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CLIMATE-SMART AGRICULTURE: ADAPTING FARMING PRACTICES TO CLIMATE CHANGE

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Abstract *Climate-smart agriculture (CSA) has emerged as a pivotal approach to addressing the interlinked challenges of climate change, food security, and agricultural sustainability. This study provides a comprehensive assessment of CSA practices, evaluating their efficacy in enhancing adaptive capacity, mitigating greenhouse gas (GHG) emissions, and improving productivity. Through a systematic review of 120 peer-reviewed studies, meta-analysis of field trial data, and case studies from diverse agro-ecological zones, we analysed three core CSA pillars: sustainable land and water management, climate-resilient cropping systems, and integrated soil fertility management. Our findings demonstrate that CSA practices can significantly improve system resilience, with conservation agriculture increasing water use efficiency by 15-30% and drought-resistant varieties sustaining yields under moderate heat stress. Regarding mitigation, practices like improved rice management and agroforestry showed potential to reduce GHG emissions by 20-50% compared to conventional methods. However, trade-offs were identified; for instance, while no-till farming enhances soil carbon sequestration, it may initially increase herbicide use. The adoption of CSA is heavily influenced by socio-economic factors, with smallholder farmers facing significant barriers including high initial investment costs, limited access to credit and information, and insecure land tenure. Successful implementation requires context-specific solutions, strong policy support, and effective knowledge dissemination systems. We conclude that CSA represents a viable pathway for transforming agricultural systems toward greater climate resilience and sustainability, but its potential can only be realized through integrated approaches that address both biophysical and socio-economic dimensions of agricultural adaptation.*

Keywords*: traditional practices, adaptation, climate-smart agriculture, resilience, mitigation.*

INTRODUCTION

The global agricultural sector stands at a critical juncture, facing the formidable challenge of producing more food for a growing population while confronting the escalating impacts of climate change. Rising temperatures altered precipitation patterns, and increased frequency of extreme weather events are already undermining agricultural productivity and threatening food security worldwide (BALAN ET AL.,2022).

Simultaneously, agriculture itself is a significant contributor to climate change, accounting for approximately 23% of total anthropogenic greenhouse gas (GHG) emissions through activities such as livestock production, soil fertilization, and land-use change (DZIEKAŃSKI ET AL., 2022). This complex interplay between climate change impacts on agriculture and agriculture's contribution to climate change has necessitated a paradigm shift in how we approach agricultural development.

In response to these challenges, the concept of Climate-Smart Agriculture (CSA) was introduced by the Food and Agriculture Organization (FAO) in 2010 as an integrated approach to transforming agricultural systems.

CSA is built upon three interconnected pillars:

(1) sustainably increasing agricultural productivity and incomes.

(2) adapting and building resilience to climate change (ARBUCKLE ET AL., 2015).

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(3) reducing and/or removing greenhouse gas emissions, where possible.

Unlike conventional approaches that often address these objectives in isolation, CSA emphasizes their simultaneous pursuit through context-specific practices and technologies. The framework encompasses a wide range of approaches, including conservation agriculture, agroforestry, improved water management, climate-resilient crop varieties, integrated soil fertility management, and precision farming technologies (ŞMULEAC ET AL., 2025).

The urgency of adopting CSA principles is underscored by climate projections indicating that without adaptation, climate change could reduce global agricultural yields by 10-25% by 2050, with the most severe impacts affecting developing countries and smallholder farmers who contribute significantly to global food production (KREFT ET AL., 2023).

While numerous CSA practices have been developed and promoted, there remains a critical knowledge gap regarding their integrated performance across the three CSA pillars, their contextual effectiveness, and the barriers to their widespread adoption, particularly among resource-constrained farmers. Many studies have examined individual practices, but a comprehensive synthesis of evidence across diverse farming systems is lacking (ABD-ELGHANY, ET AL., 2022)

This study aims to address this gap by providing a systematic assessment of CSA practices and their potential to enhance agricultural sustainability in the face of climate change (ARBUCKLE ET AL., 2015). Specifically, the research addresses the following questions:

(1) What is the evidence for the effectiveness of major CSA practices in simultaneously enhancing productivity, adaptation, and mitigation across different agro-ecological contexts?

(2) What synergies and trade-offs exist among the three CSA pillars when implementing specific practices?

(3) What are the key socio-economic, institutional, and policy factors that influence the adoption and scaling of CSA practices, particularly among smallholder farmers?

By answering these questions, this research seeks to provide actionable insights for farmers, policymakers, and development practitioners working to build more climate-resilient and sustainable agricultural systems (CRACE, 2019).

MATERIAL AND METHODS

This study employed a mixed-methods approach, combining systematic review, meta-analysis, and case study analysis to comprehensively assess CSA practices and their implementation.

Systematic literature review: a systematic search was conducted using major scientific databases (Web of Science, Scopus, Google Scholar) and organizational repositories (FAO, World Bank, CGIAR) for literature published between 2010 and 2023 (FAO, 2023). Search terms included: (“climate-smart agriculture” or “climate-resilient agriculture” or “sustainable intensification”) and (“adaptation” or “mitigation” or “productivity”) and (“practice” or “technology” or “system”). The initial search yielded over 1500 records. After removing duplicates and screening titles and abstracts,120 studies meeting inclusion criteria (empirical data on at least two CSA pillars, clear methodology, and context description) were selected for in-depth review.

Data extraction and categorization: data were extracted using a standardized form capturing study location and agro-ecological zone; specific CSA practices evaluated; methodological approach; reported impacts on productivity (yield, income), adaptation (water use efficiency, yield stability), and mitigation (GHG emissions, soil carbon); and reported barriers and enablers for adoption. CSA practices were categorized into:

- Sustainable land and water management (conservation agriculture, water harvesting)
- Climate-resilient cropping systems (diversification, improved varieties)
- Integrated soil and nutrient management (organic amendments, precision fertilization)
- Agroforestry and integrated systems

Meta-analysis: a subset of 45 studies providing quantitative, comparable data on CSA impacts was used for meta-analysis. Effect sizes were calculated as the percentage change in outcome variables (yield, water use efficiency, soil organic carbon, GHG emissions) in CSA systems compared to conventional practices. Random-effects models were used to account for heterogeneity across studies. Publication bias was assessed using funnel plots and Egger's test.

Case study analysis: three in-depth case studies were developed to examine contextual implementation factors:

Case 1: Conservation agriculture adoption in maize systems of East Africa

Case 2: Integrated rice-fish systems in Southeast Asia

Case 3: Agroforestry systems in Latin America for each case, data were synthesized on implementation processes, outcomes across CSA pillars, and socio-economic drivers of adoption.

Barrier and Enabler Synthesis: A thematic analysis was conducted on all reviewed studies to identify, code, and synthesize factors influencing CSA adoption. Patterns were analysed across different farmer categories (e.g., smallholder vs. commercial) and regions.

RESULTS AND DISCUSSIONS

Impacts of CSA practices the meta-analysis revealed significant positive impacts of CSA practices across multiple dimensions. Conservation agriculture practices (minimum soil disturbance, residue retention, and crop rotation) increased water use efficiency by 15-30% and soil organic carbon by 0.2-0.5 t C/ha/year. Improved rice management practices (alternate wetting and drying, mid-season drainage) reduced methane emissions by 30-50% while maintaining yields.

Climate-resilient crop varieties demonstrated 10-20% higher yields under drought stress conditions compared to conventional varieties (JELLASON ET AL., 2022). Agroforestry systems showed the most consistent performance across CSA pillars, enhancing biodiversity, soil fertility, and carbon sequestration simultaneously (QUARSHIE ET AL., 2023).

Synergies and trade-offs important synergies and trade-offs were identified. Conservation agriculture showed strong synergy between adaptation and mitigation goals but sometimes presented trade-offs with short-term productivity due to initial yield dips and increased weed pressure. Integrated crop-livestock systems demonstrated synergies across all three pillars when properly managed but could increase emissions if stocking densities were too high.

The analysis highlighted that context-specific implementation is crucial for maximizing synergies and minimizing trade-offs.

Adoption determinants the thematic analysis identified three categories of adoption barriers:

- Economic barriers: high initial investment costs and limited access to credit (reported in 75% of studies).
- Knowledge barriers: limited technical knowledge and access to information (68% of studies).
- Institutional barriers: insecure land tenure, weak extension services, and inadequate policy support (62% of studies).

The integrated nature of CSA solutions the results underscore that CSA is not merely a collection of discrete technologies but represents an integrated approach to agricultural system management.

The most successful CSA implementations combined multiple practices that reinforced each other's benefits. For instance, combining conservation agriculture with drought-tolerant varieties and precision nutrient management created systems with enhanced resilience to climate stresses while reducing environmental impacts (MAYONG ET AL., 2021) (PASCALAU ET AL., 2025).

This systems approach is essential for achieving the simultaneous objectives of CSA, as single practices rarely optimize all three pillars.

Contextual implementation and knowledge systems the significant variation in CSA effectiveness across different contexts highlights the importance of localized adaptation and farmer participation in technology development.

The case studies demonstrated that successful CSA adoption required co-creation of knowledge between researchers, extension agents, and farmers. Traditional knowledge systems often provided valuable insights for adapting CSA principles to local conditions.

This suggests that scaling CSA requires decentralized innovation systems rather than blanket technology transfer approaches.

Enabling environment for CSA adoption the identified barriers indicate that technological solutions alone are insufficient for widespread CSA adoption (PASCALAU ET AL., 2025). Creating an enabling environment requires integrated interventions across multiple domains. Financial mechanisms such as climate-smart credit and insurance can address economic barriers (NAAZIE ET AL., 2023).

Strengthening agricultural knowledge systems through farmer field schools and participatory research can overcome knowledge gaps. Policy reforms addressing land tenure security and providing incentives for ecosystem services can create the necessary institutional support. The most successful CSA programs combined technical support with enabling policies and market linkages.

CONCLUSIONS

This comprehensive assessment leads to several critical conclusions regarding Climate-Smart Agriculture and its role in adapting farming practices to climate change. First, the evidence clearly demonstrates that CSA practices can significantly enhance agricultural system resilience while contributing to climate change mitigation and maintaining or improving productivity.

The documented benefits, including improved water use efficiency, enhanced soil health, reduced greenhouse gas emissions, and stabilized yields under climate stress, provide a compelling case for CSA as a viable pathway for agricultural transformation.

However, these benefits are context-dependent and require careful integration of practices tailored to specific agro-ecological and socio-economic conditions.

A paramount conclusion is that successful CSA implementation requires moving beyond technological solutions to address the fundamental socio-economic and institutional barriers that hinder adoption, particularly among smallholder farmers who are most vulnerable to climate change.

The high initial costs, limited access to information and credit, and insecure land tenure identified in this study represent significant obstacles that must be overcome through targeted policies and interventions. This underscores that the challenge of scaling CSA is not primarily technical but rather socio-institutional, requiring coordinated action across multiple sectors and stakeholders.

The study also highlights that CSA is not a one-size-fits-all solution but a principles-based approach that requires local adaptation and innovation. The identification of context-specific synergies and trade-offs between productivity, adaptation, and mitigation objectives emphasizes the need for flexible implementation frameworks that allow for iterative learning and adjustment.

This adaptive management approach is essential for navigating the uncertainties associated with climate change and evolving socio-economic conditions.

Based on these conclusions, we recommend three priority actions for advancing CSA: First, invest in decentralized innovation systems that support co-creation of knowledge and context-specific solutions through strong farmer-researcher partnerships.

Second, develop integrated policy frameworks that combine technical support with financial incentives, secure land rights, and market linkages to create an enabling environment for CSA adoption. Third, establish robust monitoring and evaluation systems to track progress across CSA pillars and facilitate learning across different contexts and scales.

In conclusion, climate-smart agriculture represents a crucial paradigm shift toward more sustainable and resilient agricultural systems. While challenges remain in scaling CSA practices, the evidence indicates that with appropriate support systems and enabling conditions, CSA can simultaneously contribute to food security, climate adaptation, and mitigation goals.

The transformation to climate-smart agricultural systems is not only necessary for addressing climate change impacts but also presents an opportunity to build more productive, sustainable, and equitable food systems for future generations.

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