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Climate-Smart Agriculture for Enhancing Food Security and Environmental Sustainability: Recent Advances and Future Perspectives

Naresh Kumar[1*], Danveer Singh[2], Sushil Kumar[3]

[1]Training Assistant Farm

KVK, Kaithal, CCSHAU, Hisar

[2]M.Ss. Agronomy, CCS HAU, Hisar

[3]Training Assistant (TA), KVK Fatehabad, CCSHAU Hisar

*Corresponding Author E-mail: nareshsagar07@hau.ac.in

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ABSTRACT

Climate-smart agriculture (CSA) has emerged as a transformative approach to address the interconnected challenges of food security, climate change, and environmental sustainability. By integrating sustainable crop management, precision farming, climate-resilient crop varieties, efficient water and nutrient management, and digital agricultural technologies, CSA enhances productivity while minimizing environmental impacts. Recent advances in artificial intelligence, remote sensing, biotechnology, and conservation agriculture have significantly improved resource-use efficiency and resilience against climatic stresses. This review highlights emerging innovations, current challenges, and future prospects of CSA, emphasizing policy support, technological integration, farmer capacity building, and collaborative research for developing resilient, sustainable, and food-secure agricultural systems worldwide.

Keywords: *Climate-smart agriculture; food security; adaptation; mitigation; sustainability.*

INTRODUCTION

Global agriculture faces an unprecedented set of pressures. The world population is projected to reach nearly 9.7 billion by 2050, requiring an increase in food production of about 60% over 2005–2007 levels, while at the same time climate change is reducing yield potentials and increasing the frequency of extreme events (FAO, 2017). Anthropogenic greenhouse gas (GHG) emissions from the agriculture, forestry and other land use (AFOLU) sector account for approximately 22% of total global emissions, with agriculture alone responsible for nearly half of global methane and nitrous oxide emissions (IPCC, 2022). The agrifood system, when pre- and post-production stages are included, represents about one-third of anthropogenic GHG emissions (FAO, 2022).

Smallholder farmers in developing regions are the most exposed to climate variability, yet they also offer the largest opportunity for transformative change.

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Recognising this duality, the Food and Agriculture Organization introduced the concept of Climate-Smart Agriculture (CSA) at the 2010 Hague Conference on Agriculture, Food Security and Climate Change (FAO, 2010). CSA is defined as agriculture that sustainably increases productivity and incomes, builds resilience to climate change, and reduces or removes GHG emissions where possible (FAO, 2013; & Lipper et al., 2014).

This review synthesises evidence published up to 2022 on the conceptual foundations, key practices, adoption patterns, and outcomes of CSA. It also examines barriers to scaling and presents a forward-looking agenda for policy, finance and research. According to Lipper et al. (2014), the strength of the CSA approach lies in its explicit treatment of the synergies and trade-offs among productivity, adaptation and mitigation rather than as parallel agendas. Mitchell (2017) similarly notes that framing climate responses within a food-security priority is essential to align incentives across smallholder systems.

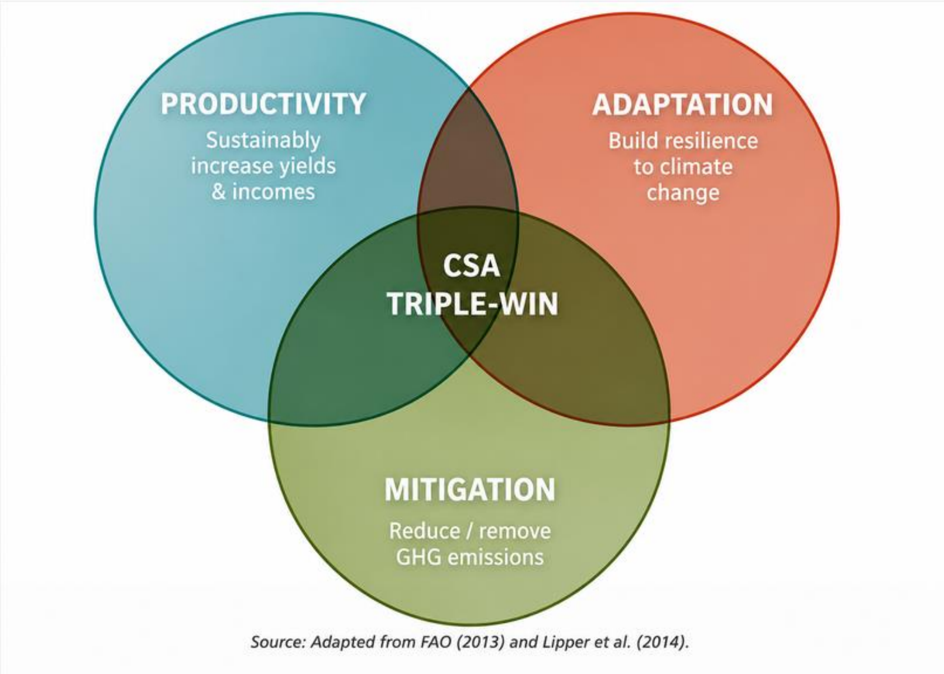

Figure1. The three pillars of Climate-Smart Agriculture

2. Conceptual Foundations of Climate-Smart Agriculture

The CSA concept emerged in response to the recognition that agriculture must simultaneously address food security and climate change (FAO, 2010). According to FAO (2013), CSA is composed of three mutually reinforcing pillars (Figure 1): (i) sustainably increasing agricultural productivity and incomes; (ii) adapting and building resilience to climate change; and (iii) reducing or removing GHG emissions where possible. Lipper et al. (2014) emphasise that CSA is not a single technology or fixed package of practices but an approach for reorienting agricultural systems under the new realities of climate change.

CSA differs from earlier sustainability frameworks in three important respects. First, it explicitly integrates climate adaptation and mitigation objectives into agricultural development planning rather than treating them as add-ons (Lipper & Zilberman, 2018). Second, it is context-specific: the relative weight of each pillar varies by ecology, farming system, and socio-economic context (Chandra et al., 2018). Third, it requires managing trade-offs explicitly; not every practice in every location will deliver a triple win (FAO, 2013).

The World Bank (2018) defines CSA as an integrated approach to managing landscapes, croplands, livestock, forests and fisheries to address the interlinked challenges of food security and climate change. As Mitchell (2017) argues, the value of this framing is its capacity to mobilise finance and policy attention around outcomes rather than discrete inputs.

Several conceptual extensions of CSA have been proposed in subsequent literature. Campbell et al. (2014) introduced the idea of climate-smart food systems, broadening the focus beyond the farm gate to include processing, storage, transport and consumption. Steenwerth et al. (2014) argued for a research agenda that addresses social differentiation, gender and equity within CSA. Chandra et al. (2018) cautioned that without explicit attention to power relations and political economy, CSA risks becoming a technocratic label rather than a transformative agenda. These critiques have shaped the more recent emphasis on inclusive, landscape-level and systems-based implementation pathways.

3. The Climate–Food Challenge

Agriculture is uniquely exposed to climate change. The IPCC Sixth Assessment Report concluded with high confidence that climate change is already negatively affecting crop and livestock productivity in many regions, particularly in tropical and subtropical areas where most smallholders are concentrated (IPCC, 2022). At the same time, the AFOLU sector accounts for approximately 22% of anthropogenic GHG emissions (Figure 2), making it both vulnerable and indispensable to climate action.

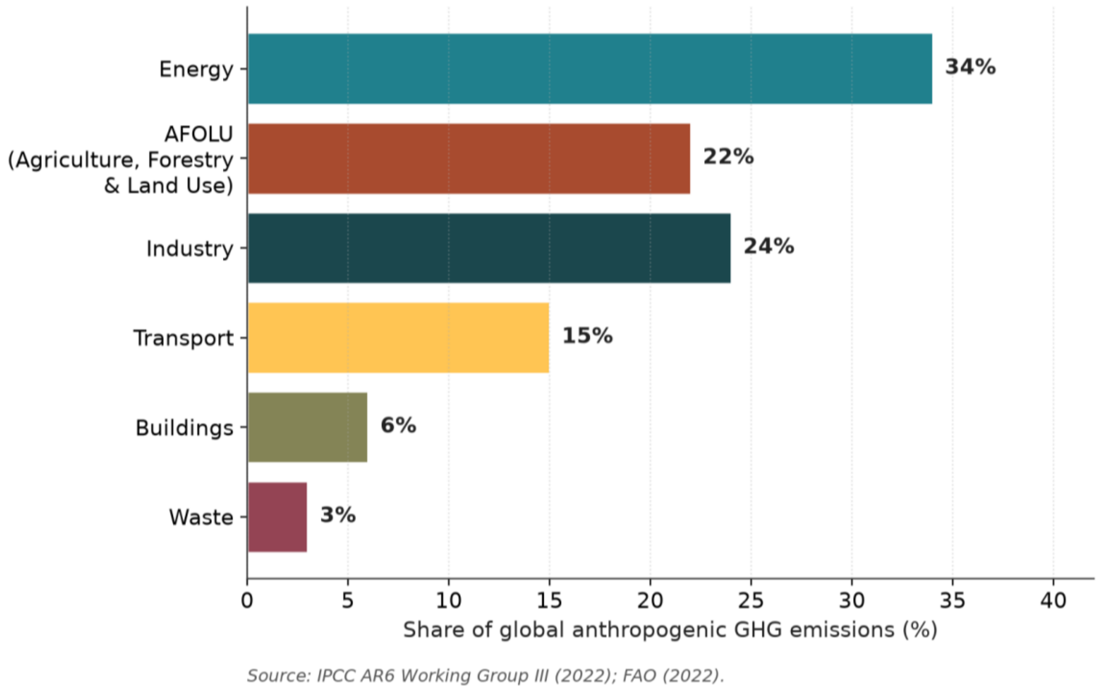

Figure2. Share of global anthropogenic GHG emissions by sector (2019).

Emissions from the broader agrifood system have grown steadily over the past two decades, with farm-gate emissions and pre- and post-production activities expanding, while land-use change emissions have declined modestly (Figure 3). FAO (2022) reports that total agrifood-system emissions reached approximately 16 Gt CO_2-eq in 2020 and remained at comparable levels in 2021–2022. The persistence of these emissions underlines the importance of CSA for the mitigation pillar.

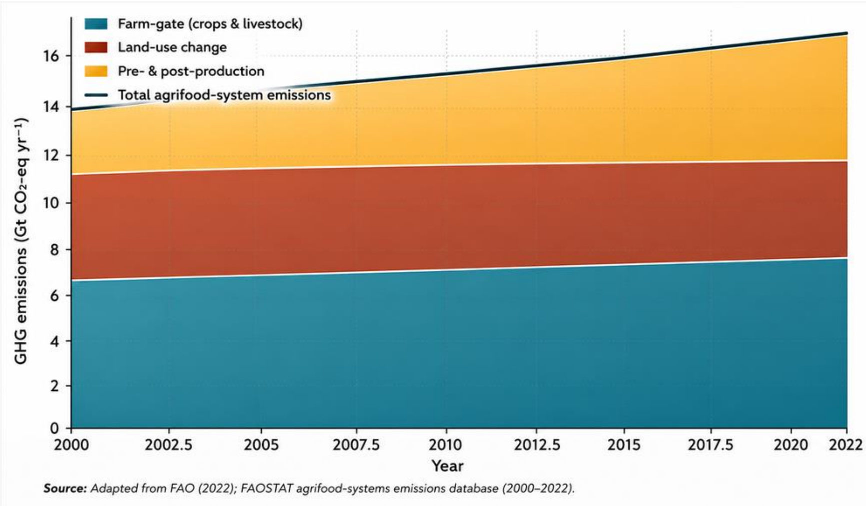

Figure3. Global agrifood-system GHG emissions, 2000–2022

Food insecurity has also worsened. FAO et al. (2022) estimated that between 702 and 828 million people faced hunger in 2021, an increase of about 150 million since the outbreak of the COVID-19 pandemic. Climate extremes were identified as a major driver, alongside conflict and economic shocks. These data confirm that achieving Sustainable Development Goal 2 (Zero Hunger) is impossible without simultaneously addressing climate risks—exactly the integrated mandate that CSA articulates (Lipper et al., 2014).

4. Key CSA Practices and Technologies

CSA encompasses a wide portfolio of practices that can be combined according to agro-ecological and socio-economic conditions. The following sub-sections describe the most widely studied and adopted interventions documented in literature up to 2022.

4.1 Conservation agriculture

Conservation agriculture (CA) integrates three principles: minimum soil disturbance, permanent organic soil cover, and crop diversification through rotations (FAO, 2011). CA improves soil organic carbon, water-holding capacity and yield stability under drought (Pittelkow et al., 2015). By 2019, CA covered an estimated 205 million hectares globally, with the largest areas in South America, North America and Australia (Kassam et al., 2019).

4.2 Agroforestry

Agroforestry combines woody perennials with crops or livestock on the same land. It provides shade, fodder, fuelwood and improved nutrient cycling, while sequestering carbon both above and below ground (Mbow et al., 2014). Zomer et al. (2016) estimated that tree cover above 10% occurs on more than 43% of all agricultural land, demonstrating the global scale and potential of agroforestry.

4.3 Improved and stress-tolerant crop varieties

Breeding for drought, heat, flood and salinity tolerance is central to CSA. Submergence-tolerant Sub1 rice varieties have raised yields by 1–3 t ha^{-1} under flooding in eastern India and Bangladesh (Dar et al., 2013). Drought-tolerant maize varieties have been adopted by millions of farmers across sub-Saharan Africa under the Drought Tolerant Maize for Africa initiative, raising yields by 20–30% in dry seasons (Fisher et al., 2015).

4.4 Water and nutrient management

Efficient irrigation methods such as alternate wetting and drying in rice, drip and sprinkler systems, and laser land levelling reduce both water use and methane emissions while maintaining yields (Aryal et al., 2020). Site-specific nutrient management and nitrification inhibitors lower nitrous oxide emissions and improve nitrogen-use efficiency (Snyder et al., 2014).

4.5 Climate-smart livestock

Livestock contribute about 14.5% of global anthropogenic GHG emissions (Gerber et al., 2013). Interventions include improved feed quality, breeding for productivity, rotational grazing and biogas digesters. Herrero et al. (2016) showed that intensification of ruminant production in mixed crop–livestock systems can reduce emissions intensity by 20–30% while improving incomes.

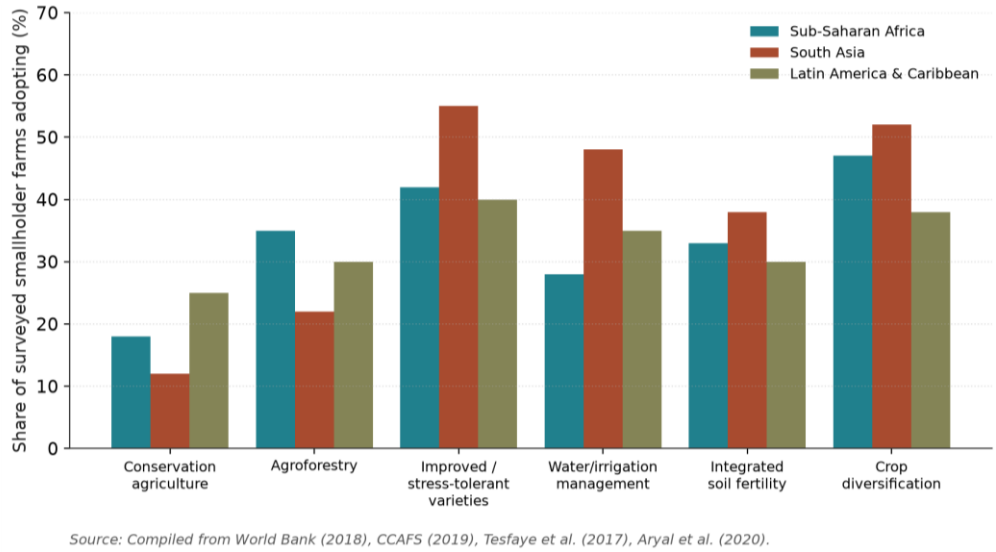

Figure4. Reported adoption of selected CSA practices among smallholder farmers, by region

5. Evidence of CSA Outcomes

A growing body of empirical evidence documents the impacts of CSA practices on the three pillars. World Bank (2018) reviewed CSA portfolios across 33 countries and found that silvopasture, conservation agriculture, agroforestry and improved water management consistently delivered triple-win outcomes. In a meta-analysis of 174 studies, Branca et al. (2013) reported that improved agronomic practices increased yields by 30–110% and soil organic carbon by 0.2–0.5 t C ha^{-1} yr^{-1}.

In sub-Saharan Africa, Tesfaye et al. (2017) found that adoption of multiple CSA practices increased maize yields by 28% and household income by 38% in Ethiopia. Aryal et al. (2020) reported that bundled CSA practices in the Indo-Gangetic Plains raised rice–wheat system productivity by 5–10% while cutting GHG emissions by up to 33%. Such findings are reinforced by Lipper and Zilberman (2018), who synthesised evidence showing that integrated CSA portfolios outperform single-practice approaches.

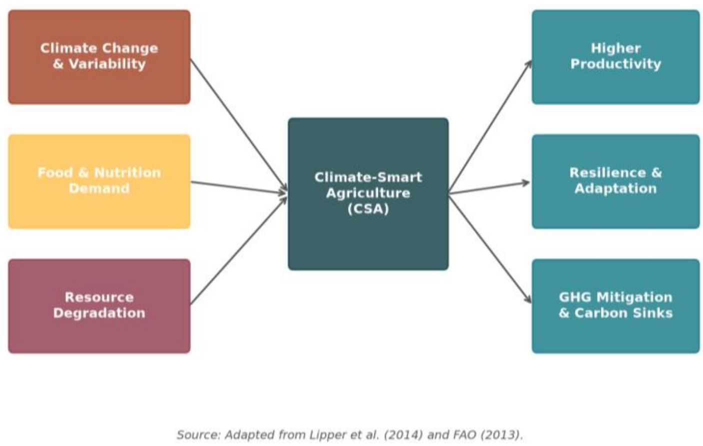

Figure5. Conceptual framework linking climate drivers, CSA and sustainability outcomes

6. Barriers and Enablers to Scaling CSA

Despite documented benefits, CSA adoption remains uneven. Barriers include limited access to credit, insecure land tenure, weak extension services, gender inequities, and high upfront costs of technologies such as drip irrigation and laser levelling (Khatri-Chhetri et al., 2017; & Mungai et al., 2017). Mitchell (2017) emphasises that policy coherence between agriculture, environment and climate ministries is critical.

Gender is a particularly important dimension. Women farmers often have less access to land, credit, training and inputs than men, which limits their capacity to adopt CSA practices despite carrying significant responsibility for household food production. Huyer (2016) reported that female-headed households in several African contexts adopt fewer CSA practices than male-headed households even when interest is comparable. Closing the gender gap in agriculture is estimated by FAO (2011) to raise yields on women's farms by 20–30%, with cascading benefits for food and nutrition security.

Enablers identified in the literature include climate information services, index-based crop insurance, farmer field schools, and inclusive value chains. The World Bank (2018) estimates that scaling CSA across low- and middle-income countries would require additional investment of US$15–25 billion per year, but the returns in avoided losses and improved livelihoods would significantly exceed these costs. Climate finance instruments such as the Green Climate Fund and Adaptation Fund are increasingly directing resources to CSA, although disbursement remains slow (Chandra et al., 2018).

7. Recent Advances (2018–2022)

Several advances have shaped CSA between 2018 and 2022. First, digital agriculture tools—remote sensing, mobile advisory platforms and machine-learning yield prediction—have made site-specific recommendations feasible at scale (Aryal et al., 2020). Second, the Koronivia Joint Work on Agriculture under the UNFCCC formalised agriculture in international climate negotiations, providing a policy anchor for CSA (FAO, 2021). Third, large-scale climate-smart village models pioneered by CGIAR demonstrated bundled adoption pathways in South Asia, East Africa and Latin America (Aggarwal et al., 2018). Fourth, the Africa CSA Implementation Plan 2022–2032 set a continental goal of reaching 25 million households by 2025 (African Union, 2022).

8. Future Perspectives

Future CSA work must address several priorities. First, monitoring and evaluation frameworks need to capture all three pillars consistently, with particular attention to nutrition, gender, and stability dimensions of food security (Rosenstock et al., 2019). Second, research should expand beyond cereals to include pulses, livestock, fisheries and orphan crops critical for nutrition security. Third, mainstreaming CSA into national agricultural investment plans, insurance schemes and curricula is essential for durable scaling. Finally, equitable access for women, youth and marginalised farmers must be a central design principle, not an afterthought (FAO, 2022).

CONCLUSION

Climate-Smart Agriculture has emerged as a coherent, evidence-based framework for reorienting food systems under climate change. By pursuing productivity, adaptation and mitigation in an integrated manner, CSA can simultaneously address food security and environmental sustainability—the twin imperatives of the twenty-first century. Evidence accumulated up to 2022 demonstrates that practices such as conservation agriculture, agroforestry, stress-tolerant varieties, precision water and nutrient management, and improved livestock systems can deliver substantial gains in yields, incomes, resilience and emission reductions. However, adoption remains constrained by financial, institutional and informational barriers. Scaling CSA will require coordinated investments in research, extension, climate finance and inclusive policy design. As Lipper et al. (2014) argued, CSA is best understood not as a destination but as a continuous process of transforming agriculture in step with a changing climate—a process whose urgency has only grown.

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