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EDITED BY
Clement Oteng,
University of Cape Coast, Ghana

REVIEWED BY
Kassa Tarekegn Erekalu,
University of Copenhagen, Denmark
Kusnandar Kusnandar,
National Research and Innovation
Agency (BRIN), Indonesia
Kwaku Adu,
University of Environment and
Sustainable Development, Ghana

*CORRESPONDENCE
Abraham Zakaria
✉ abraham.zakaria@uds.edu.gh

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Cocoa climate-smart agriculture adoption in Ghana: why the synergies and trade-offs matter for policy

Philip Neri Zuobog¹, Gazali Issahaku², Franklin N. Mabe³,
Abraham Zakaria^{3,4*} and Abdul Razak Baba⁵

¹Faculty of Law, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, ²West African Centre for Shea Innovation and Research, University for Development Studies, Tamale, Ghana, ³Department of Agricultural and Food Economics, University for Development Studies, Nyankpala, Ghana, ⁴Department of Food Security and Climate Change, University for Development Studies, Tamale, Ghana, ⁵Faculty of Biosciences, University for Development Studies, Tamale, Ghana

The role of climate-smart agriculture (CSA) in sustainable cocoa production cannot be ignored. However, studies on perceived effectiveness and the socio-economic drivers of CSA among cocoa farmers are underexplored. This study fills the gap by using Spearman's rank correlation and a multivariate probit model with 455 cocoa farmers in Ghana. Results show high adoption of agroforestry (93.48%) and hybrid planting materials (86.30%), moderate uptake of lining and pegging (52%) and cover cropping (49%), and relatively low adoption of irrigation (23%), drainage construction (30%) and off-farm diversification (33%). Most farmers perceive agroforestry, hybrid varieties, lining and pegging, and cover cropping as effective or highly effective in reducing the impacts of climate variability. In contrast, a large proportion are uncertain about the benefits of off-farm diversification, irrigation, and drainage, revealing important information and perception gaps. There are positive and significant correlations among perceived effectiveness scores (on-farm and off-farm diversification; SWC and drainage). The study found that farming experience, farm size, household size, climate information, distance to the farm, ICT ownership, membership of farmer-based organizations, and regional location significantly shape the adoption of CSA practices. Hence, to promote sustainable cocoa production, a climate-smart cocoa policy should recognize both the complementarities and trade-offs among CSA practices. Therefore, cocoa policymakers should strengthen extension and climate information systems, promote integrated, context-specific CSA packages, improve access to irrigation, and support farmer organizations.

KEYWORDS

bundle of sustainable land management, cocoa, Ghana, perceived effectiveness of CSA, synergies and trade-offs

1 Introduction

Cocoa is a major driver of economic development in the world's production economies. Cocoa production depends on rainfed agriculture in tropical regions and is one of the major cash tree crops that improve farmers' livelihoods and national economic growth in cocoa-producing countries. The tree crop not only enhances farmers' livelihoods and economic

growth in the producing countries, but also contributes to global economic growth through supply chain development. Global demand for cocoa and cocoa-based products has remained strong over the past 5 years, with global cocoa demand averaging approximately 4.9–5.1 million tons annually, despite a temporary decline to about 4.63 million tons in 2024/25 due to supply shortages and record-high prices (International Cocoa Organization, 2025; Kongor et al., 2024). This sustained demand continues to increase pressure on cocoa-producing countries to enhance productivity while meeting increasingly stringent environmental and sustainability standards. However, cocoa sustainability and productivity enhancement across production regions remain at a crossroads due to rising rainfall variability (Saspugayeva et al., 2026; Suh and Molua, 2022). For instance, rising extreme temperatures and rainfall variability have contributed to cocoa yield reductions (Bomdzele and Molua, 2023), coupled with low adoption of sustainable land-use management practices (Asante et al., 2021). Researchers projected that sustainable cocoa production and productivity in West Africa will continue to decline due to climate change and poor adoption of sustainable land management practices (Akrofi-Atitianti et al., 2018; Blaser et al., 2018; van Der Haar et al., 2023).

To mitigate the negative impact of climate variability on cocoa production sustainability, the promotion and dissemination of CSA have emerged over the past two decades (Aynalem et al., 2026). The adoption of CSA practices is particularly vital because it helps sustain cocoa productivity and incomes, strengthen resilience to climate change, and reduce or eliminate carbon emissions relative to conventional practices (Kabato et al., 2025; Ma and Rahut, 2024). However, studies have shown that the adoption of CSA practices is often partial and uneven, shaped by complex socioeconomic, institutional, and biophysical constraints (Antwi-Agyei and Amanor, 2023; Autio et al., 2021).

Ghana is the second-largest supplier of cocoa to the global market and remains a backbone of national economic growth and development. Cocoa is a source of livelihood for over 800,000 people along Ghana's cocoa value chain (Nasser et al., 2020; Yiridomoh et al., 2022). Cocoa production helps minimize deforestation and rising agricultural emissions, which are important for reversing the negative impacts of climate change (Gloy et al., 2025; Igbatayo, 2023). The Government of Ghana and the private sector have launched CSA initiatives to sustainably boost cocoa productivity and soil resilience. Some of the initiatives target ecological modernization and sustainable intensification, promoting improved and resistant varieties, shade tree management, agroforestry, fertilizer and pesticide optimization, and irrigation (Inkoom and Dadzie, 2024; Nasser et al., 2020; van Der Haar et al., 2023). Researchers have demonstrated that these CSA practices have the potential to raise productivity and incomes of cocoa farmers by around 29% per hectare compared to conventional cocoa (Akrofi-Atitianti et al., 2018).

Despite the growing interest and importance of CSA practices for sustainable cocoa production and incomes, the adoption of CSA among smallholder cocoa farmers in rural Ghana remains uneven and often low (Inkoom and Dadzie, 2024; Kaba et al., 2024). Many cocoa farmers still rely on conventional practices despite the availability of CSA practices disseminated by Ghana Cocoa Board (the state regulatory authority) and other major stakeholders in the cocoa industry (Tham-Agyekum et al., 2025; Yamoah et al., 2020). The low adoption of CSA practices among cocoa farmers is determined by intertwined socioeconomic, institutional, and biophysical factors, including land tenure, age, education, farm size, access to extension, credit, social

networks, climate awareness, and local agro-ecological conditions (Gemtoui et al., 2024; Inkoom and Dadzie, 2024; Ma and Rahut, 2024; Yiridomoh et al., 2022). For instance, tenure insecurity and limited extension services influence CSA adoption (Nasser et al., 2020; Torvikey et al., 2024; Yamoah and Kaba, 2024). Understanding how this bundle of factors influences farmers' adoption of CSA practices in rural Ghanaian cocoa landscapes is, therefore, essential to designing an effective, inclusive climate-smart cocoa policy.

Furthermore, farmers' perceived effectiveness of different CSA practices in tackling the concrete problems associated with climate change, such as drought stress, increased die-back, pests and diseases, and yield decline, needs to be explored among cocoa farmers (Ameyaw et al., 2018; Anning et al., 2022; Hashmiu, 2020; Yiridomoh et al., 2022). A study has shown that farmers' perceptions of agroforestry benefits strongly influence adoption decisions (Hashmiu, 2020). Willingness to invest in irrigation depends on how farmers weigh costs and expected benefits under their resource constraints (Gbodji et al., 2023). Also, most studies focus on the determinants of CSA practices rather than on how farmers perceive their effectiveness, which shapes adoption decisions (Inkoom and Dadzie, 2024; Ma and Rahut, 2024; Yiridomoh et al., 2022). Perceived effectiveness is a powerful predictor of CSA adoption behavior; hence, assessing these perceptions across multiple CSA practices is vital for farmer-centered policy and extension.

The policy discourses around the adoption of CSA practices among cocoa farmers in Ghana are dominated by a "triple-win" narrative that promises simultaneous gains in productivity, resilience, and mitigation through sustainable intensification practices (Asare et al., 2019; Kaba et al., 2024; Nasser et al., 2020; van Der Haar et al., 2023). Nevertheless, emerging research reveals that important synergies and trade-offs¹ have been ignored. Shade agroforestry can double cocoa yields at moderate canopy cover while increasing carbon storage (Asare et al., 2019) to combat climate change impacts. However, agroforestry requires higher labor demand and land tenure risks (Arhin et al., 2021; Inkoom and Dadzie, 2024; Kaba et al., 2024). Similarly, sustainable intensification partnerships often emphasize input-intensive production, which can increase dependence on agrochemicals, and this creates risks of deforestation if higher profitability encourages expansion (Kaba et al., 2024; Nasser et al., 2020; van Der Haar et al., 2023). Systematic cross-practice analysis of how CSA practices coexist, whether they cluster as mutually reinforcing strategies or involve trade-offs between groups of practices, remains limited in the cocoa literature. Assessing these synergies (complementarity) and trade-offs (substitutability) is crucial to move beyond generic triple-win claims toward realistic, context-specific policy instruments.

Thus, existing studies have advanced understanding of cocoa farmers' adoption of CSA decisions and their determinants in Ghana and other cocoa-producing countries (Afriyie-Kraft et al., 2020; Akrofi-Atitianti et al., 2018; Inkoom and Dadzie, 2024). However, three interrelated gaps remain: (i) an integrated analysis of socioeconomic, institutional, and biophysical drivers of cocoa climate-smart agriculture adoption in rural areas; (ii) robust

¹ The analysis focuses on cocoa Climate-Smart Agriculture (CSA) synergies and trade-offs through the interaction terms of the Multivariate Probit (MVP) model correlations, rather than isolating individual CSA impacts on yield. This methodological choice was necessary because while individual CSA practices were measured at the plot level, the yield data itself is based on farmer self-reports.

evidence on farmers' own rankings of the effectiveness of diverse climate-smart cocoa strategies in reducing climate-related farming problems; and (iii) empirical assessment of the patterns of synergy and trade-off among adopted practices. Addressing these gaps is vital for Ghana's climate-smart cocoa agenda and for international efforts to align cocoa supply chains with the Sustainable Development Goals and climate commitments (Kaba et al., 2024; Ma and Rahut, 2024; Mnuakwa et al., 2025; van Der Haar et al., 2023).

By exploring the CSA practices' perceived effectiveness and their socioeconomic determinants of adoption as well as the synergies and trade-offs, this study, built around these three objectives, can provide actionable evidence for tailoring extension, credit, land and tree tenure reforms, and private-sector sustainability programs to the realities of rural cocoa smallholders. Such evidence is indispensable for designing policies that genuinely support inclusive, climate-resilient and low-emission cocoa production in Ghana and contribute to sustainable cocoa futures globally.

2 Literature review

2.1 Factors influencing cocoa farmers' adoption of CSA practices

Climate-smart agriculture (CSA) has emerged as a central strategy for addressing the adverse effects of climate change on agricultural production, particularly in sub-Saharan Africa, where climate variability continues to threaten the livelihoods of millions of smallholder farmers (Asante et al., 2024). The CSA proposition seeks to simultaneously enhance agricultural productivity, strengthen farmers' resilience and adaptive capacity, and contribute to climate change mitigation through reduced greenhouse gas emissions. In Ghana, commonly adopted CSA practices include mulching, improved irrigation, agroforestry, organic manure application, integrated pest management, cover cropping, and soil and water conservation practices (Danso-Abbeam, 2022; Asante et al., 2024). Despite increasing policy attention toward CSA, empirical evidence remains disproportionately concentrated on food crop systems, with relatively limited research examining CSA adoption among tree crop farmers, particularly cocoa producers, who are highly vulnerable to climate variability due to the perennial nature of their production systems (Adu et al., 2026).

Existing empirical studies have identified a broad range of socioeconomic, farm-level and institutional factors influencing the adoption of CSA practices in Ghana's cocoa sector. Amerino et al. (2024), for example, examined the determinants of cocoa agroforestry adoption based on tree-density choices and found that farmer characteristics, including household size and gender, together with farm-specific factors such as farm size and labor availability, significantly influenced adoption decisions. Institutional factors, particularly membership in Farmer-Based Organizations (FBOs) and participation in agricultural training programs, further enhanced farmers' likelihood of adopting agroforestry systems. Similarly, Akrofi-Atitianti et al. (2018) evaluated the potential of CSA relative to conventional cocoa production systems to improve resilience, mitigate greenhouse gas emissions, and enhance cocoa productivity. Their findings identified farmers' age, land tenure arrangements, farm location, residential status, and access to extension services as key determinants influencing CSA adoption.

Comparable evidence has been reported that household characteristics, farm attributes, awareness of climate change, membership in farmer organizations, and access to extension services significantly influence farmers' decisions to adopt agroforestry practices (Nunoo et al., 2020). The consistency of Nunoo et al. (2020) findings suggests that both household resource endowments and institutional support systems play fundamental roles in facilitating CSA adoption among cocoa farmers. More recently, a study examined the intensity of CSA adoption among mango farmers using an integrated theoretical framework that combines the Technology Acceptance Model (TAM), the Diffusion of Innovations (DOI), and the Sustainable Livelihoods Framework (SLF) (Adu et al., 2026). The authors revealed that while larger household sizes reduced the intensity of CSA adoption, higher educational attainment, farming experience, larger farm size, improved financial capacity, and access to market information significantly increased the extent to which farmers adopted CSA technologies. The researchers' findings underscore the multidimensional nature of CSA adoption and highlight the importance of integrating behavioral, socioeconomic, and institutional perspectives to explain farmers' technology adoption decisions (Adu et al., 2026).

Although these studies have substantially advanced understanding of the determinants of individual CSA practices and adoption intensity, most employ binary-choice models, such as logistic or probit regression, that implicitly assume farmers make independent adoption decisions. This assumption is restrictive because CSA technologies are often implemented as integrated management packages rather than in isolation (Gemtoui et al., 2025; Tesfaye et al., 2021). Farmers frequently adopt multiple CSA practices simultaneously, and the adoption of one practice may either reinforce (complementarity) or reduce (substitutability) the likelihood of adopting another. Ignoring these interdependencies may result in biased parameter estimates and an incomplete understanding of farmers' adaptation strategies.

To address this limitation, recent adoption studies increasingly advocate the use of the Multivariate Probit (MVP) model, which allows the simultaneous estimation of multiple correlated binary adoption decisions while accounting for unobserved factors that jointly influence technology choices (Dessalegne et al., 2024; Oumer et al., 2025). The MVP framework explicitly captures the correlations among the error terms across different adoption equations, thereby providing empirical evidence on whether CSA practices are complements or substitutes (Mossie et al., 2026). The MVP model offers a more comprehensive analytical framework for understanding the joint adoption behavior of smallholder farmers and provides more robust evidence for designing integrated CSA policies and extension interventions that promote complementary technology packages rather than isolated practices. Given the limited application of this model within Ghana's tree crop sector, particularly among cocoa farmers, further research employing the MVP framework will generate policy-relevant evidence on the interrelationships among CSA practices and the factors driving their joint adoption.

3 Methodology

3.1 Study area

The study was conducted in Southern Ghana, where cocoa is a major cash tree crop for many farmers. The climatic conditions

in this area are highly suitable for cocoa production, as well as plantain, maize, palm, and cashew, among others. Specifically, the study focused on three Cocoa Districts in three administrative regions (Figure 1). The specific districts in Southern Ghana include Techiman in the Bono East Region, Atwima Mponua in the Ashanti Region, and Sefwi Bekwai in the Western North Region. The study districts illustrate a representative sample of the geographic diversity within the cocoa belt in Southern Ghana and span the country's climatic gradient.

3.2 Targeted population and sample size determination

The study focused on cocoa farmers in Ghana, a population estimated to comprise approximately 800,000 individuals (Akrofi-Atitianti et al., 2018). Calculating an appropriate sample size is widely recognized as a crucial statistical step in research. The calculation aims to determine an adequate sample size which can estimate results for the whole population with good precision. Following the Yamane sample size calculation formula (Yamane, 1973), the sample size was determined by:

$$n = \frac{N}{1 + N(e^2)} \quad (1)$$

From the formula above, the sample size (n) was calculated from the total estimated number of cocoa farmer households (N) of 800,000 at the 95% confidence level with a precision of ± 0.05 . The 95% confidence level enhances precision (Bryman et al., 2008) when combined with a larger sample size, as it is narrower and less variable.

Based on this calculation, the study sample size was 400 across the three districts. Nevertheless, 460 household respondents were randomly selected. Despite this, the study considered a sample size of 460 household respondents, as indicated in Table 1 below. The sample size

was adjusted to account for potential model effects and non-responses.

Furthermore, cocoa-producing regions were categorized into three strata based on climate impact zones/climate suitability for cocoa production: wet, mid, and dry (Bunn et al., 2019). The regions (Brong-Ahafo, Ashanti, and Western North) were randomly selected from each of these three strata.

Using information from the Cocoa Health and Extension Division (CHED), administrative districts (i.e., Sefwi Bekwai, Atwima Mponua, and Techiman) within the chosen areas were located during the second sampling stage. For each area, a single district was randomly selected. For the third stage, CHED provided lists of localities within the chosen districts to select several villages at random from each district. Subsequently, with assistance from Community Extension Agents, Chief farmers, assembly members, and cooperative leaders, lists of compounds within each community were compiled. From these lists, individual farm households were randomly selected using a lottery method.

3.3 Data

The primary data were sourced through structured questionnaires for cocoa farmers, an interview guide for focus group discussions and semi-structured pre-coded questionnaires for expert interviews. The structured questionnaire was administered through face-to-face interviews with the heads of sampled households or, in their absence, designated household representatives. It captured respondents' socio-demographic characteristics, climate-smart agriculture (CSA) practices adopted in cocoa production, their perceived effectiveness, barriers to their adoption, and other information. The researchers measured the frequency of CSA practice adoption on a four-point Likert scale (1 = never used, 2 = rarely used, 3 = often used, and 4 = used every year). In contrast, the perceived effectiveness of each practice was assessed on a five-point scale ranging from 0 (not effective) to 4 (highly effective).

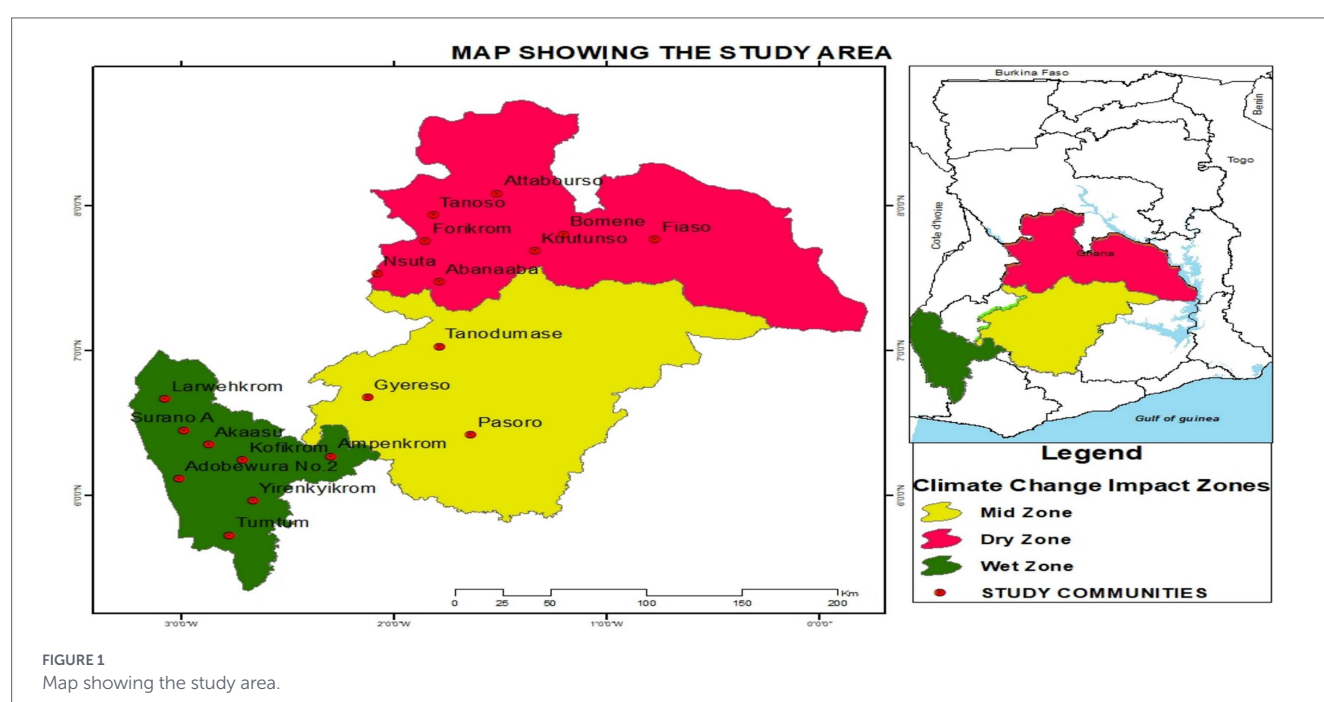


TABLE 1 Sample size distribution in the four districts.

Cocoa-producing district	Proportion of sample assigned
Sefwi Bekwai	200
Atwima Mponua	160
Techiman	100
Total	460

Following the household survey, six Focus Group Discussions (FGDs), comprising two in each study district, were conducted to validate the survey findings, clarify emerging issues, and obtain collective perspectives on the effectiveness and constraints associated with CSA practices. Each FGD included 8 participants to facilitate active participation and effective group interaction. Discussions focused on the impacts of climate change on cocoa production, CSA practices adopted, and barriers to their adoption. All the FGD discussions were conducted in the local Asante language to promote effective communication and feedback. With participants' consent, the sessions were audio-recorded, supplemented with field notes, and subsequently transcribed for analysis. Each discussion lasted approximately 45 min. To enhance the credibility and validity of the findings, the researchers employed a Computer-Assisted Personal Interview (CAPI) for the questionnaires and the interview guide, using Android phones. The researchers programmed the questionnaire and the interview guides in the KoboCollect app and administered them via face-to-face interviews by trained research assistants. The researcher monitored the data submitted to the server and ran data quality checks for inconsistencies, patterns, and outliers, providing feedback to the research assistants to improve performance.

3.4 Econometric and analytical framework

This study is underpinned by the Sustainable Livelihood Framework (SLF) developed by the Department for International Development (DFID) (Natarajan et al., 2022; Pandey et al., 2017), which provides a useful lens for examining the relationship between climate-smart agriculture (CSA) adoption and household welfare outcomes. The framework posits that a household adopts CSA practices not randomly but is shaped by five types of capital. The first capital is human capital, which includes gender, age, education, household size, farming experience, and risk-taking. This human capital captures and represents the labor viability, cognitive capacity, and decision-making profile of cocoa farmers. The second capital is natural capital, such as farm size, soil quality, home-farm distance, and agroecological zone, which reflect the environmental and physical resources available to cocoa farmers. For instance, farm size is a natural asset that dictates a cocoa farmer's capacity to adopt extensive land management practices such as agroforestry or cover cropping. The third is physical capital, which includes livestock ownership, television, radio, and mobile phones. These are assets that influence cocoa farmers' transition to modern cocoa farming production techniques and provide means to access external information. The fourth is financial and institutional capital. The type of capital relates to cocoa farmers' market access and structural support systems. These factors of capital include extension, farm distance to home, home-district distance, FBO membership, and access to climate information. These factors determine the household's integration into the formal market and extension services. Finally,

spatial or geographical capital within SLF for influencing cocoa farmers' adoption of CSA cannot be overlooked. The regional dummy variables (Ashanti, Bono East, Western North) are geographic indicators that capture latent differences in soil quality, market infrastructure, and agro-ecological conditions unique to these regions.

Drawing on this SLF framework to frame the determinants of adoption of cocoa CSA practices (Adu et al., 2026), the study structures the MVP model. It shows how the combination of these assets drives the decision to adopt cocoa-smart farming practices. Farmers could focus on human capital (education and risk-taking) as the filter through which they assess innovation's value. Experienced farmers with higher education are better equipped to process complex climate information and are more likely to adopt novel farming methods, such as hybrid planting or irrigation. Moreover, physical and financial/institutional capital are the enablers of adoption. Mobile phone access and FBO membership are key factors to consider when measuring information flow. In this study, FBOs are described as mechanisms that might mitigate the extension distance when physical reach is constrained by poor infrastructure; social networks bridge the gap. Finally, this SLF framing turns the MVP model estimation into a strategic roadmap for policy design. The study demonstrated that the adoption gap is often an asset gap. Hence, linking the SLF to the MVP model will give policymakers a clear and actionable argument that scaling climate-smart cocoa practices requires a holistic approach that addresses both household resource endowments and the institutional environment.

For estimating factors influencing the adoption of agricultural technologies, several approaches are available. For instance, count models such as Poisson or Negative Binomial regressions are used, indicating that all agricultural practices are qualitatively equivalent in adoption intensity. By giving equal weight to each technology (i.e., low-cost lining and pegging; high-cost irrigation), these models mask the distinct economic barriers and specific capital requirements of each practice, potentially resulting in overly simplistic and misleading policy proposals (Kassie et al., 2013). While network analysis provides a visually intuitive mapping of associations, it is descriptive rather than causal. As noted, those models capture the topology of adoption clusters but do not account for external factors, such as credit access, market distance, etc., that fundamentally drive a farmer's behavior (Barbuto et al., 2019; Wang et al., 2020). Relying on network metrics alone risks reducing the socio-economic reality of cocoa farming to just relational links, thereby losing sight of the primary levers of policy.

Further, Latent Class Analysis (LCA) is challenging in terms of model selection and interpretability. The task of selecting the right number of classes to construct is often guided by random statistical criteria, which are therefore not necessarily representative of distinct, meaningful socio-economic segments (Vermunt and Magidson, 2002). In smallholder cocoa households, if there is no clear, concrete narrative around which these classes can be identified, it is of little value to the design of extension services.

Finally, the choice of these complex models is a trade-off between statistical nuance and methodological stability. More advanced techniques can increase convergence instability and specification error (Greene, 2018; Wainaina et al., 2016), especially for smaller datasets. Therefore, this paper uses the Multivariate Probit (MVP) model, as it provides a good balance between the structural interdependencies of technology adoption and the transparency needed to offer actionable, evidence-based suggestions for cocoa sector development. The MVP technique addresses the error correlation by simultaneously modeling

the impacts of a set of covariates on each CSAP and generating a series of binary probit models. This method enables the identification of links between the use of various CSAPs and potential correlations between unobserved disruptions (Ahmed, 2015; Kassie et al., 2009).

It is worth emphasizing that while the MVP model is robust to the interdependence of adoption decisions, it can be supplemented by a more general study of the econometrics, and it is important to consider that the MVP model is suited for this work because it explicitly captures the hidden correlation between the error terms for multiple non-exclusive practices. By estimating these relationships simultaneously, the model provides a measure of the unobserved heterogeneity (i.e., a farmer's inherent management skills, risk appetite, or site-specific knowledge) that drives the decision to adopt bundled climate-smart agricultural (CSA) strategies. This is more compelling than independent regression models, as it can identify behavioral synergies and trade-offs and thus provide statistical evidence for getting out of the silos of agricultural policy to support integrated support systems and move toward them. Although correlation is a necessary but not sufficient condition for economic complementarity, the study interprets the MVP results in terms of latent utility interdependencies (Asfaw et al., 2016; Baiyegunhi, 2026). The correlation coefficients are a good indicator of the unobserved determinants of a CSA practice that affect the likelihood of adopting another CSA practice. To ensure robustness and to provide a more comprehensive view of adoption behavior, this study goes beyond pairwise correlations. It uses the MVP results to calculate joint adoption probabilities of specific practice bundles, which is more meaningful for policymakers than a single adoption rate alone. It is through the joint probability evaluation that the study gains a deeper insight into how different SLF assets, and therefore different combinations of them, lead to specific adoption portfolios.

To specify the MVP model, this study employed the model specifications from other empirical studies (Kangogo et al., 2021; Kassie et al., 2013) to formulate a model using nine (9) dummy variables to represent the CSA practices employed by farmers.

To mathematically frame the MVP model, let the latent utility Y_{ij}^* be denoted by a cocoa farmer i derived from adopting CSA practices j (where $j = 1, 2, 3, \dots, 9$). The observed adoption of Y_{ij} is a binary indicator where $Y_{ij} = 1$ if the latent utility is positive (actually adopted), and $Y_{ij} = 0$ otherwise.

The following structural equation defines the latent utility for each cocoa farmer j can be presented as:

$$Y_{ij}^* = \beta_j' X_i + \varepsilon_{ij}, j = 1, 2, \dots, 9$$

Where the Y_{ij}^* is the latent utility of the i -th cocoa farmer adopting the j -th practice. X_i are the explanatory factors (the livelihood assets derived from the SLF), β_j denotes the vector of parameters to be estimated for practice j -th. Finally, ε_{ij} denotes the error term, representing unobserved factors that may influence cocoa farmers' adoption of CSA practices.

The nine cocoa CSA practices used for the MVP model analysis are soil and water conservation (SWC), agroforestry, hybrid planting materials, lining and pegging (3 m*3 m), cover cropping, on-farm diversification, participation in off-farm income-generating activities, drainage construction, and irrigation. These practices were cocoa farmers' self-reported household-level measures of what they practice on their cocoa farms to enhance soil productivity.

The important part of the MVP model is that the error terms is not independent, but they are assumed to follow a multivariate normal distribution (Wooldridge, 2003):

$$\varepsilon = (\varepsilon_{i1}, \varepsilon_{i2}, \dots, \varepsilon_{i9})' \sim MVN(0, \Sigma) \quad (2)$$

The covariance matrix Σ is a symmetric 9*9 matrix with a value of 1 on the diagonal (due to identification constraints in the probit model), and ρ_{jk} denotes the off-diagonal elements (CSA practices). The elements denote the correlation coefficients between the error terms of CSA practices j and k (Wooldridge, 2002):

$$\begin{matrix} 1 & \rho_{12} & \dots & \dots & \rho_{19} \\ \rho_{21} & 1 & \dots & \dots & \rho_{29} \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \rho_{91} & \rho_{92} & \dots & \dots & 1 \end{matrix} \quad (3)$$

The parameter ρ_{jk} is vital for the study, as it captures the unobserved factors influencing the relationship between CSA practices. For instance, if $\rho_{jk} > 0$, it implies that there is synergy between CCSA practice j and k the unobserved factors such as innate cocoa farmers' skills and favorable local institutional supports that might increase the likelihood of adopting CSA practice, j also increases the likelihood of adopting CCSA practice k . Similarly, if $\rho_{jk} < 0$ it denotes a trade-off between j and k factors that influence the adoption of one cocoa CSA practice, they might hinder the adoption of the other, likely due to resource constraints such as labor or capital shortages. Finally, if $\rho_{jk} = 0$ then it implies that the adoption of cocoa CSA practices j and k is independent, conditional on the observed covariates X_i .

By estimating this MVP model, the study is essentially partitions the cocoa farmer's decision-making process into two parts: the part explained by their Livelihood Assets ($\beta_j' X_i$) and the part explained by Interdependent Strategies (ρ_{jk}), which provides the empirical basis for designing integrated cocoa development policies.

4 Results and discussion

4.1 Descriptive statistics of sampled cocoa farmers

The descriptive statistics in Table 2 provide a profile of the sampled cocoa farmers in terms of demographics, assets, farm characteristics and access to services. On average, the age of a cocoa farmer is about 51 years, and they have extensive experience in cocoa farming (22 years). This suggests that cocoa production is largely handled by mature, experienced farmers rather than youths. Household size averages about five persons, indicating moderate family labor availability for farm activities. More men are involved in cocoa production, as about 73% of cocoa farmers are men. This finding confirms that cocoa farming is male-dominated (Tham-Agyekum et al., 2023). The average year of formal education is approximately 7. Thus, many cocoa farmers have only basic or lower-secondary education.

TABLE 2 Descriptive statistics for cocoa-sampled farmers.

Variable	Mean	Std. dev.
Livestock ownership	0.363	1.423
Gender (1. male)	0.733	0.443
Age (years)	50.730	11.302
Education (years)	6.543	5.161
Household size (count)	4.813	2.581
Experience (years in cocoa)	21.783	11.213
Extension distance (Km)	6.201	6.272
District distance (KM)	13.141	18.962
Farm distance (Km)	3.029	2.470
Membership in a social group (1. Yes)	0.791	0.407
Farm size (Ha)	6.854	4.182
Television (1. Yes)	0.263	0.441
Radio (1. Yes)	0.835	0.372
Mobile phone (1. Yes)	0.841	0.366
Membership to FBO (1. Yes)	0.722	0.449
Risk taking (1. Yes)	0.861	0.346
Ashanti region	0.326	0.469
Bono east region	0.261	0.439
Western north region	0.413	0.493
Climate information access (1. Yes)	0.685	0.465

Source: Field Survey, 2024.

Livestock ownership is low but highly variable (high standard deviation), indicating that a minority keep relatively larger numbers while most keep none or very few. The mean cocoa farm size is relatively large at about 6.85 hectares, though with considerable variation, ranging from small to large holdings. Farmers travel on average 3 km to reach their farms, 6.2 km to the nearest extension office and 13.1 km to the district center, suggesting that physical access to formal services and administrative centers can be a constraint for some, given the large standard deviations.

Social and institutional participation appears high among cocoa farmers. Around 79% belong to some social group, and about 72% are members of a farmer-based organization, indicating strong social capital and potential for collective action. Access to information and communication technologies is also widespread: about 84% own a radio and 84% a mobile phone, while television ownership is lower at 26%. A large majority (86%) self-identify as willing to take risks, which could favor the adoption of new practices and technologies.

Regionally, about 33% of farmers are from Ashanti, 26% from Bono East and 41% from Western North, showing that the sample is spread across key cocoa-producing regions. Access to climate information is relatively good, with about 69% reporting they receive climate-related information, which is important for climate-smart decision-making.

4.2 Adoption of adaptation practices among cocoa farmers

Figure 2 shows very uneven adoption across cocoa CSA practices, with near-universal uptake of some structural measures and relatively

low uptake of water-related and income-diversification options. This pattern is broadly consistent with cocoa studies in Ghana and Côte d'Ivoire, where agroforestry and improved planting materials are more common than irrigation or complex SWC packages (Amerino et al., 2024; Amfo et al., 2021; Kouassi et al., 2023).

Specifically, the study reveals very high adoption levels for agroforestry and hybrid planting materials. Agroforestry (93.48%) and hybrid planting materials (86.30%) are almost universally adopted among cocoa farmers. Similar high use of shade trees or agroforestry structures has been reported for many cocoa zones, especially where policies and extension actively promote shaded cocoa or tree retention (Kumah et al., 2024; Oliver et al., 2024). Widespread use of hybrids mirrors findings that most farmers now rely on improved or hybrid cocoa varieties as part of intensification strategies (Kouassi et al., 2023; Oliver et al., 2024; Yiridomoh et al., 2022). These two practices form the core of a modern cocoa system and are often linked to extension, certification, and company- and government-led programs (Oliver et al., 2024; Yiridomoh et al., 2022).

There is moderate adoption of basic agronomic and soil practices among cocoa farmers. The higher adoption rates for lining and pegging (52.39%) and cover cropping (49.13%) reflect the fact that they are labor- and land-management-intensive activities that require few financial inputs. Lining and pegging are, in fact, primary best practices promoted extensively by cocoa extension officers, which is proof of the success of traditional extension messaging that emphasizes farm layout as the first step in productivity. Likewise, cover cropping is a simple biological action that requires minimal infrastructure, and so farmers are looking to improve soil moisture and weed control without external fertilizers. On the other hand, the moderate-to-low adoption of on-farm diversification and Soil and Water Conservation

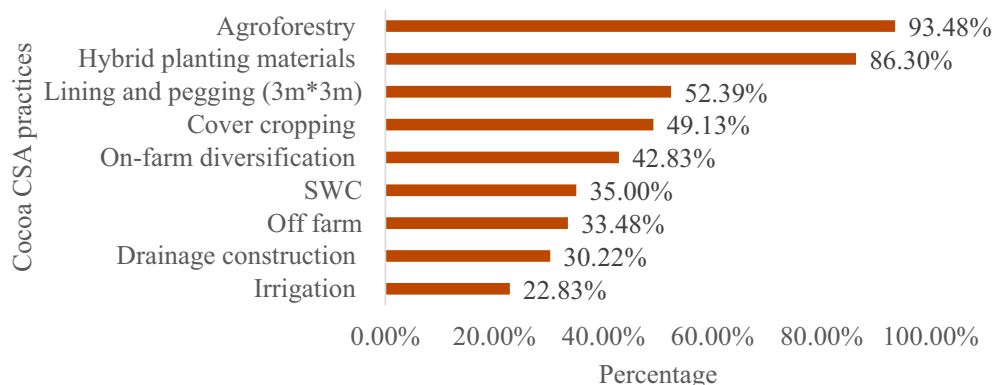


FIGURE 2
Distribution of adoption of CSA practices. Source: Field Survey, 2024.

(SWC) (35.00%) signals the influence of resource-based constraints and economic trade-offs on agriculture. Although resilient, on-farm diversification is complicated by the need for diverse planting materials, knowledge of crop cycles and the ability to cope with pest and disease interactions with the main cocoa crop. Many farmers are reluctant to diversify their plots because they fear that diversification might compete with cocoa for household labor and may only exacerbate existing land tenure uncertainty, as changing the farm structure would be considered a threat to long-term land rights.

The lower SWC adoption rate (35.00%) is the most striking manifestation of the structural gap. Unlike biological practices, SWC (such as terracing, contour drains or silt traps) is physically demanding and requires specific site-specific engineering that many smallholders may lack. Furthermore, these processes produce long-term soil health benefits at the expense of immediate land availability or significant labor hours. For the average cocoa smallholder, the “opportunity cost” of this labor is high. Without direct subsidies or community support to undertake heavy earth-moving work, SWC is less of a priority than everyday maintenance tasks (such as weeding or harvesting). Thus, adoption levels are a rational response to the “asset-constraint” reality. Cocoa farmers are not simply ignoring these practices; rather, they are choosing to put their limited land, labor and capital into the ways that will provide the best or quickest return. The study suggests that although extension messaging has been effective in promoting foundational farm management (lining and pegging) and the harder transitions to diversified, climate-resilient landscapes, these require institutional support to overcome the significant labor and financial barriers to structural conservation and farm diversification. These findings are consistent with CSA literature (Amfo et al., 2021; Yiridomoh et al., 2022).

However, the study reveals a low adoption level for irrigation, drainage, and off-farm income diversification. Irrigation (22.83%) and drainage (30.22%) have the lowest adoption among the physical practices, as in other cocoa and smallholder systems, where small-scale irrigation is capital- and knowledge-intensive (Gudina and Alemu, 2024; Kurgat et al., 2020). Off-farm income (33.48%) is also limited, despite evidence that non-farm earnings can enable investment in climate-smart practices (Agbenyo et al., 2022; Kpadonou et al., 2017; Teklu et al., 2023). Nevertheless, the relatively low participation in off-farm income activities indicates that the agricultural sector remains the primary, and often the only, economic source for these households. This is not a lack of interest but an indication of structural

obstacles in the rural economy: lack of access to liquid financial capital, labor shortages during peak cocoa seasons, as well as lack of job market development in the non-farm sector is very prevalent. Hence, farmers continue to work in this environment where the opportunity cost of turning away from cocoa is high, and the entry cost to the off-farm business is still too high, so they lean on land-based production.

Overall, cocoa farmers in Ghana have strongly adopted agroforestry and hybrid varieties, moderately adopted basic agronomy and soil cover, and lag in water-management and income diversification.

4.3 Perceived effectiveness of CSA in reducing climate change effects in cocoa

Table 3 shows the rating difference in how CSA practices are perceived to reduce climate-related problems in cocoa production. By visual inspection, agronomic/field practices appear effective, but knowledge gaps (high uncertainty) remain for several practices. The study reveals that across CSA practices, agroforestry and hybrid planting materials are highly rated by about 85% of the farmers as effective or highly effective (42.01 and 44.75%; 48.51 and 35.40%, respectively), with very low uncertain responses (only 6%) and limited ineffective/highly ineffective responses (less than 10%). This finding aligns with the literature, which shows that improved varieties and cocoa agroforestry increase yields, buffer against temperature and moisture stress, and contribute to mitigation, making them strong “triple-win” CSA options (Blaser-Hart et al., 2021; Meshesha et al., 2022; Teklu et al., 2022).

However, the study reveals that several CSA practices (off-farm diversification, irrigation, drainage, SWC, and on-farm diversification) are perceived to be effective at 40–47%, but their effectiveness is also rated as uncertain at 40–46%. The high levels of uncertainty (near 40%) for these climate-smart practices indicate that cocoa farmers face a large adoption gap, in which the perceived risk of innovation is often far greater than its technical benefits. When almost half of the respondents still believe that a particular practice is effective at all, it is clear that farmers are not just lacking information but are also coping with high subjective risk about their ability to implement these approaches in their socio-economic contexts. Also, the high level of uncertainty regarding irrigation, despite the overall effectiveness rating, is likely due to the high capital and maintenance costs of the mechanical process. In contrast to biological plant life, irrigation requires constant access to energy, special spare parts, and technical expertise that is

TABLE 3 Perceived effectiveness and uncertainty across CSA options.

Practice	Effective + Highly effective (%)	Uncertain (%)	Negatives (%)	CSA evidence highlights
Hybrid materials	83.91	5.98	10.12	Higher, more stable yields and adaptation
Agroforestry	86.76	5.48	7.76	Microclimate buffering, carbon, diversified income
Lining and pegging	72.24	21.18	6.58	Better spacing improves water and nutrient use.
Cover cropping	67.20	27.21	5.58	Soil cover, moisture, erosion control
SWC	55.81	40.47	3.72	Strong erosion reduction, carbon gains
Drainage	50.82	44.24	4.94	Reduces waterlogging, complements SWC.
Off-farm diversification	50.00	43.69	6.31	Income buffering and resilience
On-farm diversification	49.06	46.46	4.48	Risk spreading, food security
Irrigation	52.09	41.93	5.99	Productivity + adaptation, but cost issues

Source: Field Survey, 2024.

hard to acquire in remote cocoa-growing communities. In a controlled climate, there is uncertainty for farmers about the viability of irrigation in the field due to water-table fluctuations, infrastructure longevity, and the financial cost of failure. Thus, the high level of uncertainty is a hurdle to the adoption of irrigation, and cocoa farmers are reluctant to invest in technologies that could become stranded assets without sustained institutional support.

The lower confidence scores for on-farm diversification also reveal the deep-seated fear farmers have of moving away from the cocoa-centric model. For smallholders, cocoa is a long-term, high-value commodity, and there is significant concern that intercropping could compete with cocoa for soil nutrients, shade, or moisture. Uncertainty is compounded by market risk, and farmers may not know whether they have the market access to sell different crops or if the introduction of new pests and diseases will hurt their primary cocoa income. Hence, diversification is less a stability solution and more a potential source of income risk, which explains the high levels of hesitation in the data.

These perceptions ultimately dictate farmers' adoption of CSA, and a widespread "wait and see" risk-aversion mindset is prevalent. Rather than fully implement these, farmers often engage in "partial adoption," testing technologies on small experimental patches to hedge against potential losses. This behavior indicates that extension services are failing to convert awareness into the conviction necessary to scale. To overcome this, policy interventions need to move beyond simple effectiveness and put in place mechanisms that de-risk the farmer (by providing local demonstration farms, cooperative cost-sharing, and market guarantees) and provide evidence of uncertainty that can turn it into concrete confidence. These findings align with previous studies, which show that farmers see CSA as promising, but adoption and clear benefit perception depend on information, training, and context (Mairura et al., 2021; Meshesha et al., 2022; Nyang'au et al., 2021).

SWC (47% effective; 9% highly effective; only 4% negative) and drainage construction (43% effective; 8% highly effective) are widely

perceived as helpful in addressing erosion, runoff and waterlogging. Global and Ethiopian meta-analyses confirm that SWC, mulching and related practices strongly reduce soil erosion and enhance yields and soil carbon (Ma and Rahut, 2024; Teklu et al., 2022). Irrigation has slightly lower perceived effectiveness (29% effective; 23% highly effective) and almost half are uncertain (42%), mirroring meta-analytic findings that drip and deficit irrigation can greatly boost productivity but are constrained by cost and implementation complexity (Adimassu et al., 2025b). Similar mixed perceptions are reported in other regions in the global south, where irrigation is seen as effective but not universally accessible (Ceesay et al., 2025; Teklu et al., 2022; Tessema et al., 2025). Cover cropping and lining and pegging are rated very positively: about 67–72% effective/highly effective and relatively low uncertainty (27 and 21%). This matches broader CSA literature that emphasizes cover crops, improved layout and good agronomy as key to moisture conservation, weed control, and yield stability under climate stress (Adimassu et al., 2025a; Bhatnagar et al., 2024; Ma and Rahut, 2024).

The pattern suggests that farmers most clearly perceive genetic and structural system changes (hybrids, agroforestry) as effective in reducing climate impacts, consistent with cocoa-specific work showing shade trees and improved material enhance resilience and carbon storage with limited yield penalties when well designed (Akrofi-Atitianti et al., 2018; Blaser-Hart et al., 2021). Water/soil management and diversification strategies are also widely seen as effective but accompanied by high uncertainty, which aligns with global evidence that these practices are context-dependent and their benefits become clear only after some years of adoption, or with adequate support services (Belay et al., 2022; Kabato et al., 2025; Mairura et al., 2021; Saran et al., 2024). Studies from Ethiopia, Kenya, The Gambia and Ghana emphasize that positive perceived effectiveness strongly drives adoption, and that improved information, extension and climate services are crucial to convert "uncertain" perceptions into confident uptake of CSA packages (Belay et al., 2022; Nyang'au et al., 2021; Tessema et al., 2025).

TABLE 4 Spearman's rank correlation coefficients.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) On-farm Div.	1.000								
(2) Off-farm diversification	0.738***	1.000							
(3) Irrigation	0.467***	0.390***	1.000						
(4) Drainage	0.369***	0.416***	0.496***	1.000					
(5) SWC	0.331***	0.375***	0.438***	0.822***	1.000				
(6) Lining/ pegging	0.410***	0.370***	0.519***	0.392***	0.409***	1.000			
(7) Hybrid Mats.	0.304***	0.212***	0.365***	0.287***	0.270***	0.554***	1.000		
(8) Cover crop	0.235***	0.314***	0.439***	0.502***	0.508***	0.427***	0.220***	1.000	
(9) Agroforestry	0.193***	0.236***	0.171**	0.212***	0.117*	0.292***	0.490***	0.178***	1.000

Source: Field Survey, 2024. ***represents 1% significant level.

Furthermore, the Spearman rank correlation matrix examines the relationships among farmers' Likert-scale ratings (1 = highly ineffective to 5 = highly effective) for each CSA's perceived effectiveness in reversing negative climate impacts on cocoa production (Table 4). The study reveals that all the estimated coefficients are positive and highly statistically significant. These imply that farmers who perceive one measure as effective in reducing climate-related problems (drought stress, waterlogging, erosion, yield loss) also tend to rate others positively. Nevertheless, it is important to highlight that the strength of these correlations varies, suggesting the existence of perceived packages of strategies that farmers believe work best when implemented together.

The clearest cluster is around water and soil management: irrigation, drainage construction, soil and water conservation (SWC), cover cropping, and, to some extent, lining and pegging. Correlations such as drainage-SWC (0.822), drainage-cover crops (0.502), SWC-cover crops (0.508), and irrigation-drainage (0.496) indicate that farmers frequently give similar (usually high) effectiveness scores to these measures. This pattern suggests that they experience the greatest reduction in climate-related problems when these practices are combined. Empirical work on cocoa in Ghana supports this view: farmers widely adopt mulching, shade trees, leguminous intercrops, and other soil-water conservation practices as core responses to rising temperatures and erratic rainfall because they stabilize yields and increase productivity under climate stress (Akrofi-Atitianti et al., 2018; Amfo et al., 2021). Likewise, broader CSA evidence shows that cover crops, mulching and water-saving practices improve soil moisture, soil organic carbon, and yield resilience to drought and rainfall variability (Guja and Bedeke, 2025; Kabato et al., 2025; Nasser et al., 2020).

On-farm and off-farm diversification are also very strongly correlated (0.738). Farmers who rate on-farm diversification as effective tend to see off-farm income diversification as equally important for coping with climate variability. This finding is supported by other studies indicating that perceived effectiveness of crop and livestock diversification, intercropping cocoa, and off-farm activities are central strategies for spreading income risk under climate change (Amfo et al., 2021; Magesa et al., 2023). Across smallholder farming systems in Africa, diversification is one of the most common and effective adaptation strategies, supporting income smoothing and food security as climate hazards intensify (Akinyi et al., 2021; Guja and Bedeke, 2025; Niether et al., 2020).

The study further reveals that the perceived effectiveness of planting technologies and genetic improvement reduces climate risks associated with cocoa production. For instance, lining and pegging are moderately correlated with irrigation (0.519), SWC (0.409) and hybrid planting materials (0.554), while hybrids are strongly associated with agroforestry (0.490). These findings imply that farmers recognize that the effectiveness of spacing and improved cocoa varieties is best when combined with good soil moisture management and shade trees. These findings are consistent with the literature, which suggests that improved, drought-tolerant cocoa varieties, when planted in well-managed, shaded agroforestry systems, enhance yield stability, buffer high temperatures, and contribute to long-term production resilience (Akrofi-Atitianti et al., 2018; Attiogbé et al., 2024; Niether et al., 2020). These scientific findings help explain why farmers tend to rate hybrids, agroforestry, and associated management practices toward the effective or highly effective end of the Likert scale.

The relatively low but positive correlation between agroforestry and cover cropping (0.178) indicates that, while their perceived effectiveness is broadly complementary, farmers do not treat all practices as equally useful or interchangeable. Instead, they differentiate according to the specific problems they face (e.g., drought, waterlogging, or income volatility) and the costs or labor requirements of each option. It has been identified that CSA adoption behavior is shaped by perceived response efficacy, self-efficacy, and perceived costs and risks (Ceesay et al., 2025). Systematic reviews underline that the effectiveness of CSA practices generally increases when complementary practices are applied together, creating synergies in productivity, resilience and sometimes mitigation (Bhatnagar et al., 2024; Guja and Bedeke, 2025). This resonates with the strongest associations among perceived effectiveness of CSA practices from integrated packages, especially soil and water conservation (drainage, SWC, cover crops, irrigation) and diversification (on- and off-farm), with improved planting materials and agroforestry as important complements.

Generally, the correlation results suggest that cocoa farmers perceive climate-smart strategies not as stand-alone tools but as inter-linked components of a broader adaptation portfolio. Water and soil management measures, diversification, and improved planting materials in tree-based systems are collectively judged as most effective in reducing farming problems associated with climate change and variability, which is consistent with quantitative impact evaluations and

reviews from Ghanaian cocoa systems and smallholder agriculture more generally (Akrofi-Atitianti et al., 2018; Amfo et al., 2021).

4.4 Socio-economic drivers for the adoption of cocoa CSA practices

Table 5 presents the results of the multivariate probit (MVP) model, which jointly explains adoption of nine (likely cocoa climate-smart) strategies: off-farm income, on-farm diversification, agroforestry, cover cropping, hybrid planting materials, lining and pegging, soil and water conservation (SWC), drainage construction, and irrigation. The highly significant Wald chi-square and likelihood-ratio tests of the correlation coefficients (ρ) confirm the use of the MVP and that adoption decisions are statistically interdependent. This finding is aligned with other researchers (Diro et al., 2022; Oumer et al., 2025; Teklu et al., 2023). It is important to note that the signs and significance indicate whether the latent propensity to adopt each practice increases or decreases, holding other variables constant.

Starting with the socio-demographic characteristics, the study reveals that gender has no statistically significant effect on any of the nine practices. This finding contrasts with many studies, which show that male-headed households are more likely to adopt technologies due to greater access to land, education, and services (Gudina and Alemu, 2024; Dessalegne et al., 2024; Neway and Zegeye, 2022). For example, male heads in Ethiopia are more likely to adopt CSA and agroforestry (Saran et al., 2024; Tega and Bojago, 2024), and gender significantly shapes overall technology adoption in Ethiopia and Ghana (Feyisa, 2020; Neway and Zegeye, 2022). The lack of significance here suggests that gender gaps may be smaller in the cocoa production population.

Age negatively influences on-farm diversification ($p < 0.05$) and positively influences irrigation ($p < 0.05$). This finding aligns with mixed evidence that older farmers sometimes resist new practices but may be more willing to invest in long-term, capital-intensive options like irrigation once resources accumulate (Diro et al., 2022; Gudina and Alemu, 2024). Meta-analyses for Ethiopia and broader developing-country contexts show that age can either discourage or, in some cases, support adoption, depending on the technology horizon and risk profile (Ruzzante et al., 2021; Teklu et al., 2023).

Education reduces on-farm diversification ($p < 0.1$) but is not significant for other cocoa climate-smart practices. Many studies find education generally promotes adoption by improving information processing and the ability to manage complex practices (Dessalegne et al., 2024; Ruzzante et al., 2021; Tega and Bojago, 2024). The negative effect here may indicate that educated farmers specialize in fewer, more profitable enterprises or in off-farm work rather than diversifying crops on-farm (Danso-Abbeam et al., 2020; Oumer et al., 2025).

It reveals that household size significantly shapes several practices. For instance, it decreases agroforestry adoption (marginally significant at the 10% level) and lining and pegging (significant at the 5% level) but increases cover cropping and drainage construction (both significant at the 1% level). Larger households provide more labor, often favoring labor-intensive climate-smart practices such as conservation agriculture and soil fertility management (Gudina and Alemu, 2024; Dessalegne et al., 2024; Oumer et al., 2025). The positive effects on cover cropping and drainage fit this pattern, while the negative signs for agroforestry and pegging may reflect land or labor competition with staple crops or the migration of working-age members (Oumer et al., 2025; Teklu et al., 2023; Zegeye et al., 2022).

Farming experience increases on-farm diversification ($p < 0.05$) and irrigation ($p < 0.05$) but decreases the adoption of hybrid planting materials ($p < 0.01$). Experience has often been associated with greater adoption of complex, long-term technologies such as conservation, CSA packages, and irrigation (Diro et al., 2022; Dessalegne et al., 2024; Zegeye et al., 2022). The negative association with hybrids may reflect experienced farmers' attachment to local varieties or skepticism about seed markets, a pattern also noted for improved varieties in some contexts (Donkoh et al., 2019; Ruzzante et al., 2021).

Furthermore, access to extension and markets (distance) influences cocoa climate-smart practices. Extension distance strongly discourages adoption of off-farm income diversification, on-farm diversification, agroforestry, SWC and drainage ($p < 0.10$ – 0.01). This finding aligns with broader evidence that greater physical distance from extension services reduces contact, information flow, and adoption of CSA, land management, and improved agronomic practices (Gudina and Alemu, 2024; Ruzzante et al., 2021; Zegeye et al., 2022). For example, Ethiopian and Ghanaian studies repeatedly show that closer extension contact increases the uptake of conservation agriculture, crop diversification, soil fertility management, bunds, and irrigation (Donkoh et al., 2019; Dessalegne et al., 2024).

Similarly, district (administrative) distance has a more nuanced role for cocoa farmers' adoption of climate-smart practices. For instance, the study reveals that a district's distance from communities reduces on-farm diversification while increasing the adoption of cover cropping, hybrid seeds, pegging, and irrigation (all significant). Studies have shown that distance to towns and markets often reduces adoption by limiting access to inputs, credit and information (Donkoh et al., 2019; Feyisa, 2020; Zegeye et al., 2022). The positive effect here for some sustainable land practices may indicate that farmers further from district centers rely more on in-situ adaptation measures (cover crops, hybrids, irrigation) because they face more pronounced climate or market risks, similar to findings where remote farmers adopt CSA to buffer against shocks (Djido et al., 2021; Musyoki et al., 2022). Farm distance (from homestead to plots) discourages on-farm diversification and irrigation but increases agroforestry, SWC and drainage (significant at 5–1% levels). This finding is consistent with the literature that farmers tend to invest in labor-intensive soil and water conservation and agroforestry on distant or erosion-prone plots to protect land quality, while reserving nearer plots for intensive, high-management crops and irrigated production (Diro et al., 2022; Dessalegne et al., 2024; Oumer et al., 2025).

Membership in social groups has a complex pattern in relation to the adoption of cocoa climate-smart practices. The study found that membership in a social group increases off-farm diversification ($p < 0.05$) but strongly reduces hybrid adoption and pegging ($p < 0.01$ and $p < 0.1$). Social capital, as a form of membership in an FBO, usually enhances adoption through information sharing and risk pooling (Dessalegne et al., 2024; Ruzzante et al., 2021; Tega and Bojago, 2024; Teklu et al., 2023).

The negative effect on climate-smart practices could indicate group norms favor traditional varieties and planting layouts, or that groups are oriented to other technologies (e.g., non-hybrid CSA) rather than input-intensive options. Similarly, FBO membership significantly promotes hybrid seed adoption ($p < 0.05$) but strongly discourages SWC, drainage and irrigation ($p < 0.01$ – 0.10). This pattern mirrors findings from Ghana, where FBOs and research partnerships increase adoption of improved varieties and agronomic packages but not always structural conservation (Danso-Abbeam et al., 2020;

TABLE 5 Multivariate probit coefficient estimates.

Variables	(1) Off farm	(2) On-farm diversification	(3) Agroforestry	(4) Cover cropping	(5) Hybrid planting materials	(6) Lining and pegging (3 m*3 m)	(7) SWC	(8) Drainage construction	(9) Irrigation
Gender	−0.167 (0.142)	0.083 (0.141)	0.269 (0.219)	0.082 (0.173)	−0.086 (0.180)	0.082 (0.157)	0.217 (0.168)	0.192 (0.175)	0.238 (0.204)
Age	0.007 (0.008)	−0.018** (0.008)	−0.006 (0.009)	−0.009 (0.008)	−0.003 (0.011)	−0.001 (0.007)	−0.006 (0.007)	−0.007 (0.007)	0.008 (0.009)
Education	0.004 (0.012)	−0.028* (0.016)	−0.023 (0.017)	−0.019 (0.016)	0.008 (0.017)	−0.001 (0.013)	−0.004 (0.013)	−0.019 (0.012)	−0.009 (0.018)
House size	−0.041 (0.031)	0.006 (0.030)	−0.081* (0.045)	0.091*** (0.035)	−0.047 (0.042)	−0.067** (0.031)	0.012 (0.031)	0.060** (0.029)	−0.034 (0.039)
Experience	−0.008 (0.008)	0.020** (0.008)	−0.000 (0.011)	0.006 (0.009)	−0.037*** (0.012)	−0.007 (0.008)	−0.001 (0.010)	0.006 (0.008)	0.027** (0.011)
Extension distance	−0.047*** (0.013)	−0.020* (0.012)	−0.038** (0.016)	−0.008 (0.012)	0.015 (0.017)	−0.012 (0.012)	−0.046*** (0.012)	−0.058*** (0.014)	−0.017 (0.013)
District distance	0.011** (0.006)	−0.035*** (0.006)	−0.009 (0.009)	0.028*** (0.007)	0.030*** (0.007)	0.009* (0.005)	−0.009 (0.007)	−0.000 (0.008)	0.034** (0.015)
Farm distance	−0.037 (0.030)	−0.078** (0.038)	0.169*** (0.056)	−0.122*** (0.036)	−0.024 (0.042)	0.009 (0.030)	0.110*** (0.031)	0.115*** (0.030)	−0.109** (0.047)
Social group	0.520** (0.231)	−0.108 (0.223)	0.021 (0.316)	−0.028 (0.223)	−0.855*** (0.231)	−0.391* (0.231)	0.381 (0.233)	0.385 (0.251)	0.115 (0.350)
Farm size	−0.003 (0.018)	0.079*** (0.017)	0.031 (0.034)	0.007 (0.022)	0.088*** (0.027)	0.009 (0.017)	−0.012 (0.019)	−0.017 (0.018)	0.047** (0.023)
Livestock (count)	0.053 (0.049)	0.043 (0.054)	−0.006 (0.073)	0.029 (0.056)	0.045 (0.063)	0.126** (0.051)	0.014 (0.051)	−0.002 (0.043)	0.201*** (0.049)
Television	−0.197 (0.160)	0.156 (0.159)	0.215 (0.264)	0.129 (0.196)	−0.323* (0.194)	−0.254 (0.171)	0.047 (0.149)	−0.493*** (0.148)	0.884*** (0.195)
Radio	−0.196 (0.193)	−0.606*** (0.206)	0.586* (0.317)	−0.342 (0.211)	−0.221 (0.329)	−0.503** (0.205)	−0.227 (0.170)	−0.200 (0.184)	−0.232 (0.251)
Mobile phone	−0.079	0.195	−0.650*	0.613***	−0.106	0.015	0.627***	0.649***	1.244***

(Continued)

TABLE 5 (Continued)

Variables	(1) Off farm	(2) On-farm diversification	(3) Agroforestry	(4) Cover cropping	(5) Hybrid planting materials	(6) Lining and pegging (3 m*3 m)	(7) SWC	(8) Drainage construction	(9) Irrigation
	(0.194)	(0.211)	(0.375)	(0.218)	(0.301)	(0.190)	(0.206)	(0.207)	(0.271)
FBO	0.186	0.112	0.378	0.092	0.512**	0.023	−1.292***	−1.337***	−0.548*
	(0.213)	(0.227)	(0.315)	(0.222)	(0.240)	(0.210)	(0.214)	(0.254)	(0.310)
Risk taking	−0.668***	−0.616***	0.370*	0.100	−0.141	−0.013	0.123	0.185	−1.158***
	(0.216)	(0.216)	(0.223)	(0.233)	(0.234)	(0.208)	(0.222)	(0.228)	(0.303)
Ashanti region	0.274	0.364	0.591	−1.975***	−1.361***	−1.150***	−0.992**	−2.191***	−0.134
	(0.295)	(0.302)	(0.420)	(0.360)	(0.340)	(0.275)	(0.417)	(0.378)	(0.558)
Western north region	0.491**	−1.383***	0.870***	1.089***	0.342	0.424*	1.107***	0.810***	2.638***
	(0.245)	(0.266)	(0.332)	(0.245)	(0.387)	(0.243)	(0.224)	(0.277)	(0.418)
Climate information	0.372**	−0.020	0.229	0.883***	0.482**	0.805***	0.657***	0.482*	1.284***
	(0.181)	(0.171)	(0.263)	(0.197)	(0.196)	(0.174)	(0.206)	(0.252)	(0.397)
Constant	−0.222	1.817***	0.529	−0.997	2.512***	0.707	−1.013	−0.696	−4.769***
	(0.567)	(0.612)	(0.810)	(0.618)	(0.814)	(0.583)	(0.627)	(0.721)	(0.975)
Wald chi2(171) =	2223.08								
Prob > chi2 =	0.0000								
Observations	455								
Likelihood ratio test of rho21 = rho31 = rho41 = rho51 = rho61 = rho71 = rho81 = rho91 = rho32 = rho42 = rho52 = rho62 = rho72 = rho82 = rho92 = rho43 = rho53 = rho63 = rho73 = rho83 = rho93 = rho54 = rho64 = rho74 = rho84 = rho94 = rho65 = rho75 = rho85 = rho95 = rho76 = rho86 = rho96 = rho87 = rho97 = rho98 = 0: chi2(36) = 322.022: Prob > chi2 = 0.0000									

Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Reference category: Bono East Region.

Donkoh et al., 2019). Similar studies highlight that group-based seed and input projects can target hybrids and row planting, while physical conservation works often depend more on public programs and extension campaigns (Diro et al., 2022; Dessalegne et al., 2024; Reshad et al., 2025).

Notwithstanding, farm assets such as land, livestock, and household capital shape the adoption of climate-smart technologies. Farm size increases adoption of on-farm diversification, hybrid planting materials and irrigation at various significant levels. Larger farms allow experimentation with multiple technologies, better risk spreading, and more capacity to absorb losses, reflecting a consistent finding across empirical and meta-analyses (Asante et al., 2024; Oumer et al., 2025; Ruzzante et al., 2021; Tega and Bojago, 2024; Zegeye et al., 2022). Thus, land size is a robust positive determinant of adoption, particularly for improved varieties, fertilizer, zero tillage, row planting, agroforestry and conservation measures (Gudina and Alemu, 2024; Dessalegne et al., 2024; Oumer et al., 2025; Tega and Bojago, 2024).

Livestock ownership increases adoption of pegging by 5% and of irrigation by 1% at the 5% significance level. Livestock is a proxy for wealth and risk-bearing capacity, helping farmers adopt CSA practices. The strong association of livestock with irrigation implies that better-off farmers can invest in pumps, canals, or wells to enhance farm productivity. These findings are consistent with other studies that show higher livestock holdings tend to raise the adoption of capital-intensive technologies and conservation measures (Oumer et al., 2025; Teklu et al., 2023; Zegeye et al., 2022). Similarly, ownership of a television (TV) does not significantly affect most practices but reduces hybrid and drainage adoption and increases irrigation at the 1% significant level. Radio ownership, in contrast, powerfully reduces on-farm diversification and pegging but increases agroforestry at the 10% marginal significance level. Communication devices are increasingly recognized as key channels for climate and technology information (Asante et al., 2024; Diro et al., 2022; Djido et al., 2021; Musyoki et al., 2022). The mixed signs of TV ownership's association with CSA indicate that different information content (e.g., the promotion of specific technologies or off-farm opportunities) and audience targeting may steer households toward certain practices while discouraging others.

Mobile phone ownership strongly increases adoption of cover cropping, SWC, drainage, and especially irrigation, all significant at the 1% level, while reducing agroforestry adoption at the 10% significant level. Mobile-based weather information and extension tools play a vital role in increasing the adoption of water management, multiple cropping and CSA bundles among farmers. For instance, mobile phones have emerged as a critical enabler of CSA and multi-technology adoption by improving access to extension services, markets, and climate information (Diro et al., 2022; Djido et al., 2021; Musyoki et al., 2022; Teklu et al., 2023). The strong positive coefficients for several labor- and knowledge-intensive practices are consistent with this evidence.

Risk attitudes and livelihood strategies play a vital role in the adoption of CSA practices. Risk-taking attitude is negatively associated with off-farm diversification, on-farm diversification, and irrigation, all at 1% significant levels, but positively associated with agroforestry at the 10% significant level. This finding suggests that more risk-averse farmers diversify income sources and adopt irrigation as insurance. In contrast, risk-takers may prefer longer-term agroforestry investments that promise higher but uncertain payoffs. CSA adoption studies increasingly emphasize risk preferences: more

risk-averse farmers often adopt soil and water conservation and insurance-linked practices, while risk-tolerant farmers engage in input-intensive or speculative innovations (Oumer et al., 2025; Teklu et al., 2023). In Kenya, for example, risk attitudes significantly affected the adoption of terraces and ridges (Musyoki et al., 2022). Off-farm diversification as a dependent outcome is influenced by social groups (positively) and negatively by extension distance and risk-taking. Evidence from Ghana shows that non-farm income diversification generally enhances the capacity to adopt agricultural technologies by easing liquidity constraints (Danso-Abbeam et al., 2020; Oumer et al., 2025). At the same time, high dependence on off-farm income can reduce time available for on-farm practices, implying complex bidirectional effects (Danso-Abbeam et al., 2020; Teklu et al., 2023).

The regional dummies indicate large location effects. Compared with the reference region, Ashanti farmers are significantly less likely to adopt cover cropping, hybrids, pegging, SWC, and drainage, with adoption rates ranging from 1 to 5%. Western North farmers are much more likely to adopt off-farm diversification, agroforestry, cover cropping, pegging, SWC, drainage and irrigation, but less likely to diversify on-farm (significant for most). Spatial heterogeneity in CSA and technology adoption is well documented: agroecology, market access, program targeting, and cultural practices produce sharp regional contrasts even within a single country (Asante et al., 2024; Donkoh et al., 2019; Reshad et al., 2025; Teklu et al., 2023). Studies in the global south show region/location dummies are among the most robust predictors of multiple CSA and technology packages (Donkoh et al., 2019; Gudina and Alemu, 2024; Reshad et al., 2025; Zegeye et al., 2022).

Access to climate information strongly and positively affects off-farm diversification, cover cropping, hybrid seeds, pegging, SWC, drainage and irrigation ($p < 0.05$ – 0.01), with a particularly large coefficient for irrigation. This finding aligns with growing evidence that weather and climate information services (WCIS) are a key driver of CSA adoption, particularly in water management and multiple cropping (Djido et al., 2021; Musyoki et al., 2022; Teklu et al., 2023). Access to climate information via extension, radio, or mobile platforms significantly increases adoption of crop diversification, agroforestry, soil fertility management, and water-saving technologies (Asante et al., 2024; Diro et al., 2022; Djido et al., 2021).

4.5 Synergies and trade-offs for cocoa CSA practices

Table 6 demonstrates that the correlations among practices show clear bundles and trade-offs. The pairwise correlation matrix shows how farmers combine the nine strategies and whether practices tend to be complementary/synergistic (positive correlation) or substitutes/trade-offs (negative correlation).

The study revealed that off-farm income has a positive correlation with on-farm diversification (0.326) and SWC (0.242). The finding suggests that households with off-farm earnings are better able to diversify their crop mix and invest in soil conservation. Similar links between non-farm income, diversification, and adoption of climate-smart agriculture (CSA) are reported in Ethiopia, Tanzania and Southern Africa, where off-farm income relaxes liquidity constraints and supports technology uptake (Gudina and Alemu, 2024; Kurgat et al., 2020; Makate et al., 2019; Negera et al., 2022). Irrigation shows strong positive correlations with most structural and input-intensive practices such as cover cropping (0.398), SWC (0.415), drainage (0.353), pegging (0.280) and hybrids (0.156). This finding indicates a package of water

TABLE 6 Pairwise correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) Off farm	1.000								
(2) on-farm diversification	0.326	1.000							
	(0.000)								
(3) Irrigation	0.174	−0.104	1.000						
	(0.000)	(0.025)							
(4) Hybrid planting materials	−0.039	−0.128	0.156	1.000					
	(0.404)	(0.006)	(0.001)						
(5) Agroforestry	0.150	0.033	0.039	0.176	1.000				
	(0.001)	(0.482)	(0.407)	(0.000)					
(6) cover cropping	0.077	−0.148	0.398	0.214	0.083	1.000			
	(0.100)	(0.002)	(0.000)	(0.000)	(0.074)				
(7) Lining and pegging (3 m*3 m)	0.077	−0.019	0.280	0.418	0.066	0.353	1.000		
	(0.100)	(0.677)	(0.000)	(0.000)	(0.161)	(0.000)			
(8) SWC	0.242	0.019	0.415	0.120	0.102	0.300	0.298	1.000	
	(0.000)	(0.686)	(0.000)	(0.010)	(0.029)	(0.000)	(0.000)		
(9) Drainage construction	0.175	−0.005	0.353	0.138	0.078	0.281	0.258	0.778	1.000
	(0.000)	(0.914)	(0.000)	(0.003)	(0.095)	(0.000)	(0.000)	(0.000)	

Probability values are in parentheses.

management, soil protection, and improved seed practices. Comparable complementarities between irrigation, SWC, improved varieties and fertilizers are widely documented in Ethiopia and Tanzania, where multivariate probit and meta-analyses show CSA practices are often adopted jointly rather than in isolation (Adimassu et al., 2025b; Teklu et al., 2022; Wainaina et al., 2016). The very high SWC-drainage correlation (0.778) confirms that farmers who invest in soil structures also construct drainage, reflecting an integrated land and water management strategy consistent with CSA bundles described in Ethiopia, Ghana and Southern Africa (Adimassu et al., 2025b; Gudina and Alemu, 2024; Issahaku and Abdulai, 2020; Makate et al., 2019).

For hybrid planting materials, pegging and lining, and cover cropping, the study reveals that hybrid planting materials are strongly associated with pegging (0.418) and moderately with irrigation (0.156) and agroforestry (0.176), while pegging and lining also correlate with cover cropping (0.353) and SWC (0.298), all significant. This pattern suggests that once farmers adopt hybrids, they also improve planting geometry and soil management to realize their yield potential. Studies from Tanzania, Ethiopia and Malawi similarly find complementarities among improved varieties, fertilizer/soil practices and better agronomy (row planting, spacing) (Kurgat et al., 2020; Teklu et al., 2023; Makate et al., 2019). Cover cropping itself is positively related to irrigation, pegging, SWC and drainage, forming part of a conservation-oriented cluster. Meta-analyses show cover crops and conservation tillage often co-occur, enhancing soil organic carbon and resilience (Adimassu et al., 2025b; Bai et al., 2019).

Similarly, agroforestry within CSA portfolios has moderate positive links with hybrids (0.176) and weaker but positive correlations with most structural practices, though many are not statistically significant. This finding is consistent with reviews showing agroforestry is frequently part of broader CSA portfolios, combined with improved varieties and soil fertility management rather than used alone (Kurgat et al., 2020; Ntawuruhunga et al., 2023; Teklu et al., 2023). Systematic

reviews of climate-smart agroforestry emphasize its role alongside other CSA practices in boosting income, resilience and mitigation (Bai et al., 2019; Ntawuruhunga et al., 2023).

However, the study reveals a trade-off with on-farm diversification. On-farm diversification is negatively correlated with irrigation (0.104), hybrids (0.128) and cover cropping (−0.148), all significant at various levels. The finding suggests a trade-off between extensive diversification and intensive, input-heavy strategies. Farmers who specialize in irrigated hybrid systems and intensive soil management may narrow their crop mix, while more diversified farmers adopt fewer of these high-input practices. Similar trade-offs between diversification and intensive CSA technologies are noted in Tanzania, Ghana and multi-country syntheses, where crop diversity sometimes falls as households specialize in profitable, input-intensive crops (Agbenyo et al., 2022; Erekaló et al., 2024; Ma and Rahut, 2024).

Generally, the correlations show that cocoa farmers do not choose practices independently. There is a clear irrigation-SWC-drainage-cover-crop-pegging-hybrid bundle, plus supportive roles for off-farm income and agroforestry. The findings align with multivariate probit evidence and systematic reviews indicating that CSA practices are largely complementary and most effective when promoted as packages tailored to local conditions (Gudina and Alemu, 2024; Kurgat et al., 2020; Makate et al., 2019).

The correlation matrix of the findings provides a framework for understanding the complex decision-making climate for smallholder cocoa farmers, where synergies and trade-offs directly impact agricultural development policies. In cocoa farming, where farm productivity is often constrained by climate vulnerability and aging trees, these synergies and trade-offs are not merely statistical artifacts but also the working realities of the smallholder cocoa economy. These patterns need to be considered when constructing policies to move farmers toward climate-smart cocoa systems without jeopardizing their livelihoods.

For instance, when policymakers find strong synergies, such as the strong positive relation between SWC and drainage construction (0.778), these practices are regarded by cocoa farmers as a package of water management. For cocoa-specific interventions, this is crucial as cocoa is highly water-sensitive and prone to erosion and waterlogging. Policy needs, therefore, to shift from presenting these as best practices to providing a comprehensive package of assistance (e.g., subsidized land preparation and equipment) that covers both interventions simultaneously. By bringing these together in extension services delivery, the government can reduce transaction costs for cocoa farmers and ensure that farm infrastructure is implemented holistically, not just in one area, and that soil health is not compromised by erosion or flooding.

Also, the negative correlations, for example, between on-farm diversification and cover cropping (0.148) or on-farm diversification and hybrid planting materials (0.128), underscore the structural trade-offs that policymakers need to address. In the cocoa industry, these trade-offs are often linked to competition for land, labor, and capital. If a cocoa farmer is heavily invested in diversifying their income by growing non-cocoa crops, they may not have the labor to maintain cover crops for years. If policy ignores these realities and focuses on or rewards specific practices, it can inadvertently force cocoa farmers to abandon profitable diversification to comply. An honest policy will not only be effective in this regard but will also be effective in this regard. However, it will also enable the government to provide targeted support, such as mechanization or labor-sharing cooperatives, to reduce the barriers that make these practices mutually exclusive.

Finally, a prioritization based on correlations enables better resource allocation in the cocoa supply chain. In terms of the so-called hubs of synergy (irrigation, for example, has a positive correlation with almost all other adaptive strategies), policymakers can make these the foundation technologies. Irrigation schemes are not just an asset that increases yield, but they create an environment for other sustainable practices (like planting hybrid materials or cover crops) to come to fruition. Instead of spreading funds across the board, prioritization will focus on gateway practices most likely to lead to the adoption of a more resilient cocoa-farming system. By doing this data-driven sequencing, it is possible to ensure that interventions are not only technically sound but also economically and practically viable for the smallholder farmer.

5 Conclusion

The results show that cocoa climate-smart agriculture (CSA) in rural Ghana is characterized by uneven but highly interlinked adoption. Farmers strongly favor relatively low-cost, agronomically familiar practices such as agroforestry and hybrid planting materials, which they also perceive as highly effective against climate variability. This pattern aligns with wider evidence that CSA in cocoa can raise incomes and preserve forest resources when adopted in integrated systems rather than as isolated practices.

The study further concludes that synergies are clear for cocoa CSA practices: strong positive correlations among cover cropping, soil and water conservation (SWC), drainage, and lining/pegging indicate that farmers tend to adopt these as reinforcing bundles that jointly improve soil moisture, root establishment, and resilience. Similar multi-technology complementarities have been found for maize and mixed farming in Ghana and Tanzania (Asante et al., 2024; Kurgat et al., 2020). The findings further show that on-farm diversification and off-farm

strategies highlight trade-offs in labor, land, and risk management, echoing broader findings that CSA interventions can simultaneously enhance productivity while increasing labor burdens or greenhouse gas emissions (e.g., irrigation).

In addition, proximity to extension support services, farm distance, climate information, digital/ICT access, farmer-based organizations, and region reflect the national situation in which institutional access, land/tenure conditions, and credit shape both the type and intensity of CSA adoption. These findings reinforce understanding of CSA practice adoption and its costs, which are central to designing equitable climate-smart cocoa policy rather than assuming a simple “triple-win” narrative.

5.1 Policy recommendations

The findings of this study underscore that promoting individual climate-smart agriculture practices in isolation is unlikely to maximize productivity, resilience, and environmental outcomes in Ghana's cocoa sector. Instead, policy should focus on strengthening the institutional and economic mechanisms that facilitate the adoption of complementary CSA practice bundles while addressing the trade-offs that constrain farmer decision-making.

5.1.1 Harmonize extension delivery around integrated CSA bundles

A fundamental policy priority is the redesign of extension systems from promoting individual technologies to delivering integrated climate-smart cocoa packages. The evidence demonstrates that several CSA practices are complementary and yield greater benefits when adopted jointly than when adopted individually. Consequently, Ghana Cocoa Board (COCOBOD), the World Cocoa Foundation, sustainability certification organizations, development partners, and private cocoa companies should collaborate to develop a harmonized national extension framework centered on integrated climate-smart cocoa systems.

Rather than implementing fragmented training programs, extension curricula should promote complementary technology bundles comprising agroforestry, improved cocoa varieties, cover cropping, soil and water conservation, drainage management, and integrated soil fertility management. Such a harmonized extension approach would reduce conflicting technical messages delivered by different organizations, improve learning efficiency, lower transaction costs for farmers, and accelerate the diffusion of synergistic technologies across cocoa-growing landscapes. Importantly, extension recommendations should explicitly communicate both complementarities and trade-offs among practices, enabling farmers to make informed investment decisions based on their resource endowments and local production conditions.

5.1.2 Realign subsidies and climate-smart finance to promote technology bundles

Current subsidy programs and sustainability interventions remain largely commodity- or input-oriented, with limited consideration of the complementarities among CSA technologies. The findings indicate that many high-return practices, particularly irrigation, drainage infrastructure, and labor-intensive soil and water conservation investments, remain under-adopted despite their perceived effectiveness.

Future policy should therefore transition from subsidizing isolated inputs toward supporting integrated climate-smart

investment packages. COCOBOD, commercial banks, development finance institutions, and private sustainability programs should establish dedicated climate-smart financing mechanisms, including concessional credit, guarantee schemes, blended finance facilities, results-based payments, and climate-risk insurance. Such instruments would reduce liquidity constraints while encouraging farmers to adopt complementary CSA portfolios rather than isolated technologies. Public support should also incentivize labor-saving mechanization services and community-based service providers to reduce the labor burden associated with implementing multiple conservation practices simultaneously.

5.1.3 Strengthen carbon finance and ecosystem payment mechanisms

The study highlights the strategic role of agroforestry and other land-based CSA practices in simultaneously enhancing farm productivity, climate resilience, and carbon sequestration. However, uncertainties surrounding tree tenure in Ghana and benefit-sharing continue to weaken farmers' incentives to invest in long-term adoption of agroforestry practices.

Policy reforms should therefore integrate carbon finance into mainstream climate-smart cocoa programming. Payment for ecosystem services, carbon credit schemes, and jurisdictional REDD+ programs should provide direct financial incentives to farmers who adopt synergistic CSA bundles that generate measurable environmental benefits. These incentive mechanisms should be supported by transparent tree tenure arrangements, equitable benefit-sharing systems, and robust monitoring frameworks to ensure that farmers receive predictable returns from long-term investments in agroforestry and ecosystem restoration.

5.1.4 Expand rural credit and digital financial inclusion

Access to affordable finance remains one of the strongest determinants of multiple CSA adoption. Nevertheless, conventional agricultural credit systems rarely accommodate the delayed returns, investment risks, and seasonal cash-flow characteristics associated with climate-smart cocoa production.

Financial sector policies should therefore expand specialized rural credit products designed specifically for CSA investments. Mobile money platforms, digital banking services, warehouse receipt systems, and farmer credit scoring mechanisms should be integrated into cocoa value chains to facilitate timely access to loans, subsidies, insurance, and performance-based incentive payments. Strengthening digital financial inclusion would lower transaction costs, improve financial access for remote producers, and enable farmers to invest in complementary technology portfolios rather than delay adoption due to liquidity constraints.

5.1.5 Strengthen climate information and farmer institutions

The findings demonstrate that institutional support systems significantly enhance the adoption of synergistic CSA practices. Access to extension services, climate information, and farmer-based organizations (FBOs) increases farmers' capacity to coordinate

complementary investments while reducing uncertainty associated with climate variability.

Accordingly, public investment should prioritize expanding extension personnel, strengthening farmer organizations as local innovation platforms, and embedding climate advisory services within existing cocoa extension programs. Digital climate information systems, weather-index advisories, and early warning services should be to extension delivery and financial services so that farmers receive integrated technical, climatic, and financial support for implementing complex CSA packages.

5.2 Overall, policy implication

The overarching policy implication emerging from this study is that climate-smart cocoa should be treated as an integrated systems intervention rather than a collection of independent technologies. Effective policy requires aligning complementary policy levers, including harmonized extension systems, targeted subsidies, climate-smart finance, rural credit, carbon finance, secure tenure arrangements, digital financial services, and strengthened farmer institutions, to encourage farmers to adopt mutually reinforcing CSA bundles. Such an integrated policy architecture would minimize adoption trade-offs, maximize technological synergies, and simultaneously improve cocoa productivity, climate resilience, ecosystem restoration, and smallholder livelihoods, while advancing Ghana's commitments under the European Union Deforestation Regulation (EUDR), national climate policies, and REDD+ initiatives.

5.3 Limitations and suggestions for future research

All empirical studies have limitations; this study is no exception. First, the analysis relies on cross-sectional survey data collected at a single point in time. While the data provide valuable insights into farmers' adoption of cocoa CSA practices, they do not permit the identification of dynamic adoption pathways or temporal changes in CSA practices. Consequently, the estimated relationships should be interpreted as associations rather than causal effects. Longitudinal or panel data would provide a more robust basis for examining the persistence, sequencing, and evolution of cocoa CSA adoption over time.

Second, the study is based primarily on self-reported information provided by farmers. Variables such as adoption of CSA practices, access to climate information, institutional participation, and perceived benefits are subject to recall bias, reporting errors, and social desirability bias. Farmers may unintentionally misreport management practices or overstate adoption to align with perceived expectations, introducing measurement error into the estimation. Future studies could improve measurement accuracy by combining household survey data with objective field-level observations, remote sensing, geospatial information, farm records, or agronomic measurements.

Third, although the multivariate probit (MVP) model provides a flexible framework for jointly estimating the adoption decisions of multiple CSA practices while accounting for correlations among unobserved determinants, it has important limitations. The estimated error-term correlations capture statistical dependence among adoption decisions but should not be interpreted as definitive evidence of complementarities, substitution effects, or resource trade-offs between practices. Correlated adoption may arise from shared unobserved characteristics or common external constraints rather than true

technological interactions. Consequently, the MVP framework identifies adoption of cocoa CSA practices as a bundle rather than causal synergies or trade-offs among CSA practices. Similarly, the MVP model assumes jointly normally distributed error terms and treats explanatory variables as exogenous. These assumptions may not be met in practice. Several explanatory variables included in the empirical specification, particularly farmer-based organization (FBO) membership, access to climate information, mobile phone ownership, and participation in social networks, are potentially endogenous. Farmers with greater managerial ability, innovativeness, stronger risk preferences, or better information-seeking behavior may be both more likely to access these institutional resources and more inclined to adopt CSA practices. Such self-selection introduces the possibility of omitted variable bias, reverse causality, and simultaneity, potentially leading to biased coefficient estimates. As a result, the estimated effects of these variables should be interpreted as conditional associations rather than causal impacts.

Therefore, future research should address these limitations by employing panel or longitudinal datasets that enable stronger causal inference and the analysis of dynamic adoption trajectories. The application of instrumental variable approaches, control function methods, endogenous multivariate choice models, or panel estimators would help account for endogeneity arising from self-selection and unobserved heterogeneity. In cross-sectional settings, propensity score matching or inverse probability weighting may partially mitigate selection bias. Also, future studies could, where feasible, integrate experimental or quasi-experimental research designs to strengthen causal identification. Finally, combining household survey data with objective biophysical measurements and expanding the geographical scope to multiple cocoa-growing regions would improve external validity and provide a more comprehensive understanding of the complementarities, substitution effects, and long-term sustainability of CSA adoption among smallholder cocoa farmers.

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 not required 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.

References

- Adimassu, Z., Tibebe, D., Tamene, L., and Abera, W. (2025). Evaluating the effects of climate smart agricultural (CSA) practices on productivity, adaptation, and mitigation indicators in Ethiopia: a meta-analysis approach. *Heliyon* 11:e42796. doi: 10.1016/j.heliyon.2025.e42796
- Adu, K., Bour, K. B., Antwi, A. O., Pobee, P., and Sackey, F. G. (2026). Climate-smart agriculture: analysis of the determinants of adoption intensity of sustainable agronomic

Author contributions

PZ: Validation, Methodology, Conceptualization, Project administration, Writing – review & editing, Investigation, Data curation, Writing – original draft, Resources, Formal analysis, Visualization. GI: Methodology, Project administration, Conceptualization, Supervision, Writing – review & editing. FM: Methodology, Visualization, Supervision, Conceptualization, Validation, Investigation, Writing – review & editing. AZ: Visualization, Formal analysis, Conceptualization, Methodology, Writing – review & editing, Investigation, Writing – original draft. A-RB: Formal analysis, Methodology, Writing – review & editing, Validation, Writing – original draft, Conceptualization.

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practices among mango farmers in the Yilo Krobo municipality of eastern region of Ghana. *Clim. Dev.* 1–17, 1–17. doi: 10.1080/17565529.2025.2609782

Afriyie-Kraft, L., Zabel, A., and Damnyag, L. (2020). Adaptation strategies of Ghanaian cocoa farmers under a changing climate. *Forest Policy Econ.* 113:102115. doi: 10.1016/j.forpol.2020.102115

- Agbenyo, W., Jiang, Y., Jia, X., Wang, J., Ntim-Amo, G., Dunya, R., et al. (2022). Does the adoption of climate-smart agricultural practices impact farmers' income? Evidence from Ghana. *Int. J. Environ. Res. Public Health* 19:3804. doi: 10.3390/ijerph19073804
- Ahmed, M. H. (2015). Adoption of multiple agricultural technologies in maize production of the central Rift Valley of Ethiopia. *Stud. Agric. Econ.* 117, 162–168. doi: 10.7896/j.1521
- Akinyi, D. P., Karanja Ng'ang'a, S., and Girvetz, E. H. (2021). Trade-offs and synergies of climate change adaptation strategies among smallholder farmers in sub-Saharan Africa: a systematic review. *Reg. Sustain.* 2, 130–143. doi: 10.1016/j.regsus.2021.05.002
- Akrofi-Atitianti, F., Ifejiaka Speranza, C., Bockel, L., and Asare, R. (2018). Assessing climate smart agriculture and its determinants of practice in Ghana: a case of the cocoa production system. *Land* 7:30. doi: 10.3390/land7010030
- Amerino, J., Apedo, C. K., and Anang, B. T. (2024). Factors influencing adoption of cocoa agroforestry in Ghana: analysis based on tree density choice. *Sustainable Environment* 10:2296162. doi: 10.1080/27658511.2023.2296162
- Ameyaw, L. K., Ettl, G. J., Leissle, K., and Anim-Kwapong, G. J. (2018). Cocoa and climate change: insights from smallholder cocoa producers in Ghana regarding challenges in implementing climate change mitigation strategies. *Forests* 9:742. doi: 10.3390/f9120742
- Amfo, B., Ali, E. B., and Atinga, D. (2021). Climate change, soil water conservation, and productivity: evidence from cocoa farmers in Ghana. *Agric. Syst.* 191:103172. doi: 10.1016/j.agry.2021.103172
- Anning, A. K., Ofori-Yeboah, A., Baffour-Ata, F., and Owusu, G. (2022). Climate change manifestations and adaptations in cocoa farms: perspectives of smallholder farmers in the Adansi South District, Ghana. *Curr. Res. Environ. Sustainability* 4:100196. doi: 10.2139/ssrn.4131987
- Antwi-Agyei, P., and Amanor, K. (2023). Typologies and drivers of the adoption of climate smart agricultural practices by smallholder farmers in rural Ghana. *Curr. Res. Environ. Sustainability* 5:100223. doi: 10.1016/j.crsust.2023.100223
- Arhin, A. A., Antoh, E. F., Edusah, S., and Obeng-Okah, K. (2021). Prospects of agroforestry as climate-smart agricultural strategy in cocoa landscapes: perspectives of farmers in Ghana. *Sustain. Agric. Res.* 10, 20–31. doi: 10.5539/sar.v10n1p20
- Asante, B. O., Ma, W., Prah, S., and Temoso, O. (2024). Farmers' adoption of multiple climate-smart agricultural technologies in Ghana: determinants and impacts on maize yields and net farm income. *Mitig. Adapt. Strateg. Glob. Change* 29:16. doi: 10.1007/s11027-024-10114-8
- Asante, P. A., Rozendaal, D. M. A., Rahn, E., Zuidema, P. A., Quaye, A. K., Asare, R., et al. (2021). Unravelling drivers of high variability of on-farm cocoa yields across environmental gradients in Ghana. *Agric. Syst.* 193:103214. doi: 10.1016/j.agry.2021.103214
- Asare, R., Markussen, B., Asare, R. A., Anim-Kwapong, G., and Ræbild, A. (2019). On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana. *Clim. Dev.* 11, 435–445. doi: 10.1080/17565529.2018.1442805
- Asfaw, S., McCarthy, N., Lipper, L., Arslan, A., and Cattaneo, A. (2016). What determines farmers' adaptive capacity? Empirical evidence from Malawi. *Food Secur.* 8, 643–664. doi: 10.1007/s12571-016-0571-0
- Attiogbé, A. A. C., Nehren, U., Quansah, E., Bessah, E., Salack, S., Sogbedji, J. M., et al. (2024). Cocoa farmers' perceptions of drought and adaptive strategies in the Ghana–Togo transboundary cocoa belt. *Land* 13:1737. doi: 10.3390/land13111737
- Autio, A., Johansson, T., Motaroki, L., Minoia, P., and Pelikka, P. (2021). Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. *Agric. Syst.* 194:103284. doi: 10.1016/j.agry.2021.103284
- Aynalem, M., Ayalew, Z., and Terefe, A. T. (2026). Impact of climate smart agricultural practices on technical efficiency among high value vegetable farming in northwestern Ethiopia. *Cogent Food Agric.* 12:2641276. doi: 10.1080/23311932.2026.2641276
- Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P. A., Tao, B., et al. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: a meta-analysis. *Glob. Change Biol.* 25, 2591–2606. doi: 10.1111/gcb.14658
- Baiyegunhi, L. J. S. (2026). Climate change adaptation in NTFP-based livelihoods: impacts on female-headed households' income in Limpopo, South Africa. *Environ. Dev.* 57:101307. doi: 10.1016/j.envdev.2025.101307
- Barbuto, A., Lopolito, A., and Santeramo, F. G. (2019). Improving diffusion in agriculture: an agent-based model to find the predictors for efficient early adopters. *Agric. Food Econ.* 7:1. doi: 10.1186/s40100-019-0121-0
- Belay, A., Oludhe, C., Mirzabaev, A., Recha, J. W., Berhane, Z., Osano, P. M., et al. (2022). Knowledge of climate change and adaptation by smallholder farmers: evidence from southern Ethiopia. *Heliyon* 8:e12089. doi: 10.1016/j.heliyon.2022.e12089
- Bhatnagar, S., Chaudhary, R., Sharma, S., Janhvia, Y., Thakur, P., Sharma, P., et al. (2024). Exploring the dynamics of climate-smart agricultural practices for sustainable resilience in a changing climate. *Environ. Sustain. Indic.* 24:100535. doi: 10.1016/j.indic.2024.100535
- Blaser-Hart, W. J., Hart, S. P., Oppong, J., Kyereh, D., Yeboah, E., and Six, J. (2021). The effectiveness of cocoa agroforests depends on shade-tree canopy height. *Agric. Ecosyst. Environ.* 322:107676. doi: 10.1016/j.agee.2021.107676
- Blaser, W. J., Oppong, J., Hart, S. P., Landolt, J., Yeboah, E., and Six, J. (2018). Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nat. Sustain.* 1, 234–239. doi: 10.1038/s41893-018-0062-8
- Bomdzele, E., and Molua, E. L. (2023). Assessment of the impact of climate and non-climatic parameters on cocoa production: a contextual analysis for Cameroon. *Front. Clim.* 5:1069514. doi: 10.3389/fclim.2023.1069514
- Bryman, A., Becker, S., and Sempik, J. (2008). Quality criteria for quantitative, qualitative and mixed methods research: a view from social policy. *Int. J. Soc. Res. Methodol.* 11, 261–276. doi: 10.1080/13645570701401644
- Bunn, C., Läderach, P., Quaye, A., Muilerman, S., Noponen, M. R., and Lundy, M. (2019). Recommendation domains to scale out climate change adaptation in cocoa production in Ghana. *Climate Services*, 16:100123. doi: 10.1016/j.cliser.2019.100123
- Ceesay, S., Lambarraa-Lehnhardt, F., Ndiaye, M. B. O., Thiaw, D., Sawaneh, M., and Schuler, J. (2025). Farmers' perceptions of the efficacy of current climate risk adaptation and mitigation strategies on agriculture in the Gambia. *Land* 14:622. doi: 10.3390/land14030622
- Danso-Abbeam, G. (2022). Do agricultural extension services promote adoption of soil and water conservation practices? Evidence from Northern Ghana. *Journal of Agriculture and Food Research*, 10:100381. doi: 10.1016/j.jafr.2022.100381
- Danso-Abbeam, G., Dagunga, G., and Ehiakpor, D. S. (2020). Rural non-farm income diversification: implications on smallholder farmers' welfare and agricultural technology adoption in Ghana. *Heliyon* 6:e05393. doi: 10.1016/j.heliyon.2020.e05393
- Dessalegne, C. H., Yechale, K. B., Mulugeta, D. B., and Abren, G. M. (2024). Determinants of land management technology adoptions by rural households in the Goyrie watershed of southern Ethiopia: multivariate probit modeling estimation. *Heliyon* 10:e31894. doi: 10.1016/j.heliyon.2024.e31894
- Diro, S., Tesfaye, A., and Erko, B. (2022). Determinants of adoption of climate-smart agricultural technologies and practices in the coffee-based farming system of Ethiopia. *Agric. Food Secur.* 11:42. doi: 10.1186/s40066-022-00385-2
- Djido, A., Zougmore, R. B., Houessionon, P., Ouédraogo, M., Ouédraogo, I., and Diouf, N. S. (2021). To what extent do weather and climate information services drive the adoption of climate-smart agriculture practices in Ghana? *Clim. Risk Manag.* 32:100309. doi: 10.1016/j.crm.2021.100309
- Donkoh, S. A., Azumah, S. B., and Awuni, J. A. (2019). Adoption of improved agricultural technologies among rice farmers in Ghana: a multivariate probit approach. *Ghana J. Dev. Stud.* 16, 46–67. doi: 10.4314/gjds.v16i1.3
- Erekalo, K. T., Pedersen, S. M., Christensen, T., Denver, S., Gemtso, M., Fountas, S., et al. (2024). Review on the contribution of farming practices and technologies towards climate-smart agricultural outcomes in a European context. *Smart Agric. Technol.* 7:100413. doi: 10.1016/j.atech.2024.100413
- Feyisa, B. W. (2020). Determinants of agricultural technology adoption in Ethiopia: a meta-analysis. *Cogent Food Agric.* 6:1855817. doi: 10.1080/23311932.2020.1855817
- Gbodji, K. K., Quarmin, W., and Minh, T. T. (2023). Effective demand for climate-smart adaptation: a case of solar technologies for cocoa irrigation in Ghana. *Sustain. Environ.* 9:2258472. doi: 10.1080/27658511.2023.2258472
- Gemtso, M., Isakhanyan, G., and Fountas, S. (2025). Advancing climate-smart agriculture: integrating technology, behavioural insights and policy for a sustainable future. *Smart Agric. Technol.* 11:100861. doi: 10.1016/j.atech.2025.100861
- Gemtso, 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* 16:2828. doi: 10.3390/su16072828
- Gloy, N., Chemura, A., Tchindjang, M., and Gornott, C. (2025). Mapping climate change impacts on cocoa agroforestry systems in Cameroon to mitigate future deforestation. *Agron. Sustain. Dev.* 45, 1–20. doi: 10.1007/s13593-025-01042-1
- Greene, W. H. (2018). *Econometric Analysis*. 8th Edn New York, NY: Pearson Education.
- Gudina, M. H., and Alemu, E. A. (2024). Factors influencing small holder farmers adoption of climate SMART agriculture practices in Welmera woreda, Central Ethiopia. *Front. Clim.* 6:1322550. doi: 10.3389/fclim.2024.1322550
- Guja, M. M., and Bedeke, S. B. (2025). Smallholders' climate change adaptation strategies: exploring effectiveness and opportunities to be capitalized. *Environ. Dev. Sustain.* 27, 17927–17956. doi: 10.1007/s10668-024-04750-y
- Hashmi, I. (2020). Perceived climate resilience and adoption of cocoa agroforestry in the forest-savannah transition zone of Ghana. *Int. J. Environ. Clim. Change* 10, 149–161. doi: 10.9734/ijec/2020/v10i1230292
- Igbatayo, S. (2023). "Climate change and agroforestry resilience strategy in West Africa's cocoa supply chain dynamics," in *Disaster risk Reduction for Resilience: Climate Change and Disaster Risk Adaptation*, (Cham: Springer), 361–385.
- Inkoom, E. W., and Dadzie, S. K. N. (2024). Multivariate probit modeling of climate-smart adaptation choices among farmers in sub-Saharan Africa: Ghanaian study of cocoa farmers. *Clim. Change Econ.* 15:2450007. doi: 10.1142/s2010007824500076
- International Cocoa Organization (2025) *Quarterly Bulletin of Cocoa Statistics (Vol. LI, No. 2) and Quarterly Bulletin of Cocoa Statistics (Vol. LI, No. 3)* Abidjan, Côte d'Ivoire International Cocoa Organization. Available online at: <https://www.icco.org/november-2025-quarterly-bulletin-of-cocoa-statistics/>
- Issahaku, G., and Abdulai, A. (2020). 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, 396–420. doi: 10.1111/1467-8489.12357
- Kaba, J. S., Agyei, E. K., Avilineni, M. K. C., Yamoah, F. A., Issahaku, I., Ntiamoah, P., et al. (2024). Agroforestry as an old approach to a new challenge of combating climate change: a critical analysis of the cocoa sector. *Discover Agriculture* 2:92. doi: 10.1007/s44279-024-00120-4

- Kabato, W., Getnet, G. T., Sinore, T., Nemeth, A., and Molnár, Z. (2025). Towards climate-smart agriculture: strategies for sustainable agricultural production, food security, and greenhouse gas reduction. *Agronomy* 15:565. doi: 10.3390/agronomy15030565
- Kangogo, D., Dentoni, D., and Bijman, J. (2021). Adoption of climate-smart agriculture among smallholder farmers: does farmer entrepreneurship matter? *Land Use Policy* 109:105666. doi: 10.1016/j.landusepol.2021.105666
- Kassie, M., Jaleta, M., Shiferaw, B., Mmbando, F., and Mekuria, M. (2013). Adoption of interrelated sustainable agricultural practices in smallholder systems: evidence from rural Tanzania. *Technol. Forecast. Soc. Change* 80, 525–540. doi: 10.1016/j.techfore.2012.08.007
- Kassie, M., Zikhali, P., Manjur, K., and Edwards, S. (2009). Adoption of sustainable agriculture practices: evidence from a semi-arid region of Ethiopia. *Nat. Res. Forum* 33, 189–198. doi: 10.1111/j.1477-8947.2009.01224.x
- Kongor, J. E., Owusu, M., and Odoro-Yeboah, C. (2024). Cocoa production in the 2020s: challenges and solutions. *CABI Agric. Biosci.* 5:102. doi: 10.1186/s43170-024-00310-6
- Kouassi, J.-L., Diby, L., Konan, D., Kouassi, A., Bene, Y., and Kouamé, C. (2023). Drivers of cocoa agroforestry adoption by smallholder farmers around the Taï National Park in southwestern Côte d'Ivoire. *Sci. Rep.* 13:14309. doi: 10.1038/s41598-023-41593-5
- Kpadonou, R. A. B., Owiyo, T., Barbier, B., Denton, F., Rutabingwa, F., and Kiema, A. (2017). Advancing climate-smart-agriculture in developing drylands: joint analysis of the adoption of multiple on-farm soil and water conservation technologies in west African Sahel. *Land Use Policy* 61, 196–207. doi: 10.1016/j.landusepol.2016.10.050
- Kumah, F. J., Kouabenan, A., Gebrekirstos, A., Koné, D., and Adjei-Nsia, S. (2024). Do farmers' perceptions and socio-economic factors drive cocoa agroforestry and sustainable soil carbon management practices in West Africa? *Agrofor. Syst.* 98, 797–815. doi: 10.1007/s10457-023-00950-z
- Kurgat, B. K., Lamanna, C., Kimaro, A., Namoi, N., Manda, L., and Rosenstock, T. S. (2020). Adoption of climate-smart agricultural technologies in Tanzania. *Front. Sustain. Food Syst.* 4:55. doi: 10.3389/fsufs.2020.00055
- Magesa, B. A., Mohan, G., Matsuda, H., Melts, I., Kefi, M., and Fukushi, K. (2023). Understanding the farmers' choices and adoption of adaptation strategies, and plans to climate change impact in Africa: a systematic review. *Clim. Serv.* 30:100362. doi: 10.1016/j.cliser.2023.100362
- Mairura, F., Musafiri, C., Kiboi, M., Macharia, J., Ng'etich, O., Shisanya, C., et al. (2021). Determinants of farmers' perceptions of climate variability, mitigation, and adaptation strategies in the central highlands of Kenya. *Weather Clim. Extremes* 34:100374. doi: 10.1016/j.wace.2021.100374
- 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
- Ma, W., and Rahut, D. B. (2024). Climate-smart agriculture: adoption, impacts, and implications for sustainable development. *Mitig. Adapt. Strateg. Glob. Change* 29:44. doi: 10.1007/s11027-024-10139-z
- Meshesha, A. T., Birhanu, B. S., and Bezabih Ayele, M. (2022). Effects of perceptions on adoption of climate-smart agriculture innovations: empirical evidence from the upper Blue Nile highlands of Ethiopia. *Int. J. Clim. Change Strateg. Manag.* 14, 293–311. doi: 10.1108/ijccsm-04-2021-0035
- Mnukwa, M. L., Mdoda, L., and Mudhara, M. (2025). Assessing the adoption and impact of climate-smart agricultural practices on smallholder maize farmers' livelihoods in sub-Saharan Africa: a systematic review. *Front. Sustain. Food Syst.* 9:1543805. doi: 10.3389/fsufs.2025.1543805
- Mossie, H., Enyew, S., Gezie, M., and Bacs, Z. (2026). Assessing the complementarity and tradeoffs of climate smart agriculture adoption in northwestern Ethiopia. *Discov. Appl. Sci.* 8:572. doi: 10.1007/s42452-026-08509-0
- Musyoki, M. E., Busienei, J. R., Gathiaka, J. K., and Karuku, G. N. (2022). Linking farmers' risk attitudes, livelihood diversification and adoption of climate smart agriculture technologies in the Nyando basin, South-Western Kenya. *Heliyon* 8:e09305. doi: 10.1016/j.heliyon.2022.e09305
- Nasser, F., Maguire-Rajpaul, V. A., Dumenu, W. K., and Wong, G. Y. (2020). Climate-smart cocoa in Ghana: how ecological modernisation discourse risks side-lining cocoa smallholders. *Front. Sustain. Food Syst.* 4:73. doi: 10.3389/fsufs.2020.00073
- Natarajan, N., Newsham, A., Rigg, J., and Suhardiman, D. (2022). A sustainable livelihoods framework for the 21st century. *World Development*, 155:105898. doi: 10.1016/j.worlddev.2022.105898
- Negera, M., Alemu, T., Hagos, F., and Hailelassie, A. (2022). Determinants of adoption of climate smart agricultural practices among farmers in bale-eco region, Ethiopia. *Heliyon* 8:e09824. doi: 10.1016/j.heliyon.2022.e09824
- Neway, M. M., and Zegeye, M. B. (2022). Gender differences in the adoption of agricultural technology in north Shewa zone, Amhara regional state, Ethiopia. *Cogent Soc. Sci.* 8:2069209. doi: 10.1080/23311886.2022.2069209
- Niether, W., Jacobi, J., Blaser, W. J., Andres, C., and Armengot, L. (2020). Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. *Environ. Res. Lett.* 15:104085. doi: 10.1088/1748-9326/abb053
- Ntawuruhunga, D., Ngowi, E. E., Mangi, H. O., Salanga, R. J., and Shikuku, K. M. (2023). Climate-smart agroforestry systems and practices: a systematic review of what works, what doesn't work, and why. *Forest Policy Econ.* 150:102937. doi: 10.1016/j.forpol.2023.102937
- Nunoo, I., Fromm, I., and Fimpong, B. N. (2020). Factors influencing the adoption of cocoa agroforestry systems in mitigating climate change in Ghana: the case of the Sefwi Wiawso district in Western region. *Environ. Sustain. Climate Change* 2, 1–4.
- Nyang'au, J. O., Mohamed, J. H., Mango, N., Makate, C., and Wangeci, A. N. (2021). Smallholder farmers' perception of climate change and adoption of climate smart agriculture practices in Masaba south sub-county, Kisii, Kenya. *Heliyon* 7:e06789. doi: 10.1016/j.heliyon.2021.e06789
- Oliver, M., Akoto, S., and Abugre, S. (2024). Cocoa-agroforestry in Ghana: practices, determinants and constraints faced by farmers. *Afr. J. Agric. Res.* 20, 312–322. doi: 10.5897/ajar2023.16560
- Oumer, A. M., Burton, M., and Kassie, M. (2025). Dynamics of multiple sustainable agricultural intensification practices adoption: application of the intertemporal multivariate probit model. *PLoS One* 20:e0314172. doi: 10.1371/journal.pone.0314172
- Pandey, R., Jha, S. K., Alatalo, J. M., Archie, K. M., and Gupta, A. K. (2017). Sustainable livelihood framework-based indicators for assessing climate change vulnerability and adaptation for Himalayan communities. *Ecological indicators*, 79, 338–346. doi: 10.1016/j.ecolind.2017.03.047
- Reshad, M., Asfaw, Z., and Mohammed, M. (2025). Benefits and challenges of smallholder farmers adopting agroforestry: evidences from the eastern escarpment of Chercher massive, Southeast Ethiopia. *Agrofor. Syst.* 99:19. doi: 10.1007/s10457-024-01097-1
- Ruzzante, S., Labarta, R., and Bilton, A. (2021). Adoption of agricultural technology in the developing world: a meta-analysis of the empirical literature. *World Dev.* 146:105599. doi: 10.1016/j.worlddev.2021.105599
- Saran, A., Singh, S., Gupta, N., Walke, S., Rao, R., Simiyu, C., et al. (2024). Interventions promoting resilience through climate smart agricultural practices for women farmers: a systematic review. *Campbell Syst. Rev.* 20:e1426. doi: 10.3390/su15043471
- Saspugayeva, G., Zhaken, A., Agarkova, I., Mukhametzanova, Z., Samatova, I., Zhaznayeve, Z., et al. (2026). Sustainable strategies for durum wheat production under water scarcity and climate stress. *Glob. J. Environ. Sci. Manag.* 12, 453–472. doi: 10.22034/gjesm.2026.01.25
- Suh, N. N., and Molua, E. L. (2022). Cocoa production under climate variability and farm management challenges: some farmers' perspective. *J. Agric. Food Res.* 8:100282. doi: 10.1016/j.jafr.2022.100282
- Tega, M., and Bojago, E. (2024). Determinants of smallholder farmers' adoption of agroforestry practices: Sodo Zuriya District, southern Ethiopia. *Agrofor. Syst.* 98, 1–20. doi: 10.1007/s10457-023-00885-5
- Teklu, A., Simane, B., and Bezabih, M. (2022). Effectiveness of climate-smart agriculture innovations in smallholder agriculture system in Ethiopia. *Sustainability* 14:16143. doi: 10.3390/su142316143
- Teklu, A., Simane, B., and Bezabih, M. (2023). Multiple adoption of climate-smart agriculture innovation for agricultural sustainability: empirical evidence from the upper Blue Nile highlands of Ethiopia. *Clim. Risk Manag.* 39:100477. doi: 10.1016/j.crm.2023.100477
- Tesfaye, K., Tamene, L. D., Demissie, T. D., Ahmed, J. S., Haile, A., Mekonnen, K., et al. (2021). *A Framework for Bundling Climate-Smart Agriculture (CSA) and Climate Information Services (CIS) in Ethiopia*
- Tessema, M. W., Atnafe, A. D., Tora, S. E., Bantider, A., and Shure, E. (2025). Trend analysis of climate change and effect of climate-smart agricultural practices: the case of Humbo woreda, Wolaita zone, South Ethiopia. *Front. Clim.* 7:1456328. doi: 10.3389/fclim.2025.1456328
- Tham-Agyekum, E. K., Appiah, A., Ankuyi, F., Sangber-Dery, G.-M., Antwi, C., Acheampong, K. O., et al. (2023). Exploring gender inequalities and promoting equal opportunities in Ghana's cocoa industry using Harvard analytical framework. *Int. J. Hum. Educ. Soc. Sci.* 2, 625–639. doi: 10.55227/ijhess.v3i2.435
- Tham-Agyekum, E. K., Bakang, J.-E. A., Abdul-Mumin, A., Mensah, W., Adarkwa, B. O., Duah, A., et al. (2025). Harnessing climate information service use for cocoa farming sustainability in Ghana. *Clim. Dev.* 17, 270–283. doi: 10.1080/17565529.2024.2359984
- Torvikey, G. D., Dalaa, M. A., Adomaa, F. O., Abdul-Razak, S., Amoah, I. A., Kofituo, R. K., et al. (2024). Making climate-smart cocoa inclusive: towards a framework for gender transformation. *S. Afr. Rev. Sociol.* 54, 42–57. doi: 10.1080/21528586.2024.2321909
- Yamane T. (1973). *Statistics: An introductory analysis*. A Harper International Edition Jointly Published by Harper & Row, New York, Evanston & London and John Weatherhill, Inc., Tokyo.
- van Der Haar, S., Gallagher, E., Schoneveld, G., Slingerland, M., and Leeuwis, C. (2023). Climate-smart cocoa in forest landscapes: lessons from institutional innovations in Ghana. *Land Use Policy* 132:106819. doi: 10.1016/j.landusepol.2023.106819
- Vermunt, J. K., and Magidson, J. (2002). "Latent class cluster analysis," in *Applied Latent Class Analysis*, vol. 11 (), 89–106.
- Wainaina, P., Tongruksawattana, S., and Qaim, M. (2016). Tradeoffs and complementarities in the adoption of improved seeds, fertilizer, and natural resource management technologies in Kenya. *Agric. Econ.* 47, 351–362. doi: 10.1111/agec.12235
- Wang, G., Lu, Q., and Capareda, S. C. (2020). Social network and extension service in farmers' agricultural technology adoption efficiency. *PLoS One* 15:e0235927. doi: 10.1371/journal.pone.0235927
- Wooldridge, J. M. (2002). *Econometric analysis of cross section and panel data* MIT press. Cambridge, ma, 108, 245–254.

- Wooldridge, J. M. (2003). Cluster-sample methods in applied econometrics. *Am. Econ. Rev.* 93, 133–138. doi: 10.1257/000282803321946930
- Yamoah, F. A., and Kaba, J. S. (2024). Integrating climate-smart Agri-innovative technology adoption and agribusiness management skills to improve the livelihoods of smallholder female cocoa farmers in Ghana. *Clim. Dev.* 16, 169–175. doi: 10.1080/17565529.2021.2024125
- Yamoah, F. A., Kaba, J. S., Amankwah-Amoah, J., and Acquaye, A. (2020). Stakeholder collaboration in climate-smart agricultural production innovations: insights from the cocoa industry in Ghana. *Environ. Manag.* 66, 600–613. doi: 10.1007/s00267-020-01327-z
- Yiridomoh, G. Y., Bonye, S. Z., and Derbile, E. K. (2022). Assessing the determinants of smallholder cocoa farmers' adoption of agronomic practices for climate change adaptation in Ghana. *Oxf. Open Clim. Change* 2:kgac005. doi: 10.1093/oxfclm/kgac005
- Zegeye, M. B., Fikire, A. H., and Meshesha, G. B. (2022). Determinants of multiple agricultural technology adoption: evidence from rural Amhara region, Ethiopia. *Cogent Econ. Finance* 10:2058189. doi: 10.20944/preprints202106.0288.v1