeria. Asfaw and Admassie (2004) identified education as critical human capital influencing adoption, reporting that educated farmers make better decisions because they can read extension materials and understand technical information. A meta-analysis by Adewopo et al. (2025), Kendall et al. (2022), Coggins et al. (2022) confirmed that education is one of the socioeconomic determinants of technology adoption across multiple contexts, with higher educational attainment increasing the likelihood of using digital agricultural technologies. Similarly, Finizola e Silva et al. (2024) found out that level of education was a key personal factor significant in influencing adoption of CSA practices.

2.2 The importance of local knowledge and terminologies

Recent scholars have emphasized the importance of integrating farmers' local knowledge with scientific evidence for successful CSA upscaling. For instance, Ogunyiola et al. (2022) argue the need for policymakers and academics to rethink how local knowledge held by smallholder farmers hold potential for CSA adoption. Their review noted that only eight of 30 articles addressed challenges regarding inclusion or exclusion of local knowledge in CSA practices, thereby presenting a significant research gap.

Terminology plays a crucial role in how farmers perceive and adopt new technologies. Rurii and Nzengya Daniel (2026) emphasizes that adoption is not one-size-fits-all and that farmers must select practices based on their individual capacity to implement them, ensuring chosen practices are both contextually appropriate and feasible for each farmers' unique resource and constraints. This insight is directly relevant to understanding the improved variety paradox documented in several studies (Miehe et al., 2025; Nchanji et al., 2025).

Kosmowski et al. (2019) highlight that varietal adoption based on household survey has mostly relied on farmers' responses to varietal identification, but this method can give biased estimates, if farmers' responses are unable to identify improved varieties as a group or by name. Their research using DNA fingerprinting in Ghana and Zambia found large variations in adoption estimates compared to farmers self-reports, emphasizing the need for careful terminology and measurement approaches.

2.3 Research gaps and rationale

Despite the existing research on climate-smart awareness and adoption, several gaps remain. Firstly, most studies treat awareness and knowledge as unidimensional, failing to distinguish between superficial awareness, procedural knowledge and deep conceptual understanding (Krathwohl, 2002; Leslie, 2016). Secondly, few studies systematically compare these three levels across a comprehensive set of CSA practices (Teklewold et al., 2013; Kassie et al., 2015). Thirdly, the relationship between awareness and knowledge – whether they are aligned or mismatched – has received limited attention (Marenya and Barrett, 2007). Fourthly, the phenomenon where knowledge exceeds awareness (suggesting terminology mismatch) is under-explored as highlighted by (Kosmowski et al., 2019; Fisher and Carr, 2015). Fifth, the role of understanding of principles as a distinct level of cognition has not been adequately addressed in the agricultural literature (Glendenning et al., 2010; Marenya and Barrett, 2007).

2.4 Significance of the study

By identifying precisely where and why farmers drop off in understanding of CSA practices, this study enables more efficient allocation of scarce extension resources and more effective support for farmers building the knowledge they need to enhance resilience to climate change. The findings have immediate applicability for extension policymakers, and farming systems across Africa and beyond. As Vincent et al. (2018) and Singh et al. (2017) emphasize, multi-stakeholder partnerships that co-create solutions ensure climate information is not just available but usable, timely, and trusted. Similar insights Bashiru et al. (2024), Kesby (2005), and Rosenstock et al. (2016) collectively form the importance of participatory approaches – which center farmer knowledge, enable co-creation, address systemic inequalities – are essential for overcoming adoption barriers and achieving equitable, scalable outcomes in agricultural development.

3 Objectives

This study specifically aims to (1) assess farmers' levels of awareness, knowledge, and understanding of principles for 13 CSA practices; (2) compare these three levels to identify patterns of alignment and mismatch; (3) examine variation in awareness, knowledge, and principles by gender and education levels (4) analyze the progression of farmers through the three levels of understanding.

4 Materials and methods

4.1 Study area

The study was conducted in Zavala district, Inhambane province, located in southern Mozambique along the Indian Ocean coastline. Zavala district lies between latitudes 24°30' and 25°00'S and longitude 34°45' and 35°15'E, covering an area of approximately 3500square kilometers. The district is administratively divided into two administrative posts:

Zavala-sede, Zandamela, which is further sub-divided into four localities (Quissico, Muane, Zandamela, and Maculuva) with 64 villages. The region is characterized by tropical coastal climate with distinct wet and dry seasons. The wet season extends from November to March, receiving average annual rainfall between 800 and 1,200 millimeters, with coastal areas receiving higher precipitation due to oceanic influence. The dry season spans April to October with average temperatures ranging from 20 °C during cooler months to over 30 °C in warmer months. The topography consists primarily of coastal plains interspersed with sandy, low-fertility soils and small hills, these agro-ecological conditions create vulnerability to both drought and occasional floods, with the region experiencing increasing frequency of extreme weather events in recent decades.

Agriculture is the primary economic activity, with approximately 85 percent of the population engaged in farming. The farming system is predominantly rain-fed smallholder agriculture, with an estimated 30,000 farmers averaging 2.5 hectares per household. Major crops include cassava, maize, groundnuts, and fruit varieties such as mangoes, oranges and coconuts. Livestock rearing, primarily poultry, goats, cattle, and pigs complement crop production. However, poor soil fertility, limited access to modern agricultural inputs, inadequate infrastructure, and market constraints significantly challenge productivity.

The district has been the focus of numerous climate-smart agriculture interventions by governmental and non-governmental organizations. The ministry of agriculture has established climate-smart agriculture cooperatives to promote drought-tolerant seeds, and drip irrigation. The food and agricultural organization (FAO) has supported ecological training hubs utilizing model farmers to demonstrate soil conservation practices and the private-sector initiatives have introduced water-index insurance program. Green Future Zavala has implemented women-led solar irrigation projects; the community seed banks supported by the ministry of environment and CGIAR encourage biodiversity conservation. The united development program has facilitated farmer field schools on flood adaptation, and CARE international has supported collective farming practices and savings groups. This concentration of diverse CSA interventions made Zavala District a suitable context for assessing farmers' awareness, knowledge, and understanding of climate-smart agricultural practices. However, because Zavala was purposively selected for its concentration of CSA interventions, the absolute awareness figures reported in this study are likely higher than the average Mozambican district, and findings should be generalized only to contexts with similar intervention intensity (Figure 2).

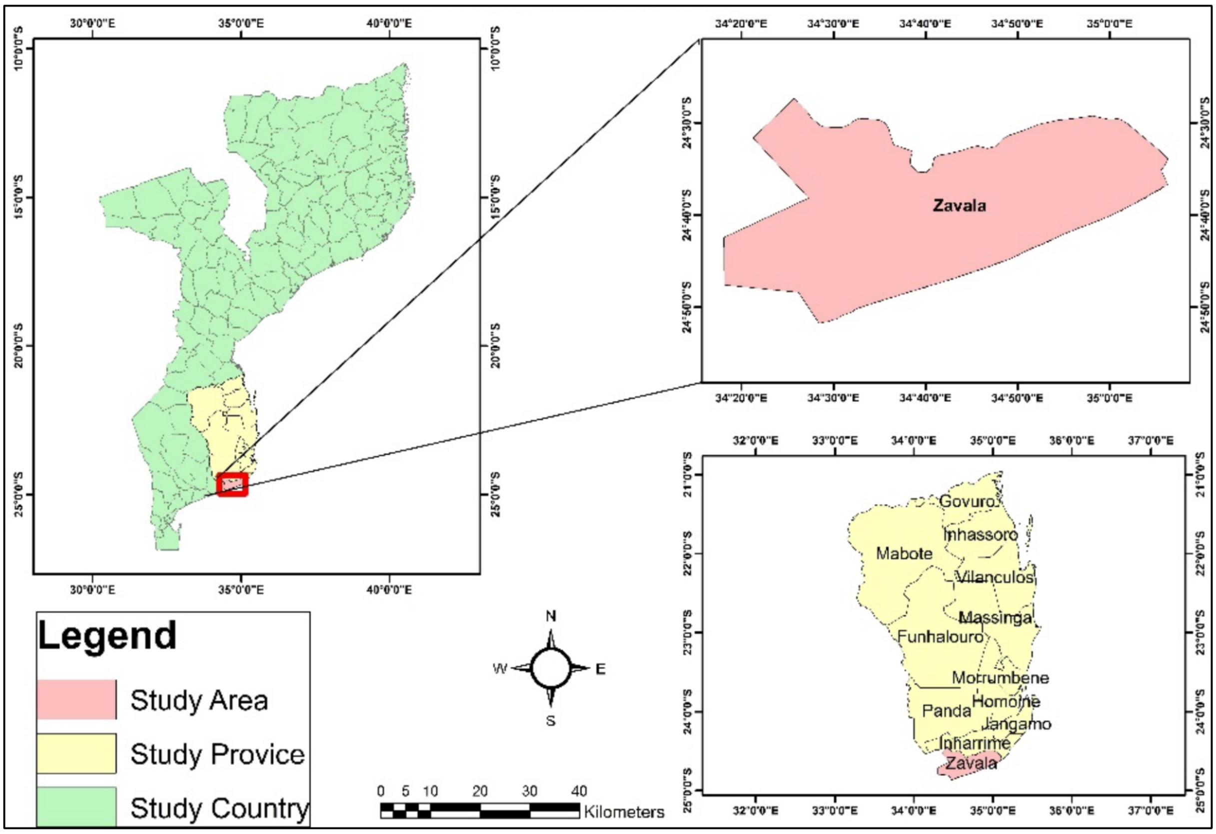

FIGURE 2
Map of the study area.

4.2 Sampling determination

The target population of this study comprised smallholder farers in Zavala District who have been engaged in agricultural production for at least 3 years. Smallholder farmers in this study are defined following the Mozambican national agricultural census classification, which characterizes smallholder farmers as those cultivating less than 5 hectares, typically operating rain-fed systems with limited external inputs and potentially exposed to climate vulnerabilities. The mean arm size in our sample was 3.2 hectares (SD = 1.5), consistent with this definition. While some regional studies use a 2- hectare threshold, Mozambique's context – characterized by low density and extensive farming systems – supports the 5-hectare classification threshold (Mather et al., 2019). The sampling frame was developed from the village register maintained by the agricultural extension offices. These registers list approximately 30,000 farmers across the district, providing a comprehensive sampling frame. The register include information on household heads, farm size, and location, enabling stratified sampling. The study used Cochran (1977) sample size determination formula for cross-sectional studies estimating a proportion.

$$n_0 = \frac{Z^2 p(1-p)}{e^2}$$

Where Z = 1.96 (for 95% confidence level).

$p = 0.5$ (maximum variability, as non-prior estimate of CSA awareness in Zavala available).

E = 0.05 (desired margin of error).

Finite population adjustment.

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}}$$

Assuming a 95% confidence level ($Z = 1.96$), 5% margin of error ($e = 0.05$) and proportion $p = 0.5$, the initial sample size was 384. Applying the finite population correction for $N = 30{,}000$ resulted in a final sample size of 379 respondents, which was rounded up to 400 to account for potential non-responses, incomplete questionnaires, and data entry errors and it also served to improve the reliability of the result. Increasing sample size beyond the minimum recommended threshold is consistent with best practices in social science research because it enhances statistical power and improves the representativeness of findings. This 400 smallholder farmers selected represented a sample size sufficient for subgroup analyses (e.g., gender, education) and for detecting medium-size effects (Cohen's d ≥ 0.3) with power > 0.80 at $\alpha = 0.05$.

4.3 Sampling procedures

A multistage sampling technique was used to obtain the required number of respondents. Multistage sampling was appropriate because the study population is geographically dispersed across several administrative posts, localities, villages, and households. The use of multiple sampling stages helped to ensure adequate representation of different socio-economic and agro-ecological conditions within the district while reducing the logistical costs of data collection.

Stage 1: Zavala district was selected due to its high dependence on smallholder agriculture and its vulnerability to climate variabilities, besides; the district has had CSA interventions promoted in the area. It also has experienced climate-related challenges affecting agricultural productivities, making it a suitable case study for investigating climate-smart agricultural adoption decisions. Caution in generalizing absolute awareness levels to less intervention-dense areas is noted in the limitations

Stage 2: Both administrative posts in the district, namely Quissico and Zandamela, were included in the study to ensure broad geographical coverage. Including the district's two administrative pots minimized sampling bias and allowed the study to capture potential variations in farming practices and climate adaptation strategies across the district.

Stage 3: All the four localities in the district were included. The inclusion of Quissico, Muane, Zandamela, and Maculuva localities ensured representation of diverse farming environments and household characteristics. These localities served as the primary sampling units for the selection of villages.

Stage 4: Villages were selected from each locality using simple random sampling. The number of villages selected from each locality was determined proportionally based on the estimated distribution of villages across the district. Out of approximately sixty-four (64) villages in the district, 32 villages were selected for the study, representing about 50 percent of the total villages. Proportionate sampling ensured that localities with more villages contribute more respondents to the final sample, thereby improving representativeness.

Stage 5: The study conducted a systematic random sampling of households within each village. Households were listed in alphabetical order and a sampling interval k was calculated as:

$$k = \frac{N\text{village}}{n\text{village}}$$

Where Nvillage = total farming households in the village, and $n$village was allocated proportionally to the village's share of district farming population (probability proportional to size). A random start between 1 and k was selected, and every *k-th* household was chosen. If a selected household was not available after three visits, the next household on the list was substituted practicing smallholder farming were selected from each sampled village. On average, 12 to 14 smallholder farmers were interviewed per village resulting in 400 respondents across the 32 villages. The distribution ensured balanced representation of farmers across administrative posts and localities.

Overall, the sampling procedure ensured that the study achieved adequate statistical representation of smallholder farmers in Zavala District. The use of sufficiently large sample size (n = 400) improves the precision of estimates and allows generalization of findings to the wider population of smallholder farmers in the district. The multi-stage sampling approach also ensured that variation in farmers' knowledge, perceptions and decision-making regarding climate-smart agriculture technologies were adequately captured across different geographical locations.

4.4 Survey instruments

A structured questionnaire was developed in three steps:

1. *Literature review*: Questions were adapted from validated instruments used in CSA adoption studies
2. *Expert review*: the draft was reviewed by three agricultural extension specialists at Eduardo Mondlane university and two district extension officers
3. *Pilot testing*: the questionnaire was pilot-tested on 30 farmers, (not included in the main sample) in a non-selected village. Based on pilot feedback, ambiguous terms were clarified, and the average interview time was adjusted to 30–45 min. No major changes to the core CSA practice list were added.

4.5 Variable measurements

4.5.1 Dependent variables (three levels for each 13 practices)

- *Awareness (B variables)*: for each practice, farmers were asked: "have you heard of [practice]?" (0 = No, 1 = Yes). No further explanation was provided at this stage.
- *Knowledge (C variables)*: only farmers who answered "Yes" to awareness were asked: "Do you know how to implement [practice] on your own farm?" (0 = No, 1 = Yes). Farmers who were not aware were coded as "0" for knowledge.
- *Understanding of principles (D variables)*: only farmers who answered "Yes" to knowledge were asked: "Do you understand the scientific principles behind why [practice] works?" The enumerator provided a simple explanation "for example, understanding why mulching keeps soil moist, not just how to speared mulch" (0 = No, 1 = Yes).

From these, the following composite scores were constructed:

- *Total awareness score*: sum of B variables across 13 practices (range 0–13).
- *Total knowledge score*: sum of C variables across 13 practices (range 0–13).
- *Total principles score*: sum of D variables across 13 practices (range 0–13).

For each of the 13 practices, separate binary indicators were creates for awareness, knowledge and understanding principles yielding.

- Progression score (per practice): 0 = no awareness; 1 = aware only (B = 1, C = 0, D = 0); 2 = aware and knowledgeable (B = 1, C = 1, D = 0); 3 = aware, knowledgeable and understands principles (B = 1, C = 1, D = 1).

A total progression score was then calculated as the sum across all practices, with a maximum possible score of 39.

- Total progression score = sum of progression scores across 13 practices (range 0–39).

- Composite "true familiarity": For each practice, TRUE = 1 if Awareness = 1 OR Knowledge = 1 was constructed (i.e., farmer has either heard of a practice or knows how to implement a practice). This addresses terminology mismatch.

Independent variables (socio-demographic and institutional):

- *Gender*: 1 – male, 2 – female (recorded by observation or self-report).
- *Education level*: categorical = 0 = no formal education, 1 = primary school(complete o incomplete), 2 = secondary school, 3 = tertiary/ university.
- *Age*: continuous (years, self-reported).
- *Farming experience*: continuous (years of active farming).
- *Household size*: number of members living in the household.
- *Group membership*: 0 – no, 1 = yes (member of any farmer cooperative, savings group, or CSA group).
- *Extension access*: 0 = no contact with extension agent in the past 12 months, 1 = at least one contact.

4.6 Data collection

Data were collected over a period of 6 weeks from August to mid-September through face-to-face interviews. A team of six enumerators was trained over 5 days in questionnaire administration, ethical protocols, and data collection procedures (Creswell, 2014). Interviews were conducted in the preferred language of respondents and each interview lasted approximately 30–45 min. Quality control measures included daily debriefing sessions, random spot checks by supervisors, and daily review of completed questionnaires for completeness and consistency.

4.7 Data analysis

All analyses were performed using SPSS version 26 with statistical significance set at $p < 0.05$ (two tailed). Descriptive statistics (frequencies, means, standard deviations, and 95% confidence intervals using the Wilson score method for proportions) were computed for all variables. Gender comparisons were conducted using independent samples t-tests (with unequal variances assumed when Levene's test was significant) and Mann–Whitney U tests. Effect sizes for t-tests were reported as Cohen's d. Education comparisons employed one-way ANOVA with Tukey Honestly Significant Difference (HSD) post-hoc tests and Kruskal-Wallis tests; effect sizes were reported as eta-squared (η^2) and omega-squared (ω^2). Paired t-tests compared awareness and knowledge for each practice at the individual farmer level. Chi-square tests examined associations between education level (collapsed into three groups: no formal/primary, secondary, tertiary) and awareness for each practice, with Cramér's V as the effect size. Pearson and spearman correlations were calculated among total awareness, total knowledge, and total principles scores.

Progression analyses tabulated the frequencies of each progression level (0–3) for each practice. Composite "true familiarity" measures were computed as the percentage of farmers who either were aware or hard knowledge for each practice. Since the progression score are ordered and bounded, robustness checks were performed using ordered logistic regression (for practice-level progression, 0–3) and tobit regression (for total progression score, censored at 0 and 39). These models confirmed that all significant predictors (gender, education, extension access) remained significant with the same direction of effects. Non-parametric alternatives (Mann–Whitney, Kruskal-Wallis, Spearman) were computed for every parametric test and confirmed the results, justifying the use of parametric tests given the large sample sizes ($n = 400$) and the Central Limit Theorem.

4.8 Ethical considerations

An ethical exemption letter was obtained from the Institutional Review Board of Eduardo Mondlane University. Informed verbal consent was obtained from all respondents prior to interviews, overseen by the district agricultural office (SDAE) of Zavala. The respondents were informed of the right to withdraw at any time without consequences. Data collection prioritized confidentiality through anonymized identification numbers. Interviews were conducted in private settings, with female respondents preferably assigned to female enumerators. No monetary compensation was provided during the entire process of data collection, and results will be disseminated through academic publications and community feedback sessions.

5 Results

5.1 Socio-demographic characteristics of respondents

Table 1 represents the socio-demographic characteristics of the 400 respondents. The sample comprised 66.3% male and 33.8% female farmers. Education level varied with 1.8% having no formal education, 42.3% primary education, 24.8% secondary education, and 31.3% tertiary/university education. Mean farming experience was 22.5 years (SD = 10.3), and mean farm size was 3.2 hectares (SD = 1.5). These characteristics are broadly comparable to smallholder farming populations in similar contexts across sub-Saharan Africa (Marenya and Barrett, 2007; Kristjanson et al., 2012).

TABLE 1 Socio-demographic characteristics of respondents ($n = 400$).

Characteristics	Category	*n*	%
Gender	Male	265	66.3
	Female	135	33.8
Education level			
	No formal education	7	1.8
	Primary school	169	42.3
	Secondary school	99	24.8
	Tertiary/ University	125	31.3
Farming Experience (years)	Mean ± SD		22.5 ± 10.3
Farm Size (hectares)	Mean ± SD		3.2 ± 1.5

Farm size reported as ± standard deviation. The 3.2 hectare average is consistent with Mozambique's national smallholder classification threshold (<5 hectares; Mather et al., 2019), though it exceeds the 2-hectare threshold sometimes used in other regional studies.

5.2 Farmer awareness of CSA practice

Table 2 presents farmers' awareness of the thirteen (13) CSA practices. Awareness ranged from 47.0 to 100%. Intercropping (B8) showed universal awareness (100%) followed by crop rotation at 90.8% and agroforestry at 90.3%. Rain water harvesting was known by 81.0% of farmers. A group of practices showed moderate awareness levels between 53.5 and 65.8%, including drought tolerant crops (65.8%), IPM (65%) bio-fertilizers (64.5%), and soil fertility management (56.0%). The lowest awareness levels was recorded for improved varieties, with only 47.0% of farmers reporting awareness of this practice. Figure 3 provides a visual representation of awareness levels across practices, clearly showing the universal awareness of intercropping and the critically low awareness of improved seeds. Figure 4 presents histogram of total CSA practice a farmer is aware of.

5.3 Farmer knowledge of CSA practice

Table 3 presents farmers' knowledge of how to implement the 13 CSA practices. Knowledge levels ranged from 39.0 to 99.0%. Intercropping had the highest knowledge at 99.0% followed by crop rotation at 91.0%, and improved varieties at 67.0%. Agroforestry and drought-tolerant crops were known by 66.0% of farmers. Notably, knowledge of rainwater harvesting was only 39%, despite 81.0% awareness – a gap of 42 percentage points. Biofertilizers also showed a substantial gap (64.5% aware versus 54.0% knowledgeable). Conversely, improved seeds showed the opposite pattern: knowledge (67.0%) exceeded awareness (47.0%).

TABLE 2 Farmers awareness of climate-smart agriculture practices (n = 400).

Practice	Aware (n)	Aware (%)	95% CI	Rank
Intercropping	400	100.0	—	1
Crop rotation	363	90.8	[87.8, 93.2]	2
Agroforestry	361	90.3	[87.2, 92.8]	3
Rainwater harvesting	324	81.0	[77.0, 84.5]	4
Drought-tolerant crops	263	65.8	[61.0, 70.3]	5
Integrated pest management	263	65.8	[61.0, 70.3]	5
Biofertilizers	258	64.5	[59.7, 69.0]	7
Soil fertility management	224	56.0	[51.1, 60.8]	8
Organic farming	221	55.3	[50.4, 60.1]	9
Conservation tillage	217	54.3	[49.4, 59.1]	10
Cover cropping	214	53.5	[48.6, 58.4]	11
Water-efficient irrigation	214	53.5	[48.6, 58.4]	11
Improved varieties	188	47.0	[42.2, 51.9]	13

CI, Confidence interval. Practices ranked from highest to lowest awareness.

5.4 Farmer understanding of principles

Table 4 presents farmers understanding of principles underlying CSA practices. Understanding of principles ranged from 27.0 to 83.5% with conservation tillage having highest understanding at 83.5%, followed by improved varieties at 81.8% and crop rotation at 81.5%. The lowest understanding of principles was recorded for rainwater harvesting at 27.0%, followed by IPM at 33.5%. For most practices, understanding of principles was lower than knowledge, with gaps ranging from 0.2 to 5.0 percentage points. However, for conservation tillage, principle understanding (85%) exceeded knowledge, suggesting that farmers may understand the concept without knowing how to implement it.

5.5 Comparison of awareness, knowledge and principles across CSA practices (n = 400)

Table 5 compares the levels of understanding across practices and reveals three distinct patterns. Figure 5 provides a visual representation of these patterns through a grouped bar chart with error bars added. Pattern 1 (awareness > knowledge): Rainwater harvesting (gap −42.0 percentage points, $t = 16.911$, $p < 0.001$), Cohen's d = 1.20, followed by agroforestry (−24.3, $t = 11.379$, $p < 0.001$, $d = 0.95$) and Biofertilizers (−10.5, $t = 7.002$, $p < 0.001$, $d = 0.62$). Pattern 2: knowledge > awareness (hidden knowledge) – for improved varieties, knowledge substantially exceeded awareness (+20.0 percentage points, $t = -5.922$, $p < 0.001$, $d = 0.48$). Soil fertility management also showed this pattern (+9.0, $t = 5.574$, $p < 0.001$, $d = 0.44$). Pattern 3: Awareness ≈ knowledge (aligned) – for the remaining eight practices, awareness and knowledge were closely aligned, differing by no more than 1.5 percentage points. Paired t-tests confirmed non-significant differences for most of these practices. The gap between knowledge and understanding of principles was significantly negative, indicating that for all practices, fewer farmers understood principles than knew how to implement them. The largest knowledge-principles gaps were for IPM (−31.5), water-efficient irrigation (−14.0), and soil fertility management (−17.5).

5.6 Distribution of farmer by awareness level

Table 6 shows the distribution of farmers by total awareness score. The distribution was strongly bimodal: 15.0% of farmers knew 0–3 practices (very low awareness), 19.5% knew 4–6 practices (low awareness), 11.3% knew 7–9 practices (moderate awareness), and 54.2% knew 10–13 practices (high awareness). Figure 6 presents a histogram for this distribution, clearly showing the polarization.

5.7 Gender differences (with effect size)

Table 7 presents total awareness, knowledge and principles scores by gender. Female farmers had significantly higher scores than male farmers across all the three levels. For total awareness: Women mean was 11.34 (SD = 2.20), men 7.47 (SD = 4.11); $t = -10.22$, $p < 0.001$,

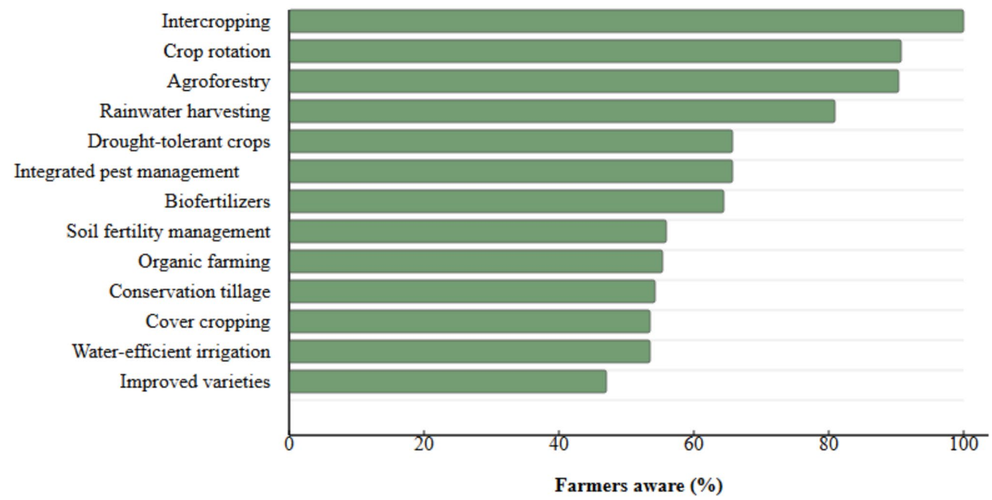

FIGURE 3
Farmers' awareness of climate-smart agriculture practices (n = 400).

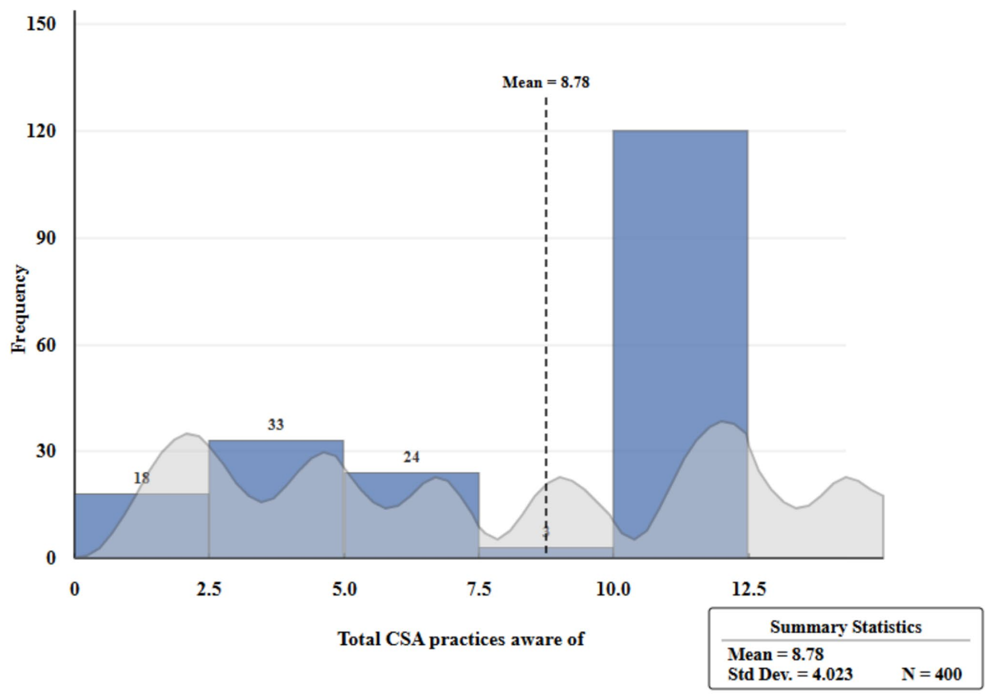

FIGURE 4
Bimodal CSA practice awareness distribution (n = 400).

Cohen is d = 1.03 (large effect). Similarly, women had higher knowledge (10.21 vs. 6.82, $t = -9.87$, $p < 0.001$, $d = 0.99$) and understanding of principles (9.45 vs. 0.24, $t = -9.23$, $p < 0.001$, $d = 0.93$). Mann–Whitney (U = 8833.0, $p < 0.001$). Figure 7 provided boxplots visualizing these gender differences

5.8 Education differences

Table 8 presents total scores by education level. Education had a powerful association on all the three measures. Farmers with no formal education were aware of only 3.29 practices (SD = 0.95), while those with tertiary education were aware of 12.40 practices (SD = 0.70) the pattern was similar for knowledge and principles.

Post-hoc tests (Tukey HSD) revealed that secondary education represented critical threshold. Farmers with secondary education (11.60 practices) differed significantly from those with primary education (4.67 practices, $p < 0.001$), but the difference between secondary and tertiary education, though statistically significant ($p = 0.001$), was relatively small (11.60 vs. 12.40).

ANOVA results confirmed highly significant differences across education levels for awareness ($F = 749.78$, $p < 0.001$, $\eta^2 = 0.65$), knowledge ($F = 933.06$, $p < 0.001$, $\eta^2 = 0.70$), and principles

TABLE 3 Farmers knowledge of climate-smart agriculture practices ($n = 400$).

Practice	Knowledgeable (n)	Knowledgeable (%)	95% CI	Rank
Intercropping	396	99.0	[97.5, 99.5]	1
Crop rotation	364	91.0	[88.0, 93.5]	2
Improved varieties	268	67.0	[62.3, 71.4]	3
Agroforestry	264	66.0	[61.3, 70.5]	4
Drought-tolerant crops	264	66.0	[61.3, 70.5]	4
Integrated pest management	260	65.0	[60.2, 69.6]	6
Soil fertility management	260	65.0	[60.2, 69.6]	6
Cover cropping	220	55.0	[50.1, 59.8]	8
Conservation tillage	216	54.0	[49.1, 58.8]	9
Organic farming	216	54.0	[49.1, 58.8]	9
Biofertilizers	216	54.0	[49.1, 58.8]	9
Water-efficient irrigation	216	54.0	[49.1, 58.8]	9
Rainwater harvesting	156	39.0	[34.4, 43.8]	13

CI, Confidence interval. Practices ranked from highest to lowest knowledge.

TABLE 4 Farmer understanding of climate-smart agriculture principles ($n = 400$).

Practice	Understand principles (n)	Understand principles (%)	95% CI	Rank
Conservation tillage	334	83.5	[79.6, 86.9]	1
Improved varieties	327	81.8	[77.8, 85.3]	2
Crop rotation	326	81.5	[77.5, 85.1]	3
Cover cropping	266	66.5	[61.8, 71.0]	4
Agroforestry	262	65.5	[60.8, 70.0]	5
Drought-tolerant crops	262	65.5	[60.8, 70.0]	5
Biofertilizers	248	62.0	[57.2, 66.6]	7
Organic farming	236	59.4	[54.6, 64.1]	8
Soil fertility management	188	47.0	[42.2, 51.9]	9
Intercropping	159	39.8	[35.1, 44.6]	10
Water-efficient irrigation	159	39.8	[35.1, 44.6]	10
Integrated pest management	134	33.5	[29.0, 38.3]	12
Rainwater harvesting	108	27.0	[22.9, 31.5]	13

CI, Confidence interval. Practices ranked from highest to lowest understanding of principle.

($F = 4.16$, $p < 0.006$, $\eta^2 = 0.03$). Note: small η^2 for principles indicates that education explains little variance in principles understanding (Figure 8).

5.9 Education and practice crosstabulations

Table 9 presents chi-square test results for the association between education level (three groups) and awareness for each practice. For eight practices, strong education gradients emerged (χ^2 values 54.999 to 391.939, $p < 0.001$). As shown in Table 9, farmers with no formal or only primary education exhibited 0% awareness for four practices: conservation tillage, cover cropping, soil fertility management, and water-efficient irrigation. For four practices (conservation tillage, cover cropping, soil fertility management, water efficient irrigation), farmers with no formal/primary education had 0% awareness, while secondary/tertiary farmers had 90–100% awareness. Cramér's V values ranged from 0.36 (moderate) to 0.99 (strong) association. Notably, improved varieties showed no education effect ($\chi^2 = 3.030$, $p < 0.220$, Cramér's V = 0.09, very small), with awareness consistently low (44–55%) across all education groups.

5.10 Correlation among awareness, knowledge and principles

Table 10 presents the correlations among total awareness, total knowledge and total principles. The correlation between total awareness and total knowledge was extremely strong (Pearson $r = 0.979$, $p < 0.001$; Spearman $\rho = 0.928$, $p < 0.001$). This near-perfect correlation raises a concern that two measures may largely capture a single underlying response tendency in this sample, potentially undermining the distinctness of the three-level framework as operationalized in this study. However, correlations with total principles were much weaker: awareness-principles (Pearson $r = 0.261$, $p < 0.001$; Spearman $\rho = 0.353$, $p < 0.001$) and knowledge-principles (Pearson $r = 0.151$, $p = 0.002$; Spearman $\rho = 0.140$, $p = 0.005$). This suggests that while awareness and knowledge were largely redundant in this study, understanding of principles represents a genuine different cognitive dimension.

TABLE 5 Comparison of awareness, knowledge, and understanding of principles across CSA practices (n = 400) with effect sizes (Select complete practices shown).

Practice	Awareness (%)	Knowledge (%)	Principles (%)	Awareness-Knowledge gap (p.p.)	*t*	*p*	Cohen's d	Pattern
Intercropping	100.0	99.0	39.8	−1.0 (n.s.)	–	–	0.03	Aligned
Rainwater harvesting	81.0	39.0	27.0	−42.0	16.91	<0.001	1.20	Awareness > Knowledge
Improved varieties	47.0	67.0	81.8	+20.0	−5.92	<0.001	0.48	Knowledge > Awareness
Agroforestry	90.3	66.0	65.5	−24.3	11.38	<0.001	0.95	Awareness > Knowledge

Knowledge gap = knowledge percentage - awareness percentage (or principle percentage–knowledge %). Negative values indicate awareness exceeds knowledge; positive values indicate knowledge exceeds awareness. *Cohen's d interpretation: 0.2 = small effect, 0.5 = medium effect, 0.8 = large effect; *Paired* *t*-tests compare awareness and knowledge percentages for each practice.

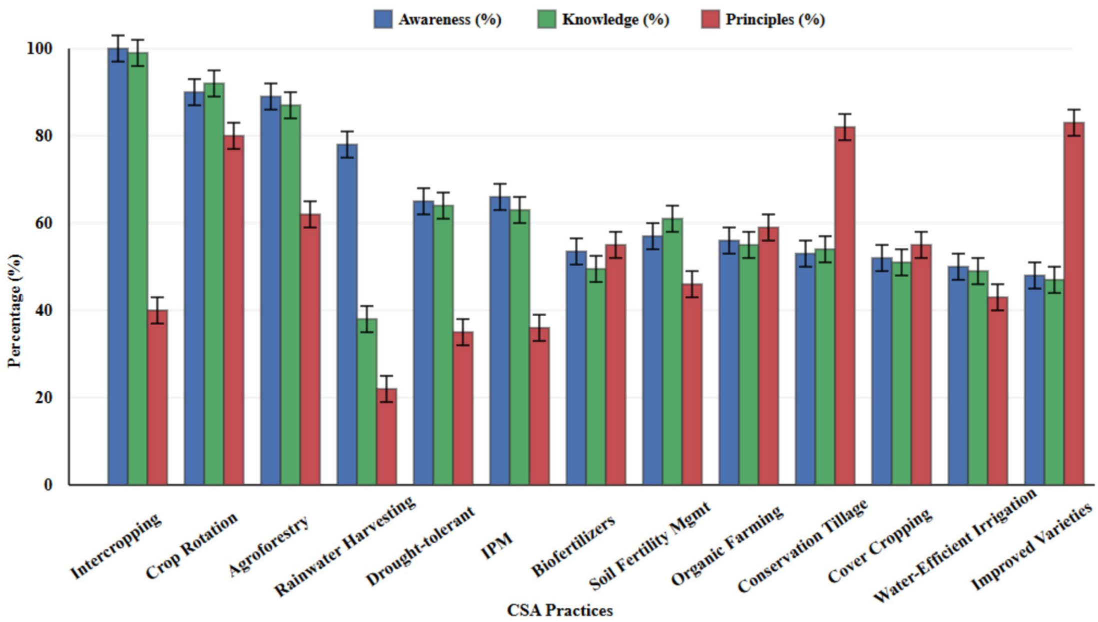

FIGURE 5
Patterns of CSA practices through a grouped bar chart (n = 400). The error bars shows confidence interval.

TABLE 6 Distribution of farmers by levels of CSA awareness (n-400).

Awareness level	Number of practices known	Frequency (n)	Percent (%)	Cumulative (%)
Very low	0–3	60	15.0	15.0
Low	4–6	78	19.5	34.5
Moderate	7–9	45	11.3	45.8
High	10–13	217	54.2	100.0
Total		400	100.0	

5.11 Composite measures: addressing the improved variety paradox

Table 11 presents composite measures (awareness OR knowledge) for selected practices. For improved varieties, the composite measure revealed true familiarity at 82.5%, compared to awareness at 47.0% and knowledge at 67.0% - a dramatic increase of 35.5 percentage points over awareness. This confirms that the low awareness is largely terminology problem. For rainwater harvesting, the composite measure (81.0%) was identical to awareness, as awareness already exceeded knowledge.

5.12 Progression analysis

Table 12 presents the progression analysis for agroforestry, showing the funnel form awareness to knowledge to principles. Of the 400 farmers, the funnel indicated that 39 (9.8%) had no awareness, 98 (24.5%) knew about agroforestry but did not know how to implement it. 2 (0.5%) Were aware and knowledgeable on implementation of agroforestry but did not understand the principles, and 261 (65.3%) had reached the deepest level of awareness, knowledge and principles (Figure 9).

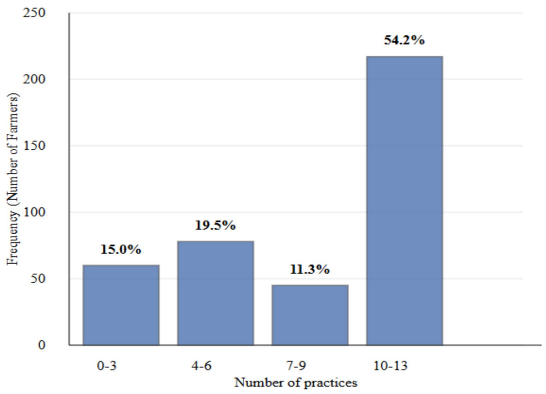

FIGURE 6
Histogram of farmers by level of CSA awareness.

5.13 Total progression score

Table 13 presents the distribution of total progression scores (sum of progression levels across 13 practices). The mean was 20.92 (SD = 11.77), median 25 out of a maximum possible 39. The distribution was polarized, with 28.2% of farmers scoring ≤ 10 (limited progression) and 51.2% scoring ≥ 25 (substantial progression). Figure 10 presents a histogram of total progression scores.

Robustness check (see Supplementary Tables S2, S3): Because the progression score is ordinal and bounded, we re-estimated the main model using ordered logistic regression (for practice-level progression, 0–3) and Tobit regression (for total progression score, censored at 0–39). Results were qualitatively identical: all significant predictors (gender, education, extension access) remained significant with the same direction of coefficients, and non-significant variables remained non-significant. Effect sizes from these non-linear models confirmed the pattern reported in Tables 7–9. The full results are presented as Supplementary Tables. These robustness checks increased confidence in the reporting associations.

TABLE 7 Awareness, knowledge, and understanding of principles by gender (*n* = 400).

Variable	Male (*n* = 265) Mean ± SD	Female (*n* = 135) Mean ± SD	*t*-value	*p*-value	Cohen's d	Mann–Whitney U	*p* (MW)
Total awareness (0–13)	7.47 ± 4.11	11.34 ± 2.20	−10.22	<0.001	**1.03**	8833.0	<0.001
Total knowledge (0–13)	6.82 ± 3.95	10.21 ± 2.45	−9.87	<0.001	**0.99**	9316.5	<0.001
Total principles (0–13)	6.24 ± 3.78	9.45 ± 2.62	−9.23	<0.001	**0.93**	15449.0	<0.001

SD, Standard deviation. All t-tests are two tailed. Equal variances not assumed based on Levene's test ($p < 0.001$). Man Whitney U tests confirm parametric results.

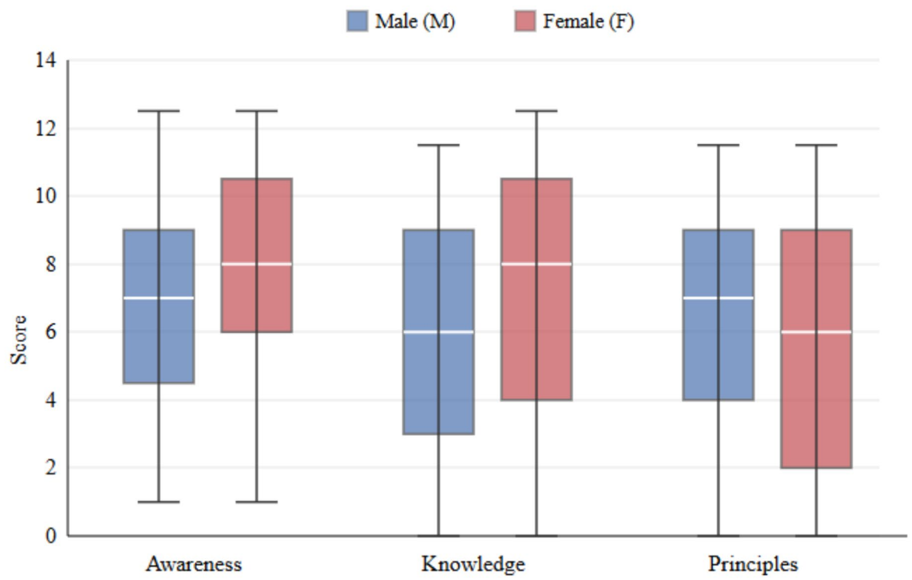

FIGURE 7
Box plots of awareness, knowledge, and principles by gender (*n* = 400).

TABLE 8 Awareness, knowledge, and understanding of principles by education level (n = 400).

Education level	n	Total awareness	Total knowledge	Total principles
No formal education	7	3.29 ± 0.95a	1.86 ± 0.69a	5.57 ± 1.99a
Primary school	169	4.67 ± 2.13b	3.60 ± 1.96b	7.18 ± 2.37b
Secondary school	99	11.60 ± 1.20c	11.10 ± 1.78c	8.04 ± 2.55b
Tertiary/University	125	12.40 ± 0.70d	12.73 ± 0.73d	7.69 ± 2.58b
F-value (ANOVA)		**749.78**	**933.06**	**4.16**
p-value		**< 0.001**	**< 0.001**	**0.006**
Kruskal-Wallis p		**<0.001**	**<0.001**	**0.007**
Kruskal-Wallis H		314.74	323.36	12.24
η^2 (eta-squared)		**0.65**	**0.70**	**0.03**
ω^2 (omega-squared)		**0.65**	**0.70**	**0.03**

Data presented as mean ± standard deviation. Within each column, means with different superscripts differ significantly at $p < 0.05$ (Tukey HSD post-hoc test). Welch's ANOVA and Kruskal-Wallis tests confirm significant differences ($p < 0.01$) due to unequal variance and non-normality.

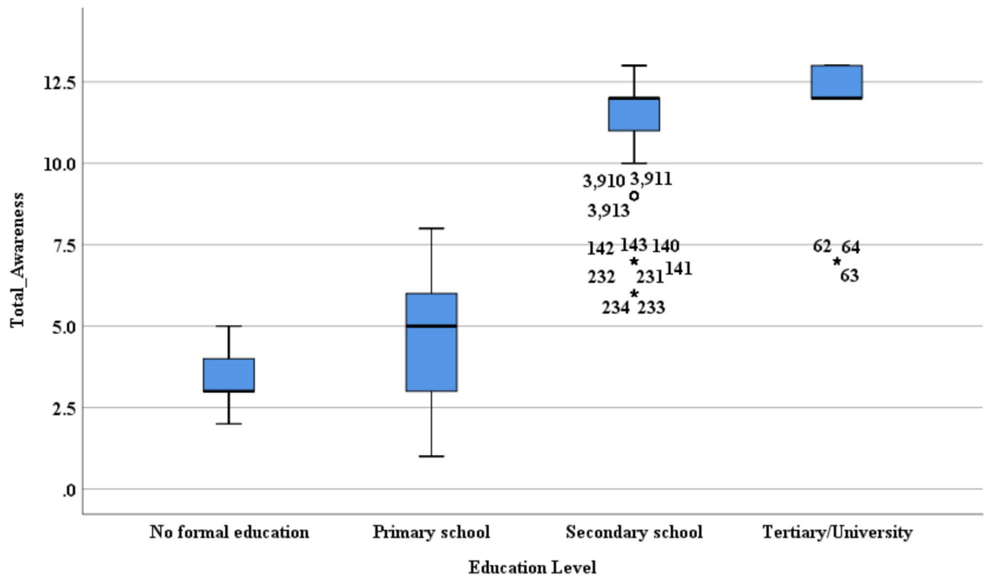

FIGURE 8
Box plot for farmers' awareness by education level (n = 400). Dramatic increase in mean awareness score between primary and secondary education is associated with strong threshold effect; low and overlapping distributions indicates limited gains in awareness at early education stage (no formal and primary education); the marginal increase in awareness at tertiary education suggests diminishing returns beyond secondary level. Reduced variability at higher education levels (tighter distributions) indicate more consistent awareness among more educated farmers; strong separation aligns with highly significant results (ANOVA $p < 0.001$; Kruskal-Wallis $p < 0.001$) reinforcing education as key associated factor of CSA practice awareness.

6 Discussion

6.1 Variation in awareness across practices

The wide variation in farmer awareness across practices (47 to 100%) associates with the interplay between traditional farming knowledge, extension effectiveness, and practice-specific characteristics (Finizola e Silva et al., 2024). The universal awareness of intercropping (100%) and crop rotation (90.8%) corresponded to the findings by Udry et al. (2024) and Marenya and Barrett (2007) who found that these practices are traditional and integral to smallholder farming systems, constituting indigenous knowledge passed across generations. Das et al. (2022), Manningtyas and Furuya (2022), and Yeleliere et al. (2022) stressed that traditional ecological knowledge is foundational for community-based farming systems, deeply rooted in local culture and practice. They note that the influence of traditional ecological knowledge on adoption of new agricultural technologies can act as important enabler when effectively incorporated with CSA innovations, or, it can be a hurdle when such technologies conflicts with established knowledge systems.

The high awareness of agroforestry (90.3%) and rainwater harvesting (81.0%) was associated with successful extension outreach for these practices. This finding is consistent with Partey et al. (2018) in Ghana, who reported 95% of farmers being aware of CSA concepts, with agroforestry and water management practices among the most widely recognized. The systematic review by Gemtou et al. (2024), Finizola e Silva et al. (2024) and Dhivya et al. (2024) identified informational factors including training, access to extension, group membership, climate information, and CSA

TABLE 9 Chi-square tests: association between education level and practice awareness.

Practice	Pearson χ^2	df	*p*-value	Cramér's V	Pattern description
Agroforestry	54.999	2	<0.001	**0.37**	Moderate gradient
Drought-tolerant crops	251.646	2	<0.001	**0.79**	Strong gradient
Improved varieties	3.030	2	0.220	**0.09**	No effect (terminology issue)
Conservation tillage	373.294	2	<0.001	**0.97**	0% awareness for less-educated (< secondary)
Integrated pest management (IPM)	251.646	2	<0.001	**0.79**	Strong gradient
Rainwater harvesting	113.894	2	<0.001	**0.53**	Strong gradient
Organic farming	147.397	2	<0.001	**0.61**	Strong gradient
Intercropping	–[1]	–	–	–	Constant (100% awareness across all education levels)
Crop rotation	51.891	2	<0.001	**0.36**	Moderate gradient
Cover cropping	363.124	2	<0.001	**0.95**	0% awareness for less-educated
Biofertilizers	259.676	2	<0.001	**0.81**	Strong gradient
Soil fertility management	391.939	2	<0.001	**0.99**	0% awareness for less-educated
Water-efficient irrigation[2]	358.200	2	<0.001	**0.95**	0% awareness for less-educated

[1]χ^2 not computed because awareness was 100% in all education categories.

TABLE 10 Correlation matrix of awareness, knowledge and principles score (*n* = 400).

Variable	Total awareness	Total knowledge	Total principles
Total awareness	1	Pearson r = 0.979**	Pearson r = 0.261**
		Spearman ρ = 0.928**	Spearman ρ = 0.353**
Total knowledge		1	Pearson r = 0.151**
			Spearman ρ = 0.140**
Total principles			1

***p* < 0.01 (two-tailed). Pearson correlation coefficient and Spearman's rank correlations presented. All correlations are significant at *p* < 0.01. The strong awareness-knowledge correlation contrasts with the much weaker correlations with principles.

awareness as consistently showing positive effects on CSA adoption. The high awareness suggests that initial awareness-raising efforts have been effective and that extension can now shift focus toward deepening knowledge and addressing implementation barriers

The moderate awareness of a cluster of eight practices (53.5 to 65.8%) suggests that extension and information services have reached approximately two-thirds of farmers, but one-third remain unaware (Ogada et al., 2021). This aligns with Teklewold et al. (2013) in Ethiopia, who found similar awareness levels for IPM and conservation agriculture, noting that practices requiring behavioral change typically exhibit lower awareness than those with visible, immediate benefits. Tolassa (2025), Agyekum et al. (2024), and Goni et al. (2025) similarly found that age, level of education, farming experience, farm size and gender were significant predictors of adoption across Ethiopia, Ghana, and Nigeria. Makate et al. (2019) and Khatri-chhetri et al. (2017) both demonstrate that awareness of CSA technologies varies significantly across farmer groups based on socio-economic characteristics, demographic factors, geographic contexts and access to extension services - highlighting that uniform awareness campaigns could be insufficient, and participatory, targeted approaches are essential to address these variations and improve adoption outcomes.

6.2 The three patterns of awareness-knowledge relationships

The identification of three distinct patterns in awareness-knowledge relationship has important implications for extension programming (Krathwohl, 2002).

Pattern 1: awareness exceeds knowledge (superficial awareness) – rainwater harvesting exhibited the largest gap 81% aware vs. 39% knowledgeable. Kato et al. (2011) have documented this "superficial awareness" phenomenon in Kenya, where they found that while rainwater harvesting was widely known, detailed knowledge of construction, maintenance and irrigation into farming systems was limited to less than 40% of farmers. They attributed this to awareness campaigns that successfully conveyed "what" and "why" but failed to provide the "how." For these practices, extension must shift from awareness raising to skills training. Farmers know the existence of these practices; now they need to learn how to implement them. This finding aligns with the work of Mulungu et al. (2025), Ayim et al. (2022), Aker (2011), and Giulivi et al. (2023) who emphasized that ICT-based extension interventions require well-designed messaging and adequate user training to be effective. Similarly, the FAO (2024) and FAO (2024) Zambia initiative demonstrates that behavior-responsive agricultural extension combining field demonstrations, participatory problem-solving, and peer exchange can successfully bridge the gap, with over 47,600 farmers trained through lead-farmer models.

TABLE 11 Composite measures true familiarity (awareness OR knowledge) (*n* = 400).

Practice	Original awareness (%)	Original knowledge (%)	Composite true (%)	Increase (p.p.)
Improved varieties	47.0	67.0	**82.5**	+35.5
Soil fertility management	56.0	65.0	71.5	+15.5
Cover cropping	53.5	55.0	64.8	+11.3
Water-efficient irrigation	53.5	54.0	63.8	+10.3
Conservation tillage	54.3	54.0	62.8	+8.5
Organic farming	55.3	54.0	63.8	+8.5
Biofertilizers	64.5	54.0	71.3	+6.8
IPM	65.8	65.5	72.5	+6.7
Drought-tolerant crops	65.8	66.0	71.3	+5.5
Crop rotation	90.8	91.0	94.3	+3.5
Agroforestry	90.3	66.0	92.5	+2.2
Intercropping	100.0	99.0	100.0	0.0
Rainwater harvesting	81.0	39.0	81.0	0.0

Composite true = MAX (awareness, knowledge). Increase = composite true % - original awareness.

TABLE 12 Progression analysis (*n* = 400).

Level	Description	Frequency (n)	Percent (%)
0	No awareness	39	9.8
1	Aware only	98	24.5
2	Aware + Knowledge	2	0.5
3	Aware + Knowledge + Principles	261	65.3
Total		400	100.0

"Aware only" = B = 1. C = 0, D = 0; "aware + knowledge" = B = 1, C = 1, D = 0; "aware + knowledge + principle" = B = 1, C = 1, D = 1.

Pattern 2: knowledge exceeds awareness (hidden knowledge) – improved varieties (47% aware vs. 67% knowledgeable) and soil fertility management (56% vs. 65%) showed this pattern. This associates with farmers possessing practical knowledge but do not recognize the formal terminology. Marenya and Barrett (2007) explained that farmers often practice soil fertility management as part of traditional farming without labeling it as a distinct "CSA practice." For improved varieties, Fisher and Carr (2015) documented that farmers had substantial knowledge of drought-tolerant maize varieties acquired through experience, but did not recognize the term "improved varieties." Miehe et al. (2025) further demonstrated that farmers' mental models of improved seeds work - including inflated expectation about "miracle seeds" – significantly influence their adoption decisions. Kosmowski et al. (2019) provide empirical evidence that farmers' self-reports of improved varieties adoption can be highly unreliable, with DNA fingerprints reveling large discrepancies compared to survey responses. Holden (2015), and Westengen and Brysting (2014) found that while farmers may be broadly aware of improved varieties, successful adoption requires deeper knowledge – including accurate understanding of seed traits and complementary management practices – demonstrating that knowledge must exceed mere awareness to realize productivity gains. The implication is that extension must align terminology with famers' language, explicitly connecting formal terms to practices farmers already use, while also managing expectation realistically.

Pattern 3: awareness and knowledge aligned – for the remaining eight practices, awareness and knowledge were closely aligned, suggesting that extension has effectively built both together. This is associated with extension success story and suggests that the integrated approaches used for these practices could serve as models for addressing gaps in other practices. The systematic review by Finizola e Silva et al. (2024) confirms that integrated approaches combining multiple information channels and support mechanisms are most effective in promoting CSA adoption. Issahaku (2019), Goni et al. (2025), and Amadu et al. (2020) further note that knowledge delivered primarily through extension services, mass media and structured program participation emerges as essential drivers of CSA adoption, although general awareness alone is insufficient without targeted training and external support to translate knowledge into practice.

6.3 The knowledge-principles gap

The consistent gap between knowledge and understanding of principles, with the largest gaps for IMP (−32.0), water-efficient irrigation (−14.0) and soil fertility management (−18.0), suggests that even among farmers who know how to implement practices, fewer understand the underlying principles. This is consistent with knowledge hierarchy proposed by Krathwohl (2002) where deeper conceptual understanding requires more intensive learning. The particularly large gap for IMP is associated with the practice having complex underlying principles that are not easily grasped through observation or simple instruction. The Alliance Biodiversity-CIAT (2025) ECREA project demonstrates that participatory on-farm experiments where farmers compare climate-informed practices in real field conditions can significantly enhance understanding of principles, with graduate students working alongside farmers to bridge academic inquiry and practical applications. Onyango et al. (2021) argue that effective upscaling

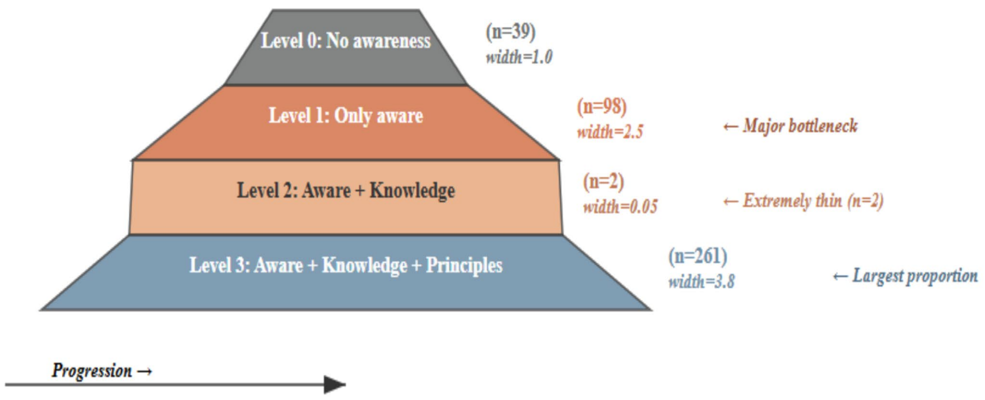

FIGURE 9
Agroforestry funnel progression from awareness to principles (n = 400). n = 39 farmers have no awareness (level 0); n = 98 are aware only (level 1 – major bottleneck). Only n = 2 farmers are at level 2 (aware + knowledge) – an extremely thin critical transition gap. The largest portion (n = 261) have reaches full understanding (level 3). Farmers tend to either remain at basic awareness or move directly to full understanding of the agroforestry practice.

TABLE 13 Total progression score distribution (n = 400).

Statistic	Value
N	400
Mean	20.92
Median	25.00
Mode	30
Std. deviation	11.77
Minimum	2
Maximum	38
Percentiles	25th: 10, 50th: 25, 75th: 30

Score range	Frequency (n)	Percent (%)	Cumulative (%)
2–10	113	28.2	28.2
11–24	82	20.5	48.7
25–38	205	51.2	100.0

Total progression sums the progression levels (0–3) across all 13 principles. Maximum = 39.

of CSA requires synergistic partnerships between scientific knowledge and farmers' traditional knowledge, suggesting that understanding of principles may be enhanced when new practices are connected to farmers' existing conceptual framework. Bayala et al. (2021) identified multi-stakeholder partnerships, capacity strengthening, and climate information integration as critical factors as CSA adoption in West Africa.

6.4 The polarized distribution of farmers

The strongly bimodal distribution of farmers by awareness levels – with 15.0% at the very low end and 54.2% at the high-end associates with extension reaching some farmers very effectively but completely misses others. This has been documented by Kristjanson et al. (2012) in Kenya, and Gulati et al. (2026) who attributed it to network effects – farmers in a well-connected communities learn many practices together through social learning, while isolated farmers learn fewer. The 15% of farmers with very low awareness (0–3 practices) represent the highest priority for extension targeting, as they seemingly are completely disconnected from agricultural innovation systems (Suri and Udry, 2022). The meta-analysis by Kante et al. (2019) found that overall pooled adoption rates for digital agricultural technologies were only 39%, highlighting the persistent challenges of reaching all farmers with innovations. Humphries et al. (2015), Gómez et al. (2024), and Bezner Kerr et al. (2019) emphasizes that co-creation with farmers, human-mediated delivery of digital content, and addressing the digital divide are essential to ensuring access for all farmers, including those currently unreached. Rosenstock et al. (2016), Ouédraogo et al. (2019) reinforce that farmers are polarized in their adoption of CSA practices due to uneven awareness, context-specific feasibility, and incomplete diffusion, creating a persistent gap between potential and actual adoption across farming systems.

6.5 Education as the strongest correlate

The powerful association of education on all three levels of understanding (F = 749.78 for awareness η^2 = 0.65) aligns with extensive literature. Goni et al. (2025) found that level of education was significant (p < 0.05) in influencing adoption of CSA practices in Ethiopia, Ghana and Nigeria. Asfaw and Admassie (2004) identified education as critical human capital influencing adoption, noting that educated farmers make better decisions because they can read extension materials and understand technical information. The meta-analysis by Kante et al. (2019) and Miehe et al. (2025) confirmed that education is among the main socioeconomic determinants of technology adoption, with higher educational attainment increases the likelihood of using agricultural technologies. Finizola e Silva et al. (2024) similarly found that educational level emerges as a key personal factor positively influencing CSA adoption. Nchanji et al. (2025) in Tanzania found that women farmers had lower levels of education with fewer technological accesses, contributing to their low uptake of climate-smart technologies.

The finding that secondary education represents a critical threshold – with farmers at this level having nearly triple the awareness of those with primary education has important implications. This threshold phenomenon suggests that secondary education correlates with high literacy, numeracy, and cognitive skill that enables farmers to access and process technical information Aker (2011) and Zhang et al. (2023).

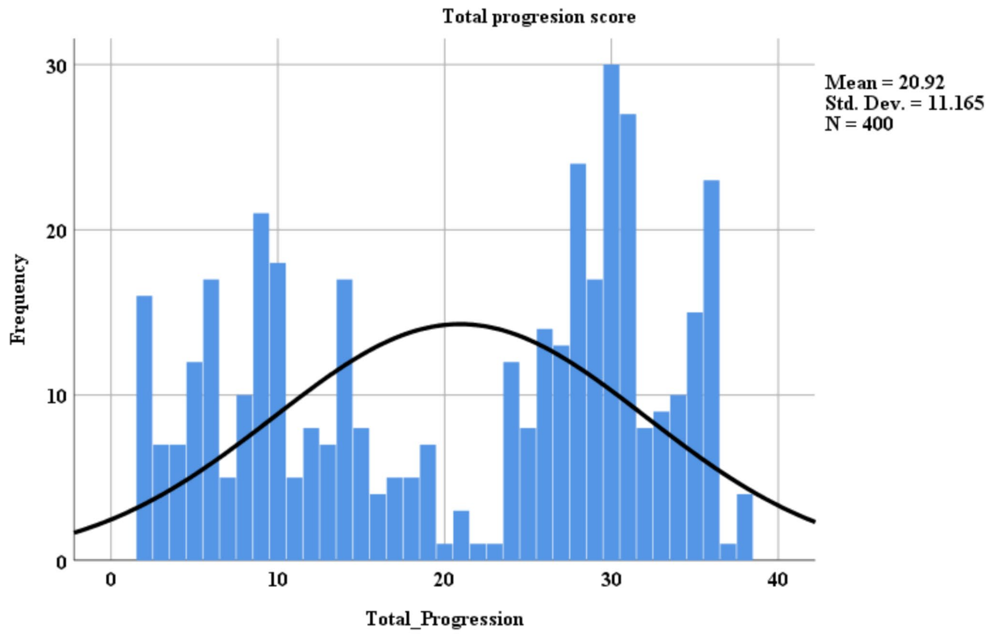

FIGURE 10
Histogram of total progression scores.

The complete absence of awareness among less educated farmers for four critical practices (conservation tillage, cover cropping, soil fertility management and water-efficient irrigation) is associated with a critical equity concern. Asfaw and Admassie (2004) warned that if extension services fail to reach less-educated farmers, technological divide might widen, exacerbating existing inequalities. This finding underscore the urgent need for low-literacy extension approaches including visual aids, demonstrations, oral communication, and peer learning, as recommended by multiple studies (Teklewold et al., 2013; Goni et al., 2025). Okori et al. (2022), Makapela et al. (2025), and Kangogo et al. (2024) demonstrates that community led learning and lead-farmer mentorship can effectively reach farmers regardless of education level.

6.6 Gender differences favoring women

The finding that women have significantly higher awareness, knowledge and understanding of principles than men (11.34 vs.7.47 practice aware) is particularly noteworthy given that older literature often reported male advantage (Doss and Morris, 2001; Ragasa et al., 2013). This aligns with recent gender-sensitive research by Nchanji et al. (2025) who found that women in Eastern Uganda had greater access to and sustained use of improved common bean varieties. The authors attribute this to women's primary responsibility for food crop, their active participation in farmer groups, and successful gender-targeted extension programs. However, this is an association, not a causal effect; cross-sectional data cannot establish that women's higher scores are caused by network effects or targeting.

Several factors may be associated with the female advantage. First, many CSA practices related to food crops, fall within women's traditional domain of responsibility (Doss and Morris, 2001; Ragasa et al., 2013). Second, women's participation in farmer groups and social networks might facilitate knowledge sharing (Kristjanson et al., 2012). Gulati et al. (2026) found that women's agricultural networks are approximately 26% larger than men's though these networks rarely overlap with men's, suggesting that women access different information sources. Third, extension services might have successfully targeted women through gender-sensitive programming in recent years (Nchanji et al., 2025). The systematic review by Finizola e Silva et al. (2024) identified group membership and social networks as important informational factors positively influencing CSA adoption. Mutenje et al. (2019) provide additional evidence that women's bargaining power and intra-house decision-making positively influence CSA adoption, highlighting the importance of gender responsive approaches that leverage women's agency to drive technology investment in southern Africa.

The finding contrasts with earlier research such as Ragasa et al. (2013) in Ethiopia, which found that men had higher access to extension services and higher adoption rates, and with the recent Tanzania study by Manono et al. (2025), which found that men dominated climate adaptation decision-making processes due to land ownership and control. Gulati et al. (2026) provide a nuanced perspective, finding that in India, when men are connected to adopters, household demands rises, but when women have similar connections, demand falls – not from unequal access (women are often better connected) but from different interpretations. Men may amplify positive experiences and women are more attentive to downside risks. The divergence in findings could reflect changing gender dynamics over time, successful gender-targeted interventions, or context-specific factors. This underscores the importance of context-specific gender analysis in agricultural research (Fisher and Carr, 2015).

6.7 The improved varieties paradox: a terminology issue

The striking finding is the improved varieties paradox: knowledge (67%) substantially exceeds awareness (47%). The composite measure (Awareness OR knowledge) revealed true familiarity at

82.5%, indicating that the low awareness is associated with a measurement artifact (Kosmowski et al., 2019; Fisher and Carr, 2015). This has profound implications for agricultural research and extension. Fisher and Carr (2015) emphasized that terminology matters in survey research – farmers might know the practice by local names rather than technical terms. The authors recommended that survey use farmer-recognized terminology and, where possible, reference specific varieties names familiar to farmers. Nchanji et al. (2025) emphasized that seed systems research and extension must employ participatory approaches that center farmer language and knowledge systems by using co-designed socio-technological innovation bundles and multi-stakeholder learning labs where farmers actively shape innovation processes rather than receiving top-down solutions.

Kosmowski et al. (2019) provided compelling empirical evidence for this phenomenon using DNA fingerprints in Ghana and Zambia. Their research found large variations in adoption estimates obtained by different survey methods compared to DNA fingerprinting results, demonstrating that farmers are often unable to identify improved varieties as a group or by name. They recommended time-intensive data collection approaches including follow-up questions, field visits to observe plant characteristics, or collecting sample materials for expert verification, each with implications for data collection costs and accuracy. Miehe et al. (2025) further demonstrated that farmers 'expectations about improved seed varieties are shaped by marketing messages, and that mismatched expectations can lead to disappointing outcomes and disadoption. Their research showed that correcting inflated expectations through information interventions led to more realistic decision-making, even if short-term adoption decreased.

This finding suggests that previous studies may have systematically underestimated farmer awareness of improved varieties and potentially other practices where formal and local terminologies diverge. Future research should incorporate qualitative pre-surveys to identify local terminologies and use multiple measures (including composite measures) to capture true familiarity. The work of Ogunyiola et al. (2022) on local knowledge integration provides framework for such participatory approaches by demonstrating that effective CSA upscaling requires the systematic inclusion of farmers' local knowledge through respectful engagement, consultative policy design, and recognition of farmers as active knowledge holders rather than passive recipients.

6.8 Progression analysis: understanding funnel

The progression analysis for agroforestry (Table 12) reveals the "funnel" from awareness to knowledge to principles, with 24.5% of farmers stuck on the "awareness only" stage. This associates with a bottleneck at the awareness → knowledge transition, and could suggests that while awareness campaigns have been successful, skill training has been inadequate (Kato et al., 2011). For improved varieties, (not shown in the table but analyzed) the bottleneck would likely be at the knowledge → principles transition, suggesting an association with farmers knowing how to use improved varieties, but may not understand why they work, limiting their ability to adapt and innovate (Glendenning et al., 2010).

This finding aligns with Krathwohl (2002) knowledge hierarchy and has important implications for extension design. Different interventions are needed for different bottleneck: awareness → knowledge bottleneck requires practical skills training, while knowledge → principles bottlenecks require deeper conceptual education. Bezner Kerr et al. (2019), Gómez et al. (2024), and Humphries et al. (2015) demonstrates that participatory on-farm experiments where farmers collaborate as co-researchers, and test alternative practices under real farm conditions, have been shown to enhance understanding and facilitate adoption of climate-smart innovations. The systematic review by Mulungu et al. (2025) found that ICT interventions could effectively address both types of bottlenecks when designed appropriately, with 76% of studies reporting increased adoption of good agricultural practices, 60% demonstrating improved awareness, 74% indicating high yields, and 68% observing enhanced income.

6.9 The weak awareness-principles correlation

The much weaker correlations between principles and both awareness (r = 0.261) and knowledge (r = 0.151) suggesting that understanding of principles co-occurs with distinct dimension of farmer cognition. Farmers can know about a practice and even know how to implement them without deeply understanding why a specific practice works. This has important implications for extension design and for understanding farmer innovation capacity. Farmers who understand principles could be better equipped to adapt practices to their specific contexts, troubleshoot problems, and innovate (Glendenning et al., 2010). Achieving principle-level understanding requires more intensive, participatory approaches such as farmer field schools, demonstration plots, and long-term engagements Kangogo et al. (2024), Okori et al. (2022), Makapela et al. (2025), and Zizinga et al. (2017). These studies show that blending climate education with behavior insights, community-led learning, and reflective learning positions communities as co-creators of change, building deeper understanding. Oxfam (2025) describes how farmers-research-extension linkage platform transforms extension from top-down transfer to collaborative learning, highlighting the importance of digital feedback mechanisms and inclusion of women and marginalized farmers. The weak correlation suggests that current extension approaches may succeed at building awareness and procedural knowledge but failing on conceptual understanding (Neufeldt et al., 2013; Lipper et al., 2014; Thornton et al., 2018).

Importantly, the near-perfect correlation between awareness and knowledge (r = 0.979; see Section 3.10) requires explicit caution in interpreting our three-level framework for this specific sample. While the conceptual distinction between awareness (heard of) and knowledge (know how to implement) remains theoretically valid and important for extension programming, these two dimensions were empirically redundant in our study context. This redundancy likely reflects the unique characteristics of Zavala District, which was purposely selected for its concentration of CSA interventions (see Section 2.1). In this intervention-intensive environment, farmers who had heard of practice were almost always able to implement it – suggesting that extension efforts have successfully bundled awareness with practical training. This study does not generalize this redundancy to other contexts with lower intervention intensity, where awareness-knowledge gaps may be substantial (as documented for rainwater harvesting and agroforestry in this sample at a practice level; see Table 5). The weak correlation between principles and both awareness (r = 0.261) and knowledge (r – 0.151) confirm that understanding of principles remains a genuinely distinct cognitive dimension, even when awareness and knowledge converge.

6.10 Implications for policy and practice

These findings have several important implications for agricultural extension:

Based on the farmers' current awareness levels, a different approach is necessary especially for farmers with very low awareness who require priority outreach programs using simplified communication methods. Awareness building campaigns focusing on low to moderate awareness farmers should introduce remaining practices; for farmers with high awareness, extension should shift to deepening knowledge through skill trainings and engaging them as educators.

The three patterns of awareness-knowledge require different responses. For instance, practices with awareness > knowledge, the priority should be skill training through farmer field schools, demonstrations, and follow-up visits; for practices with Knowledge > awareness, the priority lies in the terminology alignment using local names, and explicitly connecting formal terms to practices farmers already use. In addition, for practices with aligned awareness and knowledge, the current intervention approach needs to be maintained and probably scaled.

Given the strong education associations, extension must adopt low-literacy approach for the 44% of farmers with primary education or less. This include visual aids, demonstration, oral communication, and peer learning rather than written materials with secondary-educated farmers serving as peer educators to bridge less educated farmers in their communities. Women high awareness suggest that they represent an underutilized resources for peer education; recruiting female extension officers, and forming women farm groups could amplify this advantage. Target programs for men are needed to close the gender gaps recognizing that men's lower awareness cold reflect different gender roles and responsibilities in agriculture rather than lower capacity.

Addressing terminology mismatch through use of farmer recognized terminology. Extension materials should use local names alongside technical terms and survey should include practical descriptions rather than relying solely on labels. A target outreach for 15% of farmers with very low awareness systematically mapping these farmers to understand their characteristics, locations, and barriers to access to extension service. To reach these marginalized farmers, community-based approaches, mobile extension services, and peer farmer networks might significantly bridge the gap. The weak correlation between principles and awareness/knowledge demonstrate that achieving conceptual understanding requires intensive approaches that deepen principles understanding. Farmer field schools, long-term engagement and participatory learning approaches are crucial to achieve deep understanding that enables innovation adoption.

6.11 Limitations of the study

The study acknowledges the following limitations: first, the cross-section design captures understanding at a single point in time and cannot establish casual relationships or track changes overtime. Second, self-reported measures may be subject to recall bias or social desirability bias. Third, the binary measurement (yes/no) do not capture gradations of knowledge or principles understanding, potentially oversimplifying complex cognitive states. Fourth, the small "no formal education" group ($n = 7$) limits statistical power for comparison involving this group, though non-parametric tests and careful interpretation were used to address this. Fifth, terminology issues may have led to underestimation of awareness for some practices, as demonstrated by the composite measures for improved varieties. Sixth, because Zavala District was purposively selected for its concentration of CSA interventions, absolute awareness figures are inflated and findings should be generalized only to similar intervention-dense contexts. Seventh, the near-perfect awareness-knowledge correlation ($r = 0.979$) indicates that these two dimensions were empirically redundant in this sample. While this does not compromise the validity of our practice-level gap analyses (where substantial awareness-knowledge mismatches were still observed for specific practices like rainwater harvesting), it suggests that aggregate scores for awareness and knowledge captured largely the same underlying construct. Finally endogeneity and selection bias due to unobserved motivation, social capital, and latent ability may confound the associations between education/gender and awareness, we do not claim causality.

6.12 Recommendation for future research

Future research should (1) employ longitudinal designs to track awareness, knowledge, and principles evolve over time and in response to extension interventions. (2) Qualitative research using participatory methods could illuminate terminology issues and farmers' mental models, building on the local knowledge integration. (3) Conduct experimental studies testing different extension approaches (e.g., skills training vs. awareness campaigns vs. terminology alignment) could provide evidence-based guidance for policy interventions. (4) Network analysis could reveal how knowledge spread through communities and identify key influencers and (6) Conduct comparative research across diverse contexts.

7 Conclusion

This study assessed smallholder farmers' awareness, knowledge, and principles understanding of 13 climate-smart agricultural practices, revealing critical insights for extension programming. Awareness varied widely from universal recognition of traditional practices like intercropping to only 47 % for improved varieties. Three distinct patterns emerged superficial awareness where farmers knew of practices but not how to implement them (rainwater harvesting showed an 81 % awareness, but only 39 % knowledge). The study revealed hidden knowledge where farmers possessed practical expertise, but did not recognize formal technology such as improved varieties knowledge, which recorded 67 %, exceeding awareness at 47 %, and aligned awareness for remaining practices.

Education proved the strongest associated factor, with awareness and knowledge but weakly associated with principles proved the strongest determinant of understanding, with secondary education representing a critical threshold – farmers with secondary education had nearly triple the awareness of those with primary education. Alarmingly, less-educated farmers showed zero awareness of four critical practices, indication a complete exclusion from extension messaging. Women demonstrated significantly higher awareness, knowledge and principles than men, representing an underutilized resource for per education. The farmer population was polarized with 54 % having awareness while 15 % remained almost completely disconnected from agricultural innovation systems.

A critical caveat is warranted regarding the near-perfect awareness-knowledge correlation ($r = 0.979$) observed in this study. While the conceptual distinction between awareness and knowledge remains valuable for extension theory and practice, these two dimensions were empirically indistinguishable in our sample. This finding does not validate the three-level framework conceptually; rather it demonstrates that in high-intensity intervention contexts, awareness and knowledge may become tightly coupled. Researchers applying this framework in other settings should assess the empirical distinctness of these dimensions before treating them as separate constructs. The weak principles correlation ($r = 0.151–0.21$) suggests that deeper conceptual understanding operates independently. These findings underscore that effective extension must be differentiated, practice-specific, and sensitive to farmer demographics and language, requiring targeted awareness campaigns, gender-responsive approaches, and educationally tailored programming that build on the strong education association while reaching those currently excluded.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was waived by the Institutional Review Board of Eduardo Mondlane University for the studies involving humans. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their verbal informed consent to participate in this study.

Author contributions

CO: Resources, Formal analysis, Methodology, Software, Data curation, Writing – original draft, Conceptualization, Investigation, Visualization. EC: Resources, Methodology, Conceptualization, Validation, Writing – review & editing, Supervision.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The study was supported by Center of Excellence in Agri-Food Systems and Nutrition (CE-AFSN) (grant no. E089-MZ).

Acknowledgements

The authors sincerely acknowledge the financial support provided by Center of Excellence in Agrifood Systems and Nutrition (CE-AFSN), whose funding made this study possible. This support significantly contribute to the successful execution of the research and preparation of this manuscript. Special appreciation is extended to Professor Eunice Cavane for her invaluable guidance, mentorship, and scholarly insight throughout the research process. Her expertise and continuous encouragement were instrumental in sharing the direction and quality of this work. The authors are also grateful to Universidade Eduardo Mondlane for providing the academic environment and institutional support necessary for this research. Particular thanks are extended to Professor Luis Artur for his coordination and academic leadership, which greatly facilitated the progress of this study. We further acknowledge Professor Rogerio Chiulele for his strategic leadership and support as the CE-AFSN director, as well as Prof Sylvia Sitoe for her commitment to postgraduate academic excellence and administrative support throughout this journey. We also express our sincere gratitude to Serviço Distrital de Actividades Económicas (SDAE) in the study area for their cooperation, logistical facilitation, and support during the data collection process. Their local coordination and institutional assistance were essential in ensuring smooth engagement with communities and successful fieldwork implementation. The authors further appreciate the contributions of the field assistants, data collectors, respondents, and technical staff involved in the research. Their dedication and professionalism were instrumental in ensuring the accuracy and integrity of the study. Finally, heartfelt appreciation to all the colleagues, research participants, and stakeholders whose contributions, cooperation, and encouragement enriched this study.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. ChatGPT was used in the English language moderation.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2026.1846364/full#supplementary-material

References

Adewopo, J., McCampbell, M., Mwizerwa, C., and Schut, M. (2025). Beyond the hype: ten lessons from co-creating and implementing digital innovation in a Rwandan smallholder banana farming system. *Agriculture* 15:119. doi: 10.3390/agriculture15020119

Agyekum, T. P., Antwi-Agyei, P., Dougill, A. J., and Stringer, L. C. (2024). Benefits and barriers to the adoption of climate-smart agriculture practices in West Africa: a systematic review. *Clim. Resil. Sustain.* 3, 1–15. doi: 10.1002/cli2.79

Aker, J. C. (2011). Dial "a" for agriculture: a review of information and communication technologies for agricultural extension in developing countries. *Agric. Econ.* 42, 631–647. doi: 10.1111/j.1574-0862.2011.00545.x

Amadu, F. O., McNamara, P. E., and Miller, D. C. (2020). Understanding the adoption of climate-smart agriculture: a farm-level typology with empirical evidence from southern Malawi. *World Dev.* 126:104692. doi: 10.1016/j.worlddev.2019.104692

Asfaw, A., and Admassie, A. (2004). The role of education on the adoption of chemical fertiliser under different socioeconomic environments in Ethiopia. *Agric. Econ.* 30, 215–228. doi: 10.1016/j.agecon.2002.12.002

Awoke, M. D., Löhr, K., Kimaro, A. A., Lana, M., Soh Wenda, B. D., et al. (2024). Exploring gender dynamics in climate-smart agriculture adoption: a study in semi-arid Dodoma, *Tanzania. Frontiers in Sustainable Food Systems*, 8. doi: 10.3389/fsufs.2024.1507540

Ayim, C., Kassahun, A., Addison, C., and Tekinerdogan, B. (2022). Adoption of ICT innovations in the agriculture sector in Africa: a review of the literature. *Agric. Food Secur.* 1, 1–16. doi: 10.1186/s40066-022-00364-7

Bashiru, M., Ouedraogo, M., Ouedraogo, A., and Läderach, P. (2024). Smart farming technologies for sustainable agriculture: a review of the promotion and adoption strategies by smallholders in sub-Saharan Africa. *Sustainability* 16:817. doi: 10.3390/su16114817

Bayala, J., Ky-Dembele, C., Dayamba, S. D., Somda, J., Ouédraogo, M., Diakite, A., et al. (2021). Multi-actors' co-implementation of climate-smart village approach in West Africa: achievements and lessons learnt. *Front. Sustain. Food Syst.* 5, 1–13. doi: 10.3389/fsufs.2021.637007

Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., et al. (2019). Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agric. Ecosyst. Environ.* 279, 109–121. doi: 10.1016/j.agee.2019.04.004

Bogweh, E., Agness, N., Catherine, N., Adolph, K., Victor, K., Ochieng, F., et al. (2025). Assessing gender disparities in farmers' access and use of climate-smart agriculture in southern Tanzania. *Discov. Sustain.* 6:337. doi: 10.1007/s43621-025-01150-8

Boudalia, S., Dawit Teweldebirhan, M., Ariom, T. O., Diouf, N. S., Nambeye, E., Mwatitha Gondwe, T., et al. (2024). Gendered Gaps in the Adoption of Climate-Smart Agriculture in Africa and How to Overcome Them. *Sustainability (Switzerland)*, 16, 1–18. doi: 10.3390/su16135539

Branca, G., Braimoh, A., Zhao, Y., Ratii, M., and Likoetla, P. (2021). Are there opportunities for climate-smart agriculture? Assessing costs and benefits of sustainability investments and planning policies in southern Africa. *J. Clean. Prod.* 278:123847. doi: 10.1016/j.jclepro.2020.123847

Campbell, B. M., Thornton, P., Zougmore, R., Van Asten, P., and Lipper, L. (2014). Sustainable intensification: what is its role in climate smart agriculture? *Curr. Opin. Environ. Sustain.* 8, 39–43. doi: 10.1016/j.cosust.2014.07.002

Chandra, A., McNamara, K. E., and Dargusch, P. (2017). Climate-smart agriculture: perspectives and framings. *Clim. Pol.* 18, 526–541. doi: 10.1080/14693062.2017.1316968

Cochran, W. G. (1977). *Sampling Techniques*. 3rd Edn Hoboken, NJ: Wiley.

Coggins, S., McCampbell, M., Sharma, A., Sharma, R., Haefele, S. M., Karki, E., et al. (2022). How have smallholder farmers used digital extension tools? Developer and user voices from sub-Saharan Africa, South Asia and Southeast Asia. *Glob. Food Sec.* 32:100577. doi: 10.1016/j.gfs.2021.100577

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). SAGE Publications.

Das, M., Das, A., Seikh, S., and Pandey, R. (2022). Nexus between indigenous ecological knowledge and ecosystem services: a socio-ecological analysis for sustainable ecosystem management. *Environ. Sci. Pollut. Res.* 29, 61561–61578. doi: 10.1007/s11356-021-15605-8

Dhivya, C., Murugan, P. P., Senthilkumar, M., Asokhan, M., Ga, D., Selvi, G. R., et al. (2024). Determinants of climate-smart agricultural technology adoption: a comprehensive systematic review. *Plant Sci. Today* 11, 1–16. doi: 10.14719/pst.5156

Doss, C. R., and Morris, M. L. (2001). How does gender affect the adoption of agricultural innovations? The case of improved maize technology in Ghana. *Agric. Econ.* 25, 27–39. doi: 10.1111/j.1574-0862.2001.tb00233.x

Evenson, R. E., and Gollin, D. (2003). Assessing the impact of the green revolution, 1960 to 2000. *Science* 300, 758–762. doi: 10.1126/science.1078710

FAO. (2013). *Climate-Smart Agriculture Sourcebook*. Rome: FAO. Available online at: https://www.fao.org/3/i3325e/i3325e.pdf.

FAO. (2024). *Digital Agriculture in FAO Projects in Sub-Saharan Africa*. Food and Agriculture Organization of the United Nations.

FAO. (2024). *The 3 Pillars of Climate-smart Agriculture and the Sustainable Development Goals: Synergies and trade-offs (Brief No. 11). Food and Agriculture Organization of the United Nations*. Rome: FAO. Available online at: https://www.fao.org/documents/card/en/c/cc9901en.

Feder, G., Just, R. E., and Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: a survey. *Econ. Dev. Cult. Change* 33, 255–298. doi: 10.1086/451461

Finizola e Silva, M., Van Schoubroeck, S., Cools, J., and Van Passel, S. (2024). A systematic review identifying the drivers and barriers to the adoption of climate-smart agriculture by smallholder farmers in Africa. *Front. Environ. Econ.* 3:335. doi: 10.3389/frevc.2024.1356335

Fisher, M., and Carr, E. R. (2015). The influence of gendered roles and responsibilities on the adoption of technologies that mitigate drought risk: the case of drought-tolerant maize seed in eastern Uganda. *Glob. Environ. Chang.* 35, 82–92. doi: 10.1016/j.gloenvcha.2015.08.009

Gemtou, M., Kakkavou, K., Anastasiou, E., Fountas, S., Pedersen, S. M., Isakhanyan, G., et al. (2024). Farmers' transition to climate-smart agriculture: a systematic review of the decision-making factors affecting adoption. *Sustainability* 16:828. doi: 10.3390/su16072828

Giulivi, N., Harou, A. P., Gautam, S., and Guereña, D. (2023). Getting the message out: information and communication technologies and agricultural extension. *Am. J. Agric. Econ.* 105, 1011–1045. doi: 10.1111/ajae.12348

Glendenning, C. J., Babu, S. C., and Asenso-Okyere, K. (2010). *Review of Agricultural Extension in India: Are Farmers' Information Needs Being met? (IFPRI Discussion Paper 01048)*. International Food Policy Research Institute Available online at: https://hdl.handle.net/10568/154873.

Gómez, M., Humphries, S., Kindsvater, S., Jiménez, J., Orellana, P., Wyngaarden, S., et al. (2024). Advancing the sustainable development goals through participatory research: long-term impacts of farmer participation on sustainable land use and livelihoods in Honduras. *Agric. Food Secur.* 13:513. doi: 10.1186/s40066-024-00513-0

Goni, I. C., Garba, M., Bose, A. A., and Abdullahi, S. (2025). Factors influencing the adoption of climate smart agricultural practices in selected countries of Africa: a review. *Nigerian J. Agric. Agric. Technol.* 5, 163–169. Available online at: https://www.njaat.com.ng/index.php/njaat/article/view/1130

Gulati, K., Magnan, N., Lybbert, T. J., and Spielman, D. J. (2026). Gendered networks and demand for an agricultural technology in India. *World Dev.* 197:107182. doi: 10.1016/j.worlddev.2025.107182

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H., et al. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philos. Trans. R. Soc. B Biol. Sci.* 1639:20130089. doi: 10.1098/rstb.2013.0089

Holden, S. T. (2015). Subsidies promote use of drought tolerant maize varieties despite variable yield performance under smallholder environments in Malawi. *Food Secur.* 7:511. doi: 10.1007/s12571-015-0511-4

Humphries, S., Rosas, J. C., Gómez, M., Jiménez, J., Sierra, F., Gallardo, O., et al. (2015). Synergies at the interface of farmer-scientist partnerships: agricultural innovation through participatory research and plant breeding in Honduras. *Agric. Food Secur.* 4, 1–17. doi: 10.1186/s40066-015-0046-0

Issahaku, G. (2019). Adoption of climate-smart practices and its impact on farm performance and risk exposure among smallholder farmers in Ghana. *Aust. J. Agric. Resour. Econ.* 64:396. doi: 10.1111/1467-8489.12357

Kangogo, E., Otieno, D. J., Okello, J., Mwenye, O., and Kapalasa, E. (2024). Impact of farmer training on potato yield: a case of smallholder potato farmers in Malawi. *Front. Sustain. Food Syst.* 8, 1–10. doi: 10.3389/fsufs.2024.1496064

Kante, M., Oboko, R., and Chepken, C. (2019). An ICT model for increased adoption of farm input information in developing countries: a case in Sikasso, Mali. *Inf. Process. Agric.* 6, 26–46. doi: 10.1016/j.inpa.2018.09.002

Kassie, M., Teklewold, H., Jaleta, M., Marenya, P., and Erenstein, O. (2015). Understanding the adoption of a portfolio of sustainable intensification practices in eastern and southern Africa. *Land Use Policy*, 42, 400–411. doi: 10.1016/j.landusepol.2014.08.016

Kato, E., Ringler, C., Yesuf, M., and Bryan, E. (2011). Soil and water conservation technologies: a buffer against production risk in the face of climate change? Insights from the Nile basin in Ethiopia. *Agric. Econ.* 42, 593–604. doi: 10.1111/j.1574-0862.2011.00539.x

Kendall, H., Clark, B., Li, W., Jin, S., Jones, G. D., Chen, J., et al. (2022). Precision agriculture technology adoption: a qualitative study of small-scale commercial "family farms" located in the North China plain. *Precis. Agric.* 23:839. doi: 10.1007/s11119-021-09839-2

Kesby, M. (2005). Retheorizing empowerment-through-participation as a performance in space: beyond tyranny to transformation. *Signs J. Women Cult. Soc.* 30, 2037–2065. doi: 10.1086/428422

Khatri-chhetri, A., Aggarwal, P. K., Joshi, P. K., and Vyas, S. (2017). Farmers' prioritization of climate-smart agriculture (CSA) technologies. *Agric. Syst.* 151, 184–191. doi: 10.1016/j.agsy.2016.10.005

Kosmowski, F., Aragaw, A., Kilian, A., Ambel, A., Ilukor, J., Yigezu, B., et al. (2019). Varietal identification in household surveys: results from three household-based methods against the benchmark of DNA fingerprinting in southern Ethiopia. *Exp. Agric.* 55, 371–385. doi: 10.1017/S0014479718000030

Krathwohl, D. R. (2002). A revision of bloom's taxonomy: an overview. *Theory Into Pract.* 41, 212–218. doi: 10.1207/s15430421tip4104_2

Kristjanson, P., Neufeldt, H., Gassner, A., Sayula, G., Thiede, B., Förch, W., et al. (2012). Are food insecure smallholder households making changes in their farming practices? *Evid. East Afr.* 4, 381–397. doi: 10.1007/s12571-012-0194-z

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., et al. (2014). Climate-smart agriculture for food security. *Nat. Clim. Chang.* 4, 1068–1072. doi: 10.1038/nclimate2437

Makapela, M., Alexander, G., and Tshelane, M. (2025). Enhancing agricultural productivity among emerging farmers through data-driven practices. *Sustainability (Switzerland)* 17, 1–15. doi: 10.3390/su17104666

Makate, C., Makate, M., Mango, N., and Siziba, S. (2019). Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations: lessons from southern Africa. *J. Environ. Manag.* 231, 858–868. doi: 10.1016/j.jenvman.2018.10.069

Manningtyas, R. D. T., and Furuya, K. (2022). Traditional ecological knowledge versus ecological wisdom: are they dissimilar in cultural landscape research? *Land* 11, 1–16. doi: 10.3390/land11081123

Manono, B. O., Khan, S., and Kithaka, K. M. (2025). A review of the socio-economic, institutional, and biophysical factors influencing smallholder farmers' adoption of climate smart agricultural practices in sub-Saharan Africa. *Earth (Switzerland)* 6, 1–21. doi: 10.3390/earth6020048

Marenya, P. P., and Barrett, C. B. (2007). Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. *Food Policy* 32, 515–536. doi: 10.1016/j.foodpol.2006.10.002

Mather, D., Benfica, R., Chamberlain, J., and Pitoro, R. (2019). Population density and smallholder land access, crop intensification, and incomes in rural Mozambique. *Gates Open Res.* 3:137. doi: 10.21955/gatesopenres.1115492.1

Miehe, C., Nabwire, L., Sparrow, R., Spielman, D. J., and Van Campenhout, B. (2025). Miracle seeds: biased expectations, complementary input use, and the dynamics of smallholder technology adoption. *Econ. Dev. Cult. Chang.* 74, 305–334. doi: 10.1086/735822

Mulungu, K., Kassie, M., and Tschopp, M. (2025). Information Technology for Development the role of information and communication technologies–based extension in agriculture: application, opportunities and challenges. *Inf. Technol. Dev.* 1, 1–30. doi: 10.1080/02681102.2025.2456232

Mutenje, M. J., Farnworth, C. R., Stirling, C., Thierfelder, C., Mupangwa, W., and Nyagumbo, I. (2019). A cost-benefit analysis of climate-smart agriculture options in southern Africa: balancing gender and technology. *Ecol. Econ.* 163, 126–137. doi: 10.1016/j.ecolecon.2019.05.013

Nchanji, E., Ketema, D., and Lutomia, C. (2025). *Gender Transformative-Socio-Technical Innovation Bundles (GT-STIBs) A Tool in the CGIAR Gender Transformative Research Methodologies (GTRM)*. Toolkit November.

Neufeldt, H., Jahn, M., Campbell, B. M., Beddington, J. R., Declerck, F., De Pinto, A., et al. (2013). Beyond climate-smart agriculture: toward safe operating spaces for global food systems. *Agric. Food Secur.* 2, 1–6. doi: 10.1186/2048-7010-2-12

Ogada, M. J., Radeny, M., Recha, J., and Dawit, S. (2021). Adoption of complementary climate - smart agricultural technologies: lessons from Lushoto in Tanzania. *Agric. Food Secur.* 10:321. doi: 10.1186/s40066-021-00321-w

Ogunyiola, A., Gardezi, M., and Vij, S. (2022). Smallholder farmers' engagement with climate smart agriculture in Africa: role of local knowledge and upscaling. *Clim. Pol.* 22, 411–426. doi: 10.1080/14693062.2021.2023451

Okori, P., Munthali, W., Msere, H., Charlie, H., Chitaya, S., Sichali, F., et al. (2022). Improving efficiency of knowledge and technology diffusion using community seed banks and farmer-to-farmer extension: experiences from Malawi. *Agric. Food Secur.* 11, 1–14. doi: 10.1186/s40066-022-00375-4

Onyango, C. M., Nyaga, J. M., Wetterlind, J., Söderström, M., and Piikki, K. (2021). Precision agriculture for resource use efficiency in smallholder farming systems in Sub-Saharan Africa: a systematic review. *Sustainability (Switzerland)* 13, 1–18. doi: 10.3390/su13031158

Ouédraogo, M., Houessionon, P., Zougmoré, R. B., and Partey, S. T. (2019). *Uptake of Climate-smart Agricultural Technologies and Practices: Actual and Potential Adoption rates in the Climate-smart Village site of Mali*.

Oxfam. (2025). *Women Engagement Strategy: A case Study of Female Food Heroes (FFHs) Ethiopia's Program*. Oxfam.

Partey, S. T., Zougmoré, R. B., Ouédraogo, M., and Campbell, B. M. (2018). Developing climate-smart agriculture to face climate variability in West Africa: challenges and lessons learnt. *J. Clean. Prod.* 187, 285–295. doi: 10.1016/j.jclepro.2018.03.199

Ragasa, C., Berhane, G., Tadesse, F., and Taffesse, A. S. (2013). Gender differences in access to extension services and agricultural productivity. *J. Agric. Educ. Extens.* 19, 437–468. doi: 10.1080/1389224X.2013.817343

Rogers, E. M. (1983). *Diffusion of Innovations*. 3rd Edn Washington, DC: Free Press, Collier Macmillan.

Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). Free Press.

Rosenstock, T. S., Lamanna, C., Chesterman, S., Bell, P., Arslan, A., Richards, M., et al. (2016). *The scientific basis of Climate-smart Agriculture: A systematic Review*. Report, p. 138.

Rurii, M. W., and Nzengya Daniel, M. (2026). A scoping review of literature on adoption and impact of climate smart agricultural technologies by smallholder farmers in Africa. *Front. Clim.* 7:929. doi: 10.3389/fclim.2025.1692929

Ryle, G. (1949). *The Concept of Mind*. London: Hutchinson & Co.

Singh, R., and Singh, G. S. (2017). Traditional agriculture: a climate-smart approach for sustainable food production. *Energy, Ecology and Environment*, 2, 296–316. doi: 10.1007/s40974-017-0074-7

Suri, T., and Udry, C. (2022). Agricultural Technology in Africa. *J. Econ. Perspect.* 36, 33–56. doi: 10.1257/jep.36.1.33

Teklewold, H., Kassie, M., and Shiferaw, B. (2013). Adoption of multiple sustainable agricultural practices in rural Ethiopia. *J. Agric. Econ.* 64, 597–623. doi: 10.1111/1477-9552.12011.

Thornton, P. K., Whitbread, A., Baedeker, T., Cairns, J., Claessens, L., Baethgen, W., et al. (2018). A framework for priority-setting in climate smart agriculture research. *Agricultural Systems*, 167, 161–175. doi: 10.1016/j.agsy.2018.09.009

Tilman, D., Balzer, C., Hill, J., and Befort, B. L. (2011). Global food demand and the sustainable intensi fi cation of agriculture. 108. doi: 10.1073/pnas.1116437108

Tolassa, T. B. (2025). Adoption and impacts of improved potato variety in highlands of Guji zone, southern Oromia, Ethiopia. *Trends Agric. Sci.* 4, 133–141. doi: 10.17311/tas.2025.133.141

Udry, C., Aker, J. C., Barrett, C. B., Bergquist, L. F., and Magruder, J. (2024). Agricultural Technology in Africa. 5.

Vincent, K., Daly, M., Scannell, C., and Leathes, B. (2018). What can climate services learn from theory and practice of co-production? *Clim. Serv.* 12, 48–58. doi: 10.1016/j.cliser.2018.11.001

Westengen, O. T., and Brysting, A. K. (2014). Crop adaptation to climate change in the semi-arid zone in Tanzania: the role of genetic resources and seed systems. *Agric. Food Secur.* 3:3. doi: 10.1186/2048-7010-3-3

Wilson, L. O. (2016). *Bloom's Taxonomy Revised*. The Second Principle. Available online at: https://thesecondprinciple.com/essential-teaching-skills/blooms-taxonomy-revised/.

Yeleliere, E., Yeboah, T., Antwi-Agyei, P., and Peprah, P. (2022). Traditional agroecological knowledge and practices: the drivers and opportunities for adaptation actions in the northern region of Ghana. *Reg. Sustain.* 3, 294–308. doi: 10.1016/j.regsus.2022.11.002

Zhang, H., Mächler, E., Morsdorf, F., Niklaus, P. A., Schaepman, M. E., and Altermatt, F. (2023). A spatial fingerprint of land-water linkage of biodiversity uncovered by remote sensing and environmental DNA. *Science of the Total Environment*, 867: 161365. doi: 10.1016/j.scitotenv.2022.161365

Zizinga, A., Kangalawe, R. Y. M., Ainslie, A., Tenywa, M. M., Majaliwa, J., Saronga, N. J., et al. (2017). Analysis of farmer's choices for climate change adaptation practices in south-western Uganda, 1980–2009. *Climate* 5, 1–15. doi: 10.3390/cli5040089

Zougmoré, R., Partey, S., Ouédraogo, M., Omitoyin, B., Thomas, T., Ayantunde, A., et al. (2016). Toward climate-smart agriculture in West Africa: A review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agriculture and Food Security*, 5, 1–17. doi: 10.1186/s40066-016-0075-3