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Climate Smart Agriculture: Sustainable Farming For Food Security- A Review

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Abstract: The increasing threat of climate change poses significant challenges to global agricultural productivity, food security, and environmental sustainability. Climate Smart Agriculture (CSA) is the most suitable strategic framework to address the triple challenge of sustainably increasing productivity, reducing greenhouse gas emissions and enhancing resilience. This review provides current evidence on CSA as a roadmap for sustainable farming and long-term food security. The conceptual framework of CSA is explained with its three core pillars, namely productivity, adaptation, and mitigation and its link to sustainable agriculture and food system resilience. Key CSA practices, including conservation agriculture, agroforestry, crop diversification, integrated nutrient and pest management and climate-resilient crop varieties, were studied. The role of digital technologies such as remote sensing, crop modelling, and artificial intelligence in enhancing farm-level decision-making is discussed, along with persistent barriers to adoption among smallholder farmers. Empirical studies from Africa and other developing regions highlight the potential of CSA to improve yields, household nutrition, and climate resilience, while also highlighting the influence of socioeconomic conditions, governance, and policy design. The paper concludes with research gaps and policy recommendations for mainstreaming CSA within national agricultural strategies and global sustainability agendas, particularly the Sustainable Development Goals.

***Keywords* -** Climate Smart Agriculture, sustainable agriculture, food security, climate resilience, smallholder farmers, green-house gas mitigation.

1.INTRODUCTION

Climate change is a growing threat to global agricultural productivity, food security, and environmental sustainability. Rising temperatures and humidity, altered rainfall patterns, increased the frequency of droughts and floods, and increased pest and disease pressure are already affecting crop yields, soil health, and rural livelihoods. Agriculture is highly sensitive to climate-driven stresses such as heat, drought, flooding, nutrient deficiency, and pest outbreaks, all of which alter plant morphology, physiology, and biochemistry and can lead to substantial declines in yield and nutritional quality. By mid-century, global crop yields could fall by 3–12%, and in some regions by up to 25% by 2100, placing the food security of hundreds of millions of people at risk [**1**]. Simultaneously, the agrifood systems contribute significantly to greenhouse gas (GHG) emissions. In 2023, global emissions reached approximately 57.1 $GtCO_2e$, with the agrifood sector accounting for approximately 16.2 $GtCO_2e$—an increase of roughly 10% compared to the year 2000 [**2**]. Human activities such as deforestation, land-use change, excessive fertilizer use, and combustion of fossil fuels have accelerated global warming and destabilized agricultural systems. The world population is projected to reach about 9.7 billion by 2050, requiring an increase in crop production of roughly 60% to meet current food-demand trajectories, even as climate change, soil degradation, and water scarcity place greater pressure on the land base [**3**]. These trends underscore the urgent need for transformational strategies that reconcile higher food production with climate resilience and environmental protection.

Climate-Smart Agriculture (CSA) has emerged as a strategic framework to address the triple challenge of sustainably increasing productivity, enhancing resilience, and reducing or removing greenhouse gas emissions relative to conventional practices. CSA is closely linked to broader paradigms of sustainable agriculture and sustainable intensification, which emphasize long-term environmental health, economic viability, and social equity [**4**]. The three core pillars of CSA productivity, adaptation, and mitigation are intended to be pursued simultaneously, recognizing that many interventions create synergies across these dimensions. For example, conservation tillage and improved water management practices can maintain or even increase yields while improving soil health and reducing emissions from fuel and fertilizer use [**5**].

CSA is not merely a set of technical options but a holistic approach embedded in institutional, policy, and socioeconomic contexts [6]. The Food and Agriculture Organization of the United Nations (FAO), along with a range of international partners, has played a central role in defining and promoting CSA as a pathway to food security, climate resilience, and sustainable development [**7**]. The FAO's Climate-Smart Agriculture Sourcebook emphasizes that CSA is not a "technical fix" but a complex, multi-stakeholder process that involves governments, researchers, the private sector, and farming communities. The Global Alliance for Climate-Smart Agriculture (GACSA) has further elevated CSA in the global climate-agriculture agenda, though it has also attracted criticism for vague definitions, corporate influence, and over-reliance on synthetic inputs and genetically modified (GM) technologies [**8**].

In practice, CSA encompasses a wide range of farm and landscape-level practices, including conservation agriculture, agroforestry, crop diversification, integrated nutrient and pest management, and climate-resilient crop varieties. These approaches aim to improve soil structure, enhance water-use efficiency, reduce input dependence, and maintain biodiversity, thereby strengthening the resilience of farming systems to climate variability. Digital technologies, including remote sensing, geographic information systems (GIS), crop-modelling platforms, and artificial intelligence (AI)-driven decision-support tools are increasingly being integrated into CSA to enable precision irrigation, optimized fertilizer and pesticide application, and early detection of crop stresses. However, access to these technologies remains limited in many resource-poor, smallholder-dominated regions, where infrastructure gaps, low digital literacy, and inadequate data systems hinder adoption [**9,10**].

Empirical evidence from Africa and other developing regions underscores the potential and challenges of CSA [**11**]. Studies have shown that CSA practices can increase yields, improve dietary diversity, enhance household resilience to climate shocks, and generate more climate-positive livelihoods. However, adoption is constrained by financial barriers, weak extension systems, limited climate information services, and socio-economic inequalities. Therefore, institutional design and policy frameworks play a decisive role in scaling CSA, particularly in smallholder-dominated, climate-vulnerable regions [**12**]. Against this background, the present review synthesizes current knowledge on Climate-Smart Agriculture as a pathway toward sustainable farming and long-term food security, with a focus on conceptual foundations, core practices, technological enablers, adoption barriers, and policy implications.

2. CONCEPTUAL FRAMEWORK OF CLIMATE-SMART AGRICULTURE

Climate-Smart Agriculture (CSA) is widely understood as a systematic approach to managing agricultural systems under the conditions of climate change, with the explicit goal of sustainably improving food security, resilience, and environmental outcomes. CSA is not a rigid set of technologies but a flexible, context-specific framework that integrates climate adaptation, productivity-enhancing, and mitigation-oriented interventions within broader agricultural and rural development strategies. The literature typically describes CSA through three interrelated pillars: (1) sustainably increasing agricultural productivity and income; (2) enhancing the resilience and adaptive capacity of farming systems to climate variability and change; and (3) reducing or removing greenhouse gas emissions relative to conventional practices. These three pillars are intended to be pursued together, even though they can generate trade-offs and complementarities depending on local conditions [**13**].

Sustainable productivity, the first pillar, emphasizes the need to enhance yields and farm income without intensifying environmental degradation. This includes more efficient use of land, water, and energy, as well as reduced dependency on external chemical inputs. In many smallholder settings, CSA overlaps with the concept of sustainable intensification, which seeks to raise output per unit of land or water while maintaining or improving ecosystem services. The second pillar, resilience or adaptation, focuses on reducing the vulnerability of farms and food systems to climate-related shocks, such as droughts, floods, and pest outbreaks, through diversified cropping systems, improved water-storage options, better risk management, and access to climate information digital services. The third pillar, mitigation, involves lowering the contribution of agriculture to climate change through measures such as soil carbon sequestration, more efficient nutrient management, improved livestock feeding and manure handling, reduced deforestation and effective usage of land.

CSA is conceptually linked to sustainable agriculture and agroecology, which also emphasize the need to balance economic, social, and environmental goals [**4**]. Sustainable agriculture typically seeks to meet present-day production needs without compromising the ability of future generations to produce food by conserving natural resources, protecting biodiversity, and supporting rural livelihoods. CSA adds a distinct climate change lens to this broader sustainability agenda, explicitly linking farm-level decisions to climate risk management and global mitigation efforts. From this perspective, CSA is not only a technical pathway but also a governance and policy approach, as its effectiveness depends on enabling institutions, markets, and policy frameworks [**14**].

One key feature of the CSA framework is its context-specificity. Climate change affects agriculture in different ways across regions, production systems, farm sizes, and socio-economic groups, so generic "one-size-fits-all" solutions are unlikely to be effective. CSA therefore calls for place-based, participatory design that incorporates local knowledge, indigenous practices, and farmers' risk perceptions into intervention planning. This means that the same CSA practice, such as conservation tillage, agroforestry, or crop diversification may be configured differently in semi-arid smallholder farms, peri-urban commercial farms, or large-scale irrigated systems, depending on rainfall patterns, soil type, market access, and institutional support.

CSA is also increasingly framed as a systems-level approach that goes beyond the individual farm to the broader food-system scale. Vermeulen et al. [**15**] argue that climate change affects all stages of food systems production, processing, distribution, and consumption. So, CSA-related interventions must consider not only on-farm management but also post-harvest handling, infrastructure, trade, and nutrition outcomes. From this perspective, CSA can contribute to more efficient and equitable food systems by reducing post-harvest losses, improving market reach, and integrating climate information digital services into value-chain operations. Further, CSA is extremely embedded in policy and governance. The Food and Agriculture Organization (FAO) and partners emphasize that CSA is not a standalone project but part of national agricultural and climate policies, including Nationally Determined Contributions (NDCs) and National Adaptation Plans. The Global Alliance for Climate-Smart Agriculture (GACSA) has helped institutionalize CSA in global development discourse, though it has also sparked debate about the role of corporate actors, definitions of "smartness," and the balance between technological and socially inclusive approaches. These elements suggest that CSA is a dynamic multi-level approach that integrates farm-level innovation and local institutions with climate change governance at the global level. In other words, it is not just about food security that is sustained in the face of climate change, but also about improving agricultural development in the long term.

3. KEY CLIMATE-SMART AGRICULTURE PRACTICES

Climate-Smart Agriculture (CSA) includes a wide range of on-farm and landscape-level practices that collectively aim to enhance productivity, resilience, and mitigation outcomes across diverse agroecological contexts. These practices are often grouped into agronomic, agroforestry, livestock, water management, and postharvest domains, with several core options appearing repeatedly across empirical studies and policy frameworks [**14**]. The following discussion highlights key CSA practices and their links to the three pillars of productivity, adaptation, and mitigation.

3.1 Conservation and regenerative agriculture

Conservation agriculture, including minimum or reduced tillage, permanent soil cover (e.g., crop residues), and crop rotation, is widely recognized as a core CSA practice for improving soil health and system resilience [**5**]. By minimizing soil disturbance and maintaining ground cover, conservation agriculture reduces soil erosion, improves water infiltration capacity, and enhances soil structure and organic matter content, thereby buffering crops against drought and heavy rainfall. These benefits help sustain or even increase yields over time, especially in marginal and rainfed environments, contributing to the productivity pillar of CSA [**12**].

In addition, conservation agriculture promotes carbon sequestration in soils, reduces fuel use through fewer tillage operations, and lowers emissions associated with machinery and soil disturbance, thus supporting the mitigation. Because it also reduces dependence on external inputs such as synthetic fertilizers and irrigation, conservation agriculture can strengthen on-farm profitability and resilience to input-price shocks, linking clearly to the adaptation and economic dimensions of CSA [**16**].

3.2 Agroforestry and land-use diversification

Agroforestry systems, which integrate trees and shrubs with crops and/or livestock, are another important class of CSA practices. Trees can provide shade, reduce wind speed, and improve microclimates, thereby moderating temperature extremes and water stress in crops and animals. They also contribute to soil fertility through leaf litter, nitrogen-fixing species, and improved nutrient cycling, while supporting biodiversity and ecosystem services such as pollination and pest regulation. In this way, agroforestry simultaneously enhances productivity and resilience across mixed land-use systems [**17**].

From a mitigation perspective, agroforestry increases carbon stocks in both biomass and soil, turning agricultural landscapes into partial carbon sinks. Moreover, diversified land-use systems are generally less vulnerable to climate and market shocks than monocultures, and thus provide a more stable basis for household income and food security [**11**]. This systemic risk-reduction role makes agroforestry particularly relevant for smallholder farmers in climate-sensitive regions, where rainfall and price variability is already high.

3.3 Crop diversification and improved germplasm

Crop diversification through intercropping, mixed cropping, and crop rotation helps reduce the risk of total crop failure under erratic rainfall, pest outbreaks, and price fluctuations. By spreading production and income across multiple species or varieties, diversified systems buffer households against climate and market shocks, contributing to the resilience pillar of CSA [**18**]. Diversification also improves nutrient cycling, reduces pest and disease pressure, and can support higher overall food system output, reinforcing the productivity pillar.

Alongside diversification, the use of climate-resilient and stress-tolerant crop varieties is a key element of CSA. Drought-resistant, heat-tolerant, and salt-tolerant germplasms can help maintain yields under changing climatic conditions, particularly in regions experiencing more frequent dry spells or heatwaves. Advances in plant breeding, marker-assisted selection, and, in some contexts, genetic engineering are expanding the toolkit for developing varieties that withstand environmental stresses without compromising yield or nutritional quality [**3**]. These improved germplasm options are often bundled with better management practices (e.g., timing of planting, water-use optimization) to maximize their climate-smart potential.

3.4 Integrated nutrient and pest management

Integrated nutrient management (INM) and integrated pest management (IPM) are central to CSA's emphasis on combining productivity gains with environmental protection. INM combines organic amendments (e.g., compost, manure, green manure) with judicious use of synthetic fertilizers based on soil testing and crop requirements, thereby improving nutrient-use efficiency and reducing nitrogen losses to the environment [**12**]. This approach helps maintain or raise yields while lowering nitrous oxide emissions, a potent greenhouse gas associated with excessive or poorly timed fertilizer use.

IPM, on the other hand, reduces reliance on chemical pesticides by integrating biological control (e.g., natural enemies), resistant crop varieties, cultural practices (e.g., crop rotation, field sanitation), and targeted chemical applications when necessary. This not only mitigates pesticide residues and environmental pollution but also helps preserve beneficial insects and soil organisms, supporting long-term ecosystem health and farm resilience [**19**]. Together, INM and IPM exemplify the CSA logic of balancing higher productivity with reduced environmental harm and lower production costs for smallholders.

4. ROLE OF TECHNOLOGY AND DIGITAL INNOVATIONS

Digital agriculture and information and communication technologies are increasingly central to enabling CSA. Remote sensing, GIS, weather-based decision support systems, AI-driven models, and mobile-based climate services allow farmers to monitor soil and crop conditions, forecast weather and pest risks, and optimize irrigation and nutrient management in near-real time [**9**]. These tools can improve resource allocation, reduce input waste, and enhance preparedness for climate shocks, thereby supporting productivity and sustainability.

However, adoption of such technologies remains uneven, particularly in low- and middle-income countries. Infrastructure gaps, limited internet connectivity, low levels of digital literacy, and high upfront costs constrain accessibility for smallholder farmers. When data quality is poor or not locally calibrated, models can produce misleading recommendations, eroding trust in technology. Moreover, many digital platforms are designed for large-scale or commercial farms, with limited consideration of smallholders' cropping systems, risk profiles, and decision-making contexts. Addressing these barriers requires investments in rural connectivity, user-centered design, capacity building, and inclusive data governance [**10**].

5. ADOPTION OF CSA: EVIDENCE AND CONSTRAINTS

A robust but heterogeneous body of empirical evidence examines the adoption and impact of CSA practices. Studies from Africa and other developing regions show that CSA can increase yields, improve household nutrition, and enhance resilience to climate shocks [**20**], while also contributing directly or indirectly to emission reductions. For example, Amadu et al. synthesize evidence that CSA is associated with higher crop outputs, better food security, and greater household resilience to climate shocks. Dev et al. highlight the potential of precision farming, soil and water conservation, drip irrigation, agroforestry, and integrated nutrient management to improve both productivity and climate resilience in vulnerable regions [**12**].

Despite these positive findings, adoption rates of CSA practices remain relatively low in many developing countries. Barriers in adopting CSA include:

- Financial and infrastructural constraints: Expensive technologies (e.g., drip irrigation, improved seeds, conservation-tillage equipment), limited access to credit, poor roads, and weak storage infrastructure and marketing reduce the ability of farmers to invest in CSA.
- Knowledge and information gaps: Many smallholder farmers lack access to reliable climate information, extension services, skills and training in CSA techniques, which limits their capacity to evaluate and adopt new practices.
- Institutional Constraints: Weak extension systems, fragmented governance, and limited coordination among research institutions, government agencies, and the private sector hamper the dissemination and scaling of CSA innovations.
- Socio-economic and structural factors: Insecure land tenure, low education levels, gender disparities, and limited participation in farmer organizations constrain decision-making autonomy and access to resources.

Empirical studies from Nigeria, Kenya, Ghana, and Togo illustrate that CSA adoption is influenced by a combination of individual (e.g., education, land ownership), institutional (e.g., extension services, credit schemes), and climatic factors. Importantly, these studies show that knowledge of CSA practices alone is insufficient; enabling conditions, such as access to markets, supportive policies, and functional institutions, are equally critical for widespread adoption [**21**].

6. GOVERNANCE, POLICY, AND INSTITUTIONAL DIMENSIONS

The effectiveness of CSA largely depends on the structure of institutions and the formulation of policies. The Global Alliance for Climate-Smart Agriculture (GACSA), established under the FAO, reflects international recognition of CSA's potential to link climate, agriculture, and food security objectives [**7,14**]. GACSA promotes multi-stakeholder collaboration, knowledge sharing, and policy dialogue to support national CSA strategies. However, critics have raised concerns about the vague operational definitions, corporate influence, and perceived overreliance on synthetic inputs and GM technologies, which may undermine transparency and inclusivity.

Effective CSA governance requires clear policy guidelines, transparent decision-making, and robust support mechanisms that prioritize smallholder farmers and marginalized communities. Integrating CSA into national agricultural and climate policies, such as Nationally Determined Contributions (NDCs) and National Adaptation Plans, can help align short-term farm interventions with long-term climate and development goals [**4**]. Policy instruments (e.g., subsidies for climate-resilient seeds and conservation practices, climate risk insurance, carbon finance mechanisms, and green bonds) can provide the required financial incentives to promote adoption of CSA and mitigation co-benefits.

Strengthening research–extension–farmer linkages is also crucial. Research institutions can generate evidence-based recommendations, but these must be translated into accessible, context-specific guidance through well-functioning extension services. Decentralized governance models that empower local institutions and community organizations are needed to improve the effectiveness, targeting, and accountability of CSA programs, particularly in diverse and heterogeneous landscapes.

7. REGIONAL PERSPECTIVES AND CASE EVIDENCE

Regional evidence highlights the context-specific nature of CSA outcomes and the importance of locally tailored approaches. In Africa, where agriculture is a major source of livelihood and food security, climate change threatens rainfall patterns and crop yields, particularly in rain-fed systems. Countries such as Nigeria, Kenya, and Ghana have begun implementing CSA policies and programs, including support for conservation agriculture, agroforestry, improved seeds, and climate information services. These initiatives have shown potential to enhance smallholder resilience and income, but progress is constrained by limited policy integration, weak data systems, and inadequate extension coverage [**21**].

In sub-Saharan Africa and parts of South Asia, CSA has been framed as a means of simultaneously addressing land degradation, water scarcity, and food insecurity. Studies from Nigeria and Togo, for example, show that CSA practices such as crop diversification, conservation agriculture, and agroforestry are widely perceived by farmers as effective tools for coping with climate variability [**18**]. Households adopting CSA report improvements in food security indicators, including dietary diversity and reduced vulnerability to climate-related shocks. However, these benefits are often unevenly distributed, with women, youth, and land-poor households facing greater barriers to access and participation [**20**].

These regional experiences underscore that CSA is not a "one-size-fits-all" solution. Regional research networks, local innovation systems, and participatory action research are essential for generating context-specific evidence and scaling successful practices. Aligning CSA with regional development priorities such as poverty reduction, rural employment, and natural resource management can further strengthen its legitimacy and uptake.

8. FUTURE DIRECTIONS AND RESEARCH PRIORITIES

The successful scaling of CSA will depend on sustained interdisciplinary collaboration among scientists, policymakers, private-sector actors, and farming communities. Several directions stand out:

- **Integrating climate modelling with agronomic and genetic innovation:** Linking climate projections and downscaled climate services with crop-modelling and breeding programs can support the development of climate-resilient and resource-efficient varieties and management systems.
- **Expanding financial mechanisms:** Carbon-credit schemes, green bonds, microfinance, and climate-risk insurance can help smallholders overcome financial barriers to CSA adoption.
- **Strengthening capacity and education:** Training programs, extension reform, and farmer-led innovation platforms are essential to build adaptive capacities and support long-term behavioral change
- **Mainstreaming CSA into global sustainability agendas:** Aligning CSA with the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land), can help integrate it into broader development planning and financing architectures.

Future research should also address critical gaps in our understanding of CSA, including: (1) the long-term biophysical and socioeconomic impacts of CSA practices across different agroecological zones; (2) the trade-offs and synergies between productivity, resilience, and mitigation; (3) the role of gender, equity, and power relations in shaping CSA outcomes; and (4) the institutional and governance conditions that enable or hinder CSA scale-up. Systematic reviews and meta-analyses of CSA practices can help synthesize existing evidence and inform more targeted and evidence-based policy design.

CONCLUSION

Climate-Smart Agriculture (CSA) is an effective approach to address the challenges of climate change, food security, and sustainable farming. Practices such as conservation agriculture, agroforestry, crop diversification, and digital farming technology can improve productivity, resilience, and environmental sustainability. However, successful adoption of CSA requires supportive policies, awareness among the farmers, financial support, and access to the technology. CSA has significant potential to promote sustainable agricultural development and ensure long-term food production and security under changing climatic conditions.

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