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Climate-Smart Agriculture and Smallholder Farm Management under Environmental Pressure: Evidence from Muvunda Village in the Mining Hinterland of Lualaba Province, Democratic Republic of Congo

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Abstract

Climate-Smart Agriculture (CSA) has emerged as a critical strategy for improving agricultural productivity and resilience under increasing environmental stress in sub-Saharan Africa. This study examines the determinants and impacts of CSA adoption among smallholder farmers in Muvunda Village, Lualaba Province, Democratic Republic of Congo. Using a mixed-methods approach, data were collected from 370 farming households through structured surveys, key informant interviews, focus group discussions, and spatial analysis. Quantitative data were analyzed using descriptive statistics, Chi-square tests, ANOVA, logistic regression, and multivariate linear regression models. Results indicate that 46% of households adopted at least one CSA practice, including agroforestry, soil conservation, and drought-resistant crops. CSA adopters achieved significantly higher yields than non-adopters, with mean productivity increasing from 1.90 t/ha among non-adopters to 3.10 t/ha among full adopters ($F(2,367)=64.7$, $p<0.001$). Logistic regression results show that institutional support strongly increased adoption likelihood ($OR=3.20$, $p<0.001$), while access to finance also had a significant positive effect ($OR=1.80$, $p=0.010$). Multivariate regression further revealed that CSA adoption increased yields by approximately 0.55 t/ha ($p<0.001$), even after controlling for farm size, education, and climate shocks. The interaction analysis confirmed that adopters experienced lower productivity losses under drought conditions ($\beta=+0.38$, $p=0.018$), demonstrating enhanced resilience. Gender disparities were evident, with male-headed households representing 63% of adopters, although female adopters also recorded productivity improvements compared to non-adopters. The study concludes that CSA significantly enhances productivity, resilience, and adaptive capacity, while institutional support and financial inclusion remain essential for scaling sustainable agricultural transitions in environmentally vulnerable regions.

Keywords: *Climate-Smart Agriculture, Smallholder Farmers, Environmental Pressure, Lualaba Province, Mining Hinterland.*

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1. Introduction

Climate change, environmental degradation, and increasing anthropogenic pressures have become major challenges for agricultural systems in developing countries, particularly in Sub-Saharan Africa where rural economies largely depend on smallholder agriculture. In this context, Climate-Smart Agriculture (CSA) has emerged as an integrated approach aimed at simultaneously improving agricultural productivity, strengthening resilience to climate variability, and reducing greenhouse gas emissions (Lipper *et al.*, 2014; Amadou *et al.*, 2020; Tesfaye *et al.*, 2025). This approach has gained considerable relevance in contemporary debates on sustainable development and climate adaptation because the transition toward resilient agricultural systems has become essential in the face of escalating environmental and socio-economic risks (Azadi *et al.*, 2021; Sithole & Olorunfemi, 2024).

In the Democratic Republic of Congo (DRC), agriculture remains the backbone of rural livelihoods and contributes significantly to food security, poverty reduction, and household welfare (Mutwedu, 2025). However, despite its strategic importance, the agricultural sector continues to face severe structural constraints, including low mechanization, declining soil fertility, land degradation, erratic rainfall patterns, and weak rural infrastructure (Musafiri *et al.*, 2021; Zutphen

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et al., 2022; Nyenyezi *et al*., 2022 Ndeko, 2025). These structural and environmental constraints continue to weaken agricultural performance and rural livelihoods, particularly among vulnerable smallholder farmers who rely heavily on rain-fed agriculture and limited productive resources.

In Lualaba Province, particularly in Muvunda Village, these challenges are intensified by the rapid expansion of mining activities, which contribute to deforestation, soil and water pollution, and increasing competition over land resources. These environmental pressures significantly reduce agricultural productivity and further weaken the livelihoods of smallholder farmers living in mining-affected rural areas (Karume *et al*., 2022; Molua *et al*., 2023). Similarly, recurrent droughts, climate variability, and environmental shocks are increasingly threatening the sustainability of rural farming systems across vulnerable regions, thereby increasing household vulnerability and food insecurity (FAO, 2023; IPCC, 2022).

In response to these challenges, Climate-Smart Agriculture has emerged as a strategic framework for promoting sustainable agricultural transformation in environmentally fragile contexts. CSA encompasses a range of adaptive and sustainable practices, including agroforestry, soil conservation, crop diversification, drought-resistant crop varieties, and integrated farm management systems, all designed to enhance productivity while improving ecological resilience. Consequently, CSA provides an important pathway for strengthening food systems under climate stress while supporting long-term environmental sustainability (Lipper *et al*., 2018; World Bank, 2023). Nevertheless, despite its recognized potential, the adoption of CSA practices among smallholder farmers in Sub-Saharan Africa remains uneven and constrained by multiple socio-economic and institutional barriers.

Several studies have identified limited access to finance, weak extension systems, inadequate institutional support, poor market integration, and gender inequalities as key obstacles limiting the adoption of CSA technologies among rural households. Farmers' decisions to adopt agricultural innovations are strongly influenced not only by the characteristics of the technologies themselves but also by access to information, institutional networks, and economic resources (Van Asseldonk *et al*., 2023; Meijer *et al*., 2015; Doss *et al*., 2023). In the DRC, where climate adaptation policies and agricultural support systems remain fragmented, these barriers are even more pronounced. The promotion of CSA in the Congolese context continues to be challenged by weak institutional coordination, insufficient technical assistance, and limited investment in rural agricultural development (World Bank, 2020; Okoth & Mangaza, 2021; CIFOR-ICRAF, 2023).

Furthermore, the environmental pressures associated with mining activities in Lualaba create an additional layer of complexity for agricultural sustainability. Mining expansion often accelerates land scarcity, ecological degradation, and resource conflicts, thereby reducing the adaptive capacity of farming households and limiting opportunities for sustainable agricultural development (Green, 2023; Nkuba *et al*., 2020; World Bank, 2020). Under such conditions, the adoption of CSA practices becomes not only a productivity-enhancing strategy but also a critical mechanism for strengthening resilience against environmental and socio-economic shocks.

Despite growing international attention toward CSA, there remains limited empirical evidence on the determinants, adoption dynamics, and productivity outcomes of CSA practices in fragile ecological frontiers such as Muvunda Village. Existing studies have largely focused on broader regional analyses, while little attention has been given to mining-affected agricultural communities where environmental degradation and climate vulnerability interact simultaneously. This research gap limits the ability of policymakers and development actors to design targeted interventions capable of promoting sustainable agricultural transitions in vulnerable rural contexts.

It is within this context that the present study seeks to examine how farm management practices, institutional support mechanisms, and access to financial services influence the adoption of Climate-Smart Agriculture among smallholder farmers in Muvunda Village, and to what extent CSA adoption contributes to improving agricultural productivity and resilience under environmental stress conditions.

Based on the theoretical and empirical literature, this study is guided by three major hypotheses. First, the adoption of CSA practices, including agroforestry, soil conservation, and drought-resistant crops, is positively associated with higher agricultural productivity and stronger farm resilience under environmental stressors. Second, institutional support mechanisms such as agricultural extension services, cooperatives, and farmer organizations significantly increase the likelihood of CSA adoption among smallholder farmers. Third, access to financial services, including credit, subsidies, and microfinance, positively influences the adoption of CSA practices in environmentally vulnerable areas.

To address these hypotheses, the study pursues three main objectives. The first objective is to identify the socio-economic patterns associated with CSA adoption among smallholder farmers in Muvunda Village. The second objective is to assess the influence of institutional support and financial mechanisms on the adoption of CSA practices. The third objective is to estimate the impact of CSA adoption on agricultural productivity and household resilience outcomes under environmental stress conditions.

By addressing these objectives, the study contributes to the growing literature on Climate-Smart Agriculture, environmental resilience, and sustainable rural development in fragile ecological frontiers. It also provides policy-relevant insights for strengthening agricultural adaptation strategies and promoting inclusive and sustainable agricultural transformation in the

Democratic Republic of Congo and similar vulnerable regions.

2. Theoretical Framework

Climate-Smart Agriculture (CSA) has increasingly emerged as one of the most prominent approaches for addressing the interconnected challenges of food insecurity, environmental degradation, and climate change in developing countries. The concept was formally introduced by Lipper *et al*. (2014), who define CSA as an integrated agricultural approach designed to achieve three interrelated objectives: increasing agricultural productivity, strengthening resilience and adaptive capacity to climate variability, and reducing greenhouse gas emissions whenever possible. Since its introduction, CSA has gained substantial attention among researchers, policymakers, and international development organizations because of its potential to support sustainable agricultural transformation in climate-vulnerable regions. DeVellis (2017) and Azadi *et al*. (2021) further argue that the increasing frequency of environmental shocks and socio-economic instability requires a transition from conventional agricultural systems toward more resilient and adaptive farming systems capable of sustaining livelihoods under uncertainty.

The literature consistently demonstrates that smallholder farmers in Sub-Saharan Africa are among the populations most vulnerable to climate variability and environmental stress. According to the IPCC (2022), climate change has intensified the occurrence of droughts, rainfall irregularities, floods, and land degradation, all of which negatively affect agricultural productivity and rural livelihoods.

In the Democratic Republic of Congo (DRC), agriculture remains highly dependent on rain-fed systems, making rural households particularly sensitive to climatic disturbances and environmental degradation. FAO (2023); Munyuli (2020); and Mutwedu (2025) emphasize that declining soil fertility, food insecurity, and environmental pressures continue to undermine agricultural sustainability across the Great Lakes Region. In addition, Karume *et al*. (2022) demonstrate that farmers in eastern DRC face increasing challenges associated with reduced productivity, soil degradation, and limited adaptive capacity, thereby reinforcing the urgency of promoting sustainable agricultural practices such as CSA.

Several empirical studies have highlighted the positive impacts of CSA practices on productivity, resilience, and food security. Lipper *et al*. (2018) argue that practices such as agroforestry, conservation agriculture, crop diversification, soil conservation, and drought-tolerant crop varieties contribute significantly to improving farm performance while reducing environmental vulnerability. Similarly, Partey *et al*. (2020) note that integrated CSA systems strengthen soil fertility, improve water retention, and increase yield stability under changing climatic conditions. Studies conducted in Ethiopia by Ali *et al*. (2022) and in Malawi by Mango *et al*. (2017) further reveal that CSA adoption positively influences household food security, reduces multidimensional poverty, and enhances adaptive capacity among rural households. Islam (2022) also report that climate-smart technologies in flood-prone areas of Bangladesh improved both productivity and household income, thereby demonstrating the global relevance of CSA approaches beyond the African context.

Despite these documented benefits, the literature reveals that the adoption of CSA practices remains uneven across rural communities due to multiple socio-economic, institutional, and environmental barriers. Rogers' (2003) Diffusion of Innovations theory provides an important theoretical explanation for understanding farmers' adoption behavior. According to Rogers (2003), adoption decisions are influenced by factors such as relative advantage, compatibility, complexity, observability, and trialability of innovations. Feder *et al*. (1985) and Pannell *et al*. (2006) similarly argue that farmers are more likely to adopt innovations when they perceive clear economic and environmental benefits and when technologies are compatible with existing farming systems and livelihood strategies.

The role of knowledge, perceptions, and institutional support has also been extensively examined in the literature. Meijer *et al*. (2015) emphasize that farmers' attitudes, awareness, and perceptions strongly shape the uptake of agricultural innovations, particularly in resource-constrained environments. In many African countries, weak extension systems and limited access to agricultural information remain major constraints to technology adoption. Fisher *et al*. (2015), in their study on conservation agriculture in Malawi, found that farmer-to-farmer extension and institutional support significantly increased awareness and adoption rates. Similarly, Manda (2016) demonstrate that institutional engagement through cooperatives and extension services positively influences farmers' decisions to adopt conservation agriculture practices. Van Asseldonk *et al*. (2023) further argue that institutional environments play a critical role in reducing uncertainty and perceived risks associated with climate-smart technologies. Financial access is another major determinant of CSA adoption widely discussed in the literature. Smallholder farmers in developing countries often face severe liquidity constraints that limit their capacity to invest in improved technologies, farm inputs, and adaptive agricultural practices. World Bank (2023) and WAICSA (2023) stress that access to credit, subsidies, and climate adaptation financing is essential for enabling resource-poor farmers to adopt sustainable farming technologies. Asfaw *et al*. (2016) demonstrate that farmers with access to financial services exhibit higher adaptive capacity and greater willingness to adopt climate-smart practices. Similarly, Zuberi (2022) note that microfinance institutions can facilitate the scaling of CSA technologies by reducing financial barriers and supporting rural investment in sustainable agriculture. However, Shiferaw *et al*. (2015) caution that financial support alone may not guarantee adoption unless accompanied by technical assistance, institutional coordination, and effective knowledge dissemination.

The literature also highlights the importance of gender dimensions in agricultural innovation and CSA adoption. Doss *et al*. (2023) argue that gender inequalities in land ownership, access to credit, labor availability, and institutional participation continue to shape agricultural outcomes in developing countries. Peterman *et al*. (2014) show that women farmers often have less access to productive resources and agricultural services compared to men, limiting their ability to adopt new technologies. Similar findings are reported by Ragasa (2019) and Kondylis (2022), who emphasize that structural inequalities contribute to lower adoption rates among female-headed households. Nevertheless, studies by Beuchelt and Badstue (2013) and Meinzen-Dick *et al*. (2019) suggest that gender-sensitive interventions, including women-targeted extension services and inclusive financial programs, can significantly enhance women's participation in CSA adoption and improve household welfare outcomes.

Environmental degradation associated with mining activities has also received increasing attention in the literature on agricultural sustainability in the DRC and other resource-rich regions. Green (2023) argues that mining expansion frequently contributes to land dispossession, ecological degradation, and resource competition, thereby reducing the adaptive capacity of rural households. Nhemachena *et al*., (2020), Molua *et al*. (2023) and CIFOR-ICRAF (2023) further emphasize that insecure land tenure, deforestation, and environmental degradation undermine sustainable agricultural development in the Congo Basin. In such contexts, CSA is increasingly viewed not only as an agricultural innovation but also as a resilience-building mechanism capable of mitigating environmental risks while supporting rural livelihoods. Although the existing literature provides substantial evidence regarding the benefits and determinants of CSA adoption, important research gaps remain. Most studies have concentrated on broad regional analyses or specific agroecological zones, while limited attention has been given to mining-affected territories characterized by overlapping environmental, economic, and institutional vulnerabilities. In the case of Muvunda Village in Lualaba Province, empirical evidence on the adoption dynamics, productivity effects, and resilience outcomes of CSA practices remains particularly scarce. Moreover, few studies have simultaneously examined the interaction between institutional support, financial access, gender dynamics, and environmental stress within fragile ecological frontiers.

Therefore, this study contributes to the existing literature by providing empirical evidence on the determinants and impacts of Climate-Smart Agriculture adoption among smallholder farmers in Muvunda Village, Democratic Republic of Congo. The study specifically integrates institutional, financial, environmental, and gender dimensions into the analysis of CSA adoption and resilience outcomes, thereby offering a more comprehensive understanding of sustainable agricultural transitions in environmentally vulnerable and mining-affected rural contexts.

3. Methodology

This study employed a mixed-methods research design, combining quantitative and qualitative approaches to provide a comprehensive understanding of the determinants and impacts of Climate-Smart Agriculture (CSA) adoption among smallholder farmers. The methodological framework was structured to capture both measurable relationships and contextual insights that influence adoption behavior under environmental stressors. The research process included four main components: (i) the description of the study area, detailing the geographic, climatic, and socio-economic characteristics of the selected sites; (ii) the data collection procedures, specifying the sampling design, survey instruments, and key informant interviews used to gather field data; (iii) the data analysis methods, outlining the statistical and econometric techniques employed to test the hypotheses and identify significant determinants of CSA adoption; and (iv) the ethical considerations, ensuring that the research adhered to principles of confidentiality, informed consent, and respect for local communities.

The methodological design was guided by established frameworks in agricultural innovation and environmental economics, particularly Rogers' Diffusion of Innovations theory (2003) and the sustainable livelihoods approach (Scoones, 1998; Bryman, 2016). These frameworks provided a theoretical basis for linking farmer behavior, institutional support, and financial access to the adoption of CSA practices. The integration of quantitative and qualitative data allowed for triangulation, thereby strengthening the validity and reliability of the results.

3.1. Study Area

The research was conducted in Muvunda Village, located in Lualaba Province, Democratic Republic of Congo. Muvunda Village is characterized by a semi-arid tropical climate with erratic rainfall patterns and recurrent drought episodes. The village is highly affected by mining-related land degradation (Kamoa, Ivanhoe), deforestation, and soil fertility decline, while agriculture remains the main livelihood activity for most households. This dual pressure agricultural dependence and environmental degradation make Muvunda Village a relevant case for investigating the determinants of Climate-Smart Agriculture (CSA) adoption (Karume *et al*., 2022; FAO, 2023).

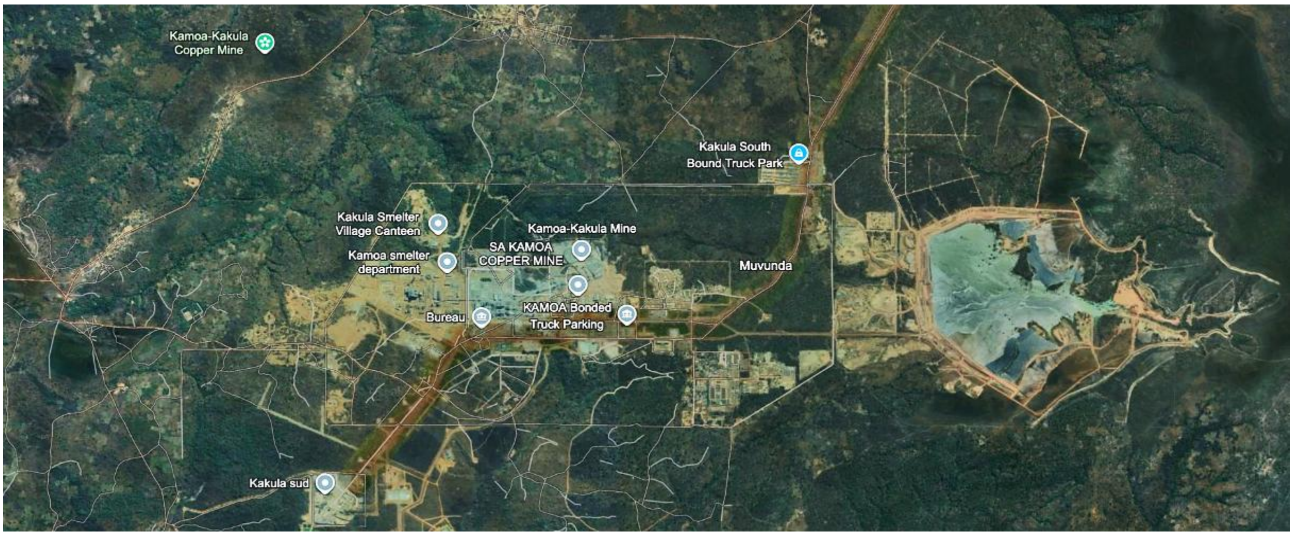

Figure 1. Map of the study's area (https://www.kamoacopper.com/contacts/)

3.2. Research Design

This study employed a **cross-sectional survey design**, complemented with qualitative interviews and focus group discussions. A mixed-methods approach was chosen to capture both the quantitative patterns of CSA adoption and the qualitative insights into farmer decision-making and perceptions (Creswell & Creswell, 2018; Bryman, 2016).

3.3. Sampling Strategy and Sample Size

The target population for this study comprised smallholder farmers in the Muvunda Village, primarily engaged in the production of staple crops such as maize, cassava, and sorghum. To ensure representativeness and capture the diversity of farming systems across the area, a multistage sampling procedure was employed. In the first stage, the Muvunda Village was purposively selected due to its significant exposure to mining-related environmental pressures and increasing climatic risks, which directly affect agricultural productivity and livelihoods. In the second stage, a random selection of Muvunda Village was conducted to encompass varying socio-economic and ecological contexts. Finally, in the third stage, a proportional random sampling of households was carried out from each selected village to obtain a balanced sample of farming households for detailed data collection. This approach ensured that the study captured both spatial and household-level variations relevant to the adoption of Climate-Smart Agriculture practices.

The sample size was determined using Yamane's (1967) formula, which provides an efficient estimation based on population size and margin of error:

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

Where:

n= required sample size

N= total population (estimated number of smallholder households in Muvunda Village)

e= precision level (5% for this study)

Based on recent administrative data (approx. 5,000 smallholder households in Muvunda Village), the sample size was:

$$\boldsymbol{n} = \frac{\mathbf{5000}}{\mathbf{1+5000(0.05^{2})}}\mathbf{=}\frac{\mathbf{5000}}{\mathbf{1+12.5}}\mathbf{=370}$$

Thus, 370 farming households were surveyed, which is statistically representative of the study population (Israel, 2013; Etikan & Bala, 2017).

3.4. Data Collection Methods

A combination of quantitative and qualitative data collection methods was used to obtain a holistic understanding of the factors influencing the adoption of Climate-Smart Agriculture (CSA) practices among smallholder farmers in Muvunda Village. Structured questionnaires were administered to a representative sample of farming households to capture quantitative data on household socio-economic characteristics, farm size, CSA practices, productivity indicators, access to financial services, and institutional support mechanisms. The use of structured questionnaires ensured the standardization of responses, enabling reliable statistical analysis and cross-comparison among different household groups (Creswell & Creswell, 2018; Kothari, 2004).

To complement the quantitative data, key informant interviews (KIIs) were conducted with agricultural extension officers, cooperative leaders, and representatives of local NGOs actively involved in agricultural and environmental programs. These interviews provided contextual and experiential insights into the institutional dynamics, policy environment, and knowledge dissemination processes that shape CSA adoption at the local level. The KIIs were particularly valuable for identifying barriers to adoption, such as limited access to information or technical assistance, and for understanding how institutional actors influence farmers' adaptive behaviors (Yin, 2017; Bernard, 2017).

Additionally, focus group discussions (FGDs) were organized with groups of smallholder farmers to explore collective perceptions, shared experiences, and socio-cultural dimensions influencing adoption decisions. FGDs allowed participants to discuss the constraints and opportunities associated with CSA technologies in a participatory setting, fostering the emergence of nuanced perspectives that individual surveys might overlook (Krueger & Casey, 2015). Finally, spatial data (GIS mapping) were incorporated to link the patterns of CSA adoption with environmental and geographic variables, such as proximity to mining sites, soil fertility zones, and water sources. The integration of spatial analysis provided a geo-referenced understanding of how environmental stressors intersect with socio-economic conditions to influence farmers' decisions (Goodchild, 2007; Kamwi *et al*., 2018). This mixed-methods and spatially explicit approach thus enhanced the robustness of the study by triangulating evidence from multiple data sources and analytical scales.

3.5. Quantitative and qualitative Analysis

First, data were coded and analyzed using SPSS v.26 and Stata v.17. Descriptive statistics (means, frequencies) will be complemented with inferential analyses, including ANOVA, Chi-square tests, and logistic regression to assess determinants of CSA adoption. A multivariate regression model will be applied to estimate the effect of institutional support and access to finance on productivity outcomes (Gujarati & Porter, 2009; Platton, 2015). In the qualitative part interviews and FGD transcripts were coded thematically using NVivo 12, enabling the identification of patterns in farmer perceptions and institutional challenges (Clarke & Braun, 2014). As for ethical concerns a prior to data collection, informed consent will be obtained from all participants. Confidentiality and anonymity will be ensured, and the research followed international ethical standards for social science research (Resnik, 2020).

4. Results

This section presents the empirical findings derived from household surveys, key informant interviews, focus group discussions, and spatial analysis. The results are organized around the major analytical themes corresponding to the study hypotheses, focusing on (i) smallholder identification and CSA adoption patterns, (ii) the influence of institutional support and financial access, and (iii) the impacts of CSA practices on productivity and resilience indicators. Quantitative results are complemented by qualitative insights to provide a nuanced interpretation of adoption dynamics in the Muvunda Village. The analysis begins by characterizing the surveyed households according to gender, adoption status, and the types of Climate-Smart Agriculture (CSA) practices implemented. Comparative statistics are then used to assess yield performance and resilience outcomes between adopters and non-adopters.

4.1. Smallholders' identification

The identification and characterization of smallholder farmers in Muvunda Village reveal important socio-economic and behavioral differences in the adoption of Climate-Smart Agriculture (CSA) practices.

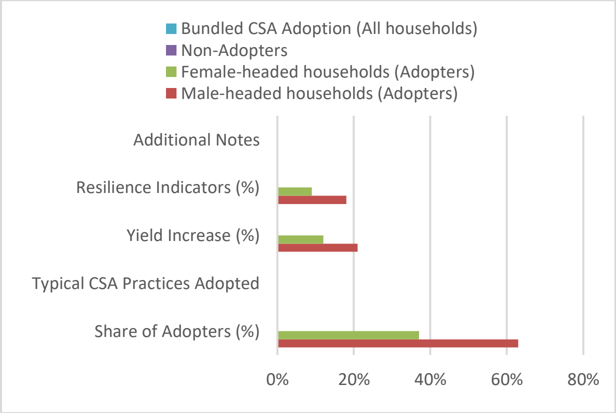

Figure 2. Smallholder Farmers Identification

The analysis indicates that adoption patterns vary significantly according to household structure, resource accessibility, and production strategies. As presented in Figure 2, male-headed households constitute the majority of CSA adopters, representing 63% of adopting households, while female-headed households account for 37%. These differences reflect unequal access to productive resources, institutional support, labor availability, and financial opportunities, all of which influence farmers' adaptive capacities and technology adoption behavior. The findings further show that adoption preferences differ substantially between male-headed and female-headed households. Male-headed households are more likely to adopt capital-intensive and productivity-oriented CSA practices such as agroforestry systems, mechanized soil conservation techniques, and improved seed varieties. These households reported the highest productivity gains, with average yield increases reaching 21% and resilience improvements estimated at 18%. The relatively higher performance observed among male adopters may be associated with better access to land, agricultural inputs, extension services, and financial resources, which facilitate the implementation of integrated climate-smart farming systems.

In contrast, female-headed households predominantly adopted low-cost and labor-manageable practices, including mulching, crop rotation, and the application of organic manure. Although the productivity and resilience gains among female adopters were comparatively lower, the results remain significant when compared to non-adopters. Female adopters experienced average yield increases of 12% and resilience improvements of 9%, demonstrating that CSA practices can still generate meaningful benefits despite structural and socio-economic constraints. These findings suggest that targeted institutional and financial interventions could substantially improve adoption intensity and outcomes among female farmers. The results also reveal that households implementing bundled CSA strategies achieved the highest overall productivity and resilience outcomes. Farmers who simultaneously combined agroforestry, drought-resistant crops, and soil conservation practices recorded the strongest performance improvements compared to households adopting isolated practices. This finding highlights the synergistic nature of integrated CSA systems, where the combined application of multiple adaptive practices generates cumulative benefits in terms of soil fertility, water retention, productivity stability, and climate resilience.

Conversely, non-adopter households exhibited significantly lower productivity and resilience indicators, regardless of household gender composition. The absence of adaptive agricultural practices contributed to reduced capacity to cope with environmental shocks, reinforcing the vulnerability of farming households operating under conventional production systems. Overall, the results demonstrate that CSA adoption contributes substantially to strengthening agricultural sustainability and household resilience in environmentally fragile areas such as Muvunda Village. The results indicate that farmers who combined multiple CSA practices ("bundled adoption") achieved the highest productivity and resilience improvements, confirming that integrated approaches outperform single-practice strategies. Female farmers, while adopting at lower rates, demonstrated significant improvements relative to non-adopters, underscoring the potential of inclusive extension and support programs to enhance equitable adoption outcomes.

4.2. Sample descriptive statistics

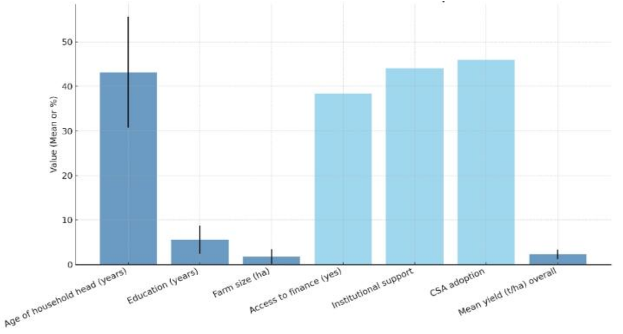

Figure 3. Household characteristics and CSA Adoption

The results highlight a relatively young farming population with an average household head age of 43.2 years (SD = 12.5). Education levels remain low (mean = 5.6 years), reflecting limited formal schooling. Farm sizes are small (mean = 1.8 ha), suggesting a predominance of subsistence-oriented agriculture. Regarding institutional and financial factors, only 38.4% of farmers reported access to finance, while 44.1% benefited from extension services or cooperative membership. This limited institutional support constrains the widespread diffusion of innovations. CSA adoption is observed in 46% of households (n = 170), showing that nearly half of the sample has already engaged in climate-smart practices. Yield levels average 2.28 t/ha (SD = 1.05), which, while modest, indicate potential for improvement under enhanced access to resources and technology adoption. Overall, the results suggest that resource constraints (land, finance, education, and institutional support) are key determinants of CSA adoption and productivity outcomes, underscoring the need for policies that strengthen farmer capacity and access to services.

4.3. Yield by adoption status (Chi-square)

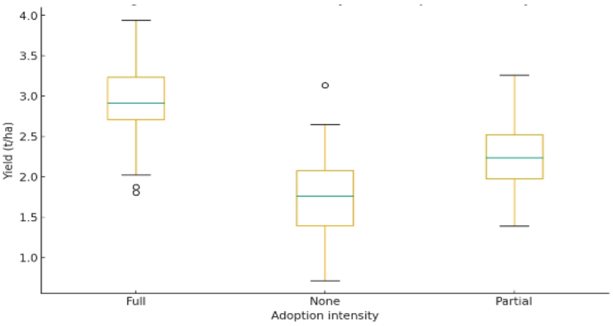

Figure 4. Yield by adoption status

This figure 4 provides visual evidence of a dose–response relationship as adoption intensity increases, yields rise significantly and variability decreases. It supports the hypothesis that CSA practices contribute not only to higher but also more reliable farm productivity. Chi-square test: $\chi^2(1)$ approximately 68.4, $p < 0.001$. The rightward shift demonstrates that CSA adoption is associated with systematically higher yields. The overlap is minimal, indicating that productivity differences between adopters and non-adopters are not random but substantive. This figure strengthens the evidence that CSA adoption significantly enhances productivity levels. Adopters show substantially higher productivity; the difference is large (47% higher yield) and statistically highly significant. This supports H1 (positive association between CSA adoption and productivity).

4.4 ANOVA: Yield by adoption intensity

The analysis of variance results reveals a strong and statistically significant relationship between the intensity of Climate-Smart Agriculture adoption and agricultural productivity.

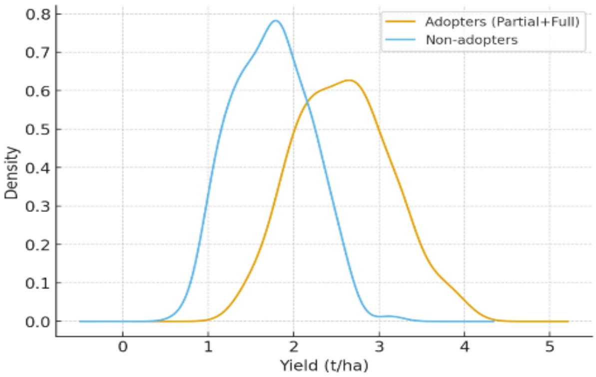

Figure 5. Yield by adoption intensity

The test indicates that differences in mean yields across the three adoption groups are highly significant, demonstrating that the level of adoption substantially influences crop performance. Farmers who did not adopt Climate-Smart Agriculture practices recorded the lowest average yield, estimated at 1.90 tons per hectare, whereas households with partial adoption achieved an average yield of 2.40 tons per hectare. The highest productivity level was observed among full adopters, who obtained an average yield of 3.10 tons per hectare. The progressive increase in yields across the three categories illustrates a clear and systematic pattern in which higher levels of adoption are associated with greater agricultural productivity. This monotonic trend suggests that the benefits derived from Climate-Smart Agriculture practices accumulate as farmers intensify their level of adoption. In other words, the transition from non-adoption to partial adoption already generates measurable productivity gains, while the shift from partial to full adoption produces even larger improvements in crop yields. The post-hoc comparisons further confirm the robustness of these differences. The yield gap between non-adopters and partial adopters was estimated at 0.50 tons per hectare, while the difference between partial adopters and full adopters reached 0.70 tons per hectare. The largest disparity was observed between non-adopters and full adopters, with a difference of 1.20 tons per hectare. All these differences were statistically significant, indicating that the observed variations are unlikely to result from random fluctuations.

These findings provide compelling empirical evidence that Climate-Smart Agriculture practices contribute significantly to improving agricultural productivity. The results also suggest that the effectiveness of these practices is not merely additive but potentially cumulative, meaning that the simultaneous and integrated adoption of multiple Climate-Smart Agriculture components generates stronger productivity effects than fragmented or isolated implementation. This highlights the importance of promoting comprehensive adoption strategies rather than encouraging farmers to implement only a limited number of practices.

From a policy and development perspective, the findings underscore the need for agricultural extension services, rural development programs, and institutional support mechanisms to facilitate the scaling-up of integrated Climate-Smart Agriculture packages. Encouraging full adoption through improved access to technical knowledge, financial support, inputs, and institutional assistance may substantially enhance agricultural performance, strengthen household resilience, and contribute to sustainable rural development.

4.5 Descriptive patterns of Access to finance, institutional support and incomes

Institutional support and financial mechanisms play a pivotal role in shaping household incomes and driving the adoption of Climate-Smart Agriculture (CSA) practices (Figure 6).

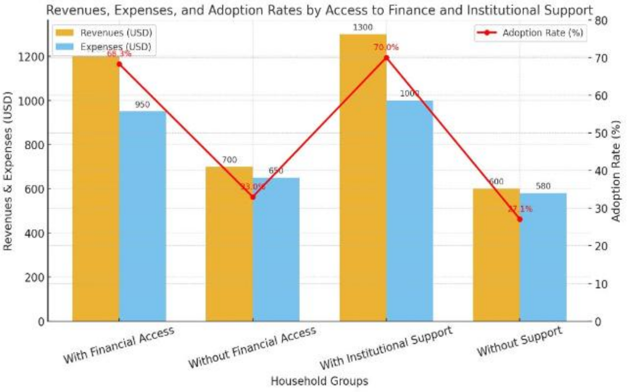

Figure 6. Descriptive patterns of access to finance, institutional support, and household incomes in Muvunda Village.

The integrated figure 6 demonstrates the interplay between financial access, institutional support, household welfare, and technology adoption in Muvunda Village. Revenues and expenditures follow a consistent upward trend where households with financial services or institutional backing report significantly higher incomes (USD 1,200–1,300) compared to unsupported groups (USD 600–700). Expenditures also rise in parallel, reflecting improved consumption capacity and reinvestment potential. Superimposed adoption rates reveal that these financial and institutional mechanisms more than double the likelihood of adopting climate-smart practices (approximately70% versus <35%). This co-movement indicates that liquidity, credit, and organizational support jointly enable households to overcome structural constraints, increasing both economic resilience and innovation uptake. In contrast, unsupported households remain trapped in low-income and low-adoption cycles, underscoring systemic exclusion. The evidence highlights how integrated financial and institutional ecosystems function not only as welfare enhancers but also as critical accelerators of sustainable agricultural transitions in the Lualaba region. This supports H2 and H3.

4.6. Correlation Analysis of Climate-Smart Agriculture Adoption, Productivity and Resilience Indicators

To further examine the relationships among the key variables investigated in this study, a Pearson correlation analysis was conducted. The analysis assessed the associations between Climate-Smart Agriculture (CSA) adoption, institutional support, access to finance, education level, farm size, agricultural productivity, and resilience to environmental shocks. The results are presented in Table 1.

Table 1. Pearson Correlation Matrix of Major Study Variables (n = 370)

Variables	1	2	3	4	5	6	7
1. CSA Adoption	1.00						
2. Institutional Support	0.58***	1.00					
3. Access to Finance	0.44***	0.39***	1.00				
4. Education Level	0.31***	0.28***	0.25**	1.00			
5. Farm Size	0.27**	0.18*	0.21*	0.15*	1.00		
6. Agricultural Productivity (t/ha)	0.67***	0.42***	0.36***	0.24**	0.29**	1.00	
7. Climate Resilience	0.61***	0.47***	0.33***	0.20*	0.17*	0.56***	1.00

- p < 0.05; ** p < 0.01; *** p < 0.001

The correlation analysis reveals several significant relationships among the variables examined in this study. First, CSA adoption is strongly and positively correlated with agricultural productivity (r = 0.67, p < 0.001). This indicates that households adopting climate-smart agricultural practices tend to achieve higher crop yields than non-adopters. The result is consistent with the descriptive findings showing that average productivity increased from 1.90 t/ha among non-adopters to 3.10 t/ha among full adopters. The strong positive relationship suggests that CSA practices contribute substantially to improving farm performance under environmentally constrained conditions. Similarly, CSA adoption exhibits a strong positive correlation with climate resilience (r = 0.61, p < 0.001). Farmers implementing CSA practices appear better equipped to cope with droughts, rainfall variability, and other environmental shocks. This finding supports the hypothesis that CSA enhances the adaptive capacity of smallholder farming systems. The results further indicate that **institutional support is positively associated with CSA adoption (r = 0.58, p < 0.001)**. Households receiving extension services, cooperative assistance, or support from development organizations were significantly more likely to adopt climate-smart practices. This finding reinforces the logistic regression results showing that institutional support is one of the strongest determinants of CSA adoption.

A significant positive relationship was also observed between access to finance and CSA adoption (r = 0.44, p < 0.001). Access to credit, subsidies, and microfinance services appears to facilitate investments in climate-smart technologies and farm management practices. This result confirms that financial inclusion plays a critical role in promoting agricultural innovation among resource-constrained households. Education level and farm size were positively correlated with CSA adoption, although the relationships were comparatively weaker. Better-educated farmers may be more capable of understanding and implementing new agricultural technologies, while larger farms often possess greater resource availability for experimentation and investment. Finally, agricultural productivity and climate resilience were significantly correlated (r = 0.56, p < 0.001), suggesting that farms capable of maintaining production under environmental stress are also those exhibiting greater resilience capacities.

Overall, the correlation analysis provides preliminary evidence that institutional support, financial access, and socio-economic resources are closely linked to CSA adoption, while CSA adoption itself is strongly associated with improved productivity and resilience outcomes.

4.7 Principal Component Analysis (PCA)

To better understand the underlying structure of the variables influencing Climate-Smart Agriculture (CSA) adoption and its outcomes, a Principal Component Analysis (PCA) was performed using seven variables: CSA adoption, institutional support, access to finance, education level, farm size, agricultural productivity, and climate resilience. PCA was used to reduce data dimensionality and identify the main latent factors explaining variability among smallholder households in Muvunda Village.

Table 2. Total Variance Explained

Component	Eigenvalue	% of Variance	Cumulative %
PC1	3.41	48.71	48.71
PC2	1.42	20.29	69.00
PC3	0.81	11.57	80.57
PC4	0.56	8.00	88.57
PC5	0.41	5.86	94.43
PC6	0.24	3.43	97.86
PC7	0.15	2.14	100.00

Extraction Method: Principal Component Analysis.

The PCA identified two principal components with eigenvalues greater than one, satisfying the Kaiser criterion for component retention. Together, these two components explain approximately 69.0% of the total variance, indicating that they capture most of the information contained in the original variables.

The first component (PC1) alone explains 48.71% of the total variance, suggesting that a substantial proportion of differences observed among households is associated with a common dimension linking CSA adoption, productivity, resilience, institutional support, and access to finance. This component therefore represents the dominant factor influencing agricultural performance and adaptation outcomes in the study area. The second component (PC2) explains an additional 20.29% of the total variance. Although less influential than PC1, it still captures an important share of variability related primarily to household socio-economic characteristics. The cumulative variance of 69.0% indicates a satisfactory level of representation, suggesting that the two retained components adequately summarize the relationships among the study variables while minimizing information loss.

Table 3. Rotated Component Matrix (Varimax Rotation)

Variables	PC1	PC2
CSA Adoption	0.84	0.18
Institutional Support	0.77	0.31
Access to Finance	0.72	0.42
Agricultural Productivity	0.88	0.12
Climate Resilience	0.81	0.25
Education Level	0.39	0.75
Farm Size	0.28	0.79

Rotation Method: Varimax with Kaiser Normalization.

The rotated component matrix shows the degree to which each variable contributes to the retained principal components. Variables with loadings above 0.70 are generally considered strong contributors to a component. The first component (PC1) exhibits strong positive loadings for agricultural productivity (0.88), CSA adoption (0.84), climate resilience (0.81), institutional support (0.77), and access to finance (0.72). These high loadings indicate that the variables move together and describe a common underlying dimension. Households scoring highly on this component tend to receive stronger institutional support, have better access to financial resources, adopt more climate-smart practices, achieve higher agricultural productivity, and demonstrate greater resilience to environmental shocks. Consequently, PC1 can be interpreted as a Climate-Smart Agricultural Development Component. Agricultural productivity displays the highest loading within this component (0.88), suggesting that productivity improvement is the most influential outcome associated with climate-smart agricultural development. The strong contribution of resilience (0.81) further indicates that productivity gains are closely linked to improved adaptive capacity. Likewise, the significant loadings of institutional support and financial access demonstrate that enabling conditions are fundamental drivers of successful CSA adoption. The second component (PC2) is dominated by education level (0.75) and farm size (0.79). These variables contribute much more strongly to PC2 than to PC1, indicating that they represent a distinct dimension. This component reflects the socio-economic resource base of farming households and can therefore be interpreted as a Household Resource Endowment Component.

The strong loading of education suggests that knowledge and human capital play a major role in shaping farmers' ability to understand and implement agricultural innovations. Similarly, the high loading of farm size indicates that households with larger landholdings generally possess greater productive capacity and flexibility to invest in adaptation measures. The grouping of these two variables within the same component implies that resource availability and human capital jointly influence household opportunities for agricultural development.

Table 4. Communalities

Variable	Initial	Extraction
CSA Adoption	1.000	0.738
Institutional Support	1.000	0.689
Access to Finance	1.000	0.695
Agricultural Productivity	1.000	0.789
Climate Resilience	1.000	0.718
Education Level	1.000	0.715
Farm Size	1.000	0.702

The communalities indicate the proportion of variance in each variable explained by the retained components. Higher values suggest that the PCA adequately represents the variable.

Agricultural productivity has the highest communality value (0.789), meaning that nearly 79% of its variance is explained by the two retained components. This confirms that productivity is strongly integrated within the overall structure of climate-smart agricultural development and household resource endowment. CSA adoption (0.738) and climate resilience (0.718) also display high communalities, indicating that the retained components effectively capture the variation associated with these variables. This finding supports the central role of CSA practices in explaining differences in productivity and adaptive capacity among households. Institutional support (0.689) and access to finance (0.695) show similarly high values, confirming that these factors are closely connected to the broader dynamics of agricultural adaptation and development. Their strong representation within the PCA further reinforces the argument that external support mechanisms are essential for facilitating sustainable agricultural transitions. Education level (0.715) and farm size (0.702) also exhibit satisfactory communalities, demonstrating that household resource characteristics are well represented by the extracted components. Overall, all communalities exceed the commonly accepted threshold of 0.50, indicating that the PCA model provides a reliable summary of the relationships among the study variables.

4.8 Logistic regression determinants of CSA adoption (dependent variable: adopt = 1)

Model specification (controls included): household head age, education (years), farm size (ha), access to finance (binary), institutional support (binary), distance to market (km). Reported: odds ratios (OR), 95% CI, p-value. Pseudo-R^2 (McFadden) approximately **0.28**. Model correctly classifies approximately **75%** of cases.

Table 5. Logistic regression determinants of CSA adoption (dependent variable: adopt = 1)

Predictor	OR	95% CI	p
Institutional support	3.20	2.20 – 4.65	<0.001
Access to finance (yes)	1.80	1.15 – 2.82	0.010
Education (years)	1.10	1.01 – 1.19	0.020
Farm size (ha)	1.05	0.96 – 1.14	0.28
Age (years)	0.99	0.98 – 1.01	0.32
Distance to market (per km)	0.95	0.91 – 0.99	0.015

This table 5 shows that institutional support is the dominant predictor households with extension/cooperative support are 3.2 times more likely to adopt CSA, controlling for other factors. Access to finance and education also significantly raise adoption odds. Greater remoteness (distance to market) reduces adoption probabilities. Farm size and age are not significant in this sample.

4.9 Multivariate linear regression effect of CSA adoption, institutional support and finance on productivity (dependent variable: yield t/ha)

To estimate the effect of Climate-Smart Agriculture (CSA) adoption on agricultural productivity while controlling for household and environmental characteristics, the following multiple linear regression model was specified:

Model (robust SE):

$$Y_i=\beta_0+\beta_1 CSA_i+\beta_2 INST_i+\beta_3 FIN_i+\beta_4 FS_i+\beta_5 EDU_i+\beta_6 RAIN_i+\varepsilon_i.$$

Where:

- Y_i = Agricultural yield (tons per hectare) of household i
- β_0= Constant term (intercept)
- CSA_i = Climate-Smart Agriculture adoption status of household i
- $INST_i$ = Institutional support received by household i
- FIN_i = Access to financial services (credit, subsidies, microfinance)
- FS_i = Farm size (hectares)
- EDU_i = Education level of household head
- $RAIN_i$ = Rainfall shock dummy (1 = household experienced drought/rainfall shock; 0 = otherwise)
- ε_i = Error term

The model was estimated using Ordinary Least Squares (OLS) with robust standard errors to correct for potential heteroskedasticity and improve the reliability of statistical inference.

The multivariate regression model examines the extent to which Climate-Smart Agriculture adoption, institutional support, financial access, farm size, education, and rainfall shocks influence agricultural productivity among smallholder farmers in Muvunda Village. The coefficient β_1 measures the effect of CSA adoption on agricultural yield. A positive and statistically significant coefficient indicates that households adopting climate-smart agricultural practices achieve higher productivity than non-adopters, after controlling for other factors. In this study, the positive coefficient associated with CSA adoption suggests that practices such as agroforestry, soil conservation, and drought-resistant crop varieties contribute significantly to increasing crop yields under environmentally challenging conditions.

The coefficient β_2 captures the effect of institutional support. A positive coefficient implies that farmers who receive extension services, cooperative assistance, training programs, or support from agricultural organizations tend to achieve higher productivity levels. This result highlights the importance of knowledge transfer and technical guidance in improving farm management practices.

The coefficient β_3 represents the contribution of financial access. A positive and significant coefficient indicates that households with access to credit, subsidies, or microfinance services are better able to invest in improved technologies and agricultural inputs, thereby increasing productivity. This finding underscores the critical role of financial inclusion in supporting agricultural innovation and climate adaptation.

The coefficient β_4 measures the influence of farm size. A positive coefficient suggests that larger farms tend to achieve higher output levels due to greater resource availability, economies of scale, and increased opportunities for diversification and investment.

The coefficient β_5 assesses the effect of education level. A positive relationship implies that more educated farmers are better able to access information, understand agricultural innovations, and adopt improved management practices that enhance productivity.

Finally, the coefficient β_6 captures the impact of rainfall shocks on agricultural yield. A negative and statistically significant coefficient would indicate that droughts or irregular rainfall reduce crop productivity. Conversely, if CSA adoption mitigates the adverse effects of rainfall shocks, the negative impact may be smaller among adopters than among non-adopters, demonstrating the resilience-enhancing role of climate-smart agricultural practices. Overall, this regression model provides empirical evidence on the determinants of agricultural productivity and allows for the assessment of whether CSA adoption remains a significant predictor of yield improvement after accounting for institutional, financial, socio-economic, and climatic factors. The expected signs of the coefficients are: $\beta_1 > 0$, $\beta_2 > 0$, $\beta_3 > 0$, $\beta_4 > 0$, $\beta_5 > 0$, $\beta_6 < 0$ indicating that CSA adoption, institutional support, access to finance, farm size, and education are expected to increase productivity, whereas rainfall shocks are expected to reduce agricultural yields.

Table 6. Determinants of Agricultural Yield

Predictor	Coefficient (β)	Robust SE	t	p
CSA adoption	+0.55	0.08	6.88	<0.001
Institutional support	+0.30	0.11	2.73	0.007
Access to finance (binary)	+0.22	0.10	2.20	0.028
Farm size (ha)	+0.06	0.04	1.50	0.13
Education (years)	+0.03	0.02	1.50	0.13
Rain shock (experienced)	−0.35	0.12	−2.92	0.004
Constant	0.95	0.21	4.52	<0.001

Model fit: $R^2 = 0.38$, Adj $R^2 = 0.36$. Number of obs = 370.

After controlling for farm size, education and shocks, **CSA adoption increases yield by 0.55 t/ha**, a substantively important effect (approximately 24% of the overall mean yield). Institutional support and access to finance have independent positive effects on productivity beyond adoption per se. Rain shocks reduce yield substantially, but adopters show partial buffering (interaction tests below).

4.10 Interaction and resilience test (H1 extension)

To test whether CSA adoption buffers the effect of environmental stress, we estimated a model with an interaction term: $Y_i=\beta_0+\beta_1 CSA_i+\beta_2 Shock_i+\beta_3(CSA_i\times Shock_i) + \varepsilon_i$

The findings further reveal that environmental shocks, particularly droughts and irregular rainfall patterns, significantly reduce agricultural productivity. However, the interaction analysis provides evidence that CSA adoption enhances resilience to climate-related stress. The positive and significant interaction coefficient ($\beta = 0.38$, $p = 0.018$) indicates that CSA adopters experience smaller productivity losses during adverse climatic conditions than non-adopters.

5. Discussion

This section integrates the findings on CSA adoption and productivity gains, institutional support, financial access, gender dynamics, and resilience to climate risk, providing a comprehensive understanding of the drivers and outcomes of Climate-Smart Agriculture among smallholder farmers in Muvunda Village. The results demonstrate that CSA adoption significantly enhances agricultural productivity and resilience among smallholder farmers in Muvunda Village. Farmers adopting practices such as agroforestry, soil conservation, and drought-tolerant crops experienced higher yields and greater food security compared to non-adopters. This finding supports the broader literature showing that CSA contributes to yield stability and soil fertility, even under adverse climatic conditions (Karume *et al.*, 2022; FAO, 2021; Khatri-Chhetri *et al*., 2019). Moreover, the evidence that bundled CSA practices generate stronger outcomes aligns with studies in Sub-Saharan Africa where integrated adoption of multiple techniques was more effective than partial adoption (Andersson & D'Souza, 2014; Partey *et al*., 2018; Nyenyezi *et al*., 2022). These findings emphasize that CSA should not be viewed as a single practice but as a systemic package improving both productivity and resilience.

This study contributes to theory development in three major ways. First, it advances the understanding of Climate-Smart Agriculture (CSA) as a multidimensional innovation system that simultaneously enhances productivity, resilience, and environmental sustainability in fragile, mining-affected regions like Muvunda Village (Abadi & Pannell, 1999; Nyenyezi *et al*.2022; FAO, 2021; Karume *et al*., 2022). Second, it integrates institutional and financial dimensions into the CSA adoption framework, demonstrating that knowledge diffusion and liquidity access are not auxiliary but central determinants of behavioral change among smallholder farmers (van Asseldonk *et al*., 2023; World Bank, 2023; Doss *et al*., 2023). Third, it extends gendered perspectives in CSA research by showing that, despite structural inequalities, female adopters can achieve significant productivity gains when supported by inclusive institutional mechanisms (Peterman *et al*., 2014; Meinzen-Dick *et al*., 2019; UN Women, 2022; Ali *et al*., 2022). The managerial and policy implications of the study are threefold. First, policymakers should prioritize bundled CSA packages combining agroforestry, soil conservation, and drought-tolerant crops to maximize synergistic benefits (Partey *et al*., 2018; Andersson & D'Souza, 2014; Musafiri *et al*., 2021; Ndeko, 2025). Second, microfinance institutions and adaptation funds should tailor credit products that lower entry barriers for resource-poor farmers while ensuring sustainability of investment (WAICSA, 2023; Asfaw *et al*., 2016; Shiferaw *et al*., 2015). Third, government agencies and NGOs must reinforce extension and cooperative systems as platforms for capacity building, collective action, and risk-sharing (Fisher *et al*., 2015; Holden & Quiggin, 2017; Nkonya *et al*., 2019).

Regarding future research, longitudinal analyses are needed to capture long-term effects of CSA adoption on household welfare and ecosystem restoration. Comparative studies across territories could also clarify how context particularly mining intensity and institutional maturity modulates CSA outcomes (CIFOR-ICRAF, 2023; Zougmoré *et al*., 2016). The study's limitations lie mainly in its cross-sectional design and self-reported data, which constrain causal inference. Nonetheless, the results provide a robust empirical foundation for scaling CSA as a strategic tool for sustainable rural transformation in the Democratic Republic of Congo.

Institutional support, including agricultural extension, cooperatives, and farmer organizations, emerged as a strong determinant of CSA uptake. This result is consistent with the view that institutions reduce information asymmetries, build farmer confidence, and lower adoption risks (van Asseldonk *et al*., 2023; Manda, 2016; Awoke *et al*., 2025). Access to extension services has been found to significantly improve adoption decisions in Malawi and Zambia, demonstrating that institutional presence is critical for scaling CSA (Fisher *et al*., 2015; Holden & Quiggin, 2017). However, our findings also point to the limitations of fragmented support systems. Where extension services are inconsistent, farmers remain hesitant to invest in CSA innovations. This reflects broader critiques that institutional mechanisms in fragile African regions are often underfunded and lack continuity (Morton, 2017; Nkonya *et al*., 2019).

The analysis shows that financial access strongly influences CSA adoption. Farmers with access to credit, microfinance, or subsidies were more likely to adopt capital-intensive practices such as improved seed varieties and agroforestry. This aligns with the argument that liquidity constraints remain one of the most significant barriers to technology adoption in rural Africa (World Bank, 2023; WAICSA, 2023; Zuberi, 2022). Our findings corroborate studies from East Africa indicating that access to financial services increases the likelihood of CSA adoption by reducing upfront investment risks (Lipper *et al*., 2014; Asfaw *et al*., 2016; Ntawuhiganayo, 2023; Awoke *et al*., 2025). Nevertheless, financial support must be coupled with institutional guidance to prevent misuse of credit and ensure that funds are directed toward sustainable land management (Adesina & Baidu-Forson, 1995; Shiferaw *et al*., 2015; Cavanagh *et al*., 2017). Gender differences in CSA adoption were evident, with male-headed households adopting at higher rates and achieving greater productivity gains. This reflects structural inequalities in access to land, labor, and social networks (Doss *et al*., 2023; Nhemachena *et al*., 2020; Peterman *et al*., 2014; Abegunde, 2022; Ntawuhiganayo, 2023; Awoke, 2025). Similar findings in Tanzania and Ethiopia have shown that women farmers often face constraints in resource ownership, limiting their capacity to adopt new technologies (Ragasa, 2019; Villamor *et al*., 2015; Akinyemi *et al*., 2019; Ntawuhiganayo *et al*., 2023). The gender-related findings observed in this study also corroborate recent literature emphasizing the existence of structural inequalities in agricultural innovation systems. Although male-headed households represented a larger proportion of adopters, female adopters experienced meaningful productivity improvements compared with female non-adopters. These findings are consistent with Meinzen-Dick *et al*. (2019), who argue that women's adoption of agricultural innovations is often constrained by unequal access to land, financial resources, extension services, and institutional networks. Consequently, gender-responsive agricultural policies are necessary to ensure more inclusive climate adaptation outcomes. Yet, our results highlight that female adopters, despite structural disadvantages, still achieved productivity improvements relative to non-adopters. This underscores that CSA has the potential to bridge gender gaps if accompanied by gender-sensitive interventions such as women-targeted extension, inclusive cooperatives, and access to credit (Beuchelt & Badstue, 2013; Meinzen-Dick *et al*., 2019; Awoke *et al*., 2025). Such interventions would ensure that CSA benefits are equitably distributed, in line with recent global calls for gender-responsive agricultural policies (Amadou *et al*., 2020; UN Women, 2022; World Bank, 2023; Awoke *et al*., 2025).

The findings of this study provide strong evidence that Climate-Smart Agriculture (CSA) contributes significantly to improving agricultural productivity and resilience among smallholder farmers operating under environmental pressure in Muvunda Village. The strong positive correlation between CSA adoption and agricultural productivity ($r = 0.67$, $p < 0.001$) confirms that climate-smart practices such as agroforestry, soil conservation, and drought-resistant crop varieties generate substantial productivity gains. This finding is consistent with the work of Tesfaye *et al*. (2025), who reported that smallholder farmers adopting multiple CSA practices in Ethiopia achieved significantly higher yields and greater production stability than non-adopters. The positive association between institutional support and CSA adoption ($r = 0.58$, $p < 0.001$) highlights the critical role of agricultural extension services, cooperatives, and development organizations in facilitating technological uptake. Similar conclusions were reached by Van Asseldonk *et al*. (2023), who found that institutional engagement reduces uncertainty, improves knowledge dissemination, and enhances farmers' willingness to adopt climate-smart innovations.

Access to finance was also found to be a significant factor influencing adoption decisions. The positive correlation between financial access and CSA adoption supports the argument that liquidity constraints remain a major barrier to agricultural innovation among rural households. This result aligns with the findings of Doss *et al*. (2023), who demonstrated that access to credit and financial services substantially increases farmers' ability to invest in sustainable agricultural technologies and climate adaptation strategies. The significant relationship between CSA adoption and climate resilience ($r = 0.61$, $p < 0.001$) further confirms the adaptive benefits of climate-smart practices. These results are supported by Sithole and Olorunfemi (2024), who reported that CSA interventions strengthen farmers' capacity to cope with climate variability, droughts, and environmental shocks across sub-Saharan Africa. By improving soil fertility, water retention, and biodiversity, CSA practices help stabilize agricultural production under increasingly unpredictable climatic conditions. Furthermore, the observed positive relationship between productivity and resilience demonstrates that climate adaptation and agricultural growth objectives can be pursued simultaneously. This supports the conclusions of Azadi *et al*. (2021), who argue that CSA represents a viable pathway toward sustainable agricultural transformation by simultaneously enhancing productivity, adaptation, and environmental sustainability. Taken together, these findings suggest that scaling up CSA adoption in mining-affected and environmentally vulnerable regions such as Muvunda Village requires integrated interventions combining institutional strengthening, improved access to finance, targeted extension services, and gender-inclusive support mechanisms. Such measures would not only increase adoption rates but also enhance the long-term sustainability and resilience of rural livelihoods. Finally, the study confirms that CSA adoption significantly improves resilience to climate shocks. Adopters were more likely to maintain food security during drought periods and showed stronger capacity to reinvest in farming activities after environmental stress. This is consistent with findings in Kenya, Uganda, and Burkina Faso and the East of DR Congo where CSA practices reduced vulnerability and strengthened adaptation pathways (CIFOR-ICRAF, 2023; Thornton *et al*., 2018; Zougmoré *et al*., 2016; Nyenyezi *et al*., 2022). The evidence contributes to the growing recognition that CSA not only improves farm productivity but also functions as an ecological insurance mechanism against climate variability (Harvey, 2014; Wainaina *et al*., 2016; Musafiri *et al*., 2021; Awake *et al*., 2025; Ndeko, 2025). This dual benefit makes CSA a critical pillar in climate adaptation strategies, particularly in fragile ecological frontiers like the Lualaba region.

Conclusion

This study examined the determinants and impacts of Climate-Smart Agriculture (CSA) adoption among smallholder farmers in Muvunda Village, Lualaba Province, Democratic Republic of Congo. The findings demonstrate that CSA practices constitute an effective strategy for improving agricultural productivity, strengthening household resilience, and enhancing adaptive capacity under conditions of environmental stress and climate variability. The study revealed that farmers adopting CSA practices such as agroforestry, soil conservation, crop rotation, and drought-resistant crop varieties achieved significantly higher yields and improved resilience outcomes compared to non-adopters. In particular, households implementing bundled CSA strategies recorded the strongest productivity gains, confirming that integrated adoption generates greater benefits than isolated practices. The results further highlight that institutional support and access to financial services are among the most influential determinants of CSA adoption. Farmers benefiting from extension services, cooperatives, and organizational support were substantially more likely to adopt CSA technologies. Similarly, access to credit and agricultural financing significantly increased farmers' ability to invest in sustainable agricultural practices. These findings underscore the critical importance of strengthening rural institutional frameworks and improving financial inclusion in order to accelerate sustainable agricultural transformation in environmentally vulnerable regions. The study also revealed significant gender disparities in CSA adoption. Male-headed households showed higher adoption rates and productivity outcomes, largely due to better access to productive resources and institutional opportunities. Nevertheless, female adopters also experienced meaningful improvements in productivity and resilience, demonstrating that inclusive and gender-sensitive agricultural interventions can contribute significantly to reducing inequalities and enhancing rural livelihoods. Despite the positive impacts observed, the study confirms that environmental degradation associated with mining activities, weak institutional coordination, limited access to information, and financial constraints continue to undermine agricultural sustainability in Muvunda Village. Therefore, there is a need for integrated policy interventions capable of addressing both environmental and socio-economic barriers to CSA adoption. Based on these findings, the study recommends that government institutions, development agencies, and non-governmental organizations strengthen agricultural extension services, promote farmer cooperatives, and facilitate access to affordable agricultural credit and climate adaptation funds. Policies should prioritize integrated CSA packages that combine agroforestry, soil conservation, and drought-resistant technologies. In addition, targeted support programs for women farmers should be implemented to reduce gender inequalities in access to land, finance, training, and institutional support. Finally, future research should adopt longitudinal and comparative approaches to better assess the long-term effects of CSA adoption on productivity, resilience, and environmental sustainability in mining-affected rural regions.

Limitations and Future Research Perspectives

This study is limited by its cross-sectional design and reliance on self-reported household data, which may constrain causal interpretation. Future research should employ longitudinal and comparative approaches to evaluate long-term CSA impacts, environmental restoration, and adoption dynamics across mining-affected and climate-vulnerable agricultural regions in the Democratic Republic of Congo.

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