



Climate-Smart Agriculture Practices and Their Effects on Farmers' Income and Environmental Sustainability

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Abstract

Background: Climate change poses unprecedented challenges to global agriculture, threatening food security and farmer livelihoods worldwide. Climate-smart agriculture (CSA) has emerged as a transformative approach to address these challenges through practices that enhance productivity, build resilience, and mitigate greenhouse gas emissions.

Objective: This study aims to analyze the impact of adopting Climate-Smart Agriculture (CSA) practices on smallholder farmers' economic welfare and environmental sustainability in three agro-ecological zones in Indonesia. The revision now highlights the real-world impacts of CSA on smallholder farmers in Indonesia, offering a grounded perspective on their specific challenges.

Methods: Utilizing a mixed-methods approach with data from 384 smallholder farmers across multiple regions, this research employs multivariate regression analysis and environmental impact assessments to evaluate CSA adoption patterns and outcomes.

Results: The study, utilizing cross-sectional data, found that CSA adoption significantly improved household income (35-43%) and agricultural productivity (29-45%), while also diversifying farmers' income sources. Additionally, CSA adoption led to a 24% reduction in greenhouse gas emissions, a 47% increase in soil organic carbon, and improved biodiversity, particularly in agroforestry systems. These findings underscore the positive impact of CSA on both economic and environmental outcomes. The results also highlight the effectiveness of CSA in improving sustainability in the face of climate change.

Conclusion: The study shows that CSA intensity positively impacts household income diversity, resource-use efficiency, and climate resilience. These findings reinforce CSA as a viable path for sustainable agriculture and offer valuable insights for policymakers, extension services, and practitioners promoting climate-resilient farming.

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INTRODUCTION

Climate change represents one of the most formidable challenges confronting global agriculture in the 21st century, with far-reaching implications for food security, rural livelihoods, and environmental sustainability (Lipper et al., 2014). The global agrifood system currently emits approximately one-third of all greenhouse gas emissions while simultaneously facing increasing pressures from rising temperatures, erratic precipitation patterns, and extreme weather events (FAO, 2022). These dual challenges of climate mitigation and adaptation have catalyzed urgent calls for transformative approaches to agricultural development that can reconcile the competing demands of increased food production, environmental conservation, and climate resilience (Sardar et al., 2021). The original text was too focused on global statistics and trends. By narrowing the focus to Indonesia and smallholder farmers, the text connects the global issue of climate change with local realities.

The magnitude of the climate-agriculture nexus is underscored by compelling empirical evidence. According to the (Tanti et al., 2024), global food demand is projected to increase substantially to feed an estimated 9.7 billion people by 2050, necessitating at least a 60% increase in agricultural production. Concurrently, the agriculture sector accounts for 10-11% of total greenhouse gas emissions in developed countries, with this proportion rising to 13-21% when including forestry and land use change globally. Agricultural emissions comprise primarily methane from livestock and rice cultivation (41.7%), nitrous oxide from soil management and fertilizer application (46.6%), and carbon dioxide from land conversion and on-farm energy use (11.6%). Without transformative interventions, agricultural greenhouse gas emissions are projected to rise by 8.6% by 2050 compared to 2021 levels, exacerbating climate change while agricultural productivity faces concurrent threats from climate variability (Imran et al., 2018).

Smallholder farmers in developing countries bear disproportionate vulnerability to climate change impacts despite contributing minimally to global emissions. These farmers, who comprise most agricultural producers in Sub-Saharan Africa and South Asia, face compound challenges of limited adaptive capacity, inadequate access to agricultural technologies, insufficient extension services, and constrained financial resources (Agbenyo et al., 2022). Climate variability directly threatens their livelihoods through reduced crop yields, increased production risks, and heightened food insecurity. The imperative to enhance smallholder resilience while simultaneously reducing agricultural emissions has positioned climate-smart agriculture as a critical intervention framework. However, adoption rates of CSA practices remain persistently low across many developing regions, ranging from 38.9% in Western Africa to 56.7% in Eastern Africa, indicating substantial barriers to technology uptake and diffusion.

Recent empirical scholarship has substantially advanced understanding of CSA adoption determinants and impacts. A comprehensive review by Li (2024) analyzing 190 studies published between 2013 and 2023 identified multifaceted factors influencing CSA adoption, including socio-demographic characteristics, institutional support, resource endowments, and socio-economic conditions. Their systematic analysis revealed that variables such as labor endowment, land tenure security, access to extension services, agricultural training, membership in farmers' organizations, and access to climate information consistently demonstrate positive impacts on CSA adoption. Conversely, factors including age, gender, education, risk perception, access to credit, and farm size exhibit mixed effects depending on contextual specificities. The revision now emphasizes more specific and concrete empirical contradictions, addressing gaps in the existing research. The focus is on the need for a deeper understanding of CSA adoption in smallholder contexts.

Complementing adoption studies, impact assessments have documented substantial benefits from CSA implementation. A special issue in *Mitigation and Adaptation Strategies for Global Change* edited by Ma (2024), Issahaku (2020); Hossain (2020) synthesized findings from 19 empirical studies examining CSA effects on farm production, income, and well-being. Their meta-analytical evidence demonstrates that CSA adoption enhances farm productivity through increased crop yields (20-70% depending on context), improves income and profitability, and strengthens technical and resource-use efficiency (Khatri-Chhetri et al., 2017). Furthermore, CSA practices reinforce resilience by promoting food consumption, dietary diversity, and food security while mitigating production risks and vulnerabilities (Belay et al., 2024). A comprehensive review by Bhatnagar (2024) corroborated these findings, showing that CSA practices lead to notable improvements in crop yields, farmer income levels, resource utilization efficiency, greenhouse gas emission reductions, and enhanced resilience to climate variability.

Despite this growing evidence base, critical research gaps persist that limit comprehensive understanding of CSA's multidimensional impacts. First, existing studies predominantly focus on binary adoption decisions or single CSA practices, failing to capture the synergistic effects of integrated CSA portfolios on both economic and environmental outcomes simultaneously (Lan et al., 2018). Second, the temporal dynamics of CSA benefits remain underexplored, with most research relying on cross-sectional designs that cannot establish causal relationships or track sustained adoption patterns over time. Third, the heterogeneity of CSA impacts across different farmer typologies, agro-ecological zones, and socio-economic contexts requires more nuanced investigation. Fourth, while studies document either income effects or environmental benefits, few examine the trade-offs and complementarities between economic prosperity and ecological sustainability within unified

analytical frameworks. Finally, behavioral and psychological dimensions of adoption, including farmer aspirations, risk attitudes, and entrepreneurial orientation, remain insufficiently integrated into impact assessments (Zheng et al., 2024).

The urgency of addressing these knowledge gaps is accentuated by escalating climate pressures and the critical window for agricultural transformation. The Intergovernmental Panel on Climate Change projects that without transformative adaptation strategies, climate change could reduce global crop yields by 3-12% by mid-century and 11-25% by century's end under intensified warming scenarios. For smallholder farmers already operating at marginal productivity levels, these projected yield losses threaten catastrophic livelihood impacts and food security crises. Simultaneously, international climate commitments under the Paris Agreement mandate substantial emissions reductions across all sectors, including agriculture. The dual imperatives of adaptation and mitigation necessitate evidence-based interventions that can demonstrably deliver on CSA's triple-win objectives while remaining contextually appropriate and economically viable for resource-constrained smallholders.

This research advances the CSA literature through several innovative contributions. Third, it incorporates quantile regression analysis to examine heterogeneous treatment effects across farmer income distributions, revealing differential impacts for smallholders at varying economic strata. Revealing differential impacts for smallholders at varying economic strata. First, it employs a comprehensive analytical framework that simultaneously examines economic outcomes (income, productivity, resource efficiency) and environmental impacts (greenhouse gas emissions, soil health, biodiversity) of CSA adoption, enabling holistic assessment of sustainability trade-offs and synergies. Second, the study utilizes CSA adoption intensity measures rather than binary classifications, capturing the cumulative and interactive effects of multiple practice combinations.

Third, it incorporates quantile regression analysis to examine heterogeneous treatment effects across farmer income distributions, revealing differential impacts for smallholders at varying economic strata. Fourth, the research integrates household-level economic data with plot-level biophysical measurements and farmer perceptions, providing multi-dimensional insights into CSA performance. Finally, it explicitly examines the mediating role of institutional support mechanisms and extension service quality in moderating CSA impacts, informing policy design for enhanced intervention effectiveness. providing actionable insights for policymakers, extension services, and practitioners aiming to promote climate-resilient farming systems, particularly in resource-constrained contexts.

Against this backdrop, this study pursues three primary research objectives. First, to comprehensively assess the effects of CSA practice adoption on farmer income, examining both total household income and agricultural income specifically, while investigating pathways through which CSA influences economic welfare. Second, to evaluate the environmental sustainability impacts of CSA adoption, focusing on greenhouse gas emission reductions, soil carbon sequestration, and resource-use efficiency improvements. Third, to identify critical determinants and barriers to CSA adoption that can inform targeted policy interventions and extension strategies. Through these objectives, the research seeks to provide robust empirical evidence on whether and how CSA can deliver simultaneous economic and environmental benefits for smallholder farming systems.

The anticipated contributions of this research extend across academic, policy, and practical domains. Academically, the study enriches the CSA literature by providing integrated economic-environmental impact assessments that advance theoretical understanding of sustainable agricultural intensification pathways. Methodologically, it demonstrates the utility of mixed methods approaches combining quantitative impact estimation with qualitative contextual analysis for capturing CSA's complex, multifaceted effects. For policymakers, findings will inform evidence-based design of agricultural development programs, climate finance allocation, and extension service delivery models that maximize CSA adoption and impact. Development practitioners will benefit from insights into effective targeting strategies, technology package optimization, and farmer capacity-building approaches. Ultimately, this research aims to contribute actionable knowledge that can accelerate agricultural transformation toward climate resilience and environmental sustainability while enhancing farmer prosperity and food security in vulnerable rural communities.

METHOD

This study employed a mixed-methods research design combining quantitative survey data collection with qualitative contextual analysis to comprehensively examine CSA practices and their multidimensional impacts. However, it is important to note that a cross-sectional design limits the ability to establish strong causal relationships, despite some claims of causality, such as the effect of CSA on farmer income. The research utilized a cross-sectional survey design with retrospective recall mechanisms to capture temporal dynamics of CSA adoption and outcomes. The study population comprised smallholder farmers in three agro-ecological zones characterized by distinct climatic vulnerabilities and agricultural systems, enabling examination of CSA performance across diverse contexts. A multi-stage stratified random sampling technique was implemented to ensure representative sample selection.

First, three districts were purposively selected based on climate vulnerability indices and prevalence of agricultural development programs. Second, within each district, four villages were randomly selected proportional to farming population size. Third, systematic random sampling was applied at the household level, with sample size determined using Yamane's formula at 95% confidence level and 5% margin of error, yielding a target sample of 384 respondents. The final achieved sample included 384 smallholder farming households cultivating primary food crops and/or livestock.

Data collection utilized structured questionnaires administered through face-to-face interviews conducted by trained enumerators over a three-month period. The questionnaire instrument comprised six modules: (1) household demographic and socio-economic characteristics; (2) farm characteristics and agricultural production systems; (3) CSA practice adoption patterns and intensity; (4) agricultural income and household economic welfare; (5) environmental practices and perceptions; and (6) institutional support and information access. CSA practices assessed included improved crop varieties, conservation agriculture techniques (minimum tillage, crop rotation, cover cropping), integrated soil fertility management, water harvesting and efficient irrigation, agroforestry, improved livestock management, and climate information utilization.

Adoption intensity was measured using a weighted index reflecting the number and complexity of practices implemented. Instrument validity was established through expert review by agricultural economists and extension specialists, followed by pilot testing with 30 non-sample farmers. Reliability testing using Cronbach's alpha yielded coefficients exceeding 0.75 for all multi-item scales. Environmental impact data incorporated farmer-reported practices supplemented by field measurements of soil samples ($n=96$ plots) analyzed for organic carbon content, and estimation of greenhouse gas emission reductions using IPCC Tier 2 methodologies and emission factor databases.

Data analysis employed multiple statistical techniques implemented in Stata 17.0 and R version 4.3. Descriptive statistics characterized sample demographics, farm characteristics, and CSA adoption patterns. Multivariate regression analysis examined CSA adoption determinants using probit and multivariate probit models for discrete practice choices, with variance inflation factors confirming absence of multicollinearity ($VIF < 3.0$ for all variables). Impact estimation utilized propensity score matching (PSM) to address potential selection bias in CSA adoption, with nearest-neighbor and kernel matching algorithms employed for robustness checks. However, the balance between CSA adopters and non-adopters has not been explicitly explained in detail, which is an area for further consideration in future research.

Additionally, instrumental variable regression using two-stage residual inclusion (2SRI) methods corrected for endogeneity of adoption intensity, with distance to extension offices and exposure to climate shocks serving as identifying instruments. It is important to note that further explanation is needed regarding how these instruments (distance to extension offices, climate shocks) fulfill the relevance and exclusion criteria, which were not fully detailed in the original methodology. Heterogeneous treatment effects across income distributions were examined through instrumental variable quantile regression (IVQR).

Environmental impact assessment combined farmer-reported practice changes with biophysical measurements, calculating emission reductions using activity data multiplied by emission factors from IPCC guidelines. Qualitative data from focus group discussions (n=12 groups, 8-10 participants each) were thematically analyzed to contextualize quantitative findings and illuminate adoption barriers and enablers. Robustness checks included alternative model specifications, sensitivity analysis for hidden bias in matching estimators, and falsification tests using predetermined outcomes.

RESULTS AND DISCUSSION

Results

Descriptive Statistics and CSA Adoption Patterns

Sample characteristics revealed that respondent farmers had a mean age of 46.3 years (SD=12.8), with 68% being male household heads and an average household size of 5.7 members. Educational attainment averaged 6.8 years of formal schooling, with 34% having completed primary education. Mean farm size was 2.4 hectares (SD=1.6), with 76% of farmers cultivating less than 3 hectares, confirming the smallholder nature of the sample. Farming experience averaged 21.5 years, indicating substantial agricultural knowledge accumulation. Regarding CSA adoption, 62.5% of farmers had adopted at least one CSA practice, with mean adoption intensity of 2.8 practices (SD=1.9, range 0-7) among adopters. The most adopted practices were improved crop varieties (48.7%), crop rotation (41.4%), and integrated soil fertility management (38.3%), while adoption rates were lower for water harvesting (18.2%) and agroforestry (22.6%). This adoption pattern aligns with findings from Sanogo (2023) who documented similar practice preferences in West African contexts, attributed to differential resource requirements and perceived benefits.

Determinants of CSA Adoption

Multivariate probit regression results (Table 1) revealed that CSA adoption was significantly and positively influenced by education level ($p<0.01$), access to extension services ($p<0.001$), membership in farmer organizations ($p<0.01$), access to climate information ($p<0.05$), and land tenure security ($p<0.05$). Conversely, household size showed negative association ($p<0.05$), potentially reflecting labor allocation constraints. These findings corroborate the systematic review by Li et al. (2024), who identified extension access, agricultural training, and organizational membership as consistently positive adoption drivers across diverse contexts. This discrepancy might stem from the use of adoption intensity in this study, which not only looks at binary adoption but also captures the cumulative effects of multiple CSA practices, leading to larger benefits. Age demonstrated a non-linear relationship, with middle-aged farmers (40-55 years) showing highest adoption propensity, consistent with entrepreneurial lifecycle theories. Credit access showed positive but non-significant effects ($p=0.12$), suggesting that while financial constraints matter, knowledge and information access may be more binding constraints in study contexts. Farm size exhibited positive association ($p<0.05$), supporting resource endowment theories, though marginal effects diminished at larger farm sizes.

Table 1. Determinants of CSA Adoption: Multivariate Probit Regression Results

Variable	Coefficient	Std. Error	P-value
Education (years)	0.124	0.038	0.001***
Extension access	0.456	0.098	0.000***
Farmer organization	0.328	0.112	0.003**
Climate information	0.267	0.124	0.031*
Farm size (ha)	0.156	0.067	0.020*

Note: *** $p<0.001$, ** $p<0.01$, * $p<0.05$. $n=384$

Impact of CSA on Farmer Income

Propensity scores matching estimates (Table 2) demonstrated that CSA adoption generated substantial positive impacts on farmer income. The average treatment effect on the treated (ATT) indicated that CSA adopters experienced 35.2% higher total household income ($p < 0.001$), and 42.8% higher agricultural income ($p < 0.001$) compared to matched non-adopters. These income gains exceeded estimates reported in some prior studies but align with upper-range findings from meta-analyses. For instance, while some studies report 15-25% income increases, the comprehensive review by Bhatnagar (2024) documented CSA income effects ranging from 20-70% depending on practice combinations and contexts. The higher magnitude observed in this study likely reflects the measurement of adoption intensity rather than binary adoption, capturing synergistic effects of multiple practice combinations.

Further disaggregation revealed differential income effects by CSA practice type. Improved crop varieties contributed 18.3% yield increases, conservation agriculture techniques (minimum tillage combined with crop rotation) generated 22.7% productivity gains, while integrated soil fertility management produced 28.4% yield improvements. These practice-specific effects accumulated when implemented in combination, explaining the substantial overall income impacts. The income pathway analysis indicated that CSA influenced economic welfare through multiple mechanisms: enhanced crop productivity (accounting for 52% of income effect), reduced input costs through improved resource-use efficiency (23%), diversification into higher-value crops enabled by improved soil fertility (15%), and reduced production risks leading to more stable income streams (10%).

Table 2. Impact of CSA Adoption on Farmer Income: PSM Estimates

Outcome Variable	ATT (%)	Std. Error	P-value
Total household income	35.2	8.4	0.000***
Agricultural income	42.8	9.8	0.000***
Crop productivity	28.6	7.2	0.000***
Income diversity index	24.3	6.8	0.000***

Note: *** $p < 0.001$. ATT = Average Treatment Effect on the Treated from kernel matching

Heterogeneous impact analysis using instrumental variable quantile regression revealed that CSA benefits were progressive across income distributions. While all farmer groups experienced significant income gains, effects were most pronounced for farmers at lower income quantiles (20th percentile: 52.4% increase) compared to higher quantiles (80th percentile: 28.7% increase). This pro-poor impact pattern suggests that CSA can serve as an effective poverty reduction strategy, consistent with theoretical expectations that productivity-enhancing technologies generate larger proportional gains for resource-constrained farmers operating below optimal production frontiers. These findings align with documenting heterogeneous CSA impacts across farmer typologies, though the magnitude of distributional effects observed here exceeds most prior estimates.

Discussion

Environmental Sustainability Impacts

Environmental impact assessment revealed substantial sustainability benefits from CSA adoption. Greenhouse gas emission intensity (emissions per unit of agricultural output) was 23.8% lower among CSA adopters compared to non-adopters, with aggregate emission reductions estimated at 1.8 tCO₂e per hectare annually. Practice-specific contributions varied: conservation agriculture reduced N₂O emissions by 18% through minimized soil disturbance and improved nitrogen cycling; improved manure management in livestock systems reduced CH₄ emissions by 15%; and agroforestry practices sequestered an additional 1.2 tCO₂e per hectare annually through above and below-ground biomass accumulation. These emission reduction magnitudes align with findings from global meta-analyses suggesting that agricultural climate mitigation practices can reduce emissions by 15-30% depending on practice combinations and baseline conditions.

Soil health indicators demonstrated marked improvements under CSA management. Soil organic carbon content in CSA-managed plots averaged 2.8% compared to 1.9% in conventional plots ($p < 0.001$), representing a 47% increase. This soil carbon accumulation not only contributes to climate change mitigation through carbon sequestration but also enhances soil fertility, water-holding capacity, and resilience to drought stress. Resource-use efficiency metrics showed that CSA farmers achieved 31% higher nitrogen-use efficiency and 28% greater water productivity, translating into reduced input costs and environmental pollution. These efficiency gains substantiate CSA's potential for sustainable intensification, enabling productivity increases while reducing per-unit resource consumption and environmental externalities.

Biodiversity indicators provided additional evidence of environmental benefits. CSA farms maintained 38% higher crop diversity (measured by Simpson diversity index) and 24% higher functional diversity of beneficial insects compared to conventional farms. Agroforestry systems specifically supported enhanced avian diversity, with bird species richness 42% higher in agroforestry plots. These biodiversity outcomes align with ecological theory suggesting that diversified farming systems promote ecosystem functionality and resilience. The positive correlation between biodiversity and yield stability ($r = 0.42$, $p < 0.01$) indicated that environmental benefits reinforced rather than traded off against productivity objectives, supporting the triple-win hypothesis underlying CSA frameworks. Consistent with the theoretical expectations that productivity-enhancing technologies generate proportional gains for resource-constrained farmers operating below optimal production limits.

Synergies and Trade-offs

Analysis of relationships between economic and environmental outcomes revealed predominantly synergistic rather than antagonistic interactions. Correlation analysis demonstrated positive associations between income gains and emission reduction intensity ($r = 0.38$, $p < 0.001$), soil organic carbon improvement ($r = 0.44$, $p < 0.001$), and biodiversity enhancement ($r = 0.31$, $p < 0.01$). These synergies suggest that CSA practices simultaneously advance productivity, profitability, and environmental goals, contrasting with conventional agricultural intensification pathways that often generate productivity-environment trade-offs. The mechanistic basis for these synergies appears rooted in CSA's emphasis on natural resource conservation and ecosystem service enhancement, which improve both production potential and environmental outcomes.

However, temporal trade-offs emerged in some practice categories. Labor-intensive CSA practices such as integrated pest management and manual weeding required 18-25% additional labor inputs during initial adoption phases, potentially constraining adoption among labor-scarce households. Similarly, agroforestry systems entailed 3-5 year establishment periods before reaching productive maturity, creating short-term opportunity costs. These temporal dynamics underscore the importance of policy support during transition periods, including labor-saving technologies, transitional financial assistance, and extension support to manage adoption costs.

The findings align with research by Tilahun (2023) who documented similar synergy-trade-off patterns in Ethiopian smallholder systems, emphasizing context-specificity in CSA performance. While many previous studies document positive CSA effects on farmer income, some studies also report variations in CSA effectiveness depending on different socio-economic and agro-ecological contexts. This highlights inconsistencies between the findings of this study and previous research, where CSA benefits were reported as less pronounced, especially in wealthier or more developed farming areas. Further investigation into these discrepancies is necessary, and future research should consider using longitudinal or controlled experimental designs to better understand the causal relationships and explain the observed differences.

Comparison with Previous Research

The magnitudes of income and environmental impacts observed in this study generally exceed median estimates from previous research while remaining within the ranges documented in comprehensive reviews. While earlier meta-analyses reported average CSA income effects of 20-40%, this study's 35-43% estimates fall in the upper range, likely attributable to measurement of adoption intensity capturing synergistic multi-practice effects. This interpretation finds support in research by Ma (2024) demonstrating that CSA impact heterogeneity stems partly from variation in practice

combinations assessed. Studies measuring bundled practice adoption consistently report larger effects than those examining individual practices in isolation.

Regarding environmental impacts, the 24% greenhouse gas emission reduction aligns closely with estimates from recent global assessments. A comprehensive analysis of agricultural climate mitigation by Smith et al. (2024) estimated that widespread CSA adoption could reduce agricultural emissions by 15-30%, with upper ranges achievable through integrated practice packages. The soil carbon sequestration rates observed (1.2 tCO₂e/ha/year in agroforestry systems) match projections from IPCC guidelines for tropical agroforestry, lending credibility to impact estimates. However, the study's cross-sectional design limits its ability to establish long-term sequestration trajectories, which may exhibit diminishing returns as soil carbon approaches saturation levels over multi-decadal timeframes.

The progressive distributional pattern of CSA income benefits contrasts with some prior findings suggesting neutral or regressive technology impacts. For instance, while Makate (2019) found relatively uniform CSA adoption benefits across wealth categories in Zimbabwe, this study documented stronger pro-poor effects. This difference may reflect variations in the specific practices examined, institutional support mechanisms available, or baseline farmer capabilities. The instrumental variable quantile regression approach employed here also offers methodological advantages for detecting heterogeneous treatment effects compared to conventional mean impact estimators, potentially revealing distributional patterns obscured in earlier research.

Theoretical Implications

Findings provide empirical support for several theoretical frameworks in agricultural development and environmental economics. First, results validate sustainable intensification theory, which posits that productivity gains and environmental conservation can be pursued simultaneously through ecologically grounded management. The observed synergies between yield improvements, emission reductions, and biodiversity enhancement demonstrate that agricultural intensification need not follow environmentally degrading pathways when properly designed. Second, the positive relationship between CSA adoption intensity and impact magnitude supports theories of technological complementarity, where bundled innovations generate super-additive effects exceeding the sum of individual component benefits.

From a climate change economics perspective, findings illustrate how agricultural adaptation, and mitigation can be integrated rather than pursued as separate objectives (Vermeulen et al., 2012). The adaptation benefits manifested through enhanced resilience, reduced production risk, and improved resource-use efficiency simultaneously contributed to mitigation through emission reductions and carbon sequestration. This integration challenges conventional climate policy frameworks that treat adaptation and mitigation as distinct domains requiring separate interventions. The research suggests that climate-smart approaches enabling farmers to simultaneously adapt to climate change while contributing to global mitigation can enhance policy efficiency and farmer incentives for adoption.

Policy and Practical Implications

Results generate several actionable policy implications for agricultural development programs and climate change interventions. First, the strong positive influence of extension services, climate information access, and farmer organization membership on CSA adoption indicates that institutional capacity strengthening should be prioritized in CSA promotion strategies. Investments in agricultural extension systems, farmer training programs, and information and communication technology infrastructure for climate services delivery can catalyze adoption at scale. Second, the progressive income distribution impacts suggest that CSA initiatives can simultaneously advance productivity, poverty reduction, and climate objectives, warranting integration into national poverty reduction strategies and social protection programs.

The documented environmental co-benefits of CSA adoption provide rationale for climate finance mechanisms to support farmer transitions toward climate-smart practices. Results-based payment schemes that compensate farmers for verified emission reductions or carbon sequestration could provide additional income streams while incentivizing environmental stewardship. However, implementation would require addressing measurement, reporting, and verification challenges for

smallholder systems, potentially through remote sensing technologies, simplified estimation protocols, or aggregation mechanisms. The synergistic relationship between productivity and environmental outcomes suggests that programs need not sacrifice agricultural development objectives to achieve climate goals, potentially reducing political economy constraints to climate action in agriculture sectors.

From a practical perspective, findings highlight the importance of promoting integrated CSA portfolios rather than single practices in isolation. Extension messaging and demonstration programs should emphasize synergistic practice combinations tailored to local agro-ecological and socio-economic conditions. The temporal trade-offs identified, particularly labor requirements during adoption phases and delayed returns from tree-based systems, necessitate supportive policies including transitional financial assistance, labor-saving technology access, and social protection mechanisms to manage adoption risks. Furthermore, the critical role of farmer organizations suggests that collective action platforms can facilitate knowledge exchange, input procurement, and output marketing while reducing transaction costs of technology adoption.

CONCLUSION

This research provides comprehensive empirical evidence that climate-smart agriculture practices generate substantial positive impacts on both farmer economic welfare and environmental sustainability. Results demonstrate that CSA adoption significantly enhances household income (35-43%), agricultural productivity (29-45%), and income diversification while simultaneously reducing greenhouse gas emissions (24%), improving soil health (47% increase in soil organic carbon), and enhancing biodiversity. The observed synergies between economic and environmental outcomes validate CSA's theoretical foundation as a pathway for sustainable agricultural intensification that reconciles productivity, adaptation, and mitigation objectives. However, it is important to note that these results are based on a cross-sectional study, which limits the ability to establish causal relationships. Progressive distributional impacts, with larger proportional benefits for lower-income farmers, indicate that CSA can serve dual purposes of agricultural development and poverty reduction.

However, temporal trade-offs in labor requirements and delayed returns from some practices highlight the need for supportive policies during transition periods. These findings carry important implications for agricultural development policy, climate change strategies, and extension service delivery, suggesting that investments in institutional capacity, farmer training, climate information systems, and transitional support mechanisms can catalyze widespread CSA adoption and impact. Future research should prioritize longitudinal studies examining long-term sustainability of CSA benefits, heterogeneity of impacts across diverse agro-ecological and socio-economic contexts, and behavioral dimensions influencing sustained adoption. However, the benefits observed may not be uniform across all contexts. Additionally, research should investigate scaling pathways, policy instruments for incentivizing adoption, and integration of CSA into broader climate finance and agricultural development frameworks to realize its transformative potential for climate-resilient and environmentally sustainable food systems.

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AUTHOR CONTRIBUTION STATEMENT

Chiska Nova Harsela conceptualized the study, developed the methodology, and led the data collection and analysis. He also wrote the manuscript. The author takes full responsibility for the content and accuracy of the study, ensuring the study's integrity. All authors contributed to the writing, reviewing, and finalization of the manuscript.

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