CLIMATE SMART AGRICULTURE, FOOD SECURITY AND SUSTAINABLE DEVELOPMENT

GLOBAL ISSUES & LOCAL PERSPECTIVES volume One

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate Smart Agriculture, Food Security and Sustainable Development** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which climate smart agriculture (CSA) food security, Sustainable Development issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue climate smart agriculture, food security, and sustainable development necessary in policy making process that will stimulate increase in food production and environmental sustainability.

Climate Smart Agriculture, Food Security and Sustainable Development: *Global Issues & Local Perspectives* is organized in three parts. Part One deals with The Concept of **Climate Smart Agriculture**, Part Two is concerned with The Concept of **Food Security And** and Part Three deals with the Concept of **Sustainable Development**

Eteyen Nyong; October 2025

Chapter Thirteen

Role of Climate-Smart Agriculture in Addressing Challenges of Food Security and Climate Change in Africa

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Outline

10.0 Introduction

Agriculture remains the backbone of many African economies and livelihoods, supplying food, employment and foreign exchange across the continent (FAO, 2020). Agriculture plays a pivotal role in Africa's socio-economic landscape, contributing significantly to GDP, employment, and food security. The sector accounts for over 30% of Africa's GDP and is a livelihood source for over 60% of the population (FAO, 2020). However, Africa's agricultural systems are increasingly vulnerable to the effects of climate change, which threatens both food security and economic stability. Climate change, characterized by rising temperatures, erratic rainfall, droughts, and floods, poses significant risks to agricultural productivity, food availability, and rural livelihoods (IPCC, 2022). The agricultural sector in Africa is already facing substantial challenges, with soil degradation, water scarcity, and the loss of biodiversity severely undermining the continent' s capacity to produce sufficient food for its rapidly growing population. Over 65% of Africa' s agricultural land is reported to be affected by soil degradation, which includes processes such as erosion, nutrient depletion, and desertification (Lal, 2021). These issues are exacerbated by a combination of inappropriate farming practices such as monocropping, overgrazing, and the excessive use of chemical fertilizers-and the effects of climate change, including altered rainfall patterns, rising temperatures, and more frequent extreme weather events (FAO, 2020).

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Climate change is amplifying risks to African agriculture through increases in temperature, shifts in rainfall patterns, more frequent droughts and floods, and expanded pest and disease ranges, thereby threatening food security and rural livelihoods (IPCC, 2022). Climate-Smart Agriculture (CSA) has emerged as a global framework to reconcile food security objectives with climate mitigation and adaptation goals by promoting context-specific bundles of practices, enabling services and targeted finance mechanisms (Lipper et al., 2017). This manuscript reviews evidence on the role of CSA in addressing food security and climate change in Africa, identifies gaps and trade-offs in current knowledge, and provides recommendations for policy, finance and research priorities to scale CSA effectively (Wakweya et al., 2024).

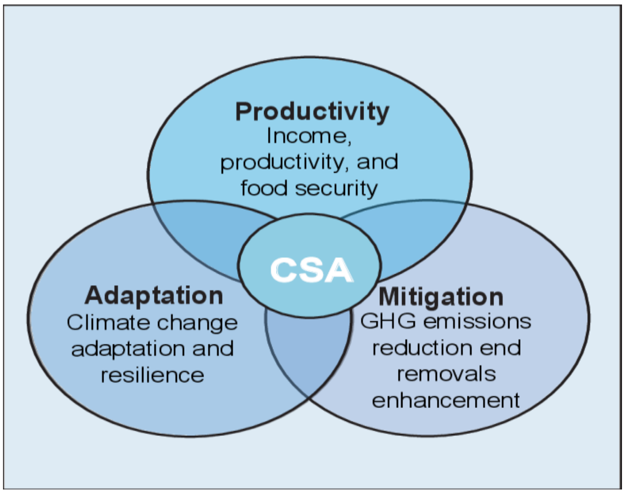

Figure 10.1: The Core Pillars of Climate Smart Agriculture

10.2 Objectives

To examine how Climate Smart Agriculture (CSA) can strengthen food security and reduce climate vulnerability across African agro-ecosystems by increasing productivity, building resilience, and lowering greenhouse gas emissions while informing policy and practice. The specific objectives are:

i) Identify and synthesize the major climate and food-security challenges facing African farming systems, value chains, and rural livelihoods.

ii) Define Climate Smart Agriculture and catalog the most relevant CSA practices and technologies for diverse African agroecological zones.

iii) Estimate the potential of CSA practices to reduce or sequester greenhouse gas emissions in African agricultural landscapes.

iv) Investigate institutional, policy, financial, and market conditions that facilitate or hinder CSA adoption at farm, community, and national scales.

v) Analyze the cost-effectiveness, financing options, and short-term versus long-term economic returns of adopting CSA measures.

vi) Develop actionable recommendations for policymakers, extension services, donors, and private actors to scale up CSA in ways that are context-appropriate and socially inclusive.

10.3 Extended Literature Review

10.3.1 Conceptual Foundations of Climate Smart Agriculture (CSA)

CSA is defined by three interlinked objectives-sustainably increasing productivity and incomes, adapting and building resilience of agricultural and food systems, and reducing or removing greenhouse-gas emissions where possible-and emphasizes the need for context adaptation and integrated packages of interventions (Lipper et al., 2017).

Climate-Smart Agriculture is conceptually grounded in the integration of three core objectives-productivity, adaptation and mitigation-so that interventions are evaluated by their combined potential to raise agricultural yields, strengthen farm and system resilience to climate variability, and reduce or sequester greenhouse-gas emissions; this tripartite framing shifts decision-making from single-goal agronomy to multi-objective systems planning (Owoyemi, et al., 2025). CSA emphasizes bundling of practices rather than single interventions, recognizing that durable gains in food security and climate outcomes typically arise from packages that combine varietal choice, soil-health management, water-saving techniques and agroforestry tailored to local biophysical and socioeconomic contexts. The conceptual model places smallholder livelihoods and risk management at its centre, treating diversification of crops and income, erosion of seasonal vulnerability, and maintenance of ecosystem services as explicit pathways through which CSA delivers welfare and resilience benefits. Crucially, CSA's theory of change links on-farm management actions to landscape processes—soil organic carbon dynamics, water cycling and biodiversity—so that local practice choices are considered for their aggregated impacts and for potential trade-offs such as yield versus emission intensity or short-term income versus long-term soil capital. Underpinning these elements is an emphasis on context specificity and iterative learning: CSA is not a fixed blueprint but a decision-support approach that requires locally calibrated evidence, participatory planning and adaptive governance to align agronomic options with market, tenure and policy realities.

10.3.2 Climate-Smart Agriculture (CSA) and its applications in Africa

Climate-Smart Agriculture (CSA), as defined by the Food and Agriculture Organization (FAO, 2018), is an integrated approach that aims to increase agricultural productivity sustainably, enhance resilience to climate change, and reduce greenhouse gas emissions. CSA incorporates various adaptation and mitigation techniques that enable farmers to cope with climate variability while ensuring long-term food security. Several Climate-Smart Agriculture (CSA) practices have been successfully implemented across African countries to enhance resilience and food security. One of the most widely adopted strategies is the use of drought-resistant crop varieties, which help farmers cope with erratic rainfall patterns and prolonged dry spells. For instance, improved maize, millet, and sorghum strains have been introduced in regions such as East and Southern Africa to sustain yields under water-limited conditions (Nyasimi et al., 2017). These improved crop varieties have been developed through biotechnological innovations and selective breeding programs to enhance their drought tolerance and nutritional value (Tesfaye et al., 2018). Another key adaptation strategy is the implementation of water-efficient irrigation techniques, particularly in arid and semi-arid regions where water scarcity poses a significant challenge. Techniques such as drip irrigation and rainwater harvesting have been successfully deployed in countries like Kenya, Ethiopia, and South Africa, helping smallholder farmers optimize water use efficiency (Gebrechorkos et al., 2019). Drip irrigation, in particular, delivers water directly to the roots of plants, reducing evaporation losses and improving water productivity by up to 50% compared to traditional flood irrigation (Rockström et al., 2018).

The successful adoption of these CSA practices demonstrates their potential to enhance agricultural resilience, increase food security, and reduce farmers' vulnerability to climate change. However, their scalability remains dependent on supportive policies, financial investments, and access to extension services that promote farmer education and technology adoption (FAO, 2020). Despite these advancements, CSA adoption remains limited due to financial constraints, lack of access to technology, and limited awareness among smallholder farmers (Thornton et al., 2018). Additionally, while CSA emphasizes resilience and productivity, concerns have been raised regarding the affordability and scalability of these technologies for resource-poor farmers (Lipper et al., 2014).

10.3.3 CSA and mitigation co-benefits in African landscapes

Climate-smart agriculture (CSA) practices in African landscapes can generate measurable mitigation co-benefits when they increase soil carbon stocks, reduce emissions intensity, or lower fuel and input use, with residue retention, reduced tillage, agroforestry and improved nutrient management among the most consistently cited interventions for sequestration and emissions reductions (Springer Synthesis, 2021; Rusinamhodzi et al., 2024). Empirical evidence indicates that sustained residue retention and improved soil management lead to gradual increases in soil organic carbon at field scale, while agroforestry strips and integration of perennial biomass contribute both to carbon storage and to diversified farm returns that support long-term stewardship (Springer Synthesis, 2021; Frontiers Review, 2024). Mitigation potential is context dependent: well-drained, moderate-rainfall systems with appropriate residue management show clearer sequestration gains, whereas poorly drained or highly disturbed soils may sequester less or require different approaches; monitoring, measurement and permanence are critical for credible carbon accounting and any linkage to carbon finance mechanisms (Rusinamhodzi et al., 2024; Performance Review, 2025). Trade-offs emerge particularly in mixed livestock–cropping systems where intensification or greater stocking without complementary feed and manure management can raise methane and nitrous oxide emissions, underscoring the need for integrated designs that pursue productivity, adaptation and mitigation jointly (Frontiers Review, 2024; Rusinamhodzi et al., 2024).

Realizing mitigation co-benefits at scale requires programmatic and policy measures that go beyond technical prescriptions to address competing residue uses, upfront cost barriers and governance of landscape-level resources, because isolated plot-level gains will not sum to durable landscape sequestration without coordinated residue management, alternative energy options and community-level fodder strategies (Rusinamhodzi et al., 2024; FRR Regional Review, 2023). Financing modalities that reduce initial investment hurdles—targeted vouchers, group equipment hire and micro-leasing—combined with payments for ecosystem services or soil stewardship can incentivize the sustained practices needed for carbon accrual, provided robust, transparent monitoring systems capture both agronomic and household trade-offs (FRR Regional Review, 2023; Performance Review, 2025). Gender-sensitive approaches and adaptive extension that support farmer experimentation strengthen the social feasibility of mitigation-oriented CSA, while risk-based targeting of interventions to agroecologies suited to mulch-based moisture conservation and carbon accumulation improves cost-effectiveness and program success (Frontiers Review, 2024; Thierfelder et al., 2015; Rusinamhodzi et al., 2024).

10.3.4 Barriers to adoption documented in the literature

Barriers to adoption of climate-smart practices in African agricultural contexts are multifaceted, combining biophysical mismatches, resource constraints, and socio-institutional obstacles that together limit uptake and sustained use. Biophysical constraints include unsuitable soil drainage or excessively high rainfall that make residue retention and reduced-tillage counterproductive without local adaptation, producing neutral or negative yield responses that undermine farmer confidence in innovations (Rusinamhodzi et al., 2024; Thierfelder et al., 2015). Resource limitations manifest as high upfront costs for equipment and inputs, increased labour demands for residue management and planting into mulch, and direct competition for residues used as livestock feed, fuel and thatch, all of which substantially reduce the feasibility of practices for resource-poor households (Thierfelder et al., 2015; Rusinamhodzi et al., 2024). Market and value-chain gaps, including poor postharvest infrastructure and limited access to profitable markets, diminish incentives to invest in productivity-raising CSA measures, while weak seed systems and limited availability of locally adapted varieties constrain effective crop diversification (FRR Regional Review, 2023; Frontiers Review, 2024). Social and institutional barriers—gendered control over labour and resources, low extension capacity, inadequate financing modalities, and absence of policies or incentives that remunerate soil stewardship—further impede equitable adoption and scaling, making bundled, context-sensitive interventions and risk-based targeting essential for overcoming these layered constraints (Frontiers Review, 2024; Rusinamhodzi et al., 2024; Performance Review, 2025).

10.3.5 Financing and scaling lessons from recent reviews

Financing and scaling lessons from recent reviews emphasize that successful expansion of CSA requires blended finance, targeted subsidies, and locally appropriate business models that lower upfront costs while creating durable incentives for continued practice adoption (FRR Regional Review, 2023; Rusinamhodzi et al., 2024). Reviews show that short-term subsidies or input vouchers can kick-start adoption of equipment and planting into mulch, but long-term scaling depends on complementary service provision—group equipment hire, micro-leasing, and value-chain linkages that convert productivity gains into marketable surplus and incomes (FRR Regional Review, 2023; Frontiers Review, 2024). Payment for ecosystem services and soil-stewardship remuneration hold promise for bridging the gap between private farmer costs and public climate benefits, yet their feasibility hinges on robust monitoring, transparent measurement of carbon or ecosystem outcomes, and credible permanence safeguards to satisfy buyers and communities (Springer Synthesis, 2021; Performance Review, 2025). Institutional coordination at landscape scale is repeatedly flagged: interventions must reconcile competing residue uses through community fodder banks, alternative energy options and cooperative arrangements to ensure residues are available for mulching without undermining livestock systems (Rusinamhodzi et al., 2024; FRR Regional Review, 2023). Gender-sensitive financing channels and extension modalities that reduce labour burdens for women, paired with demonstration sites and farmer field schools, increase uptake rates and help adapt technologies to local labour and resource realities (Frontiers Review, 2024; Thierfelder et al., 2015). Finally, risk-based targeting to agroecologies where practices are biophysically appropriate, combined with phased financing that ties support to measurable agronomic outcomes, improves cost-effectiveness and the likelihood that programmatic investments will yield sustained landscape-level impacts (Rusinamhodzi et al., 2024; Performance Review, 2025).

10.4 Methods

10.4.1 Review protocol and search strategy

The review followed a structured synthesis approach, searching peer-reviewed literature (2020–2025) and grey literature databases for terms including “climate-smart agriculture”, “CSA”, “food security”, “Africa”, “adaptation” and “mitigation” and prioritizing empirical studies, program evaluations and policy analyses with measurable outcomes (Frontiers review, 2024). Inclusion criteria required studies to report on at least one measurable outcome related to productivity, resilience, food security or greenhouse-gas effects, or to present detailed implementation, finance or institutional analyses applicable to African contexts (FRR regional review, 2023).

10.5 Case studies in Climate-Smart Agriculture

10.5.1 Agroforestry corridor for soil restoration and diversified incomes

Farmer groups plant multipurpose trees along contours and field margins to rebuild soil organic matter, provide fodder and fruit, and generate timber and non-timber income while sequestering carbon (FAO case studies, 2021). Agroforestry corridors rehabilitate degraded landscapes by combining contour tree planting, live hedges and alley cropping that reduce erosion, increase surface water infiltration and accelerate rebuilding of soil organic matter and structure (FAO, 2013). These practices improve microclimates at the field scale—reducing wind and radiant stress, buffering temperature extremes and increasing soil moisture retention—which stabilizes yields under erratic rainfall (Mbow et al., 2019). Integration of nitrogen-fixing species and deep-rooted trees enhances nutrient cycling and reduces the need for costly external fertilisers, improving long-term soil fertility and lowering input-related greenhouse-gas intensity (Springer chapter, 2021). Corridor designs that link farm-level strips with riparian buffers and watershed restoration reduce downstream sedimentation and support landscape connectivity for pollinators and beneficial natural enemies, delivering biodiversity co-benefits alongside production gains (Frontiers research, 2024). Establishing sentinel plots and periodic soil coring in corridors enables low-cost monitoring of soil-organic-carbon accrual and surface condition trends, providing the empirical basis for results-based payments or carbon-linked incentives (Performance Review, 2025).

Agroforestry corridors diversify and stabilize household incomes by producing marketable tree products-fruit, fodder, fuelwood, timber and non-timber forest products—that smooth seasonal cash flows and reduce reliance on a single staple crop (AGRA policy brief, 2023). Combining corridor planting with nursery micro-enterprises and local processing (drying, value-added fruit products, fodder bales) creates off-farm employment and increases local value capture for smallholders (Wider Program Reviews, 2022). Corridor models that formalize land-use agreements, clarify tree and land tenure and embed benefit-sharing rules reduce the risk of dispossession and increase incentives for long-term stewardship by women and tenant farmers (IPCC, 2023). Scaling corridors cost-effectively requires blended finance to subsidize early-stage establishment costs, technical assistance to ensure species-site matching, and market linkages for diversified products so that corridors graduate to farmer-financed maintenance over time (Blended Finance Playbook, 2025). Finally, participatory design-engaging producer groups, local government and downstream users-builds local ownership, aligns corridors with landscape planning and ensures that agroforestry contributes measurably to both food security and climate mitigation goals (AICCRA / CORAF, 2022).

10.5.2 Conservation agriculture with residue retention and minimal tillage

Conservation agriculture (CA) practices is characterized by reduced or minimal tillage, permanent soil cover through retained residues or cover crops, and diversified rotations—are increasingly adopted by smallholders to boost water infiltration, reduce surface runoff and erosion, and stabilize yields under increasingly erratic rainfall patterns, with sustained residue retention and minimal soil disturbance also contributing over time to higher soil organic carbon and improved soil structure that support longer-term productivity and resilience (Thierfelder et al., 2015; Rusinamhodzi et al., 2024). Adoption pathways typically involve pragmatic local adaptations—such as tied ridging, basin planting or rip-line seeding—to address specific drainage and rainfall regimes and avoid negative outcomes on poorly drained soils, while residue management requires negotiating trade-offs with livestock feed and fuel uses that often constrain uptake among resource-limited households (Thierfelder et al., 2015; Rusinamhodzi et al., 2024). Labour and equipment implications are significant: planting into mulch can raise labour demands or prompt small-scale mechanization needs, so financing mechanisms (group hire, micro-leasing, targeted vouchers) and demonstration-based extension (farmer field schools, sentinel plots) materially improve adoption fidelity and help farmers manage weeds, nutrient cycling and residue decomposition to accelerate agronomic benefits and potential carbon sequestration (FRR Regional Review, 2023; Performance Review, 2025).

10.5.3 Drought-tolerant seed dissemination and seed-system strengthening

Micro-irrigation supported by village-level solar pump clusters and pay-as-you-go (PAYG) pump schemes has expanded opportunities for resilient, market-oriented horticulture by enabling year-round production of high-value vegetables and fruits that substantially raise household incomes and reduce dependence on erratic rainfall (Livelihoods Centre and program reviews, 2021). These systems improve water-use efficiency through drip or micro-sprinkler delivery that targets the root zone, cutting evaporation losses and allowing farmers to stretch limited water supplies across more productive crop cycles, while cluster models lower per-farm capital costs by sharing generation and storage infrastructure and using smart metering or mobile payments to recover costs and manage equitable access (Livelihoods Centre and program reviews, 2021; FRR Regional Review, 2023). By linking producers to local and regional value chains, solar irrigation hubs can convert productivity gains into stable cash flows that justify continued maintenance and equipment replacement, and they create opportunities for off-farm employment around pump servicing, produce aggregation and postharvest handling (Frontiers Review, 2024).

Despite these benefits, program evaluations highlight several constraints that shape long-term viability and equitable impacts: upfront establishment costs and the need for reliable financing or subsidy pathways; governance challenges in allocating limited water among competing users within and between villages; technical maintenance capacity and supply chains for spare parts; and gendered access barriers where women may lack control over water payments or the mobility to participate in market channels (Livelihoods Centre and program reviews, 2021; Performance Review, 2025). Successful scaling therefore typically blends targeted finance (PAYG credit, micro-leasing, co-financing), training for local technicians and farmer groups, formalized rules for water allocation and cost-sharing, integration with postharvest and market development interventions, and gender-sensitive modalities to ensure inclusive participation and benefit sharing, thereby increasing the probability that solar micro-irrigation clusters become self-sustaining contributors to resilient horticultural livelihoods (FRR Regional Review, 2023; Performance Review, 2025).

10.5.4 Micro irrigation and solar pump clusters for resilient horticulture

Village-level solar irrigation hubs and pay-as-you-go (PAYG) pump schemes have expanded opportunities for high-value horticulture by enabling year-round production of vegetables and fruits, which raises household incomes, reduces reliance on erratic rainfed cropping and improves on-farm water-use efficiency through targeted delivery methods such as drip and micro-sprinkler systems (Livelihoods Centre and program reviews, 2021). Clustered solar models lower per-farm capital outlays by sharing generation, storage and distribution infrastructure and use digital metering or mobile payments to recover costs and allocate water equitably, while supporting productivity gains that can justify ongoing maintenance and replacement costs when linked to reliable market channels (Livelihoods Centre and program reviews, 2021; FRR Regional Review, 2023). These systems also create local employment opportunities in pump servicing, aggregation and postharvest handling, and when paired with improved agronomic practices they raise production intensity without proportionally increasing water withdrawals, thereby improving water productivity at the landscape scale (Frontiers Review, 2024).

Programs and evaluations highlight critical constraints to durable, equitable scaling: significant upfront establishment costs require blended financing or subsidy mechanisms; governance arrangements are needed to manage competing water demands within and between communities; technical capacities and spare-parts supply chains must be strengthened to sustain operations; and gendered barriers can limit women's access to finance, control over water payments and participation in market linkages (Livelihoods Centre and program reviews, 2021; Performance Review, 2025). Successful scaling pathways therefore combine targeted finance (PAYG credit, micro-leasing, co-financing), community-based governance rules and cost-sharing mechanisms, technical training for local technicians and farmer groups, integration with value-chain and postharvest interventions, and explicit gender-sensitive modalities to ensure inclusive access and benefit sharing, increasing the likelihood that solar micro-irrigation clusters become self-sustaining contributors to resilient horticultural livelihoods (FRR Regional Review, 2023; Performance Review, 2025).

10.5.5 Integrated soil fertility management and balanced nutrient use

Integrated soil fertility management (ISFM) combines organic amendments, site-specific fertilizer recommendations and legume-based rotations to increase nutrient use efficiency, raise yields and stabilize soil fertility while reducing environmental risks associated with blanket mineral fertilizer application. Bundled input packages—compost or manure, targeted mineral blends calibrated to soil tests, and grain-legume rotations or intercropping—improve synchrony between nutrient supply and crop demand, which elevates agronomic efficiency and often produces higher and more reliable yields than single-component interventions (Frontiers Review, 2024; FRR Regional Review, 2023). Evidence from field trials and program evaluations shows that when ISFM is combined with extension and input aggregation mechanisms, smallholders realize clearer yield gains and reduced fertilizer waste, while the presence of legumes and organic matter reduces the need for high mineral N rates that drive nitrous oxide emissions, thereby lowering GHG intensity per unit of production (Rusinamhodzi et al., 2024).

Operationalizing ISFM at scale requires attention to supply chains, finance and institutional capacity because site-specific recommendations depend on accessible soil testing, reliable input markets for diversified fertilizer blends and sustained advisory services to interpret results for farmers (FRR Regional Review, 2023). Short-term barriers include the transaction costs of soil analysis, upfront costs of organic amendments or inoculants, and labour for legume management, which can be alleviated by group procurement, micro-leasing of equipment for manure processing and demonstration plots that show combined benefits (Performance Review, 2025; Frontiers Review, 2024). From a policy perspective, subsidies and vouchers are most effective when reoriented toward blended packages rather than single inputs, and monitoring frameworks should capture both agronomic outcomes (yields, nutrient use efficiency) and environmental indicators (soil organic carbon, N_2O flux proxies) to validate mitigation co-benefits and support potential payment-for-ecosystem-service schemes that remunerate long-term soil stewardship (Performance Review, 2025).

10.5.6 Post harvest cold chain and value chain upgrades to reduce losses

Investments in community cold rooms, improved drying facilities and hermetic storage, when paired with farmer aggregation and strengthened market linkages, substantially reduce post-harvest losses and stabilize producer prices by extending the marketing window for perishable and semi-perishable crops, smoothing supply gluts and enabling farmers to time sales for better returns (FAO/AGRA, 2021). Practical examples show that village-level cold storage hubs and mobile cold-chain services increase farmers' bargaining power with buyers, reduce distress sales after harvest peaks, and create opportunities for collective branding and higher-value market entry, which in turn strengthens incentives to adopt climate-smart production practices that raise quality and shelf life (FAO/AGRA, 2021; Frontiers Review, 2024).

Beyond direct loss reduction, value-chain upgrades generate local employment in logistics, cooling maintenance and value-added processing (drying, grading, packing), catalyze investments in upstream productivity and postharvest handling, and facilitate compliance with market standards required for formal processors and export markets (FRR Regional Review, 2023). Successful scaling depends on affordable finance and business models—co-operative ownership, pay-as-you-store fees or public-private partnerships—robust aggregation mechanisms to ensure steady throughput, gender-sensitive access arrangements so women benefit equitably, and integrated planning that links cold-chain rollout to transport, input supply and extension services to lock in the production incentives and climate-resilience gains (FAO/AGRA, 2021; Performance Review, 2025).

10.6 Priority CSA practices: Summarized Evidence and Operational Considerations

10.6.1 Improved genetics (drought-tolerant and early-maturing varieties)

Early-maturing and drought-tolerant varieties reduce exposure to terminal droughts and have lowered crop failure incidence in several rainfed settings when seed systems ensured timely access to quality seed (Lipper et al., 2017). Operational considerations include strengthening seed systems, timeliness of distribution, and bundling with advisory support to ensure appropriate agronomic management (FRR Regional Review, 2023).

10.6.2 Conservation agriculture and residue management

Conservation agriculture (CA) rests on three interlinked principles—minimum soil disturbance, permanent soil cover through residues or cover crops, and crop diversification via rotations or intercropping—and residue management is its operational cornerstone because retained residues reduce evaporation, protect against raindrop impact and increase infiltration

(Thierfelder et al., 2015; Rusinamhodzi et al., 2024). Where soils drain well and rainfall is moderate, CA commonly increases soil moisture availability by improving infiltration and reducing surface runoff, and sustained residue retention can gradually raise soil organic carbon and deliver modest field-scale carbon sequestration as part of broader soil health gains (Rusinamhodzi et al., 2024; Springer Synthesis, 2021). Empirical responses in sub-Saharan Africa are heterogeneous: positive yield effects occur in some soils and climates but can be neutral or negative in poorly drained or very high-rainfall environments unless CA is locally adapted through practices such as tied ridging, rip line seeding, basin planting or reduced-tillage variants (Rusinamhodzi et al., 2024; Thierfelder et al., 2015). Short-term trade-offs arise because residues are also essential for livestock feed, fuel and thatching, and because residue management and planting into mulch increase labour or require small-scale mechanization with upfront costs, constraining adoption among resource-limited households (Thierfelder et al., 2015; Rusinamhodzi et al., 2024).

Addressing these barriers calls for bundled, locally adapted CSA packages that combine residue retention with cover crops, agroforestry strips or targeted nutrient amendments to reduce initial yield penalties and accelerate benefits, supported by demonstration plots and farmer field schools to build capacity in residue management, weed control and rotation design (Frontiers Review, 2024; FRR Regional Review, 2023). Scaling CA at landscape level requires coordinated interventions to reduce competing residue uses—for example community fodder banks or alternative fuel initiatives—complemented by gender-sensitive modalities because men and women often control different resources and labour tasks, and by financing mechanisms such as input vouchers, group equipment hire or micro-leasing to lower upfront costs for tools (Rusinamhodzi et al., 2024; Frontiers Review, 2024; FRR Regional Review, 2023). Monitoring should combine plot-level indicators (soil moisture, residue cover, yields) with household measures (labour allocation, residue uses) and risk-based targeting toward well-drained, suitable rainfall regimes to improve program success, while policy measures that remunerate soil stewardship and invest in community solutions strengthen the enabling environment for durable CA adoption (Performance Review, 2025; Springer Synthesis, 2021).

10.6.3 Water-harvesting and small-scale irrigation

Water-harvesting and small-scale irrigation capture, store and apply rainfall or surface water to extend crop water availability beyond the rainy season and thereby reduce farm and household exposure to intra- and inter-annual rainfall variability (FRR Regional Review, 2023). Simple on-farm water-harvesting techniques such as *zai* pits, contour bunds, tied ridges and micro-catchments increase infiltration, raise root-zone moisture and can boost yields of staple crops during dry spells when matched to local soils and slopes (Frontiers Review, 2024). Household and community storage options including roof catchments, micro-ponds and rehabilitated earth dams combined with affordable lift technologies (solar, treadle or low-cost electric pumps) create reliable micro-irrigation that enables dry-season gardening and crop diversification (MDPI study, 2024). Where implemented at scale and with landscape coordination, water-harvesting can contribute to aquifer recharge, reduce downstream flood peaks and support multiple uses (domestic, livestock, irrigation) if allocation rules and environmental safeguards are in place. Simple water-harvesting measures typically have low technical complexity and strong cost-effectiveness for smallholders, but their performance is context-dependent and requires careful siting and design to avoid waterlogging or increased salinity in marginal landscapes (Frontiers Review, 2024).

Small-scale irrigation schemes are most effective when embedded in participatory management arrangements such as water-user associations that establish operation and maintenance (O&M) rules, collect modest fees and coordinate equitable water distribution, thereby sustaining infrastructure beyond project cycles (FRR Regional Review, 2023). Economic viability for smallholders depends on matching irrigated enterprises to proximate market opportunities so that higher yields translate into reliable income streams and repayment capacity for any capital support provided (Wider Program Reviews, 2022). Affordable finance models-including targeted subsidies timed to cropping calendars, micro-leasing of pumps and pay-as-you-go solar systems-lower upfront barriers to entry while promoting ownership and incentivizing maintenance (MDPI study, 2024). Risk management measures such as integrated salinity monitoring, pest surveillance and drainage planning reduce unintended environmental trade-offs associated with intensified irrigation (IPCC, 2023). Gender-sensitive design is critical because irrigation can shift labour burdens and control over cash crops, and interventions that secure women's access to irrigable plots and provide targeted training increase equitable food-security outcomes (Frontiers Review, 2024).

10.6.4 Integrated nutrient management and precision application

Integrated nutrient management (INM) combines organic, inorganic and biological nutrient sources to optimize soil fertility and crop nutrition while minimizing environmental losses across farming systems (Kumar et al., 2022). INM seeks to synchronize nutrient supply with crop demand in time and space so plants receive the right nutrients at the right rate and at the right growth stage (Singh & Kumar, 2021). Organic amendments such as compost, manure, green manures and biochar increase soil organic matter, improve structure and water-holding capacity, and thereby enhance nutrient retention and long-term fertility (Reddy et al., 2021). Biofertilizers and microbial inoculants including Rhizobium, Azospirillum, phosphate-solubilizing bacteria and mycorrhizae can increase biological nutrient supply and improve plant nutrient uptake when integrated into INM packages (Verma et al., 2021). Precision application augments INM by using site-specific data from soil tests, proximal sensors and remote sensing to apply variable fertilizer rates within and between fields, improving nutrient-use efficiency (Patel et al., 2020). Variable-rate application technologies (VRT), decision-support systems and digital soil maps translate sensor outputs and spatial diagnostics into actionable fertilizer prescriptions that reduce over-application and correct patchy nutrient deficits (Frontiers Review, 2025).

Precision placement methods such as banding, deep placement of urea and localized macro-nutrient placement increase recovery of applied nutrients and reduce volatilization and leaching compared with broadcast application (Kumar et al., 2022). Controlled-release and coated fertilizers timed to crop uptake curves and split applications aligned with critical growth stages further synchronize supply and demand and lower peak nutrient losses (Agro-chemistry Review, 2023). On-farm nutrient omission trials and adaptive field experiments are essential to identify locally limiting nutrients and to calibrate INM recommendations for G×E×M contexts (Adolwa et al., 2025). Integrating livestock manure management with crop nutrient planning creates circular nutrient flows that lower dependence on imported mineral fertilizers and build soil organic matter over time (Reddy et al., 2021). Decision-support systems that combine weather forecasts, crop models and soil nutrient status enable risk-informed nutrient recommendations under increasing climate variability (Frontiers Review, 2025).

Despite agronomic and environmental benefits, smallholder uptake of INM plus precision tools is constrained by costs of testing, limited access to affordable sensors, low digital literacy and restricted seasonal credit, requiring tailored service and financing models (Adolwa et al., 2025). Farmer-centric delivery-on-farm testing, participatory demonstrations and extension-brokered interpretation of soil results-accelerates learning and adaptation of INM recommendations to local practices (Adolwa et al., 2025). Service models that bundle soil testing, custom fertilizer blending and pay-as-you-go application services reduce entry barriers and improve adoption among resource-constrained farmers (EERCE, 2023). Policy support for fertilizer quality standards, subsidized soil testing infrastructure and subsidy redesign that rewards balanced nutrient use strengthens the enabling environment for INM (EERCE, 2023). Monitoring nutrient balances at farm and landscape scales through periodic soil testing and input–output accounting informs sustainable intensification and helps prevent long-term nutrient depletion or accumulation (Performance Review, 2025).

10.6.5 Post-harvest handling, storage and value addition

Post-harvest handling, storage and value addition reduce food losses, extend shelf life and convert seasonal surpluses into marketable products, thereby directly increasing food availability and farmer incomes across African supply chains (El-Ramady et al., 2025). Proper harvesting timing, gentle handling, prompt threshing and effective cleaning minimize mechanical damage and contamination that otherwise accelerate quality deterioration and mycotoxin development in cereals and pulses (MDPI, 2024). Drying to safe moisture levels before storage is a critical control point because inadequate or uneven drying greatly increases the risk of insect infestation, mold growth and aflatoxin accumulation during storage (MDPI, 2024). Affordable on-farm and village-level drying technologies (improved solar dryers, raised platforms, tarpaulins) reduce post-harvest weight and quality losses compared with open-sun methods and improve the marketability of produce (El-Ramady et al., 2025). Hermetic storage technologies (purdue-type bags, metal silos, airtight containers) effectively control storage pests without chemical fumigants and can reduce losses during storage by up to two-thirds compared with traditional jute bags (MDPI, 2024). Community and farmer-managed warehouses linked to warehouse receipt systems enable smallholders to time sales for better prices, access collateralized finance and smooth seasonal income volatility (AGRA policy brief, 2023). Scaling warehouse receipt systems requires standardized grading, certified storage providers and regulatory oversight to ensure trust in receipts and to make stored commodities bankable collateral (AGRA policy brief, 2023). Improved storage also preserves nutritional quality and reduces food safety risks, which is essential for diets and public health outcomes in food-insecure regions (El-Ramady et al., 2025). Value-addition through simple processing—cleaning, grading, milling, drying fruit, oil extraction, and packaging—raises product value, extends shelf life and opens new market segments for smallholders (JASIC review, 2025). Local processing enterprises create employment opportunities, retain value in rural areas and reduce vulnerability to price shocks by enabling the sale of processed goods with longer shelf life (JASIC review, 2025). Cold-chain investments for perishables (vegetables, fruits, dairy) substantially reduce losses in high-value horticulture and improve nutritional outcomes by making fresh produce available year-round near urban markets (Wider program reviews, 2022). However, cold chain deployment must be matched with affordable energy solutions (solar, efficient refrigeration) and business models that spread fixed costs across producer groups to be viable for smallholders (Wider program reviews, 2022). Reducing post-harvest losses also lowers the resource footprint of food production by conserving water, land and inputs embodied in lost crops, thereby contributing indirectly to climate mitigation goals (El-Ramady et al., 2025). Gender dimensions matter because women often manage processing and small-scale storage activities, so targeted training, access to microfinance and tenure over processing assets improve both adoption and household welfare (Frontiers review, 2024). Effective interventions combine technology, services and market linkages-training in good post-harvest practices, investment in appropriate storage, and integration with buyers and finance-to convert productivity gains from Climate-Smart Agriculture into durable food security and climate-resilient livelihoods (FRR regional review, 2023).

10.7 Measured Impacts on Yield, Resilience and Food Security

10.7.1 Yield outcomes and variability reduction

Bundled Climate-Smart Agriculture (CSA) interventions typically increase mean crop yields by combining improved genetics, soil-water management and timely agronomy that address multiple yield-limiting factors simultaneously (Frontiers Review, 2024). Meta-analyses across African contexts report average yield gains that vary by practice mix and baseline conditions but are consistently larger for bundled packages than for single interventions (FRR Regional Review, 2023). Improved and drought-tolerant varieties often produce immediate yield increases by shortening crop cycles and avoiding terminal moisture stress, thereby reducing the probability of total crop failure in dry years (Lipper et al., 2017). Conservation agriculture elements such as residue retention and reduced tillage enhance soil moisture conservation and produce progressive yield improvements as soil structure and organic matter build over multiple seasons (Springer Synthesis, 2021). Small-scale irrigation and water-harvesting measures deliver rapid yield boosts by extending the growing season and enabling supplementary watering during critical phenological stages (FRR Regional Review, 2023). Integrated nutrient management and precision application improve nutrient use efficiency and raise attainable yields where nutrient deficits had constrained production (Performance Review, 2025). When CSA components are combined with effective extension and input supply, adoption fidelity rises and observed yield benefits are larger and more persistent (Frontiers Review, 2024).

Beyond mean yields, CSA reduces interannual yield variability by buffering crops against climatic shocks through moisture-conserving practices, improved varieties and available supplementary irrigation (IPCC, 2023). Empirical studies document lower coefficients of variation in yields among adopters of CA and drought-resilient varieties, indicating more stable production across erratic seasons (FRR Regional Review, 2023). Yield stability gains translate into fewer years of crop failure for households in marginal zones, which improves food availability and reduces vulnerability to seasonal shortages (Frontiers Review, 2024). However, heterogeneity in variability reduction is substantial: benefits are contingent on soil type, rainfall regime, tenure security and farmers' resource endowments, which condition both biological responses and adoption sustainability (Performance Review, 2025).

10.7.2 Household food security and dietary outcomes

Climate-Smart Agriculture (CSA) can increase household food availability by raising stable on-farm production through combined measures such as improved varieties, conservation agriculture and small-scale irrigation, thereby reducing the frequency and depth of seasonal food shortfalls (Frontiers Review, 2024). When production gains are preserved through improved post-harvest handling and storage, CSA directly increases marketable surplus and home consumption, improving household food access and reducing months of inadequate food provisioning (FRR Regional Review, 2023). Nutrition outcomes improve where CSA promotes crop diversification (legumes, vegetables, fruits) and supports year-round horticulture through irrigation, thereby increasing household dietary diversity and micronutrient availability (iFEED /Frontiers integration, 2022). However, measurable dietary improvements depend on value-chain integration: without reliable aggregation, storage and market linkages, production gains often fail to translate into sustained changes in diets or nutrition status (Wider Program Reviews, 2022). Evidence from multi-season studies shows that CSA bundles yield larger and more persistent improvements in food consumption scores and household dietary diversity indices than single practices, especially when combined with nutrition-sensitive complementary interventions (Frontiers Review, 2024). Household intra-seasonal stability improves as CSA reduces yield variability and crop failure risk, which in turn lowers reliance on negative coping strategies such as meal skipping or distress asset sales during shocks (IPCC, 2023). Gender dynamics mediate dietary outcomes because women commonly control food preparation and small livestock and are primary beneficiaries when CSA programs include women-targeted support, thereby amplifying improvements in household food use and child diets (Frontiers Review, 2024). Access to markets and cash income from CSA-led surpluses enables dietary diversification by allowing households to purchase nutrient-dense foods when self-production is insufficient, linking income effects to nutrition outcomes (MDPI, 2024). Risks remain: poorly designed intensification without balanced nutrient management can reduce food safety and quality, while inequitable access to CSA inputs can widen dietary gaps between better-resourced and marginal households (Springer Synthesis, 2021). Monitoring frameworks that combine household food security indicators (FCS, HDDS, months of adequate food) with biomarker or anthropometric measures in longitudinal panels are essential to credibly demonstrate the nutrition impacts of CSA over time (Performance Review, 2025). Policy and program design that couples CSA with targeted social protection, nutrition education and investments in post-harvest and market infrastructure maximizes the probability that productivity gains will produce sustained improvements in household diets and nutritional status (FAO, 2020).

10.7.3 Income diversification and livelihood resilience

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Income diversification through Climate-Smart Agriculture (CSA) expands household revenue sources by enabling the production of multiple crops, high-value horticulture and tree products that reduce reliance on a single staple and spread risk across enterprises (Frontiers Review, 2024). Diversified on-farm enterprises such as legumes, vegetables and agroforestry products generate seasonal cash flows that allow households to smooth consumption and purchase dietary staples and micronutrient-rich foods when own-production is insufficient (FRR Regional Review, 2023). Small-scale value-addition and processing of CSA outputs (milling, drying, oil extraction, fruit processing) increase product value and create local off-farm employment that retains greater income in rural economies (Wider Program Reviews, 2022). Contract farming and linkages with off-takers for irrigated horticulture unlock credit and input supply, enabling farmers to move into higher-margin enterprises and diversify income portfolios (Wider Program Reviews, 2022). Diversification into livestock and fodder systems within CSA packages strengthens livelihood resilience by providing alternative income and food sources during crop failures and by recycling nutrients through integrated manure management (IPCC, 2023). Nonfarm diversification stimulated by CSA-related enterprises (transport, storage, processing services) further reduces household vulnerability by creating wage opportunities and reducing dependence on agricultural wages alone (Von, 2025).

Income diversification reduces vulnerability to climate shocks because multiple, asynchronous income streams lower the probability that a single climatic event will eliminate all household incomes (Livelihood Diversification studies, 2021). Empirical studies in semi-arid West Africa find that households employing both farm and nonfarm diversification strategies report higher resilience metrics and better recovery after droughts than undiversified households (Adzawla et al., 2021). Risk-reducing diversification also encourages prudent investment in productive assets and in human capital such as schooling and health, amplifying long-term resilience and intergenerational welfare (Lipper et al., 2017). However, successful diversification requires access to markets, reliable extension, affordable finance and infrastructure, otherwise attempts to enter new enterprises can increase exposure to market volatility and indebtedness (FRR Regional Review, 2023). Seasonal liquidity constraints are a common barrier to profitable diversification, making tailored financial products (seasonal loans, pay-as-you-go technologies) and aggregation services essential complements to CSA interventions (Von, 2025).

10.7.4 Mitigation metrics and evidence limitations

Reliable measurement of mitigation outcomes from Climate-Smart Agriculture (CSA) requires indicators that capture both on-farm carbon pools (aboveground biomass, belowground biomass, soil organic carbon) and fluxes (net greenhouse-gas emissions including CO_2, CH_4 and N_2O) to reflect true net climate impacts of interventions (IPCC, 2019). (IPCC, 2019) Soil organic carbon (SOC) change is a central mitigation metric for many CSA practices but SOC responds slowly to management, exhibits high spatial heterogeneity and demands replicated baseline and long-term monitoring to detect statistically robust changes (Kuyah et al., 2020). (Kuyah et al., 2020) Aboveground woody biomass from agroforestry is relatively easier to measure with plot inventories and allometric models, yet scaling requires periodic remeasurement and attention to species composition, wood density and management regimes that affect carbon stocks (Zomer et al., 2016). Greenhouse-gas fluxes from soils, particularly N_2O, are episodic and sensitive to short-term soil moisture and fertilizer timing, making point-measurements poor proxies for seasonal or annual emissions without intensive temporal sampling or validated modeling approaches (Springer Synthesis, 2021). Remote sensing offers scalable proxies such as NDVI, tree cover change and biomass indices that can indicate landscape-level trends, but these proxies require calibration with ground data and cannot directly distinguish soil carbon changes or gaseous fluxes without ancillary measurements (Frontiers Review, 2024).

Transaction costs and verification burdens constrain the use of mitigation markets for smallholders because standard carbon accounting approaches require baselines, additionality demonstrations, leakage assessments and permanence assurances that are costly and technically demanding (Springer Synthesis, 2021). Simplified, lower-cost verification approaches-combining remote sensing for land-cover change with sentinel plot sampling and participatory reporting-show promise for reducing costs but need validation to ensure accuracy and to prevent perverse incentives or gaming (Frontiers Review, 2024). Uncertainty in baseline land use and prior management practices increases the risk of over- or under-estimating mitigation benefits, particularly in systems with shifting cultivation or mixed cropland and fallow cycles common across parts of Africa (FRR Regional Review, 2023). Permanence risk for sequestration in soils or trees is elevated under insecure tenure, land-use change pressures and fire regimes, meaning that measured carbon gains today may be reversed unless governance and long-term stewardship are addressed (IPCC, 2023). Measurement frameworks that ignore co-benefits (biodiversity, water regulation, livelihood resilience) risk undervaluing

CSA's broader societal value, yet integrating multi-metric valuation into payment systems complicates verification and benefit-sharing designs (Lipper et al., 2017).

10.8 Adoption Pathways, Drivers and Constraints

10.8.1 Financial access and incentive structures

Access to finance and well-designed incentives are central to enabling smallholders to adopt capital-intensive and behavior-changing Climate-Smart Agriculture measures, because many high-impact practices require upfront investments that farmers cannot self-finance (FRR Regional Review, 2023). Seasonally-timed credit and input vouchers that align disbursements with planting windows substantially increase uptake of improved seed, fertilizer and small irrigation technologies by matching finance to farmers' cash-flow constraints (Von, 2025). Micro-leasing and pay-as-you-go business models for pumps, planters and solar equipment lower entry barriers for resource-constrained households by converting large capital costs into manageable, performance-linked payments (MDPI study, 2024). Blended finance that layers concessional public capital, grant-funded technical assistance and private co-investment mobilizes funds for longer-payback infrastructure such as community storage, irrigation and nurseries that individual smallholders could not fund alone (Von, 2025). Targeted, time-bound input subsidies catalyze early adoption when combined with extension services and a clear phase-out plan to avoid market distortion and dependency (EERCE, 2023). Results-based payments and simplified carbon or resilience credits can create recurring revenue streams for verified practices but require low-cost verification, transparent benefit-sharing and safeguards against elite capture to be equitable for smallholders (Springer Synthesis, 2021). Contract farming and buyer-financed input credit reduce market and price risk for adopters by guaranteeing off-take and sometimes providing in-kind inputs, which accelerates uptake of high-return CSA innovations in peri-urban and market-proximate zones (Wider Program Reviews, 2022). Aggregation through producer organizations improves bankability, lowers transaction costs for lenders and enables collective investments in shared assets, making it easier to channel larger loans or grants toward community infrastructure (FRR Regional Review, 2023). Insurance and risk-sharing products, including index-based weather insurance, complement credit by protecting both lenders and farmers from covariate climate shocks that otherwise inhibit investment in CSA (Frontiers Review, 2024). Subsidy and finance designs that ignore gendered constraints risk excluding women and youth, so targeted financial products and group lending modalities are necessary to ensure inclusive access to CSA investments (Frontiers Review, 2024). Digital finance and mobile payment platforms reduce delivery costs and improve transparency for small, frequent transactions such as voucher redemption and pay-as-you-go services, but require parallel investments in digital literacy and agent networks (MDPI study, 2024). Public policy plays a catalytic role by de-risking private investment through credit guarantees, matching grants and by supporting the regulatory frameworks needed for warehouse receipt systems and collateralization of stored produce (AGRA policy brief, 2023). Monitoring and adaptive management of finance windows—tracking repayment rates, inclusion metrics and environmental safeguards-ensure that incentive structures are fiscally sustainable and socially equitable as CSA scales (Performance Review, 2025). Ultimately, combining tailored seasonal finance, blended public-private funding for infrastructure, demand-side incentives and strong producer aggregation produces the most robust pathway for scaling CSA while protecting the poorest and improving resilience to climate variability (Von, 2025).

10.8.2 Extension, advisory and digital services

Extension and advisory services translate Climate-Smart Agriculture (CSA) research into actionable on-farm practices by delivering localized, timely information on varietal choices, planting dates, integrated pest and nutrient management, and water-saving techniques (Springer chapter, 2023). Effective extension strengthens farmer capacity to adopt bundled CSA packages by combining demonstration plots, farmer field schools and participatory learning that build skills for residue management, agroforestry care and irrigation maintenance (AFAAS policy brief, 2024). Decentralized and pluralistic advisory systems that engage public extension, private agribusiness agents and farmer-based organizations improve reach and allow tailoring of messages to different socioeconomic groups, increasing adoption fidelity (FRR Regional Review, 2023). Digital agronomy platforms-mobile apps, SMS advisories, decision-support dashboards and short instructional videos-scale extension reach cost-effectively and provide rapid weather, market and pest alerts that are critical under increasing climate variability (Frontiers digital review, 2025). Blended delivery models that pair digital tools with trusted face-to-face facilitation preserve the social learning and trust needed for complex, multi-component CSA practices while leveraging digital analytics for targeting and feedback (Frontiers digital review, 2025). Interactive digital services that integrate local language audio, visual content and AI-driven personalization increase accessibility for low-literacy farmers and enable peer-to-peer knowledge exchange that accelerates diffusion (Frontiers digital review, 2025). Capacity gaps among extension agents—limited training on CSA packages, data literacy and digital tool use—constrain impact unless complemented by sustained in-service training, coaching and performance incentives (AFAAS policy brief, 2024). Financing models that subsidize last-mile advisory costs, support extension startup kits and foster public-private partnerships help sustain advisory coverage in low-return or remote areas where market signals alone are insufficient (FRR Regional Review, 2023). Monitoring and adaptive management of advisory performance using simple metrics (practice adoption rates, farmer satisfaction, yield proxies) combined with digital monitoring dashboards enable rapid course corrections and evidence-based scaling decisions (MDPI study, 2024). Policy support that invests in national AEAS capacity, open data standards for digital agronomy, and inclusive procurement rules for private providers ensures advisory systems remain accountable, gender-responsive and aligned with national CSA priorities (IPCC, 2023).

10.8.3 Institutional coordination and governance

Institutional coordination and governance are central to scaling Climate-Smart Agriculture because CSA actions cut across ministries, research institutions, extension services, finance agencies and private sector actors, requiring clear mandates and coordinated planning to avoid duplication and policy conflicts (Frontiers Review, 2024). Effective national CSA strategies embed CSA targets within NDCs, agricultural development plans and sector budgets so that mitigation and adaptation objectives are translated into resourcing and measurable programs (IPCC, 2023). Multi-stakeholder platforms and thematic alliances at national and regional levels facilitate stakeholder dialogue, align priorities, mobilize financing and support peer learning between countries and programs (AICCRA / CORAF, 2022). Decentralized institutional arrangements that clarify roles for local government, water-user associations, producer organizations and community groups improve implementation fidelity and strengthen local stewardship of natural resources (AU Framework for IDAWM, 2015). Integrated monitoring, evaluation and learning frameworks that combine agronomic, socioeconomic and greenhouse-gas indicators enable adaptive governance and evidence-based course corrections as CSA is scaled (Performance Review, 2025). Legal and regulatory reforms—secure land and tree tenure, transparent water allocation rules, and standards for seed, fertilizer and storage—

reduce uncertainty, lower risks for smallholders and increase the permanence of climate-smart investments (FRR Regional Review, 2023). Financial governance instruments such as targeted subsidies, credit guarantees and results-based payments must be coordinated across ministries and donors to avoid fragmented incentives and to deliver coherent, time-bound support to adopters (Von, 2025). Public-private partnership frameworks that define risk-sharing, quality assurance and procurement standards accelerate private investment in seedling nurseries, irrigation, storage and processing infrastructure while protecting smallholder interests (Wider Program Reviews, 2022). Gender-responsive governance mechanisms that mainstream women's representation in producer groups, advisory boards and benefit-sharing arrangements ensure that CSA interventions are inclusive and do not entrench existing inequalities (Frontiers Review, 2024). Transparent data governance, open standards and interoperable digital platforms improve accountability, enable targeting of services and finance, and reduce transaction costs for monitoring CSA outcomes (Frontiers digital review, 2025).

10.8.4 Equity considerations and inclusive modalities

Equitable design of Climate-Smart Agriculture (CSA) interventions requires explicit attention to who controls land, water and tree tenure because insecure or unequal rights discourage long-term investments in soil health and agroforestry that deliver climate and food-security benefits (FRR Regional Review, 2023). Women, youth and marginalized ethnic groups often face constrained access to inputs, credit and extension services, so CSA programs must include targeted outreach, adapted financing products and gender-sensitive extension to avoid widening existing inequalities (Frontiers Review, 2024). Payment and incentive mechanisms—subsidies, vouchers, results-based payments or carbon credits—must be designed with progressive targeting and transparent benefit-sharing rules to prevent elite capture and to ensure smallholders and tenant farmers receive measurable gains (Springer Synthesis, 2021). Inclusive producer aggregation models such as cooperatives, village savings groups and farmer business hubs lower transaction costs, improve bargaining power and make smallholders bankable for seasonal credit and off-taker contracts that support CSA uptake (FRR Regional Review, 2023). Social protection linkages—cash transfers, public works and input subsidies timed to planting seasons—buffer liquidity constraints and enable the poorest households to adopt higher-return but upfront-costly CSA practices (Von, 2025). Extension and digital advisory services must be locally adapted in language, format and delivery channel and combined with face-to-face facilitation to reach low-literacy users and ensure women and remote communities can act on CSA recommendations (Frontiers digital review, 2025). Monitoring and evaluation systems should include disaggregated indicators (by gender, age, wealth and location) and social safeguards so that programs can detect exclusion early and adapt modalities to strengthen inclusion (Performance Review, 2025).

Inclusive modalities also require financial products explicitly tailored to differing risk profiles, with micro-leasing, pay-as-you-go and group-based lending lowering entry barriers for resource-constrained adopters (MDPI study, 2024). Designing community-level infrastructure investments—shared irrigation, post-harvest storage and nurseries—with co-management arrangements ensures broad access while building local ownership and maintenance capacity (AU Framework for IDAWM, 2015). Capacity building that prioritizes women leaders, youth entrepreneurs and marginalized groups in governance roles within producer organizations strengthens voice and improves equitable allocation of CSA benefits (Frontiers Review, 2024). Safeguards around land rights and tenure reform are essential to secure permanence of agroforestry and soil-building investments and to prevent dispossession that undermines both equity and climate outcomes (IPCC, 2023). Transparent grievance mechanisms, participatory planning and public reporting increase accountability and reduce the risk that incentives and services flow disproportionately to better-off households (AGRA policy brief, 2023). Finally, mainstreaming equity into national CSA strategies—through inclusive policy targets, budget lines and cross-sectoral coordination—ensures that scaling pathways are both effective in climate and food outcomes and fair in their distribution of benefits across Africa's diverse rural populations (AICCRA / CORAF, 2022).

10.9 Finance Instruments: Design, Evidence and Pilot Lessons

10.9.1 Targeted subsidies and seasonal vouchers

Targeted subsidies and seasonal vouchers lower upfront barriers to adopting Climate-Smart Agriculture (CSA) technologies by aligning support with critical decision moments such as seed purchase and planting, thereby increasing timely uptake of improved seed, fertilizers and small irrigation equipment (FRR Regional Review, 2023). Properly-designed vouchers that restrict eligible purchases to verified climate-smart inputs (drought-tolerant seed, soil-health amendments, solar pumps) steer public spending toward practices with measurable CSA benefits and reduce wasteful or non-aligned subsidy leakage (Springer Synthesis, 2021). Seasonal timing of disbursements matched to cropping calendars improves the effectiveness of subsidies because farmers receive liquidity when input demand is highest, increasing the probability that inputs are used as intended and that planting windows are met (Von, 2025). Digital voucher platforms and e-vouchers improve targeting, traceability and redemption logistics, reduce administrative costs and curb fraud while enabling rapid scale-up through dealer networks, but require investments in agent networks and digital literacy to reach remote and low-connectivity communities (MDPI study, 2024). Progressive targeting criteria—means testing, geographic poverty overlays or gender-responsive eligibility—help ensure that the poorest and women-headed house-holds benefit, preventing subsidies from disproportionately accruing to better-off farmers (Frontiers Review, 2024).

Complementary services such as extension, demonstration plots and bundled technical assistance are essential to turn subsidized inputs into sustained CSA adoption and measurable productivity and resilience gains (AICCRA / AUDA-NEPAD, 2023). Graduated subsidy designs with clear phase-out pathways and market-development objectives avoid long-term dependency and encourage private sector entry and supply-chain strengthening for CSA technologies (EERCE, 2023). Voucher schemes linked to quality assurance and certified dealer networks protect farmers from counterfeit or low-quality inputs and improve incentives for local suppliers to stock climate-relevant products (AGRA policy brief, 2023). When combined with complementary finance (micro-leasing, pay-as-you-go) and aggregation through producer organizations, seasonal vouchers can catalyze durable investments in irrigation, post-harvest storage and soil-health practices that increase incomes and reduce climate vulnerability (Wider Program Reviews, 2022). Monitoring and adaptive management—using redemption data, uptake metrics and impact evaluations—are required to refine targeting, measure cost-effectiveness and ensure subsidies deliver equitable CSA outcomes without fiscal distortion (Performance Review, 2025).

10.9.2 Blended finance for infrastructure and scaling

Blended finance mobilizes concessional public capital, grants and technical assistance to de-risk investments and attract private capital for long-lived, climate-smart agricultural infrastructure such as community irrigation, cold chains and storage hubs that individual smallholders cannot finance alone (CLIC & ISF Advisors, 2025). By layering concessional capital and guarantees with commercial loans, blended vehicles improve the risk-return profile of projects and enable investment in the "missing middle" of rural agrifood systems—local aggregators, processors and shared infrastructure that unlock market access for smallholders (Climate-Smart Blended Finance Playbook, 2025). Targeted technical assistance bundled into blended deals strengthens local project development capacity, supports business model refinement and reduces early-stage execution risk that typically deters private investors from rural infrastructure (ISF Advisors case studies, 2025). Blended facilities that focus on climate-resilient public goods—watershed restoration, road improvements and renewable energy for cold chains—create system-level enabling conditions that raise the viability of downstream private investments in value addition and market linkages (CPI & FAO analysis, 2024). Innovative concessional structures such as catalytic first-loss reserves, revenue-participating grants and subsidized interest rates can shorten commercial payback periods and crowd in later-stage investors while preserving incentives for project sustainability (Blended Finance Playbook, 2025). Robust governance, transparent contracting and measurable social and environmental safeguards in blended transactions are essential to ensure benefits reach smallholders, avoid elite capture and deliver validated climate and food-security outcomes (AGRA and regional reviews, 2023).

10.9.3 Results-based payments and simplified carbon schemes

Results-based payments (RBP) reward verified delivery of climate or productivity outcomes, aligning financial flows with farm-level practice changes such as soil-carbon building, agroforestry establishment and greenhouse-gas emission reductions (Springer Synthesis, 2021). Results-based approaches reduce upfront fiscal footprints by paying for measurable outcomes rather than inputs, thereby encouraging cost-effective, locally adapted interventions (Von, 2025). RBPs linked to agricultural performance indicators—soil organic carbon accrual, tree survival rates or reduced fertilizer-related N_2O emissions—create incentives for sustained stewardship and maintenance of climate-smart practices (Performance Review, 2025). When combined with technical assistance and concessional bridging finance, RBPs overcome liquidity constraints that otherwise prevent smallholders from adopting practices with delayed returns (Frontiers Review, 2024). Clear, simple performance metrics and short payment cycles improve farmer trust and program uptake by reducing verification delays and cash-flow uncertainty (Springer Synthesis, 2021). Pilot RBPs that incorporate co-benefit metrics for productivity and food security prevent perverse trade-offs where carbon outcomes might otherwise reduce yields or household nutrition (IPCC, 2023). Transparent benefit-sharing rules and community-level aggregation reduce transaction costs and guard against elite capture, making RBPs more equitable for smallholder groups (AGRA policy brief, 2023). Scaling RBPs requires interoperable monitoring systems, standardized protocols and pooled finance mechanisms to smooth donor cycles and ensure predictable buyer demand for verified outcomes (Performance Review, 2025).

Simplified carbon schemes tailor carbon accounting and verification to the realities of smallholder contexts by using conservative default factors, tiered sampling and remote-sensing proxies calibrated with sentinel plots (Frontiers Review, 2024). Low-cost, simplified methodologies lower entry barriers to carbon markets while safeguarding environmental integrity through conservative baselines and periodic ground validation (SAIIA policy briefing, 2023). Bundling carbon credits with productivity or resilience payments enhances the attractiveness of schemes to farmers and buyers by explicitly valuing non-carbon benefits such as yield stability and soil health (World Bank CSA synthesis, 2024). Simplified schemes that pay at community scale—using pooled measured gains across cooperatives or landscape units—reduce per-farmer verification costs and encourage collective stewardship of shared resources (Climate Policy Initiative 2025). To maintain credibility, simplified approaches must include safeguards for permanence, additionality and leakage, paired with tenure clarity and long-term stewardship incentives (IPCC, 2019). Digital registries, mobile reporting and dealer networks improve traceability and timely payments, but must be complemented by capacity building in data literacy and governance at the local level (MDPI study, 2024). Policymakers can catalyze uptake by recognizing simplified methodologies in national carbon frameworks, offering co-financing for first-loss reserves and integrating carbon buyers into blended finance for landscape infrastructure (Climate Policy Initiative, 2024). Continuous evaluation and iterative refinement of simplified schemes—grounded in pilot evidence and participatory monitoring—

ensure they remain robust, inclusive and aligned with food-security objectives as they scale across African contexts (Frontiers Review, 2024).

10.9.4 Market instruments and contract farming

Market instruments such as price incentives, warehouse receipt systems and commodity exchanges improve smallholder farmers' ability to store surpluses, time sales for better prices and access collateralized credit, thereby strengthening the market pull for climate-smart investments (AGRA policy brief, 2023). Forward contracts and offtake agreements reduce price and demand risk for producers of climate-smart crops, enabling farmers to invest in higher-return practices such as irrigation, improved seed and certified inputs with greater confidence (Wider Program Reviews, 2022). Quality standards, grading and traceability systems raise market value for sustainably produced commodities and create incentives for farmers to adopt practices that improve product quality and reduce post-harvest losses (Performance Review, 2025). Transparent market information services and digital marketplaces lower search costs, improve price discovery and link smallholders to urban buyers who value consistent volumes and quality—conditions that favor investments in climate-smart production and storage (MDPI study, 2024). Public-sector price supports and targeted purchase programs can stabilize demand during market shocks and act as a guaranteed outlet for climate-smart production during scale-up phases, but must be carefully designed to avoid crowding out private buyers (FRR Regional Review, 2023).

Contract farming arrangements provide bundled services—input supply, technical assistance, credit and assured markets that lower barriers to entry for smallholders into higher-value, climate-smart enterprises such as irrigated horticulture and certified grains (Wider Program Reviews, 2022). Well-structured contracts with clear quality specifications, timely payment terms and dispute resolution mechanisms protect smallholders from exploitation and improve trust between producers and buyers, increasing the likelihood of sustained CSA adoption (AGRA policy brief, 2023). Aggregation through cooperatives or lead-farmer models reduces transaction costs for buyers, enables compliance with bulk quality requirements and spreads the costs of climate-smart inputs and services across many producers (FRR Regional Review, 2023). Linking contract farming to climate-risk instruments—index insurance, price floors or weather-contingent payments-mitigates covariate risks that otherwise deter private buyers from contracting smallholders in climate-vulnerable zones (Frontiers Review, 2024). Safeguards-transparent contracting, legal literacy training, third-party monitoring and inclusive eligibility criteria—are essential to ensure contract farming and market instruments deliver equitable benefits and do not entrench power asymmetries that disadvantage women and poorer households (Springer Synthesis, 2021).

10.10 Value-chain and post-harvest complements

Strengthening value chains reduces post-harvest losses by improving aggregation, quality grading and timely transport from farm to market, which preserves both quantity and nutritional quality of produce and increases farmer incomes (AGRA policy brief, 2023). Investments in decentralized processing-milling, drying, cold-storage, oil extraction and minimal packaging-transform seasonal surpluses into higher-value, longer-shelf products that widen market opportunities and reduce vulnerability to price collapses during harvest gluts (AICCRA technical report, 2022). Quality assurance, standards and traceability systems raise buyer confidence and reward climate-smart production with price premiums, creating market incentives for practices that reduce losses and improve product consistency (Performance Review, 2025). Farmer aggregation through cooperatives and out-grower schemes lowers per-unit costs for post-harvest services, enables bulk investment in shared infrastructure and improves access to finance by creating bankable enterprises rather than dispersed smallholders (FRR Regional Review, 2023). Training in good post-harvest handling—proper harvesting times, sorting, hygienic packing and safe drying-reduces contamination and weight loss, improving both food safety and marketability, especially for perishable horticulture and animal-source foods (CGIAR post-harvest report, 2023). Affordable, context-appropriate technologies such as improved solar dryers, hermetic bags and small cold rooms slash losses at farm and village levels and are most effective when bundled with training and reliable energy solutions (MDPI study, 2024).

Linking value-chain improvements to finance and market instruments (warehouse receipt systems, commodity platforms, contract farming) enables smallholders to store for better prices, access collateralized loans and secure forward contracts that justify investments in quality and storage (AGRA policy brief, 2023). Public-private partnerships that co-finance processing hubs, transport corridors and market facilities reduce upfront costs, accelerate commercialization and help establish sustainable business models for post-harvest services (Wider Program Reviews, 2022). Gender-sensitive value-chain development recognizes women's central role in processing and marketing, and targeted support-secure access to processing assets, credit and training-magnifies household food and income benefits (Frontiers Review, 2024). Digital market linkages and real-time price information reduce search costs for farmers, improve coordination between producers and buyers, and enable demand-led production that decreases mismatches that cause post-harvest gluts and waste (MDPI study, 2024). Integrated policy support-standards for inputs and processing, incentives for private investment in cold-chains, and subsidies timed to catalyze local processing-ensures that post-harvest complements scale equitably and deliver measurable food-security and climate resilience benefits (Von, 2025).

10.11 Monitoring, Evaluation and Scalable Metrics

10.11.1 M&E framework linking adoption to food security and mitigation

An effective M&E framework links measurable on-farm adoption indicators (practice uptake rates, area under CSA practices, and fidelity to recommended management) to food-security outcomes so that changes in production, dietary diversity and months of adequate food can be causally attributed to CSA adoption. The framework must explicitly include mitigation metrics-soil organic carbon stocks, aboveground biomass from agroforestry, and farm-level greenhouse-gas flux proxies (or modeled N_2O estimates tied to fertilizer regimes)-to capture both sequestration and emission changes alongside productivity gains. A theory-of-change approach that specifies pathways from inputs and behaviors to intermediate outcomes (soil health, yield stability) and final impacts (household food security, net GHG balance) clarifies what to measure, when to measure it and which counterfactuals or control sites are required for attribution. Indicator selection should combine core, comparable metrics for regional aggregation (e.g., hectares adopted, FCS, HDDS, tCO2e sequestered per ha) with context-specific indicators that capture local diets, cropping systems and tenure arrangements. Sampling design must balance statistical rigor and cost by combining sentinel sites and panel households for long-term causality with larger, lighter cross-sectional surveys for coverage and representativeness. Remote sensing and geospatial mapping provide scalable adoption and landscape change proxies (cover change, tree canopy, biomass indices) that must be calibrated with ground truthing to estimate area-based mitigation and to detect leakage or land-use displacement. Short-cycle monitoring (seasonal yield and food-security modules) paired with less frequent intensive measurements (soil cores, flux campaigns) captures both rapidly changing welfare outcomes and the slow dynamics of carbon, enabling timely program adaptation. Data systems should be interoperable, use open standards and include disaggregation by gender, age and wealth to detect equity impacts and differential adoption that affect both food security and permanence of mitigation benefits.

10.11.2 Low-cost verification approaches for results-based payments

Low-cost verification for results-based payments (RBP) can rely on conservative default emission and sequestration factors paired with periodic spot checks to reduce continuous monitoring costs while maintaining scientific credibility (Frontiers Review, 2024). Community-level aggregation of outcomes — paying cooperatives or landscape units for pooled measured gains rather than individual smallholders — lowers per-beneficiary transaction costs and encourages collective stewardship of practices such as agroforestry and soil-building (CLIC & ISF Advisors, 2025). Remote-sensing proxies (tree cover, NDVI trends, biomass indices) calibrated to sentinel ground plots provide scalable area-based verification for land-use and biomass changes, dramatically reducing the need for dense field sampling if calibration is robust and periodically refreshed (Frontiers Review, 2024). Tiered sampling strategies that combine broad, low-intensity surveys with targeted intensive measurements on statistically selected sentinel sites strike a cost-accuracy balance appropriate for program scaling (Springer Synthesis, 2021). Mobile data capture, e-registries and simple farmer reporting tools (photo-time stamps, GPS-tagged inputs redemption records) improve traceability and speed payments while creating auditable digital trails that reduce fraud and verification overhead (MDPI study, 2024). Use of conservative baselines and additionality tests that favor under-estimation rather than optimistic accounting protects environmental integrity and simplifies verification by lowering disputes over counterfactuals (SAIIA policy briefing, 2023).

Low-cost verification mixes automated and human checks by using algorithmic anomaly detection on remote and mobile data to flag suspicious claims for targeted field audits, concentrating costly verification where risk is highest (Frontiers digital review, 2025). Community verification and participatory monitoring engage producer organizations in data collection and preliminary validation, lowering costs and strengthening local ownership while requiring safeguards to avoid bias or elite capture (AGRA policy brief, 2023). Simplified protocols that measure easy, verifiable intermediate outcomes (tree survival rates, hectares under verified practice, voucher redemption receipts) enable quicker payment cycles and more transparent RBP administration (Performance Review, 2025). Blending RBP with up-front bridging finance and technical assistance mitigates the liquidity barrier for smallholders and reduces pressure on instant, high-frequency verification by allowing time-staggered payments tied to independently auditable milestones (Von, 2025). Digital registries and interoperable data standards facilitate pooled verification across buyers and programs, lowering duplicate audit costs and supporting scale while requiring investments in data governance and capacity building (CPI & FAO analysis, 2024). Piloting low-cost approaches with rigorous impact evaluation and periodic independent audits builds the evidence base needed to refine conservatism levels, sampling intensity and the mix of remote versus ground verification as programs scale (Frontiers Review, 2024).

10.11.3 Data systems and institutional roles

Robust data systems that integrate geospatial, agro-meteorological and household survey data are essential for tracking adoption of Climate-Smart Agriculture practices, enabling timely targeting of extension and finance to areas of greatest need. Interoperable e-registries and mobile data capture reduce duplication, speed verification for results-based payments and vouchers, and create auditable trails that improve transparency across ministries, donors and private partners. National and regional platforms that consolidate sentinel site measurements, remote-sensing proxies and farmer-reported outcomes support scalable estimation of both food-security impacts and landscape-level mitigation while lowering transaction costs for verification and reporting.

Clear institutional roles and mandates ensure that data systems translate into action: ministries of agriculture curate agronomic and extension data, environment agencies manage GHG accounting and land-use datasets, and national statistical offices provide sampling rigor and household panel design. Decentralized units and producer organizations must be resourced to collect ground truth and participate in participatory monitoring so that local realities inform national indicators, safeguard equity and sustain stewardship of agroecological investments.

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Governance arrangements that define data standards, open-access protocols and responsibilities for quality assurance accelerate multi-stakeholder coordination, unlock blended finance for infrastructure and enable evidence-based policy cycles that align CSA adoption with food-security and climate objectives.

10.12 Conclusion

CSA presents a flexible, evidence-informed pathway to strengthen food security and climate adaptation across Africa when interventions are bundled, tailored to local agro-ecologies, supported by aligned finance and extension systems, and linked to value chains and monitoring frameworks that ensure benefits are realized and verified (Lipper et al., 2017). Scaling CSA at national and regional levels requires integrated policy coordination, investment in human and institutional capacity, and pragmatic verification mechanisms to unlock blended finance and results-based incentives that make CSA economically attractive and equitable for smallholders (IPCC, 2023).

12.13 Policy recommendations

i) Prioritize integrated CSA packages that combine improved genetics, soil and water management, and post-harvest investments tailored to agro-ecological zones (Lipper et al., 2017).

ii) Develop blended finance facilities that align seasonal subsidies, concessional loans for infrastructure and private capital, with clear governance and aggregation mechanisms (Von, 2025).

iii) Strengthen decentralized extension and digital climate services to deliver locally adapted CSA bundles and support women and youth inclusion (EERCE, 2023).

iv) Invest in value-chain infrastructure and market systems (aggregation, storage, processing, digital market information) to translate production gains into stable incomes (FRR regional review, 2023).

v) Pilot low-cost verification approaches for results-based payments, including simplified soil sampling, remote sensing proxies and participatory reporting, to facilitate carbon and resilience finance for smallholders (Springer synthesis, 2021).

Table 1 — Priority CSA practices, food security benefits and key enablers

Practice category	Primary food security benefit	Key enabling conditions
Improved genetics (drought/early-maturing)	Reduced crop failure risk; stabilized yields	Functional seed systems; timely distribution (Lipper et al., 2017)
Conservation agriculture (residue retention; minimum till)	Improved soil moisture and yield stability	Farmer training; residue management incentives (Springer Synthesis, 2021)
Agroforestry and perennials	Diversified food/income; microclimate buffering	Seedling supply; tenure clarity; multi-year support (IPCC, 2023)
Water-harvesting and micro-irrigation	Extended cropping seasons; dry-season production	Infrastructure finance; maintenance governance (FRR Regional Review, 2023)
Post-harvest storage and processing	Reduced losses; increased marketable surplus	Aggregation infrastructure; investment in storage (Wider Program Reviews, 2022)

Table 2: Finance instruments and suitability for African smallholders

Instrument	Typical finance scale	Suitability notes
Targeted input subsidies / vouchers	Small-medium	Catalyze early adoption if time-bound and targeted (EERCE, 2023)
Microcredit / seasonal loans	Small	Effective if aligned to cropping calendar and group guarantees (FRR Regional Review, 2023)
Concessional infrastructure loans	Medium-large	Enables irrigation/storage; requires aggregation/cooperatives (Von, 2025)
Results-based payments / carbon credits	Medium	Potential recurring income; needs low-cost verification (Springer Synthesis, 2021)
Contract farming / off-taker credit	Variable	Works well near urban/peri-urban value chains with reliable buyers (Wider Program Reviews, 2022)

Table 3: Suggested M&E indicator matrix linking CSA inputs to food security outcomes

CSA input	Adoption indicator	Food security outcome indicator	Mitigation/resilience proxy
Drought-tolerant varieties	% households planting improved varieties	Yield per ha; months of adequate food	Crop failure incidence (years) (FRR Regional Review, 2023)
Conservation agriculture	Area under CA (ha)	Yield variability (CV); soil moisture index	Soil organic carbon sample plots (Springer Synthesis, 2021)

CSA input	Adoption indicator	Food security outcome indicator	Mitigation/resilience proxy
Water-harvesting / irrigation	# functional structures	Dry-season production; dietary diversity	Area irrigated; resilience score (Frontiers Review, 2024)
Post-harvest storage	# households using improved storage	Post-harvest loss percentage; marketable surplus	Reduced food loss metric (Wider Program Reviews, 2022)

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