



Climate-Smart Agriculture for Smallholder Adaptation and Food Security in Vulnerable Regions: A Practice-Oriented Implementation Review

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Abstract

Climate change and food insecurity are converging crises that disproportionately affect smallholder farmers in vulnerable regions. Smallholders, who typically farm less than two hectares, remain central to food production in Sub-Saharan Africa, South Asia, Southeast Asia, and parts of Latin America, yet they face insecure tenure, weak market access, and limited access to credit, irrigation, and extension services that magnify their exposure to climate shocks. Climate-smart agriculture (CSA) has emerged as a framework that seeks to sustainably increase productivity, strengthen adaptation and resilience, and, where feasible, reduce greenhouse gas emissions. This practice-oriented narrative review synthesises peer-reviewed studies, institutional reports, and implementation resources around five organising questions: how climate hazards affect smallholder production and food security; which CSA practices are technically relevant; what is known about their effectiveness and adoption; which institutional and financial conditions enable implementation; and how lessons vary across regions. The review finds that water management, soil and vegetation conservation, crop diversification and improved varieties, and livestock-related practices each offer context-specific benefits, but that adoption depends heavily on farm resources, education, credit access, and extension contact rather than technical merit alone. Financial constraints, weak extension systems, and fragile seed, market, and tenure institutions are identified as the principal barriers to scaling, while microfinance, farmer organisations, demonstration-based learning, and gender- and youth-inclusive programme design emerge as the strongest enablers. Regional case studies from the Sahel, the East African highlands, South Asia, Southeast Asia, and Latin America illustrate that successful scaling depends as much on institutional and policy alignment as on technical soundness. The review concludes that CSA is most effective when it is locally adapted, institutionally supported, adequately financed, and explicitly attentive to equity, gender, and long-term sustainability, and it recommends that implementation be treated as an adaptive, participatory process rather than a fixed technology package.

Keywords: Climate-smart agriculture, Smallholder farmers, Climate adaptation, Food security, Resilience, Sustainable agriculture

1. Introduction

Global food insecurity remains high, with an estimated 720 to 811 million people affected by hunger in 2020 during the pandemic period (FAO et al., 2021). Climate change is increasingly

recognised as a threat multiplier that undermines food production, disrupts supply chains, and intensifies existing inequalities in agrifood systems (FAO, 2021). Smallholder farmers are particularly vulnerable because they often depend on rain-fed agriculture, cultivate marginal lands, and have limited access to credit, irrigation, insurance, and extension services (FAO, 2013). Without effective adaptation, climate change is expected to reduce yields of key staple crops in many vulnerable settings, with important implications for food availability, income, and nutrition (Rezaei et al., 2023). These pressures make climate-smart agriculture a practical and policy priority for governments, development agencies, and farming communities (World Bank, 2018).

Smallholders are commonly defined as farmers operating less than two hectares of land, although operational definitions vary across contexts (FAO, 2015). Farms under two hectares account for most of the world's farms and contribute about one-third of global food production, with higher importance in some low- and middle-income regions (Lowder et al., 2021). In Sub-Saharan Africa, South Asia, Southeast Asia, and Latin America, smallholders remain central to domestic supplies of cereals, legumes, roots, tubers, and horticultural crops (Ricciardi et al., 2018). Yet they frequently face insecure tenure, weak market access, limited mechanisation, and low access to high-quality seed, fertiliser, and advisory services (World Bank, 2018). These structural constraints magnify exposure to climate shocks and reduce adaptive capacity (FAO, 2021).

Climate-smart agriculture is usually defined as agriculture that sustainably increases productivity, enhances resilience and adaptation, and reduces or removes greenhouse gas emissions where feasible (FAO, 2023). The concept is best understood as a broad framework rather than a single technology package, because its practical content varies according to agroecology, livelihood systems, and policy context (FAO, n.d.). For implementers, the value of CSA lies in using it to compare and combine practices that can improve farm performance under climate stress while remaining feasible for resource-constrained households (World Bank, 2024). This review adopts a practice-oriented perspective and focuses on implementable lessons for planners, extension systems, NGOs, and public agencies working with smallholder producers (FAO, 2023).

2. Review Approach

This article is a practice-oriented narrative review. It synthesises peer-reviewed studies, institutional reports, and implementation resources relevant to smallholder climate adaptation and food security. The evidence is organised around five questions: how climate hazards affect smallholder production and food security; which climate-smart agriculture practices are technically relevant; what is known about effectiveness and adoption; which institutional and financial conditions enable implementation; and how lessons vary across regions.

The review does not claim systematic-review coverage or meta-analytic effect estimates. Evidence was compared for consistency across agronomic, household, and policy outcomes, with particular attention to context, equity, feasibility, and the difference between short-term productivity gains and longer-term resilience. Because the underlying studies use different designs, crops, locations, and outcome measures, the synthesis emphasises patterns and implementation implications rather than pooled causal estimates.

3. Review Findings

3.1 Climate Change Impacts on Smallholder Agriculture and Food Security

Rising temperatures are altering growing seasons, increasing heat stress, and changing crop suitability zones across many smallholder production systems (Rezaei et al., 2023). Many staple crops, including maize, wheat, and rice, experience marked yield penalties when exposed to high temperatures during flowering and grain filling (Hasegawa et al., 2022). Changes in

rainfall timing and intra-seasonal variability are also disrupting traditional planting calendars and reducing the reliability of rain-fed agriculture (Niles & Salerno, 2018). Droughts, floods, cyclones, and other extreme events are becoming more disruptive to farm assets, crop cycles, and local food markets (FAO, 2021). Soil degradation, nutrient depletion, salinisation, and new pest and disease pressures further intensify climate-related production risks (FAO, 2013).

These agronomic stresses translate directly into food-security consequences for smallholder households (Niles & Brown, 2017). Lower yields reduce on-farm food availability and diminish cash income available for purchasing food, paying school fees, or servicing debt (Niles & Salerno, 2018). In years of severe climate shocks, households may sell livestock, withdraw children from school, or reduce meal quality and frequency as coping strategies (FAO, 2021). Climate variability also contributes to price volatility in staple food markets, which further harms poor rural and urban households that are net food buyers (FAO et al., 2021). Nutritional impacts are especially serious for women and children because climate-linked food insecurity is associated with lower dietary diversity, reduced micronutrient intake, and greater risk of child undernutrition (FAO et al., 2021).

Vulnerability to these impacts is not evenly distributed across rural populations (FAO, 2024). Women farmers often have less secure land rights, less access to credit, inputs, and extension, and greater unpaid labour burdens, all of which constrain adaptation options (FAO, 2024). Younger farmers may face land-access barriers and uncertain returns that encourage migration out of agriculture (World Bank, 2018). Poorer households, tenant farmers, and marginalised ethnic or indigenous groups often have the least capacity to absorb losses or invest in adaptation (FAO, 2013). Effective implementation of CSA therefore requires explicit attention to social differentiation and not only to agroecological risk (FAO, 2024).

3.2 Climate-Smart Agriculture Practices and Technologies for Smallholders

Water management is one of the most consistently relevant CSA domains for smallholders in vulnerable regions (FAO, 2023). Rainwater harvesting through ponds, tanks, contour bunds, trenches, and terracing can increase water availability and stabilise production under variable rainfall (FAO, 2024). Small-scale irrigation options such as treadle pumps and drip irrigation can substantially improve water-use efficiency and enable dry-season production in some settings (FAO, 2024). Participatory groundwater management is also increasingly important in areas where aquifer depletion threatens long-term production sustainability (World Bank, 2018). Implementers need to align water interventions with local hydrology, labour availability, and community rules for access and maintenance (FAO, 2023).

Soil and vegetation management practices form a second major group of CSA options (FAO, 2023). Conservation agriculture, mulching, contour bunding, terracing, composting, manure application, and agroforestry all aim to improve soil structure, water retention, nutrient cycling, and resistance to erosion (Corbeels et al., 2014). Evidence suggests that yield benefits can be positive but are often delayed and highly context-specific, especially for conservation agriculture (Corbeels et al., 2014). Agroforestry can diversify income and improve microclimates, but it requires tenure security, seedling access, and willingness to wait for medium-term returns (Morel et al., 2024). In practice, implementers should treat these interventions as transition strategies that need sustained extension support rather than one-off technology transfers (World Bank, 2024).

Crop diversification and varietal improvement are among the most accessible CSA options for many smallholders (FAO, 2023). Intercropping, relay cropping, mixed varietal planting, and the use of drought-, heat-, flood-, or salinity-tolerant varieties can reduce risk and improve resilience under climate stress (World Bank, 2018). Diversification into legumes, vegetables, and underutilised cereals such as millet and sorghum can also improve soil fertility and household dietary diversity (FAO, n.d.). However, improved seed access depends heavily

on functioning seed systems, local adaptation trials, and the affordability of seed for poorer farmers (FAO, 2023). Community-based seed systems and participatory variety selection are therefore especially valuable in marginal and under-served settings (FAO, 2023).

Livestock-related CSA includes improved forages, better herd management, climate-tolerant breeds, manure recycling, and crop-livestock integration (FAO, 2013). These practices can improve feed security, reduce pressure on rangelands, and increase productivity per animal (FAO, 2023). Integrated pest management, biological control, and resistant varieties also reduce chemical dependence and support system resilience under changing pest and disease pressures (FAO, 2023). Knowledge platforms such as farmer field schools, climate-smart villages, and digital advisory tools are critical because many CSA options are knowledge-intensive and require local experimentation (World Bank, 2024). For smallholders, technology works best when combined with institutions that support learning, access, and adaptation over time (World Bank, 2018). Table 1 summarises the main CSA practice categories discussed above, together with their principal benefits, implementation considerations, and evidence strength.

3.3 Evidence on CSA Effectiveness, Adoption, and Livelihood Impacts

Evidence on the effectiveness of CSA is positive overall but highly heterogeneous across practices, crops, and agroecological settings (Omotoso et al., 2024). Water management interventions often show some of the strongest production gains in water-stressed systems, especially where irrigation or rainwater harvesting reduces crop failure risk (FAO, 2024). Conservation agriculture can improve soil quality and moisture retention, but yield responses range from negative to moderately positive depending on rainfall, soils, mulch availability, and management intensity (Corbeels et al., 2014). Crop diversification and climate-tolerant varieties generally improve stability and can raise output under stress conditions, even when average yield gains are modest (World Bank, 2018). Agroforestry and integrated systems frequently show delayed but substantial benefits in resilience, total productivity, and environmental performance (Morel et al., 2024).

CSA adoption is shaped not only by technical merit but also by farm resources, social conditions, and institutional support (Jellason et al., 2022). Education, land size, labour availability, credit access, and extension contact are repeatedly associated with higher adoption of CSA practices (Tilahun et al., 2024). Technologies that are visible, compatible with current farming systems, and relatively low-risk tend to spread faster than those requiring large upfront investment or long waits for returns (World Bank, 2024). Wealthier farmers often adopt earlier because they can absorb initial costs and experimentation risks more easily than poorer households (Tilahun et al., 2024). Women farmers frequently face lower adoption because of unequal access to land, finance, information, and decision-making power (FAO, 2024).

Food-security benefits from CSA tend to arise through multiple pathways rather than through yields alone (Kandel et al., 2024). Diversified systems can increase dietary diversity, reduce hunger gaps, and stabilise income across seasons (Niles & Salerno, 2018). Biofortified and nutrient-dense crops have shown promise for improving micronutrient intake when seed access and utilisation are adequate (FAO, n.d.). Still, evidence on effects on stunting, wasting, and other anthropometric outcomes remains more limited than evidence on production or adoption (FAO et al., 2021). This means implementers should treat nutrition gains as plausible but not automatic, and should integrate explicit nutrition objectives into programme design (FAO, 2021).

3.4 Implementation Barriers, Enablers, and Policy Frameworks

Financial barriers remain among the most important constraints to CSA implementation at scale (World Bank, 2018). Many CSA options require upfront labour, tools, irrigation

equipment, tree seedlings, or improved seed that poorer smallholders cannot easily finance (Tilahun et al., 2024). Limited credit access and high informal lending costs increase the perceived risk of investing in new practices under uncertain weather and market conditions (Jellason et al., 2022). Knowledge barriers are also substantial because many extension systems are under-resourced and unable to provide the repeated, context-specific guidance that CSA often requires (World Bank, 2024). Weak seed and input systems, poor roads, thin markets, and tenure insecurity further reduce incentives for long-term investment (FAO, 2013).

At the same time, there is strong evidence that enabling institutions can substantially improve uptake and sustainability (World Bank, 2024). High-quality extension, farmer organisations, demonstration plots, and peer-to-peer learning can improve trust, experimentation, and local adaptation of technologies (FAO, 2023). Microfinance, savings groups, and index-based insurance can reduce liquidity constraints and help households absorb adoption risk (World Bank, 2018). Inclusive design is especially important, because gender-responsive targeting, women's group support, and explicit strategies for youth engagement improve the reach and fairness of interventions (FAO, 2024). Implementers should therefore view CSA not only as a technical package but as an institutional process that requires capacity building and social inclusion (World Bank, 2024).

Policy frameworks matter because they determine whether CSA remains a pilot agenda or becomes embedded in national systems (World Bank, 2018). Integration of CSA into agricultural policy, national adaptation plans, and food-security strategies can improve coherence across sectors and attract financing (FAO, 2021). Public investment in rural infrastructure, irrigation, extension reform, research, and market access is often more important than short-term technology promotion alone (FAO, 2021). Climate finance can support scaling, but access to such funding often depends on project preparation capacity, monitoring systems, and institutional coordination (World Bank, n.d.). For this reason, implementation planning should include governance and financing design from the outset rather than treating them as downstream issues (World Bank, 2024). Table 2 summarises the principal barrier domains, enablers, and policy or programme responses relevant to scaling CSA.

3.5 Regional Case Studies and Contextual Applications

In the Sahel, CSA efforts such as zai pits, half-moons, stone bunds, and farmer-managed natural regeneration have shown that land restoration and water harvesting can substantially improve productivity and resilience in drought-prone areas (FAO, 2024). These successes have depended heavily on community participation, local knowledge, and continued institutional support (Okoronkwo et al., 2024). In the East African highlands, terracing, agroforestry, improved seed, and soil and water conservation have improved incomes, reduced erosion, and strengthened resilience in mixed farming systems (Tilahun et al., 2024). However, land scarcity, youth migration, and uneven market access continue to affect uptake and sustainability (Okoronkwo et al., 2024). These cases underline that successful scaling in Africa depends on combining technical adaptation with land, labour, and institutional realities (World Bank, 2018).

South Asia offers important lessons on the role of profitability and policy alignment in CSA adoption (World Bank, 2018). In the Indo-Gangetic plain, zero-tillage wheat, residue management, water-saving practices, and climate-tolerant varieties have spread where farmers could see clear cost savings and production benefits (World Bank, 2018). In South India, drip irrigation, millet revival, and horticultural diversification illustrate how CSA can support both water efficiency and more nutritious production systems (FAO, n.d.). Yet groundwater depletion, policy lock-in around dominant cereals, and weak market development for alternative crops remain major challenges (FAO, 2021). These experiences show that scaling requires supportive policy incentives as much as technical evidence (World Bank, 2024).

In Southeast Asia, rice-based and delta systems illustrate the value of integrated approaches such as rice-fish systems, aquaculture integration, and mangrove restoration (FAO, n.d.). These strategies can diversify income, improve diets, and reduce dependence on chemical inputs when supported by appropriate extension and market linkages (FAO, 2023). In Latin America, agroforestry, integrated crop-livestock-forest systems, and indigenous crop diversity strategies have supported resilience and environmental co-benefits in both Andean and tropical systems (World Bank, n.d.). But regional cases also show that deforestation pressures, violence, migration, and uneven market power can undermine adoption even when technical options are sound (FAO, 2021). The broader lesson is that contextual fit and supportive institutions determine whether CSA becomes transformative or remains fragmented (World Bank, 2024).

3.6 Synthesis, Research Gaps, and Future Directions

The evidence reviewed here suggests that CSA can improve productivity, resilience, and sustainability for smallholders, but only when interventions are tailored to local conditions and supported by strong institutions (FAO, 2023). Diversification of crops, water sources, income streams, and ecological functions appears especially important for managing climate risk (Kandel et al., 2024). There is no one-size-fits-all CSA package, and the same practice can perform very differently across soils, rainfall regimes, labour contexts, and market environments (Corbeels et al., 2014). This makes adaptive implementation, iterative learning, and participatory design central rather than optional (World Bank, 2024). Programmes that ignore social differentiation and power relations risk widening rather than reducing rural vulnerability (FAO, 2024).

Important evidence gaps remain despite the rapid growth of CSA scholarship (Jellason et al., 2022). Long-term data on productivity, soil health, resilience, and nutrition outcomes are still limited in many low-income smallholder settings (FAO, 2023). More evidence is needed on heterogeneous impacts by gender, wealth, and household type, as well as on the cost-effectiveness of competing implementation strategies (FAO, 2024). Research is also needed on how CSA interacts with migration, off-farm employment, climate finance, and changing value chains (World Bank, n.d.). For practitioners, the main implication is that implementation should be accompanied by robust learning systems rather than assuming that successful pilots will automatically scale (World Bank, 2024).

Future directions for practice are clear (FAO, n.d.). First, CSA should be embedded in wider rural-development and food-system strategies rather than implemented as isolated technology projects (FAO, 2021). Second, financing, extension transformation, inclusive farmer organisations, and local governance reform are as important as the technical content of interventions (World Bank, 2018). Third, digital tools, climate services, and nutrition-sensitive agriculture offer promising innovations, but only if they are accessible and adapted to smallholder realities (World Bank, 2024). Finally, equitable implementation demands deliberate attention to women, youth, and marginalised farmers who often face the largest adaptation burdens but receive the least support (FAO, 2024). In that sense, the future of CSA is not only about climate adaptation but also about rural justice, institutional inclusion, and resilient food systems (FAO, 2021).

Table 1. Climate-Smart Agriculture Practices, Benefits, and Implementation Characteristics

CSA practice category	Examples	Main benefits	Key implementation considerations	Evidence strength
Water management	Rainwater harvesting, drip irrigation, water-efficient rice systems	Improved water-use efficiency, drought buffering, off-season production (FAO, 2024)	Needs capital, maintenance, local governance, hydrological fit (World Bank, 2018)	Strong (FAO, 2024)
Soil and vegetation conservation	Conservation agriculture, mulching, terracing, agroforestry, manure, compost	Better soil structure, moisture retention, erosion control, carbon storage (Corbeels et al., 2014)	Benefits may be delayed, labour demands can be high, local adaptation is essential (Morel et al., 2024)	Moderate to strong (Corbeels et al., 2014)
Crop diversification and improved varieties	Intercropping, relay cropping, tolerant varieties, legumes, millets	Risk spreading, yield stability, dietary diversity, soil benefits (FAO, n.d.)	Depends on seed access, market demand, and extension support (FAO, 2023)	Strong (World Bank, 2018)
Livestock and crop-livestock integration	Improved forage, adapted breeds, manure reuse, silvopasture	Higher productivity per animal, feed security, nutrient recycling (FAO, 2013)	Needs feed planning, labour, and advisory support (FAO, 2023)	Moderate to strong (FAO, 2013)
Knowledge and institutional innovations	Farmer field schools, climate-smart villages, digital advisories, seed systems	Better learning, diffusion, contextual adaptation, access to information (World Bank, 2024)	Requires trusted intermediaries, organisational capacity, inclusive outreach (FAO, 2023)	Strong for enabling adoption (World Bank, 2024)

Table 2. Major Barriers, Enablers, and Policy Responses for Scaling CSA

Barrier domain	Typical barriers	Key enablers	Policy or programme responses
Finance	High upfront costs, low liquidity, weak credit access (Jellason et al., 2022)	Microfinance, savings groups, insurance, results-based finance (World Bank, 2018)	Targeted subsidies, agricultural credit reform, climate-finance access (World Bank, n.d.)
Knowledge	Weak extension, poor information credibility, low literacy (World Bank, 2024)	Demonstration plots, farmer field schools, peer learning, digital tools (FAO, 2023)	Extension reform, local-language communication, capacity building (FAO, n.d.)

Institutions and markets	Weak seed systems, poor roads, thin markets, tenure insecurity (FAO, 2013)	Farmer organisations, reliable input suppliers, secure tenure (World Bank, 2018)	Rural infrastructure, land policy reform, market-linkage programmes (FAO, 2021)
Equity and inclusion	Women's limited access to land, credit, and extension, youth exclusion (FAO, 2024)	Women's groups, targeted outreach, inclusive governance (FAO, 2024)	Gender-responsive programming, youth enterprise support, equity metrics (World Bank, 2024)

4. Conclusion

Climate-smart agriculture can strengthen smallholder productivity, adaptation, and food security, but no practice is climate-smart in every setting. The most credible implementation strategy combines locally tested agronomic options with reliable extension, finance, seed and input systems, secure resource access, and meaningful participation by women, young people, and marginalised producers. Programmes should therefore be designed as adaptive portfolios, monitored for distributional as well as average outcomes, and revised as climate, market, and livelihood conditions change.

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Conflict of Interest Statement

The author declares no conflict of interest.

Data Availability

Not applicable.

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