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Determinants of adoption of climate-smart agricultural technologies among smallholder coffee farmers in Western Uganda

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ABSTRACT
Promoting the adoption of climate-smart agricultural technologies (CSATs) is crucial for helping smallholder coffee farmers maintain high yields in the face of climate change. However, farmers remain reluctant to adopt CSATs, which results in low coffee productivity in Uganda. This research examined the factors influencing the adoption of CSATs in Western Uganda. Data were collected from 236 coffee farmers in the Mbarara district using a well-developed and pretested questionnaire. The multivariate Probit model (MVP) was employed in the data analysis to account for the correlation among the binary outcome variables. The descriptive results showed that 5%, 98%, 16%, 70%, 32% and 86% of the farmers adopted timely harvesting, rainwater harvesting, pesticides, minimum tillage, agroforestry and mulching, respectively. Multivariate Probit results showed that age, education, farming experience, land size, market distance, farm income, marital status, non-farm income, access to credit, group membership, training in climate-smart agriculture (CSA) and household size significantly influenced the adoption of CSATs. Policy takeaways from the study include equipping farmers with knowledge of CSA and connecting them to accessible credit options, such as village savings and loan associations. Farmers should be encouraged to participate in agricultural programs on radio, television and social media, as well as training and demonstrations organized by extension officers.

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Introduction

Coffee serves as a major cash crop and a key contributor to export revenues worldwide (Rutherford, 2006), ranking second only to crude oil in global economic trade importance (FAO, 2014). Coffee accounts for a larger share of the gross domestic product in East and Central African countries (Mafusire et al., 2010) and provides livelihood for millions of people working in farming, processing, marketing and exporting activities (Nzeyimana et al., 2013; Rutherford, 2006). Uganda is the second-largest coffee producer in Africa after Ethiopia, and ranks eighth globally, just ahead of Mexico (Ngure & Watanabe, 2024). It exports approximately 301,336 tons of coffee annually to international markets, accounting for 20% of its total exports (Canwat, 2023).

Acknowledging the significant contribution of coffee to national development, the Ugandan government has prioritized investment in the crop through its development programs (Alela et al., 2024). These comprise the Uganda Coffee Development Authority (UCDA), the National Agricultural Advisory Services , the Plan for Modernization of Agriculture , the Poverty Eradication Action Plan and the Development Strategy and Investment Plan (Canagarajah & Diesen, 2011). The programs were designed to improve coffee production, household income and reduce poverty among Ugandan families (Chiputwa et al., 2015).

Despite the role of coffee in Ugandan economic progress, its production is increasingly threatened by climate change, including intense droughts, irregular rainfall and floods (Legesse et al., 2024; Tiwari et al., 2018). Climate change causes a decrease in rainfall intensity, which in turn lowers coffee output (World Bank, 2022).

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In addition, climate change brings about powerful winds that can harm coffee plantations, including seedbeds and established trees (Gaard, 2015). Also, frequent infestations of coffee by pests and diseases are due to climate variability (USAID, 2014). Furthermore, unpredictable rainfall can delay the flowering of coffee and reduce its productivity (Weldemichael, 2019). If coffee flowers late, the beans may sell at reduced prices due to market instability (Chiputwa et al., 2015). The World Coffee Research projects that by 2050, climate change will render 60% of coffee-producing regions unsuitable for cultivation (Bilen et al., 2022). Overall, climate change is placing adverse pressure on coffee cultivation in Uganda, impacting both yield and bean quality, thereby hindering the growth of the local coffee sector and contributing to poverty (Lemma & Megersa, 2021).

To address these issues, the country has promoted CSATs to strengthen coffee resilience to climate change and improve yields (Nega & Kimeu, 2002). CSATs refer to methods, practices and innovations developed to support farmers in adapting to climate change, boosting agricultural productivity and, when possible, minimizing greenhouse gas emissions (Schmidt & Bunn, 2021). These technologies are designed to foster farming systems that are more adaptive, environmentally sustainable, and efficient in resource use, especially in the face of growing climate uncertainty and long-term ecological changes (Mthethwa et al., 2022). Key CSATs that have been promoted include rainwater harvesting for irrigation, mulching, minimum tillage, agroforestry, timely harvesting and integrated pest management (IPM; Tiwari et al., 2018). Rainwater harvesting can be utilized to sustain coffee seedbeds during periods of delayed rainfall (Mwangi & Kariuki, 2015). Mulching is useful for soil and water conservation (Nzeyimana et al., 2017; World Bank, 2022). Several benefits are associated with minimum tillage, including improved soil structure, reduced erosion and the conservation of soil fertility (Ngoma et al., 2016). Timely coffee harvesting helps reduce post-harvest losses from excess rain and high temperatures (Bilen et al., 2022). Agroforestry serves as a dual-benefit strategy, enhancing farmers' income and lessening climate change effects (World Bank, 2022). IPM also helps lower pest and disease infestations in coffee production, leading to higher yields (Coulibaly et al., 2021). In Rwanda, the use of organic inputs has proven effective in retaining soil moisture, increasing nutrient reserves and ultimately enhancing soil fertility (Nzeyimana et al., 2013). Likewise, the successful implementation of cover crops in coffee cultivation enhanced water infiltration, soil carbon storage and nutrient availability in Brazil (Production & In, 2011). Therefore, the adoption of CSATs is crucial for advancing agricultural output (Diro et al., 2022; Pagliacci et al., 2020).

Although the advantages of adopting CSATs are well recognized (Andati et al., 2022; Aryal et al., 2018), their adoption among smallholder farmers in Uganda remains insufficiently studied. A small number of studies conducted in Uganda on the adoption levels of CSATs among small-scale coffee growers reveal that uptake remains inadequate, thereby limiting crop production. As an example, research on CSAT adoption in Northern Uganda reported adoption levels of 10.8% for zero tillage, 24.2% for trenches, 12.5% for trash lines, and 15.8% for inorganic fertilizers (Alela et al., 2024). A separate study conducted in Bududa District, Eastern Uganda, examining the extent of CSAT adoption among coffee farmers, found that 10% had embraced the use of organic fertilizer, 25% had adopted intercropping, and 15% had implemented cover cropping (Faisal et al., 2021). However, these studies were conducted in regions that exhibit distinct biophysical and socio-economic characteristics compared to Mbarara District (Uganda Bureau of Statistics, 2016), where the current research was undertaken.

Numerous empirical studies have explored the factors influencing the uptake of CSATs among coffee farmers in various parts of the world, including Ethiopia (Diro et al., 2022), Peru (Guevara-Fernandez & Oliva-Cruz, 2025), Rwanda (Alexis et al., 2021) and Indonesia (Djufry et al., 2022). These studies consistently highlight the roles of farmer characteristics, institutional dynamics and farm-level conditions in shaping the adoption of CSATs. However, findings on the determinants of CSATs' adoption in coffee production vary significantly across regions and countries, underscoring the need for localized and context-specific analyses (Anang et al., 2021; Andati et al., 2022; Aryal et al., 2018; Kule, Agole, et al., 2025; Kule, Obia, et al., 2025).

In Uganda, limited research has explored the determinants influencing the adoption of Climate-Smart Agricultural Technologies (CSATs) among smallholder coffee farmers. For instance, Alela et al. (2024) investigated the drivers of adoption intensity for integrated soil fertility management (ISFM) in Northern Uganda, revealing that factors, such as the size of land devoted to coffee farming, availability of credit, insurance and agricultural inputs were positively and significantly linked to its uptake. Conversely, household size exhibited a strong negative association with the adoption of this practice. Similarly, Faisal et al.

(2021) analyzed the factors influencing the adoption of CSATs among coffee farmers in Bududa District on Mt. Elgon, identifying access to credit, extension services, marital status and educational attainment as significant positive contributors. Nonetheless, these studies did not address critical knowledge gaps concerning farmer-related, institutional and farm-specific factors that influence the adoption of CSATs in the context of coffee production in Mbarara District.

Consequently, gaining insight into the extent and primary drivers of CSATs adoption is essential for enhancing agricultural productivity and efficiency in Mbarara District in particular, and Uganda in general. This research investigated the influence of farmer characteristics, institutional and farm factors on the uptake of CSATs by smallholder coffee farmers. In particular, this study addressed the following key questions: i) What farmer characteristics affect the adoption of CSATs? ii) Which institutional factors influence the adoption of CSAT? iii) What socio-economic variables affect the uptake of CSATs? The study enhances understanding of how farmer attributes, institutional dynamics and farm-related factors affect the adoption of CSATs among smallholder farmers. The findings presented herein can support government agencies and development partners in establishing suitable institutional frameworks to promote the adoption of CSATs, thereby boosting agricultural productivity. Furthermore, the insights from this article can inform policymakers in formulating policies aimed at improving the socio-economic well-being of smallholder farmers. This research likewise enriches the international dialogue surrounding the adoption of CSATs, a subject of ongoing global importance.

The subsequent sections of this article are structured as follows: theoretical background, conceptual framework, literature review, methodology, findings, discussion, conclusion, policy implications and future research suggestions.

Theoretical background

The study is anchored on the utility maximization theory (UMT) (Danso-Abbeam et al., 2017). The UMT suggests that an individual will decide to adopt a technology after evaluating the available alternatives and opting for those that maximize their expected utility. According to Ojo et al. (2023) and Zegeye et al. (2022), a farmer will choose a given technology if the utility of that (new) technology is higher than the old one or other alternatives. Moreover, Atube et al. (2021) suggested that technology adoption occurs when the expected benefits from that technology are higher than those from non-use. In the context of this research, farmers are more likely to adopt any of the CSATs, such as pesticides, mulching, minimum tillage, rainwater harvesting, timely harvesting and agroforestry, if they perceive that these technologies offer superior benefits, for example, reduced production risks or higher yields compared to existing practices. Therefore, farmers can choose one or more of these practices on their coffee farms because they are likely to improve productivity compared to existing technologies or their absence. Practically, the direct measurement of perceived utility is unfeasible (Alela et al., 2024). Hence, perceived utility was obtained from the farmer, institutional and farm factors (Kule, Agole, et al., 2025; Kule, Obia, et al., 2025; Omara et al., 2021; Rebecca et al., 2018). This study views farmer factors, institutional factors, and farm factors as obstacles to the adoption of CSATs. Accordingly, the UMT is deemed relevant for this analysis, as it interprets farmers' decisions to adopt CSATs through the lenses of farmer, institutional and farm factors.

The adoption of agricultural practices, commonly defined as the decision to implement a particular method (Rogers, 1995), is a crucial element in advancing development within low-income economies (Burhanuddin et al., 2009). Accepting or declining a new farming method is not a decision made on the spot (Feder et al., 1985). It emerges through a step-by-step process, with the first stage involving awareness of the technique's availability (Gao et al., 2020). After becoming aware of the practice, users often proceed to a phase of critical reflection, examining how easily it can be applied, its cost-effectiveness and the likely gains (Anang et al., 2021; Simtowe et al., 2016). Following this, the individual may engage in a trial run or small-scale testing of the method (Mthethwa et al., 2022; Rogers, 1983). The outcomes of the testing phase inform the user's final decision to either apply or decline the use of the agricultural innovation (Rogers, 1995; Straub, 2009).

Researchers have segmented the variables influencing adoption into various thematic classifications. Illustratively, Kule, Agole, et al. (2025), Kule, Obia, et al. (2025) classified the drivers of adoption into socio-economic factors, including household size, age, gender, land ownership, land tenure system, labor use and the number of dependents in the household, among others. In a similar vein, Omara et al. (2021) and Avane et al. (2022) segmented the influences on adoption into three main areas: perceptions of farmers, institutional frameworks and socio-economic variables. Alela et al. (2024) organized these drivers into categories, including farmer, institutional and socio-economic characteristics. Accordingly, the study organized the drivers of adoption under farmer-related, institutional and socio-economic categories. Socio-economic factors included age), education (Alemayehu et al., 2024), farming experience (Alela et al., 2024), marital status (Ojo et al., 2023), household size (Midamba et al., 2024), gender and non-farm income (Kifle et al., 2022). The institutional predictors include group membership (Sanogo et al., 2023), access to credit (Alemayehu et al., 2024), access to training on climate-smart agricultural practices and market distance (Kassie et al., 2013). Lastly, the farm factors were land size (Kassie et al., 2013) and farm income (Kifle et al., 2022). Based on the reviewed literature, these explanatory variables appear to significantly influence the adoption of CSATs, as illustrated in Table 1. Thus, considering a k^{th} farmer, to maximize utility U by taking up m^{th} CSAT, which may be influenced by X_m explanatory variables (Table 1), the farmer will adopt m^{th} CSAT if $Y_{im}^{*} = U_{im}^{*} - U_0 > 0$, implying that the farmer obtains the benefits of adopting m^{th} CSAT. As a result, this study classifies the determinants influencing the adoption of CSATs into farmer, institutional and farm factors, as depicted in the conceptual framework below.

Conceptual framework

The conceptual framework (Figure 1) represents the connection between the dependent variables (adoption of CSATs) and the influencing factors (farmer factors, institutional factors and farm factors). Specifically, it explores farmer factors including age, education, farming experience, marital status, household size, gender and non-farm income. The institutional predictors include group membership, market distance, access to credit and training on climate-smart agricultural practices. Lastly, the farm factors, for instance, land size and farm income. These influencing factors are assumed to affect the dependent variable, namely the adoption of CSATs.

Literature review

Determinants of the adoption of climate-smart agricultural technologies

Global studies

Analyzing the determinants of CSATs' adoption is vital in agricultural policy formulation. Several studies have been conducted on the global adoption of CSATs. However, the results of these studies suggest a need for region-based studies. This is due to conflicting results reported by different authors worldwide.

Table 1. Explanatory variables for the MVP model.

Dependent variables	Measurement	Types	Hypothesis
Pesticides	1-Adopted, 0-Otherwise	Binary	
Minimum tillage	1-Adopted, 0-Otherwise	Binary	
Mulching	1-Adopted, 0-Otherwise	Binary	
Timely harvesting	1-Adopted, 0-Otherwise	Binary	
Rain-water harvesting	1-Adopted, 0-Otherwise	Binary	
Agroforestry	1-Adopted, 0-Otherwise	Binary	
Independent variables			
Age	Years	Continuous	±
Education	Years	Continuous	+
Household size	Number	Continuous	±
Experience	Years	Continuous	+
Land size	Acres	Continuous	+
Farm income	Ugandan shillings	Continuous	+
Distance	Kilometers	Continuous	−
Gender	1-Male, 0-Otherwise	Binary	±
Marital status	1-Married, 0-Otherwise	Binary	+
Credit	1-Yes, 0-Otherwise	Binary	+
Group membership	1-Member, 0-otherwise	Binary	+
Climate-smart agriculture training	1-Yes, 0-Otherwise	Binary	+
Non-farm income	Ugandan shillings	Continuous	±

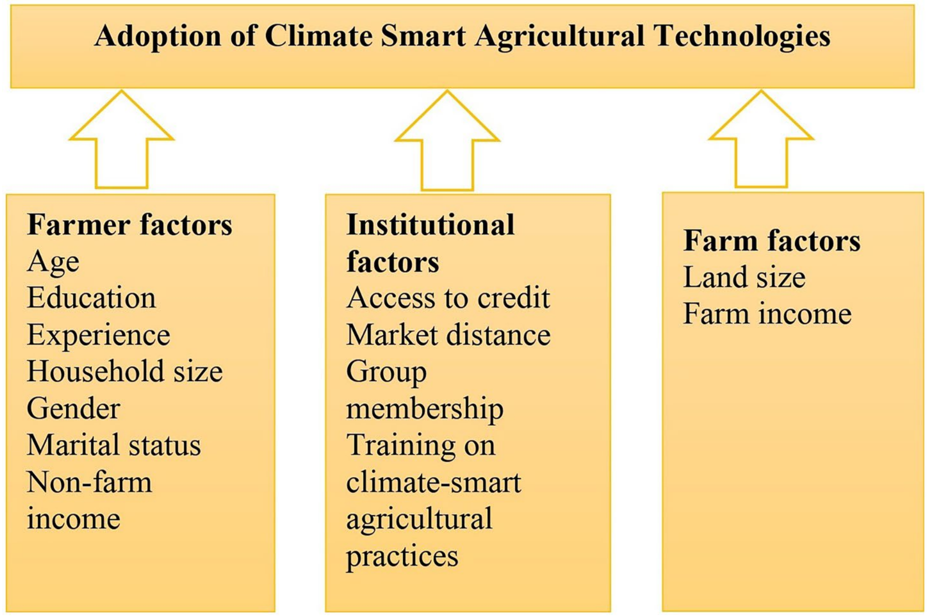

Figure 1. Conceptual framework.

The Multivariate results from research conducted in Nigeria by Omodara et al. (2023) among 100 cassava farmers revealed that education reduces the likelihood of adopting CSATs such as organic manure. Conversely, Alemayehu et al. (2024) reported a positive relationship between education and the adoption of CSATs in Ethiopia, highlighting a contradiction in the literature concerning the influence of education on CSAT adoption. Alemayehu et al. (2024) further indicated that age has a positive impact on the adoption of improved crop varieties, while exerting a negative effect on the adoption of mixed farming practices in Ethiopia. The multinomial logistic regression results presented by Ndiwa et al. (2024) suggested that age reduces the probability of adopting drought-resilient crops but supports the adoption of crop diversity in Kenya.

Credit access, which is theoretically hypothesized to have a positive effect on the adoption of CSATs, was reported to reduce the rate of CSAT adoption according to the Tobit results by Kalu and Mbanasor (2020) in Nigeria. Kinyua et al. (2022) reported that access to credit has no significant effect on the adoption of CSATs among farmers in Kenya. Odawa et al. (2024), using binary logistic regression in Somalia, found that credit plays a key role in the adoption of CSATs among smallholder farmers. Thus, based on these methods, these studies have reported different results. This may be attributed to the policies and practices in these countries.

Saadu et al. (2024) conducted a study in Nigeria among 317 smallholder farmers to assess the drivers of CSATs' adoption using a probit model. Their findings revealed that membership in social groups was positively associated with the adoption of CSATs among farmers. In contrast, a study conducted in Ghana by Harajatu (2019) involving 160 farmers found that group membership was negatively correlated with the adoption of improved maize varieties, a key climate-smart agricultural technology. The conflicting results in the two countries may be attributed to differences in sample size and research locations.

The results of a study conducted in Uganda by Atube et al. (2021), employing a binary logistic model, revealed a negative relationship between household size and the adoption of CSATs. Their findings showed that farmers with large households were 0.087 times less likely to adopt fallowing than their counterparts with small households. Similarly, the Tobit model results of Midamba et al. (2024) revealed that the adoption of climate-smart agricultural practices was negatively influenced by household size. Specifically, Midamba et al. (2024) reported that large households were 18% less likely to adopt CSATs than those with fewer household members. Nevertheless, Getnet et al. (2022) found that household size had no statistically significant influence on the adoption of CSATs in Nigeria. Contrary to these two studies, Nyang'au et al. (2021) reported a positive association between household size and the adoption of CSATs in Kenya. The three studies also present different results regarding the effect of household size on the adoption of CSATs.

In summary, researchers have presented conflicting results on the influence of farmer, institutional and farm factors on the global adoption of CSATs. This is evident in the studies done by (Alemayehu et al., 2024; Ayal et al., 2023; Kalu & Mbanasor, 2020; Kassa & Abdi, 2022; Kifle et al., 2022; Kinyua et al., 2022; Mthethwa et al., 2022; Muriithi et al., 2021; Negera et al., 2022; Sanogo et al., 2023). Generally, conflicting findings are due to disparities in sample size, analytical methods, study areas, sampling approaches and government policies, among others. This affirms that global studies on CSAT adoption do not have a universal consensus.

Climate-smart agricultural technologies in coffee farming

Research indicates that adopting climate-smart methods in coffee farming benefits individual farms and also supports wider landscape-scale and global environmental enhancements (Bilen et al., 2022). An extensive literature review was conducted by Bracken et al. (2023), drawing on insights from 80 studies that explore the CSATs that are suitable for coffee growing. Key among the recommended CSATs include agroforestry, mulching, irrigation, IPM and soil and water conservation practices, among others.

As reported by Adimassu et al. (2013), Ethiopian farmers utilize diverse CSATs in coffee production, such as rotational cropping to improve crop performance, the incorporation of agroforestry practices, the application of organic manure, mulching, compost, mineral amendments like lime and the creation of drainage channels.

In Brazil, successful outcomes have been documented from the use of cover crops in coffee cultivation, for instance, signal grass has been shown to enhance soil carbon storage, nutrient availability and water infiltration (Production & In, 2011). Likewise, Diro et al. (2022) found that coffee farmers had adopted CSATs, namely manure application, minimum tillage, intercropping, use of improved forage and physical soil and water management practices to improve production and productivity in Ethiopia.

In a similar vein, Pinard et al. (2014) found that in the eastern Democratic Republic of Congo, Tanzania, Uganda, Burundi and western Kenya, coffee is occasionally cultivated alongside agroforestry tree species, such as Calliandra calothyrsus, Tephrosia vogelii, Leucaena leucocephala and banana. According to Mulumba and Lal (2008), the integration of nitrogen-fixing tree species promotes organic matter decomposition and nitrogen supply *via* tree biomass, thereby aiding in soil stabilization, limiting erosion, decreasing soil disturbance and enhancing the soil's chemical and physical properties.

Factors influencing the adoption of climate-smart agricultural technologies in coffee farming

Earlier research has shown that diverse socio-economic factors affect the adoption of CSATs. Existing research consistently shows that access to agricultural extension information is a determinant in the adoption process of technologies. Farmers with adequate access to information tend to be more open to adopting new technologies. A study conducted in Malaysia (Djufry et al., 2022) on the drivers of coffee farmers' adoption of CSATs found that access to climate-related data was a major constraint to the adoption of CSATs. The study recommended the adoption of facilities geared toward strengthening climate information systems, which were crucial to advancing the adoption of CSATs within coffee production systems. This research finding is further supported by results from an investigation into the drivers of CSATs' adoption in Ethiopia's coffee-growing regions, which suggested that access to agricultural extension information and ownership of communication devices such as radios were significantly and positively associated with the adoption of CSATs by coffee farmers (Diro et al., 2022).

Experience in farming is considered one of the key socioeconomic determinants shaping the uptake of agricultural innovations. Having farmed for many years, they have cultivated a wide range of contacts and support systems in the sector. Farming expertise enables producers to choose technologies that best match their local agro-ecological and soil conditions. Consequently, they are better informed about new technologies and their benefits, which supports timely and effective adoption. A study conducted in Nensebo Woreda, Ethiopia, employing a Multinomial Logit Model to investigate the drivers of adoption of CSATs to adapt to climate variability in coffee farming, indicated that age and agricultural experience positively and significantly affected the adoption of CSATs (Eshetu et al., 2021).

Existing research presents inconsistent evidence, indicating both beneficial and detrimental effects of group membership on the adoption of agricultural practices. When farmers join supportive networks like production groups, a positive correlation often emerges, as such platforms facilitate the sharing of knowledge on yield-enhancing CSATs. However, farmers who align themselves with groups centered on saving rather than production may become more cautious with spending, leading to lower rates of technology adoption. Research conducted in Vietnam indicated that participation in social groups had a positive impact on the uptake of CSATs in coffee production (Trung et al., 2025). On the contrary, empirical evidence from coffee cooperatives in Southwest Ethiopia suggests that membership offered no measurable advantage in terms of CSATs' uptake, coffee productivity and income over non-membership (Shumeta & D'Haese, 2016).

The size of the family unit is considered a crucial variable in determining whether agricultural technologies are adopted. Empirical findings suggest that larger household sizes are associated with increased food expenditure, which reduces their financial capacity to adopt CSATs such as fertilizer. Alternatively, a higher household size can serve as a source of farm labor, facilitating the use of labor-intensive technologies such as mulching. According to a recent analysis by Eshetu et al. (2021), household size exhibits a significant positive relationship with the adoption of CSATs in coffee production in Southwest Ethiopia. In contrast, Alela et al. (2024) identified a significant negative relationship between household size and the intensity of adoption of ISFM practices in coffee farming in northern Uganda. An increase of one household member was associated with a 7% reduction in adoption intensity. This outcome was attributed to the tendency of larger households to prioritize food expenditures over investing in CSATs. Another investigation conducted in Ethiopia by Diro et al. (2022) on the adoption of CSATs in coffee production revealed that households with more members showed a significant and negative correlation with the use of manure. Despite being a low-cost input, manure was perceived to deliver lower yields than chemical fertilizers. This, coupled with the need to ensure household food security, caused larger families to focus their limited resources on alternative priorities rather than manure utilization.

Distance from markets influences the uptake of CSATs. High transportation costs and restricted access to critical inputs such as improved coffee seeds, fertilizers, agrochemicals and equipment are common challenges faced by farmers in remote regions (Urgessa Waktola & Fekadu, 2021). Moreover, their access to advisory services and training related to the use of new CSATs is often limited. Those living far from market centers typically lack timely and reliable information on prices, demand patterns and seasonal fluctuations. Also, in the absence of clear economic motivation, they may be reluctant to adopt CSATs that enhance productivity or improve coffee quality. An investigation by Alela et al. (2024) into the adoption of ISFM practices among smallholder coffee growers in mid-northern Uganda demonstrated that proximity to trading hubs significantly enhances farmers' access to inorganic fertilizers. In contrast, increased distance from both input and output markets is associated with reduced implementation of such CSATs. Research conducted in Vietnam by Trung et al. (2025) found that coffee farmers based in isolated regions, far from markets, were notably less inclined to adopt CSATs in coffee farming than those living in closer proximity to market hubs.

Access to credit plays a crucial role in the uptake of CSATs. Many of the CSATs, such as drip irrigation systems, enhanced coffee seed varieties, solar-powered irrigation pumps and conservation-based farming tools, require substantial initial investments. In the absence of credit or financial support, smallholder farmers frequently lack the means to cover these upfront costs, even when the technologies promise long-term savings or increased profitability (Alexis et al., 2021). Farmers with limited access to credit are often compelled to rely on low-cost, conventional methods, despite their lower productivity or resilience (Diro et al., 2022). A study conducted by Bwiza et al. (2024) among small-scale coffee producers in Kalehe Territory, Democratic Republic of Congo, highlighted access to credit as one of the key factors influencing the adoption of CSATs. However, within Ethiopia's coffee-growing regions, the availability of credit was linked to a decline in manure usage, as farmers with financial access often preferred chemical fertilizers, likely due to ease of application and reduced labor demands (Diro et al., 2022). This suggests that financing choices can shape the types of CSATs adopted, occasionally prioritizing immediate efficiency over long-term sustainability.

Education typically enhances the chances that farmers will embrace CSATs. Education enhances farmers' understanding and acceptance of technologies, including improved coffee varieties, chemical inputs and irrigation. Farmers with formal education are often more receptive to change and more capable of analyzing the potential benefits and risks of adopting new CSATs (Eshetu et al., 2021). They also tend to actively seek out and absorb information from extension agents, workshops and farmer networks. Moreover, educational attainment is frequently linked to improved access to financial services, market opportunities and institutional support, all of which contribute to greater adoption of CSATs. An investigation into the use of CSATs, such as mulching, shade management, organic manure, cover cropping and contour farming by Arabica coffee growers in Bududa District found that educational attainment positively influenced their adoption (Faisal et al., 2021). Another study conducted in Luya, Amazonas, Peru, explored the determinants of CSATs' adoption in coffee farming and revealed that farmers' educational attainment had a positive impact on their use of fertilizers (Guevara-Fernandez & Oliva-Cruz, 2025). Conversely, educational attainment may hinder the uptake of CSATs by drawing individuals away from farming. Higher levels of education often lead to urban careers or non-agricultural employment, leading to decreased engagement in agricultural activities. As a result, they may view CSATs as irrelevant or lacking sufficient return on investment. Moreover, educated individuals might scrutinize such technologies more critically, regarding them as overly simplistic, unsuitable or lacking scientific credibility. A study examining the factors influencing the adoption of CSATs among Mexican coffee producers found a negative correlation between adoption and educational attainment (Ubertino et al., 2016).

Non-farm income plays a notable and intricate role in shaping the adoption of CSATs. Its impact can be either beneficial or limiting, depending on the specific context and the nature of the technologies (Diro et al., 2022). Several CSATs, such as drip irrigation, improved coffee varieties and agroforestry systems, demand substantial upfront capital. In this context, income earned from non-agricultural sources complements farm earnings by providing households with the financial flexibility required to acquire necessary inputs or equipment (Alela et al., 2024). Additionally, it lessens reliance on seasonal farming income, thereby improving cash flow stability. Farmers with consistent non-farm earnings are often more inclined to adopt innovative practices, as their financial cushion mitigates the risks associated with potential yield failures (Faisal et al., 2021). However, in certain situations, engagement in non-farm activities can divert labor away from farming, which may diminish both interest in and commitment to labor-intensive CSATs (Trung et al., 2025). A study by Bwiza et al. (2024) found that for coffee farmers in Kalehe Territory, Democratic Republic of Congo, non-farm income played a crucial role in encouraging the use of CSATs., Conversely, an investigation conducted in Ethiopia's Jimma Zone by Diro and Erko (2019) revealed that farmers who did not adopt improved coffee varieties possessed notably higher non-farm earnings than those who did. This suggests that income derived from non-agricultural activities may divert attention or resources away from the adoption of productivity-enhancing CSATs.

Gender plays a crucial role in the adoption of CSATs within coffee production. Men are more likely than women to implement CSATs, largely due to a blend of systemic, cultural, financial and organizational barriers (Atube et al., 2021). Overlapping barriers ranging from land rights and access to extension services to cultural norms frequently hinder women's involvement (Ochago, 2018). However, when women are empowered, they are fully capable of adopting and benefiting from these innovations. Research conducted by Gurmessa et al. (2022) to assess the sustainability and gender-related aspects of a coffee value chain development initiative in Ethiopia revealed that several of the introduced CSATs were embraced and maintained by mainly women coffee farmers. Women were primarily engaged in the production process, while men predominantly handled decision-making and the marketing of coffee outputs. A separate study carried out in Mexico by Ubertino et al. (2016) on the influence of gender in the adoption of CSATs found that male coffee farmers are more inclined than their female counterparts to apply fertilizers to enhance coffee yields. However, another study revealed that women are more than mere contributors to climate-smart agriculture (CSA) as they frequently serve as its foundation in coffee-growing areas. By embracing innovative practices and transforming the value chain, their leadership in the adoption of CSATs can be activated through targeted support and gender-inclusive approaches (Ochago, 2018).

Notably, the studies reviewed above have primarily explored the farmer, institutional and farm factors influencing the adoption of CSATs in coffee production across countries and regions with socio-economic contexts that differ from those in Western Uganda. Overall, existing literature on the drivers of CSAT adoption in coffee farming presents mixed results regarding the impact of farmer, institutional and farm factors, highlighting the importance of localized research. In light of these gaps, this study sought to investigate the factors influencing the adoption of CSATs among coffee farmers in Mbarara, Western Uganda.

Methodology

Study area

This study was conducted in the Mbarara district in western Uganda. The sub-counties of focus were Kagongi, Rubindi and Rwanyamahembe in Kashari County, as shown in Figure 2. The selection of Mbarara District was based on its position in the cattle corridor, which is prone to recurrent droughts. The district has a notable reputation for coffee cultivation, predominantly found in Kagongi, Rubindi, and Rwanyamahembe sub-counties. The neighboring districts of Mbarara include the Ibanda, Kiruhura, Isingori, Rwampara, Sheema and Buhweju districts. The district is situated at a latitude of 00°36′ South and a longitude of 30°36′ East. The district consists of one City and 19 sub-counties. It covers approximately 1,778.4 square kilometers, with an average elevation of 1800 m (5900 ft) above sea level. Mbarara District receives an average annual rainfall of 1200 mm, with temperatures ranging from 17 °C to 30 °C. However, temperatures and rains are inconsistently distributed and show fluctuations during the rainy season. Agriculture (Uganda Bureau of Statistics, 2016) serves as the main source of livelihood for the majority of Mbarara's residents. Besides coffee, the region produces a variety of crops, including Irish potatoes, maize, beans, millet, cabbage, tomatoes, matoke and sweet bananas. Most households depend

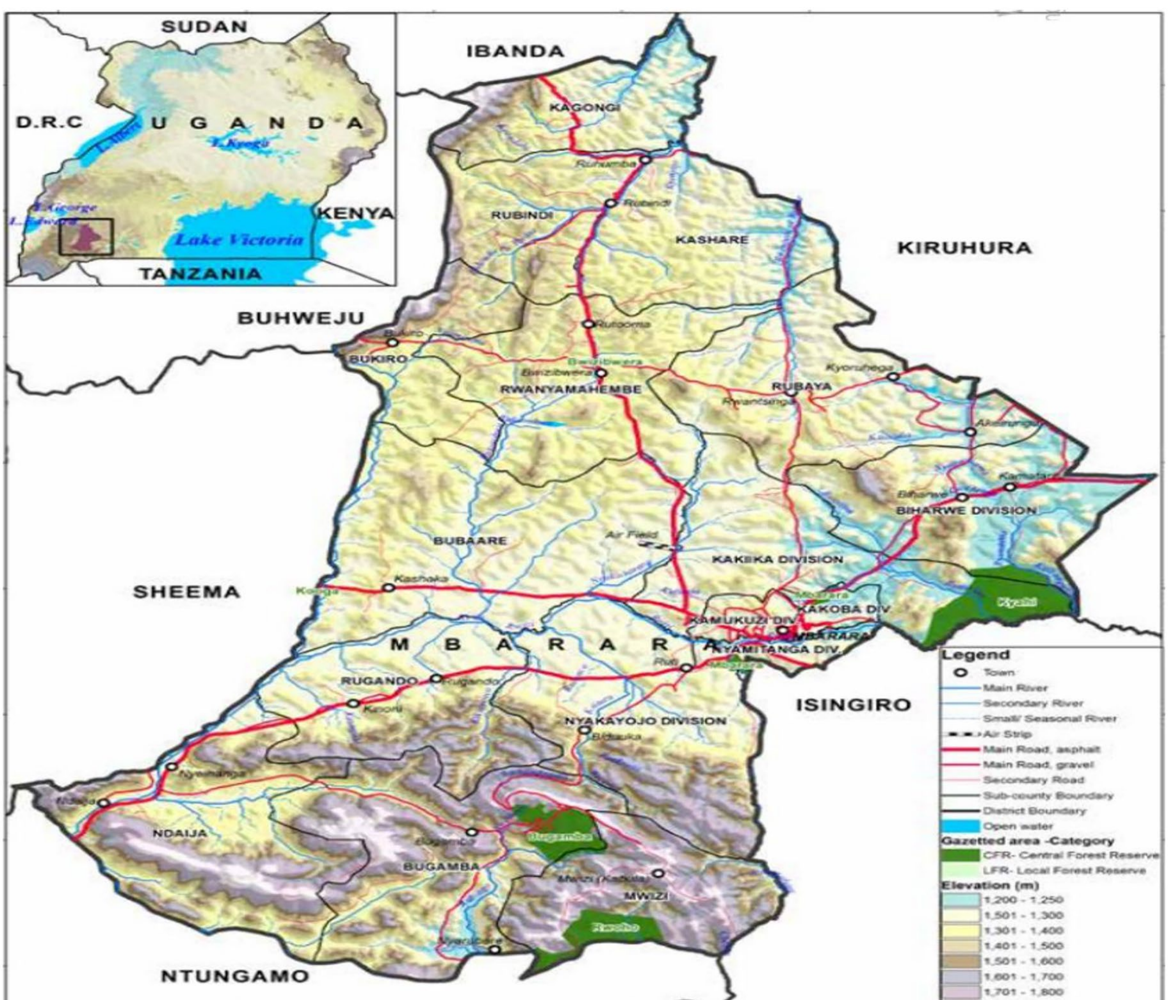

Figure 2. Study area.

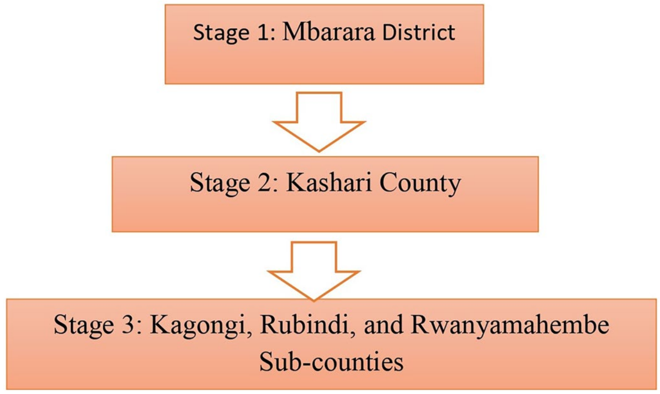

Figure 3. Multistage sampling summary.

on coffee as a primary source of income, while other crops and livestock support their subsistence needs. In light of the area's increasingly erratic rainfall patterns, research focused on strengthening resilience to the adverse impacts of climate change is both timely and essential.

This study adopted both multistage and simple random sampling techniques (Sugri et al., 2021). In the first stage, the Mbarara District was purposively sampled, as it is the leading coffee district in the western region (Figure 3). Accordingly, Kashari County was purposively selected because it had more coffee farmers than other counties in the district. Lastly, Kagongi, Rubindi and Rwanyamahembe were sampled because of their mass engagement in coffee farming. According to NAADS reports, there are 3062 coffee farmers in the three selected sub-counties (Mulumba & Lal, 2008). The required sample size was determined using the method developed by Kothari (2004), which is stated as follows:

$$n = \frac{z^2 p(1-p)}{e^2}$$

where n is the sample size, p is the proportion of coffee farmers in the three selected sub-counties (= 0.189), z is the Z value corresponding to the 95% confidence interval ($Z = 1.96$), and e is the precision or acceptable error, set at 5%. According to UBOS (2018), the proportion of coffee farmers in the three selected sub-counties in Mbarara District is 18.9%.

Therefore, $n = \frac{3.8416\, X\, 0.189(1-0.189)}{0.0025}$

$$n = \frac{0.5888366064}{0.0025}$$

$$n = 235.5$$

$$n \cong 236 \text{Respondents}$$

Data collection

After an extensive review of the literature, researchers formulated the questionnaire to encompass all relevant variables, including farmer socio-demographic characteristics, institutional factors, farm-related attributes and data on the adoption of climate-smart agricultural practices. Before initiating the primary data collection, the questionnaire was pre-tested with a sample of 30 coffee farmers in Nyamitanga sub-county, Mbarara District, located in western Uganda. Questions that respondents found challenging to understand were revised and refined in consultation with agricultural experts from the Faculty of Agriculture and Environment at Gulu University. For example, the question 'Are you aware of CSATs like minimum tillage, rainwater harvesting, mulching, agro-forestry, etc?' was revised to 'Which of the following CSATs do you use on your coffee farm? (minimum tillage, rainwater harvesting, mulching, agro-forestry, others specify…)'. This preliminary study aimed to ensure that the questionnaire items were clear, reliable, relevant and closely aligned with the research objectives. Researchers obtained verbal informed consent from all participants before conducting the interviews. This stage was followed by collecting primary quantitative data from the farmers using face-to-face interviews. A well-trained team of enumerators supported the data collection by asking questions and recording farmers' responses. The research received ethical approval from the Gulu University Research and Ethics Committee (GUREC), with authorization granted under the reference number GUREC-2020-403, and adhered to its standards and procedures. These include privacy, confidentiality, respect and verbal consent. Verbal consent was deemed suitable for this study, as many respondents were not literate; the research also posed no risk to participants, with non-sensitive questions such as inquiries about farmers' use of CSATs. The verbal consent process was audio-recorded and securely stored. Data collection lasted for three weeks. Consequently, researchers prepared data for formal econometric analysis.

Econometric analysis

The study considered six binary CSATs, i.e. pesticides, mulching, minimum tillage, rainwater harvesting, timely harvesting and agroforestry. Farmers may choose more than one practice, resulting in either a positive or negative association between binary CSATs. A binary probit or logistic model assumes the correlation of multiple binary outcomes; hence, it is unsuitable for analysis. Following Wandera et al. (2024), the multivariate Probit Model (MVP) is suitable for assessing the determinants of choice of CSATs because it considers the negative and positive correlations among the binary independent variables. Furthermore, Kassie et al. (2013) also supported the use of the MVP model when assessing the drivers of the adoption of multiple correlated agricultural practices that either supplement (positive association) or suppress (negative association) each other. The MVP model employed for the analysis features binary dependent variables (CSATs), as represented in Equation (1).

$$Y^*_{im} = \beta_m X_{im} + \varepsilon_{im} \tag{1}$$

where $m = 1\ldots$

$$Y_{im} = \{ \begin{matrix} 1 if\, Y^*_{im} > 0 \\ 0\, if\, Y^*_{im} < 0 \end{matrix} \tag{2}$$

where Y^*_{im} represents the latent variable, Y_{im} represents the set of dependent variables (CSATs), X_{im} represents the explanatory variables summarized in Table 1, β_m represents the regression coefficients and ε_{im} is the error term.

Results and discussions

Socio-demographic characteristics of the farmers

Table 2 presents the socio-demographic characteristics of the surveyed farmers. The findings show that the average age of the respondents was 47.5 years, suggesting that farmers in their productive years are

Table 2. Socio-demographic characteristics of the farmers.

Socio-demographics	Measurement	Mean	Standard deviation
Age	Years	47.54	12.90
Family size	Number	5.00	2.42
Land size	Acres	1.82	1.20
Experience	Years	13.42	9.50
Coffee income	Ugandan shillings	1,907,980	1,619,710
Market distance	Kilometers	7.01	2.92
Gender	1-Male, 0-Otherwise	0.85	0.36
Marital status	1-Married, 0-Unmarried	0.78	0.24
Extension	1-Yes, 0-Otherwise	0.64	0.47
Credit	1-Yes, 0-Otherwise	0.36	0.30

capable of adopting a wide range of CSATs. The mean household size comprised five individuals, suggesting that sufficient labor was available to support the adoption of CSATs such as pesticide application and mulching.

On average, farmers cultivated 1.82 acres of land under coffee, generating an income of approximately 1,907,980 Ugandan shillings from coffee sales. The respondents had an average of 13.42 years of farming experience, indicating a substantial level of expertise, social networks and decision-making ability conducive to adopting CSATs. Notably, the farmers resided an average of 7 km from the nearest trading centers, a relatively short distance that allows convenient access to agricultural inputs and services, including pesticides and seeds.

Furthermore, the data showed that 85% of the farmers were male, reflecting the trend that cash crop farming, such as coffee production, is predominantly male-dominated due to its higher income potential (Alela et al., 2024). Regarding marital status, 78% of the farmers were married. In terms of institutional support, 64% of the respondents had access to agricultural extension services, while 36% had access to credit. Extensive access to extension services may promote the uptake of various CSATs, whereas restricted credit access could constrain the adoption of capital-intensive practices.

Adoption of climate-smart agricultural practices

Figure 4 depicts the adoption of CSATs. This study evaluated six CSATs that are low-cost and readily available to farmers. These include practices such as timely harvesting of coffee to reduce post-harvest losses (Midamba & Kizito, 2022). Pesticides were also adopted because they minimized pest and disease infestation, such as tailed caterpillars and skeletonizers, as is evident in many coffee-growing areas in Uganda (Olango et al., 2024). Rainwater harvesting helps maintain coffee nurseries, resulting in healthy coffee seedlings that increase productivity (Mwangi & Kariuki, 2015). Minimum tillage, a practice that improves soil fertility, was also used in this study (Ngoma et al., 2016). Finally, agroforestry and mulching were included as practices that are beneficial in managing the effects of climate change (Nzeyimana et al., 2013, 2017; World Bank, 2017).

According to the findings, only 5% of farmers engaged in timely harvesting. This low adoption rate can be attributed to shifting weather patterns, which have disrupted the uniform ripening of coffee cherries, thereby complicating the scheduling of harvest activities. Moreover, the Western Uganda lowlands of Mbarara, where the study was conducted, are susceptible to heavy rainfall and flooding during the coffee harvest season. Consequently, harvest timing is often dictated by weather conditions rather than crop maturity. Furthermore, some Robusta coffee strains in the area show inconsistent ripening patterns, making repeated harvests necessary and resulting in greater labor and time investments. Coffee harvesting itself is highly labor-intensive, and early in the harvest season, labor shortages are common due to low yields and limited financial incentive for workers. Some farmers also manage several scattered

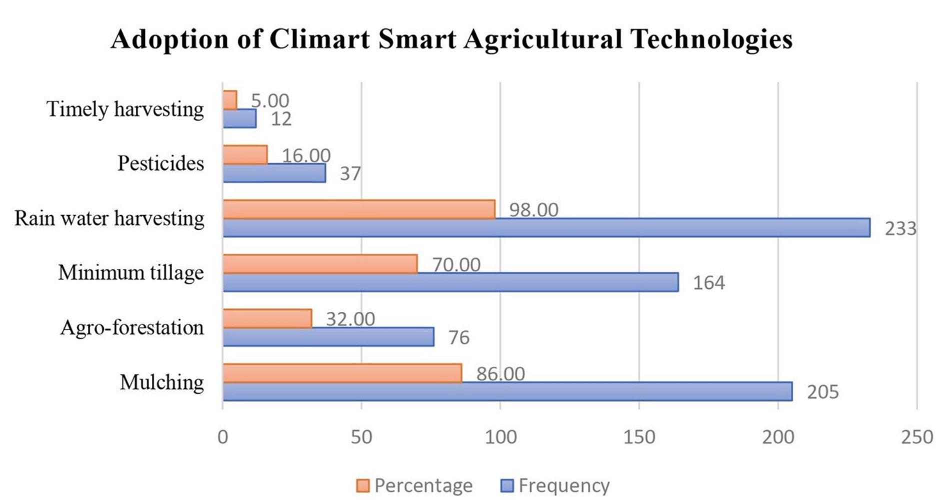

Figure 4. Adoption of climate smart agricultural technologies.

small coffee plots, making it difficult to harvest them all simultaneously, which causes delays. Extension services primarily focus on crop production, with limited attention given to harvesting and post-harvest practices. This lack of support contributes to the slow uptake of timely harvesting techniques. As a result, few farmers have adopted timely coffee harvesting in the region.

Only 16% of farmers reported using pesticides, likely due to the limited financial resources of smallholder coffee growers. For these farmers, the recurring expense of purchasing pesticides represents a considerable economic strain. Additionally, insufficient training in pesticide application may contribute to hesitancy, driven by concerns over potential health risks. Some farmers adopt organic practices and IPM techniques to reduce reliance on agrochemicals. Moreover, certain hazardous pesticides may be banned or restricted by regulatory authorities. The increasing demand for chemical-free products among consumers further reduces the use of pesticides. Since most of Uganda's coffee is exported to international markets with strict requirements for low or zero pesticide residues, this indicates that pesticide use among coffee farmers remains low due to a combination of financial, regulatory, health and market-related factors.

Agroforestry practices were adopted by only 32% of the coffee farmers. This low adoption rate may be due to limited awareness of agroforestry's long-term benefits, such as increased resilience to climate variability, improved pest control through ecological balance and soil conservation. Moreover, establishing agroforestry systems often requires upfront investments that many small-scale farmers cannot afford. As a result, most farmers did not implement agroforestry in coffee production, leaving their crops more vulnerable to environmental stressors.

Conversely, rainwater harvesting was practiced by 98% of the farmers, primarily to irrigate coffee nurseries and young plants during dry spells. This practice gained popularity in response to increasingly erratic and declining rainfall linked to climate change, prompting farmers to seek alternative water sources. As such, rainwater harvesting played a critical role in sustaining coffee seedlings through drought conditions until the return of the rainy season.

Minimum tillage was also widely adopted, with 70% of farmers implementing this technique. Its popularity can be attributed to reduced fieldwork requirements, such as less hoeing, which lowered labor demands, time commitments and the need for costly farming tools. Additionally, maintaining surface residues helped conserve soil moisture by reducing evaporation, thereby shielding coffee plants from drought stress and supporting higher yields.

Coffee farmers (86%) adopted mulching, likely influenced by extension services that raised awareness about its benefits, such as conserving soil and water, enhancing soil fertility and promoting overall soil health. Additionally, the widespread availability of mulching materials, such as coffee husks and grass facilitated their adoption among farmers.

Multicollinearity

Variance inflation factors (VIFs) were used to check for multicollinearity among the independent variables. Following Akinwande et al. (2015) and Ouko et al. (2022), the minimum VIF should not be less

Table 3. Multicollinearity test.

Independent variables	VIF	1/vIF
Age	2.20	0.454
Education	2.14	0.466
Household size	1.79	0.557
Experience	1.75	0.571
Land size	1.75	0.572
Farm income	1.50	0.666
Distance	1.49	0.670
Gender	1.38	0.725
Marital status	1.37	0.730
Credit	1.21	0.823
Group membership	1.08	0.924
Climate-smart agriculture training	1.06	0.947
Non-farm income	1.05	0.950
Mean VIF	1.52	

ViF: variance inflation factor

than one and the maximum should not be greater than 10. Table 3 reports that the VIF ranged from a minimum of 1.05 to a maximum of 2.20. This suggests that there was no multicollinearity among the independent variables.

Correlation of the binary dependent variables (CSATs)

As recommended by Kassie et al. (2013) and Legesse et al. (2024), correlations among the binary dependent variables (CSATs) should be examined before proceeding with MVP model estimation. The results in Table 4 show a significant correlation among the CSATs considered in this study. Timely planting and pesticide had a significant positive correlation coefficient ($p < 0.01$). Mulching and minimum tillage also showed a significant negative correlation ($p < 0.05$). Other CSATs with negative correlations include agroforestry, minimum tillage and rainwater harvesting. The significant association among CSATs justifies the use of MVP in the analysis, but not binary models, such as Probit and Binary logistic (Legesse et al., 2024). Binary models apply to a single practice (Gemeda et al., 2023; Khutlang & Brian, 2024; Oyetunde-Usman et al., 2021).

Determinants of adoption of climate-smart agricultural technologies among smallholder coffee farmers

MVP model fitness

The MVP model demonstrated a strong fit with the data (Table 5), as indicated by its high statistical significance at the 1% level. This result suggests that not all the regression coefficients in the model are

Table 4. Correlation of the binary dependent variables (CSATs).

CSATs	Pesticides	Mulching	Agroforestry	Minimum tillage	Rain-water harvesting	Timely harvesting
Pesticides	1					
Mulching	0.039	1				
Agroforestry	0.047	0.080	1			
Minimum tillage	0.007	−0.148**	−0.173***	1		
Rain-water harvesting	0.042	0.056	0.051	−0.119**	1	
Timely harvesting	0.197***	−0.068	0.019	0.015	0.068	1

Note. *** and ** denote statistical significance at the 1% and 5% levels, respectively.
Source: Based on analysis of data from the 2020 field survey.

Table 5. Determinants of adoption of climate-smart agricultural technologies.

	Pesticides		Mulching		Agroforestry		Minimum tillage		Rainwater harvesting		Timely harvesting	
Variables	Coefficient	$p >$ |z|	Coefficient	$p >$ |z|	Coefficient	$p >$ |z|	Coefficient	$p >$ |z|	Coefficient	$p >$ |z|	Coefficient	$p >$ |z|
Age	−0.210	0.813	0.078*	0.906	0.150	0.761	−0.545	0.325	0.791*	0.100	0.221	0.635
Education	−0.025	0.963	0.251**	0.024	−0.491	0.158	0.519	0.169	0.250	0.466	0.370	0.246
Household size	−0.170**	0.033	−0.365	0.272	−0.033	0.895	0.545*	0.061	0.490*	0.066	0.342***	0.001
Experience	0.186	0.586	0.090	0.671	0.093	0.651	0.616***	0.009	−0.188	0.362	−0.133	0.513
Land size	−0.279	0.571	0.248	0.450	0.928***	0.001	0.513	0.129	−0.380	0.262	0.513*	0.062
Farm income	0.221**	0.028	−0.011	0.919	0.019**	0.035	0.220	0.869	0.137	0.259	−0.027	0.772
Distance	−0.316	0.430	−0.678**	0.027	0.049	0.840	−0.557**	0.050	−0.494*	0.060	−0.472*	0.063
Gender	−0.704	0.228	−0.233	0.632	0.029	0.922	−0.320	0.429	0.261	0.373	0.115	0.702
Marital status	0.187	0.402	−0.168	0.357	0.203*	0.099	0.046	0.787	0.233**	0.049	−0.012	0.927
Credit	0.068***	0.000	0.543***	0.010	0.017	0.929	−0.225	0.315	0.022	0.920	0.231	0.252
Group membership	0.536**	0.038	0.015	0.964	0.005	0.986	0.425***	0.045	0.471	0.157	0.533*	0.096
CS training	0.013	0.981	0.093	0.791	0.435	0.132	0.747**	0.029	−0.024	0.941	−0.128	0.667
Non-farm income	−0.033	.384	−0.022	0.425	−0.079***	0.007	0.043	0.185	−0.027	0.300	−0.011	0.648
Likelihood ratio test of rho21 = rho31 = rho41 = rho51 = rho61 = rho32 = rho42 = rho52 = rho62 = rho43 = rho53 = rho63 = rho54 = rho64 = rho65 = 0; log likelihood = −658.149												
Prob > χ^2	0.000											
Wald χ^2 (78)	1196.47											

Note. CS, ***, * and ** represent climate smart, significance levels at the 1%, 10% and 5% thresholds, respectively. rho signifies correlation between CSATs. 1 = Pesticide; 2 = mulching; 3 = Agroforestry; 4 = Minimum tillage; 5 = Rainwater harvesting; and 6 = Timely harvesting.
Source: **A**uthor's analysis of field survey data, 2020.

zero, leading to the rejection of the null hypothesis. The Wald chi-squared statistic was 1196.47, highlighting the model's robustness. Additionally, the log-likelihood value of −667.58 further supports the model's goodness of fit.

Age

Age of farmers positively influenced the adoption of mulching and rainwater harvesting practices (Table 5). The likelihood of adopting these CSATs was higher among older farmers compared to their younger counterparts. This may be attributed to the greater experience and accumulated knowledge that older farmers possess regarding the advantages of specific CSATs. Older farmers also concentrate on certain CSATs, such as mulching, unlike younger farmers, who have not experienced all CSATs. This results in a higher likelihood of older farmers adopting water conservation practices such as mulching and watering. Our findings support those of Bedeke et al. (2019) and Sanogo et al. (2023), both of whom highlighted the role of age in increasing the likelihood of CSAT adoption in Ethiopia and Mali. Similarly, Gemeda et al. (2023) observed that age is a positive and significant predictor of CSAT adoption in Southern Ethiopia. Conversely, this result differs from Milkias (2020), who noted that older farmers were less prone to adopting bountiful teff cultivars in Ethiopia. Similarly, Odawa et al. (2024) found that older farmers may be reluctant to adopt CSATs due to the physical demands associated with labor-intensive technologies. This demonstrates the relevance of a farmer's age in facilitating the adoption of CSATs.

Education

The study suggested that education has a positive impact on the adoption of CSATs. The results confirmed this hypothesis, showing that education significantly enhanced the likelihood of farmers adopting mulching practices. Educated farmers were more inclined to use mulch compared to their less-educated counterparts. This supports the idea that skills and knowledge are essential for enhancing the economic efficiency of any agricultural activity (Paltasingh, 2016). Therefore, education plays a key role in equipping farmers with the necessary skills and knowledge that lead to the adoption of CSATs. This justifies the positive effect of education on the adoption of mulching, a practice that boosts water conservation in the soil. These results are in agreement with Kumar et al. (2023), who reported that higher education levels among farmers correlated with greater adoption of water conservation practices in India. Similarly, the MVP findings of Legesse et al. (2024) indicated a positive correlation between education and the adoption of CSATs in Ethiopia. However, a systematic review examining the factors influencing CSATs' adoption among smallholder farmers in Africa revealed a negative association with education (Silva et al., 2024). This illustrates the pivotal influence of farmers' education on the adoption of CSATs, suggesting that promoters should factor this in their technology promotion initiatives.

Household size

The results also showed that a larger household size had a positive impact on the adoption of labor-intensive practices such as minimum tillage, rainwater harvesting and timely harvesting. A negative correlation was observed between household size and the use of pesticides. This inverse relationship is likely due to the cost of pesticides, as larger households often allocate a significant portion of their income to basic household needs, limiting their ability to afford such inputs. However, larger households provide ample labor that supports the adoption of labor-demanding practices like timely harvesting, rainwater harvesting and minimum tillage. When labor is readily available, farmers are more likely to implement these practices. According to the findings presented by Atube et al. (2021), household size is a negative predictor of CSATs, such as farrowing in Northern Uganda. Additionally, Ndiwa et al. (2024) observed that the number of family members was associated with differing impacts on the adoption of CSATs in Kenya, exerting a negative influence on the use of cover crops but a positive effect on the adoption of drought-resistant crops. The tendency of larger household sizes to favor the adoption of low-cost, labor-intensive agricultural technologies while being less inclined toward expensive alternatives highlights the need for agricultural technology promoters to raise awareness among farmers about how to create affordable, homemade CSATs. This approach would leverage the available labor in larger households and encourage the adoption of technologies suited to their household capacity.

Years of coffee farming

Experience in coffee production positively influenced the adoption of minimum tillage. Farmers with a longer history of coffee cultivation were more likely to implement minimum tillage practices compared to those with fewer years of experience in coffee cultivation. As farming experience accumulates, farmers tend to acquire practical skills, expand their networks through interactions with extension agents and peers, and build social capital, all of which encourage the uptake of minimum tillage. Additionally, experienced farmers often have better access to institutional support, such as credit, markets and membership in farmer groups, further facilitating the adoption of CSATs. Therefore, farmers with plenty of farming experience are far better off adopting CSATs than their fellows, who have few years of farming experience. In Mali, Sanogo et al. (2023) also reported similar results, indicating the positive effect of farming experience on the adoption of CSATs. Moreover, Massresha et al. (2021) affirmed that farmers with a wealth of experience are better adopters in Ethiopia. Nonetheless, this research finding contrasts with Milkias (2020), who reported that experienced farmers were less inclined to adopt agricultural technologies in Ethiopia. This highlights that farming experience can have varying effects on farmers' adoption of agricultural technologies, depending on their specific encounters with the innovations. It underscores the importance of leveraging farmers' experience in experiential learning-based technology promotion programs.

Land size

Consistent with the findings of Kumar et al. (2023) in South India, landholding size had a positive impact on the adoption of CSATs such as agroforestry and timely harvesting. Farmers with larger land parcels were more inclined to implement agroforestry practices and harvest their coffee crops promptly. The favorable influence of land size on agroforestry adoption is largely attributed to the availability of additional space, which reduces competition between coffee plants and other tree species. In contrast, farmers with smaller plots focused exclusively on coffee production, leaving little or no room for integrating other trees. Moreover, larger landholdings are often associated with increased farm income, which can incentivize timely harvesting to minimize post-harvest losses that might otherwise reduce profitability. Thus, farmers with more extensive land resources are better positioned to adopt both agroforestry and timely harvesting. Similar outcomes regarding the positive relationship between land size and CSAT adoption have been reported by Gemeda et al. (2023) in Ethiopia, Kalu and Mbanasor (2020) in Nigeria and Kinyua et al. (2022) in Kenya. Also, Alela et al. (2024) reported a positive influence of land size on the adoption of ISFM practices in Northern Uganda. These studies underscore the crucial role that landholding size plays in facilitating the uptake of CSATs. Therefore, it is essential for agricultural technology promoters to align technology dissemination efforts with farm size, ensuring that farmers with varying landholdings are encouraged to adopt technologies appropriate to the scale of their farms.

Farm income

Revenue generated from coffee sales positively influenced the adoption of agroforestry and pesticide use. Farmers with higher earnings were more likely to implement agroforestry practices and apply pesticides in coffee cultivation compared to those with lower incomes. Integrating trees into farming systems often necessitates the purchase of seedlings from local markets, and higher income levels enhance farmers' ability to afford such inputs. Consequently, wealthier farmers are more inclined to adopt agroforestry. Similarly, the use of pesticides involves financial investment, making it more accessible to farmers with greater financial resources than to those with limited means. Our results are similar to those of Atube et al. (2021), who showed that income increased the adoption of pesticides and agroforestry by 50% and 38%, respectively, in Uganda. Moreover, Kumar et al. (2023) also reported a positive effect of farm income on CSATs' adoption among smallholder farmers in India. These insights stress the necessity of guiding farmers to channel part of their income into adopting CSATs on their farms to secure consistent and improved crop yields.

Market distance

Proximity to the nearest market was found to positively influence the adoption of mulching, minimum tillage and rainwater harvesting. Specifically, farmers located closer to markets were more likely to adopt these CSATs. Markets function as key social hubs where farmers regularly interact and exchange knowledge. Moreover, trading centers often host extension services, including training sessions and practical demonstrations on agricultural technologies. These locations also serve as primary points for accessing essential farming inputs, such as water storage tanks, seedlings and pesticides. Thus, being located near the market increases the chances of adopting CSATs. This conforms with the findings reported by Alemayehu et al. (2024), whose results showed that the nearer the farmers are located to the markets, the higher the intensity of CSATs' adoption in Ethiopia. Similarly, Legesse et al. (2024) reported that nearness to the market positively influences the adoption of CSATs in Ethiopia. This suggests a growing need to strengthen transportation links in rural areas to improve farmers' access to and adoption of new technologies.

Marital status

As anticipated, marital status exhibited a significant positive influence on the adoption of agroforestry and rainwater harvesting among farmers. Married individuals were more likely to adopt these practices compared to their unmarried counterparts. For married farmers, rainwater harvesting served multiple purposes, including household use and nursery management. Additionally, married farmers typically had larger household sizes, which increased their water needs and thus encouraged the adoption of rainwater harvesting. The implementation of agroforestry also demands considerable labor input, and the larger family units associated with married farmers provided the necessary labor, thereby facilitating greater adoption compared to unmarried farmers with smaller households. This is affirmed by the results of Ojo et al. (2023); Sanogo et al. (2023), who found that marital status significantly influences the adoption of CSATs in Nigeria and Mali, respectively. This arises from the tendency of marriage to expand household size, which in turn supports the adoption of labor-demanding CSATs by farmers. This points to the necessity of considering social aspects such as marital status when categorizing prospective technology adopters, ensuring each group receives technologies aligned with their context.

Access to credit

Access to credit was positively associated with the adoption of pesticides and mulching. Farmers who had access to financial services were more likely to implement these practices compared to those facing financial limitations. Ojo et al. (2023) emphasized the importance of agricultural credit in facilitating the adoption of CSATs in Nigeria, noting that credit enhances farmers' ability to purchase inputs like pesticides, which require monetary investment. Mulching, particularly on larger farms, is labor-intensive and credit enables farmers to hire the necessary labor for its application. Therefore, access to credit plays a crucial role in promoting the adoption of both pesticides and mulching. A separate study in Northern Uganda by Alela et al. (2024 showed that farmers' access to credit increased the likelihood of adopting ISFM by 5.6%. Access to credit enhances farmers' capacity to acquire agricultural inputs. Furthermore, in Kenya, Ndiwa et al. (2024) reported a similar result, showing the positive effect of credit on the adoption of CSATs such as irrigation. In addition, the findings of a study conducted in Ethiopia by Massresha et al. (2021) suggest that credit increases the adoption of CSATs. In contrast, Kalu and Mbanasor (2020) showed an inverse association between credit and the adoption of CSATs in Nigeria. These findings underscore the significance of linking farmers to trustworthy financial service providers to strengthen their purchasing power and promote the uptake of CSATs.

Group membership

As affirmed by the findings of Pham et al. (2021), membership in social groups such as table banking and farmer-based groups, among others, is positively associated with the adoption of pesticides and minimum tillage. The findings suggested that members of social groups were more likely to adopt pesticides and minimum tillage than non-members of social groups. This is similar to the findings of Ahmed et al. (2023), who found that adoption of CSATs was high among members of social groups. A review study by Agyekum et al. (2024) also identified the benefits of participation in social groups as uptake of technologies such as CSATs among the farmers. Farmers affiliated with groups are better positioned to obtain information on CSATs through peer sharing from early adopters or through collective training provided by extension officers, as most rural capacity-building programs are structured to engage groups rather than individuals (Atube et al., 2021). Additionally, such groups improve shared access to farm inputs and advisory services at reduced costs compared to standard market prices (Atube et al., 2021; Banik et al., 2013). This insight also corresponds with the conclusions of Neves et al. (2021), who found that involvement in cooperatives promoted the adoption of agricultural technologies in Brazil. This affirms the necessity of encouraging farmers to collaborate through groups for mutual gain.

Climate-smart agriculture training

The findings also revealed that access to CSA training positively influenced the adoption of minimum tillage. Farmers who participated in such training were more likely to implement minimum tillage practices. CSA training equips farmers with essential knowledge and practical skills required to adopt climate-resilient technologies. Through these sessions, farmers are also introduced to other modern adaptation strategies that can enhance coffee productivity. Thus, training serves as a vital mechanism for promoting the effective adoption of climate-smart agricultural practices. Similar outcomes were reported by Ferrer et al. (2023) in Vietnam, who found that training significantly enhanced the uptake of CSATs. Also, a study by Kule et al. (2023); Kule, Agole, et al. (2025), Kule, Obia, et al. (2025) in Eastern Uganda indicated that participation in agricultural training substantially increased farmers' uptake of ISFM by 55.4% and IPM by 37.0%. This improvement is linked to better access to extension services, which strengthened farmers' awareness of the value of these technologies. These findings are also consistent with those of Kumar et al. (2023) in India, who documented a positive correlation between training on CSATs and the adoption of climate-smart practices. This underscores the importance of farmers taking part in extension-led training programs to better manage the challenges posed by climate change on their farms.

Non-farm income

The multivariate probit analysis revealed a negative relationship between non-farm income and the adoption of agroforestry. As off-farm income increases, the likelihood of farmers adopting agroforestry decreases. Agroforestry is a labor-intensive practice, requiring either the hiring of labor or a significant time commitment from the farmer to manage both tree and crop components. However, engagement in non-agricultural activities, such as small businesses, casual labor and other income-generating ventures reduces the time available for managing integrated farming systems. As a result, farmers involved in off-farm income activities are less likely to adopt labor-demanding CSATs. These findings are in agreement with those of Odawa et al. (2024) and Pham et al. (2021), who also reported a negative impact of off-farm income on the adoption of CSATs in Nigeria and Vietnam, respectively. Conversely, other studies, including Kumar et al. (2023), found that non-farm income can positively influence the adoption of capital-intensive CSATs by providing additional financial resources for their acquisition. This demonstrates that off-farm income does not automatically lead to the adoption of agricultural technologies. Thus, farmers need to be encouraged to allocate such income toward technological investments by drawing on affordable local labor and materials.

Conclusion

Coffee is one of the leading cash crops in Uganda and contributes significantly to the gross domestic product. The crop plays a role in eradicating poverty among farmers. However, climate change is a threat to coffee production. Thus, the adoption of CSATs is a viable solution to the effects of climate variability. Strikingly, farmers in Uganda tend to be reluctant to adopt smart agricultural practices that boost coffee productivity. Therefore, understanding the factors associated with farmers' decisions to adopt CSATs is essential for boosting coffee productivity. This study aimed to assess the determinants of CSATs' adoption in Western Uganda using Multivariate Probit analysis. The results showed moderate adoption of climate-smart agricultural practices. The econometric findings also depicted that variables such as age, education, years in coffee farming, household size, land size, farm income market distance, marital status, credit, membership to social groups, non-farm income and training on CSA were significant predictors of adoption of CSATs among farmers in Western Uganda. Accordingly, the study infers that these aspects are the main determinants of CSAT adoption among smallholder farmers in Western Uganda.

Based on the econometric analysis, the following policy recommendations are proposed to enhance the adoption of CSATs among farmers. There is a need to build farmers' capacity through targeted training and advisory services, complemented by regular follow-ups from extension agents. The enhanced farmers' capacity can significantly improve their appreciation of CSATs and increase uptake. Farmers should be guided towards affordable sources of credit, such as village savings and loan associations, which allow borrowing and flexible repayment after harvest. This will facilitate greater CSAT adoption owing to improved farmer access to the funds required for input purchases like pesticides. This would help address the financial constraints associated with capital-intensive technologies like pesticides and increase the adoption of CSATs. Extension staff should promote access to agricultural knowledge through mass media platforms, such as radio, television and other digital outlets, where farmers can gain valuable insights on the application and advantages of CSTs and increase their adoption. There is also a need to put in place adult education initiatives, including short-term agricultural training, certificate programs and specialized workshops, that can enhance farmers' technical skills, awareness and social networks, thereby fostering greater adoption of CSATs. Young and less-experienced farmers, who often lack sufficient agricultural knowledge, should be prioritized in extension efforts. These farmers should receive structured training and be linked with experienced peers to facilitate learning and practical exposure in the application of CSATs. The knowledge and experience gained can enable young farmers to adopt CSATs on their farms and achieve sustainable agricultural production and productivity.

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Author contributions

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Disclosure statement

The authors declare no competing interests.

Ethical approval

This study was approved by the Gulu University Research Ethics Committee (GUREC).

Informed consent

Informed consent was obtained from all the participants included in the study.

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Data availability statement

The dataset for this study is available from the corresponding author upon reasonable request.

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