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Climate-smart food systems: integrating adaptation and mitigation strategies for sustainable agriculture in South Africa

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Aim: Climate change presents significant challenges to food security, particularly in vulnerable regions like South Africa. This review examines climate-smart food systems (CSFS) as an integrated approach to enhancing agricultural resilience, mitigating greenhouse gas emissions, and ensuring sustainable food production.

Introduction: The agricultural sector must simultaneously adapt to shifting climatic conditions and reduce its environmental impact.

Methods: This study synthesizes current literature on adaptation strategies, such as drought-resistant crops, precision agriculture, and agroecological practices, alongside mitigation efforts, including carbon sequestration, emissions reductions in livestock, and circular food systems.

Results: Findings highlight key barriers to CSFS implementation, including financial constraints, inadequate technical support, and fragmented policies. Policy interventions, multi-stakeholder collaborations, and emerging technologies are crucial in overcoming these challenges.

Discussion: Strengthening governance, financial mechanisms, and knowledge-sharing platforms is essential for the widespread adoption of climate-smart strategies.

Conclusion: By aligning adaptation, mitigation, and policy efforts, South Africa can foster a resilient agricultural sector that supports food security and sustainable development in the face of climate change.

KEYWORDS

climate-smart food systems, climate-resilient agriculture, adaptation strategies, mitigation policies, sustainable food production, South Africa

1 Introduction

Climate-smart food systems (CSFS) refer to integrated approaches in agriculture and food production that enhance resilience to climate change while minimizing environmental impact and ensuring food security. The Food and Agriculture Organization (FAO) defines climate-smart agriculture (CSA) as a strategy that simultaneously pursues three key objectives: (1) sustainably increasing agricultural productivity, (2) adapting and building resilience to climate change, and (3) reducing greenhouse gas emissions where possible (FAO, 2013). Expanding this approach to food systems involves a holistic perspective that includes production, processing, distribution, and consumption, embedding sustainability at every stage. A climate-smart food system thus integrates climate adaptation and mitigation strategies across the entire food value chain. This includes precision agriculture, drought-resistant crops, improved soil management techniques, and circular food systems emphasizing waste reduction and resource efficiency (Smith et al., 2020). By fostering innovation and resilience, climate-smart food systems aim to transform agricultural economies, especially in climate-vulnerable regions like South Africa.

Climate change poses significant risks to agriculture, threatening global and local food security. Rising temperatures, erratic rainfall patterns, prolonged droughts, and extreme weather events have reduced crop yields, lowered livestock productivity, and increased pests and diseases (IPCC, 2021). These impacts are particularly severe in South Africa due to its semi-arid climate and reliance on rain-fed agriculture. The agricultural sector faces a dual challenge: ensuring food production for a growing population while coping with climatic stresses. Shifts in climatic conditions have already affected staple crop yields. For instance, maize production, a critical food source in the region, is highly sensitive to temperature variations, with a projected yield decline of up to 30% under high-emission scenarios (Roncoli et al., 2022). Additionally, increased heat stress and reduced pasture quality affect livestock production, leading to lower meat and dairy yields (Oduniyi et al., 2020). The cumulative effect of these stressors is food price volatility, threatening the affordability and accessibility of nutritious food for vulnerable populations.

Given the complexities of climate change, standalone adaptation or mitigation strategies are insufficient to ensure long-term agricultural sustainability. An integrated approach is required to align adaptation measures to enhance resilience while mitigating emissions from food production processes (Vermeulen et al., 2019). Adaptation strategies such as agroecology, conservation agriculture, and climate-smart irrigation techniques help farmers cope with changing climatic conditions. Simultaneously, mitigation efforts, including reducing methane emissions from livestock, carbon sequestration through regenerative agriculture, and enhancing circular economy principles, can lower the carbon footprint of food systems. Importantly, these strategies must be supported by strong policy frameworks, financial incentives, and knowledge-sharing platforms to ensure their successful implementation (FAO, 2020). South Africa's commitment to climate-smart strategies is reflected in national policies such as the Climate Change Bill and initiatives like the Agricultural Disaster Risk Management Framework (Department of Agriculture, Forestry and Fisheries, 2017). However, challenges remain, including limited access to financing, gaps in technical knowledge, and resistance to change at the farm level (Mthembu et al., 2021). Bridging these gaps requires multi-stakeholder collaboration, ensuring that research, policy, and practice align toward achieving a sustainable food future.

1.1 Conceptual framework

Climate-smart food systems (CSFS) require a holistic approach integrating adaptation strategies, mitigation efforts, and policy support to achieve long-term sustainability. These components do not function in isolation; instead, they reinforce one another, creating synergies that enhance agricultural resilience, reduce environmental impact, and ensure food security. Understanding these interconnections is essential in structuring the review to provide a comprehensive perspective on how climate-smart agriculture can be effectively implemented. As illustrated in Figure 1, climate-smart food systems require a combination of adaptation and mitigation strategies supported by strong policy frameworks. Adaptation strategies such as drought-resistant crops and precision agriculture (Figure 1, left) enhance resilience, while mitigation measures like carbon sequestration (Figure 1, center) contribute to emission reductions. Effective governance (Figure 1, right) ensures the integration of these strategies into national and global agricultural policies. This interconnectedness is crucial for structuring the review because it ensures a comprehensive, systemic approach rather than a fragmented discussion of isolated strategies.

1.2 Schematic hypothesis illustrating the interconnectedness of adaptation, mitigation, and policy measures within climate-smart food systems (CSFS)

The central hypothesis demonstrates that Climate-Smart Food Systems (CSFS) are underpinned by the integrated implementation of adaptation strategies, mitigation measures, and robust policy frameworks, all of which are interdependent and mutually reinforcing. Adaptation strategies such as drought-resistant crops, precision agriculture, and agroecological practices build resilience by helping agriculture withstand climate stresses. Mitigation measures, including carbon sequestration through regenerative agriculture, improved livestock management, and circular food systems, effectively reduce greenhouse gas emissions associated with agricultural activities. Both adaptation and mitigation measures are operationalized and enhanced through supportive policy environments, notably the Climate Change Bill and the Agricultural Disaster Risk Management Framework, which establish conducive conditions for climate-smart practices. The interconnectedness of these strategies yields synergistic outcomes, notably increased resilience, lower environmental impacts, and improved food security. Crucially, the effectiveness and sustainability of these integrated approaches depend on institutional support characterized by strong governance, robust financial mechanisms, and collaborative knowledge-sharing platforms. Collectively, these strategies form a coherent framework that ensures sustainable, resilient agricultural systems capable of addressing climate change and securing long-term agricultural productivity in South Africa (see Figure 2).

1.3 Methodological note on literature review

This narrative review synthesizes literature from peer-reviewed journals, institutional reports, and policy documents relevant to climate-smart food systems (CSFS) in South Africa. The search focused on publications between 2010 and 2024 to capture both foundational and emerging trends. Databases consulted included Scopus, Web of Science, and Google Scholar, using keywords such as "climate-smart agriculture," "sustainable food systems," "adaptation strategies," "mitigation," and "South Africa agriculture." Priority was given to studies presenting empirical evidence or comprehensive frameworks related to climate-resilient practices in agriculture. Inclusion criteria comprised relevance to South African or Sub-Saharan contexts, alignment with adaptation

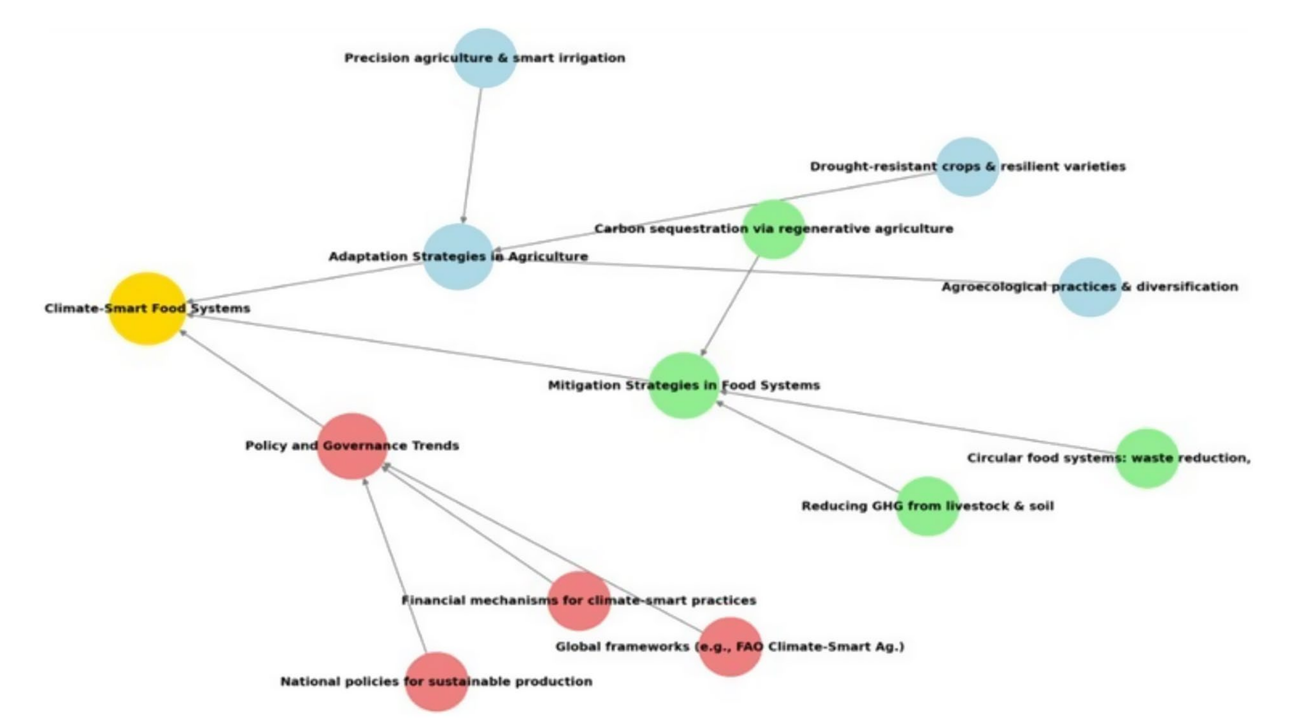

FIGURE 1
Conceptual framework for climate-smart food systems.

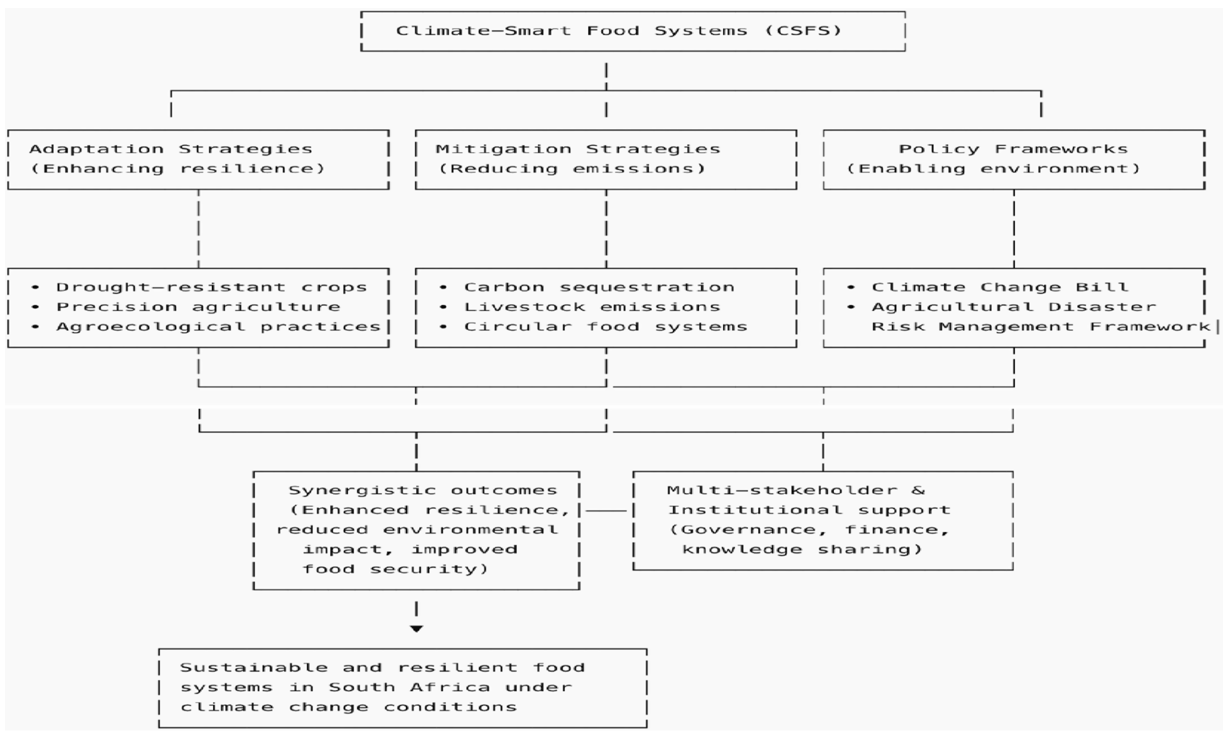

FIGURE 2
Schematic hypothesis illustrating the interconnectedness of adaptation, mitigation, and policy measures in climate-smart food systems.

and mitigation objectives, and policy applicability. Sources that were non-peer-reviewed, purely opinion-based, or outside the thematic focus of agricultural sustainability or climate policy were excluded to maintain thematic rigor and consistency. Although not a systematic review, this methodological approach aimed to ensure thematic breadth, contextual relevance, and evidence-based insights.

2 Adaptation strategies in agriculture: a systemic approach to climate resilience

Agriculture is one of the sectors most vulnerable to the impacts of climate change, making adaptation strategies crucial for ensuring food security and sustainable livelihoods. As illustrated in Figure 1, adaptation strategies in agriculture must be integrated with mitigation efforts and supported by robust policy frameworks to be truly effective. The three primary adaptation strategies, drought-resistant crops, precision agriculture, and agroecological practices, enhance food systems' resilience and contribute to environmental sustainability. A synthesis of relevant literature provides critical insights into how these strategies function and their interconnected role in building climate-resilient agricultural systems.

2.1 Drought-resistant crops and climate-resilient varieties

The adoption of drought-resistant crops is a fundamental adaptation strategy that allows farmers to maintain productivity even under extreme weather conditions. Climate change has intensified water scarcity in many agricultural regions, necessitating the development and use of crop varieties that can withstand prolonged drought and erratic rainfall patterns. Breeding programs have increasingly focused on improving genetic resistance to drought stress, particularly utilizing wild crop relatives and underutilized species that naturally possess greater resilience (Rosero et al., 2020). Similarly, the role of genetic advancements in improving water-use efficiency (WUE) in crops helps to buffer the worst effects of climate change on agricultural productivity (Hatfield and Dold, 2019).

In Sub-Saharan Africa, significant progress has been made in deploying climate-resilient maize varieties. Research by Cairns and Prasanna (2018) indicates that over the past 15 years, more than 300 climate-resilient maize varieties featuring drought, heat tolerance, and disease resistance have been introduced across millions of hectares. These efforts have strengthened the resilience of smallholder farmers most vulnerable to climate shocks. However, in parts of South Africa, such as Limpopo Province, the use of drought-resistant varieties is beneficial. It does not automatically translate into higher profitability unless complemented by appropriate market access and financial incentives (Joseph et al., 2020). Cultivating drought-resistant crops contributes to adaptation and mitigation by reducing reliance on irrigation, thereby conserving water resources and minimizing energy-intensive irrigation processes. However, their success depends on policy support, research investment, and farmer education, as highlighted in Figure 1. Adopting rates may remain low without such enabling mechanisms, particularly among resource-constrained smallholder farmers.

2.2 Precision agriculture and smart irrigation technologies

Precision agriculture and smart irrigation technologies have emerged as key strategies to address the agricultural challenges faced by sub-Saharan Africa, including South Africa. The incorporation of technological innovations such as soil moisture sensors, satellite imaging, and Geographic Information Systems (GIS) has shown potential in enhancing the efficiency of resource utilization and improving crop yields (Onyango et al., 2021). Despite these advantages, adoption by smallholder farmers remains relatively low, primarily due to constraints such as limited awareness, inadequate infrastructure, and the high initial investment required (Dyantyi and Njenga, 2022).

Research suggests that combining smart irrigation technologies with institutional frameworks like Agricultural Innovation Platforms can significantly boost agricultural productivity and profitability (Bjornlund et al., 2020). However, successful adoption and scaling of these technologies require comprehensive extension services, tailored training programs, and sustained awareness campaigns targeted at smallholder farmers (Serote et al., 2021). Leveraging existing mobile phone infrastructure and developing innovative financing mechanisms could play pivotal roles in overcoming some of these adoption challenges (Wanyama et al., 2024). The active involvement of governmental institutions and collaborative partnerships among stakeholders is essential for the effective implementation and sustained use of these technological innovations (Monteiro et al., 2010).

Despite their clear benefits, precision agriculture technologies face significant adoption barriers across developing regions. These challenges include high initial setup costs, insufficient technical knowledge among smallholder farmers, and inadequate infrastructure development. Policies and strategies aimed at providing financial incentives, capacity-building initiatives, and substantial infrastructure improvements are necessary to facilitate broader adoption. Without targeted and effective interventions, precision agriculture may continue to remain inaccessible to the majority of smallholder farmers.

Smart irrigation technologies, specifically, hold considerable promise in improving water use efficiency and agricultural productivity. Empirical studies highlight the potential of these technologies to reduce water consumption by approximately 30% while simultaneously increasing crop yields by up to 125% (Durga et al., 2024). Nonetheless, several persistent challenges impede their widespread implementation. In South Africa, critical barriers include inadequate communication channels, financial constraints, unstable land tenure systems, and insufficient farmer training programs (Serote et al., 2021).

To effectively address these barriers, it is crucial to capitalize on the existing mobile phone networks to facilitate data collection and promote innovative financing models (Wanyama et al., 2024). Successful implementation and diffusion of smart irrigation technologies will necessitate coordinated efforts among governments, academic institutions, industry stakeholders, and international organizations. Additionally, supportive policies and targeted investments in technology diffusion and capacity building will be fundamental in overcoming existing hurdles (Wanyama et al., 2024; Durga et al., 2024).

2.3 Agroecological practices and crop diversification

Agroecological practices, particularly crop diversification, are increasingly recognized for their potential to enhance agricultural sustainability and resilience in South Africa. These nature-based methods facilitate climate adaptation by improving biodiversity and soil health and reducing reliance on synthetic inputs. Among the most effective agroecological strategies, crop diversification mitigates risks associated with monoculture farming, thereby strengthening agricultural resilience (Kabiti, 2021). Such practices have proven particularly beneficial for smallholder farmers by enhancing crop yields, improving soil fertility, and optimizing water use efficiency (Zenda and Rudolph, 2024).

Adoption of agroecological practices among farmers is influenced significantly by rainfall patterns, market accessibility, and household characteristics (Manyanga et al., 2023). Crop diversification strategies, including polycultures, crop rotations, and agroforestry, support greater biodiversity and deliver essential ecosystem services, notably natural pest control (Altieri, 2019). Specifically within South Africa, increasing crop diversity has been positively correlated with improved crop productivity and survival rates (Bellora et al., 2017). Despite these benefits, barriers such as technological limitations and risk management challenges often impede adoption, especially among resource-poor farmers (Hitayezu et al., 2016). As illustrated in Figure 1, robust governance mechanisms promoting agroecological practices through education, incentives, and integrated land-use planning are essential. Supporting these governance frameworks is vital for achieving a sustainable and climate-resilient agricultural sector.

In South Africa, several region-specific challenges complicate the implementation of agroecological practices and crop diversification strategies. In the Eastern Cape, farmers adapt their crop combinations to distinct agro-ecological zones to manage climate-related risks; however, further research is required to fully understand potential yield advantages and limitations (Kabiti, 2021). In KwaZulu-Natal's Midlands, limited land and labor availability are significant technological constraints that disproportionately affect poorer farmers (Hitayezu et al., 2016). Moreover, the effectiveness of conservation agriculture (CA) research in South Africa is hindered by poor documentation, short trial durations, and inadequate data collection, alongside a notable mismatch between research priorities and major crop-producing regions (Swanepoel et al., 2018). Nonetheless, smallholder farmers have successfully adopted diverse agroecological practices, including indigenous crop cultivation, conservation agriculture, intercropping, and improved water management techniques, with measurable benefits for crop resilience and soil fertility (Zenda and Rudolph, 2024). These insights underscore the necessity for tailored, region-specific strategies and improved research methodologies to enhance the sustainability of agricultural systems in South Africa.

2.4 The role of policy in strengthening adaptation strategies

As illustrated in Figure 1, adaptation strategies are most effective when aligned with policy frameworks that promote climate-smart agriculture. Climate change adaptation policies in South Africa have evolved significantly over the past two decades, with a proliferation of initiatives across national, provincial, and local levels (Khavhagali et al., 2023). The government has implemented stringent measures to reduce vulnerability and enhance adaptive capacity (Odeku and Meyer, 2010). However, there is a lack of coherence in health-related adaptation policies, particularly at the provincial level (Quintana et al., 2024). Co-production of adaptation plans with local stakeholders has shown promise in aligning climate strategies with developmental priorities (Ziervogel et al., 2016). Adaptation strategies are socially differentiated, necessitating policies that support heterogeneous responses to various stresses (Ziervogel et al., 2006). Key determinants of farm-level adaptation include access to credit, extension services, and climate change awareness (Nhemachena et al., 2014). Despite progress, challenges remain in mainstreaming adaptation into everyday practice and long-term planning across all government spheres (Ziervogel et al., 2014).

3 Mitigation strategies in food systems: addressing emissions, carbon sequestration, and circularity

Mitigation strategies in food systems are critical in reducing agriculture's environmental impact while ensuring sustainable food production. Figure 1 illustrates that these strategies are interconnected with adaptation measures and policy frameworks to create a holistic approach to climate-smart agriculture. The three key mitigation strategies, reducing greenhouse gas emissions from livestock and soil management, carbon sequestration through regenerative agriculture, and circular food systems that emphasize waste reduction, bioenergy, and nutrient recycling, are central to achieving climate-resilient and sustainable agricultural systems.

3.1 Reducing greenhouse gas emissions from livestock and soil management

Agricultural activities contribute significantly to global greenhouse gas emissions, particularly through livestock production and soil management (Gerber et al., 2013). Enteric fermentation from ruminants is the largest single emission source, followed by manure management and soil-related emissions (Tongwane et al., 2021; Eckard et al., 2010). Mitigation strategies include improving feed efficiency, breeding low-emitting animals, and using feed additives to reduce enteric methane (Gerber et al., 2013). For manure management, reducing storage time, anaerobic digestion, and proper land application techniques can decrease emissions (Montes et al., 2013). Soil management practices such as improving nitrogen use efficiency, carbon sequestration, and adopting conservation tillage can mitigate N_2O and CO_2 emissions (Smith et al., 2008). The global technical mitigation potential from agriculture by 2030 is estimated at 5,500–6,000 Mt. CO_2-eq/year, with additional potential from biomass energy production (Smith et al., 2008). Table 1 presents key studies that emphasize the role of livestock and soil management practices in mitigating greenhouse gas emissions in food systems. Each study highlights specific practices that contribute to reducing emissions, enhancing carbon sequestration, and promoting sustainable agricultural methods. The key impact column summarizes the primary objective or outcome of each practice concerning climate change mitigation. Mitigation strategies for livestock emissions, such as precision feeding, improved manure management, and silvopastoral systems, help reduce CH_4 and N_2O emissions while improving farm efficiency and productivity. However, as Figure 1 highlights, these

TABLE 1 Mitigation strategies for livestock and soil management.

Study	Practices	Impact
Prag and Henriksen (2020)	Transitioning to plant-based diets, improving livestock feeding.	Reducing methane emissions.
Villalatz and Nicholas (2023).	Regenerative grazing, improved pasture management.	Sequestering CO2, converting degraded lands into carbon sinks.
Thapa et al. (2016)	Enhanced nitrogen use efficiency, low-carbon fertilizers, energy-efficient farming.	Lowering emissions from fertilizers and soil management.
Mishra et al. (2024)	Conservation agriculture, agroforestry, improved nutrient management.	Reducing emissions and increasing carbon sequestration.

strategies must be supported by policy incentives such as carbon credit schemes and regulatory frameworks to be widely adopted.

3.2 Carbon sequestration through regenerative agriculture

Regenerative agriculture practices in South Africa show promising potential for carbon sequestration and soil restoration. Studies demonstrate that converting cropland to permanent pasture can increase soil organic carbon (SOC) stocks by 29.6–93.9% over 10–95 years (Preger et al., 2010). Conservation agriculture principles, including no-till and crop rotation with residue retention, significantly enhance SOC and reduce CO2 emissions (Muzangwa et al., 2021). Thicket restoration using *Portulacaria afra* can sequester 0.12–0.42 kg C m − 2 yr. − 1, while fallowing renosterveld vegetation can sequester 13 Mg C ha − 1 (Mills et al., 2013). Regenerative agriculture addresses climate change mitigation and offers co-benefits such as improved biodiversity, nutrient cycling, and farm profitability (Wiltshire and Beckage, 2023). However, further research is needed to address limitations and optimize the implementation of these practices across different environments (Wiltshire and Beckage, 2023). Table 2 summarizes key studies that examine regenerative agricultural practices for carbon sequestration. Each study identifies specific practices that enhance soil carbon storage and outlines the key focus of these strategies in climate-smart agriculture. These studies highlight regenerative agriculture as a critical tool for climate mitigation. However, the success of carbon sequestration depends on incentives for adoption, such as carbon pricing mechanisms, research funding, and regulatory support, as emphasized in Figure 1.

3.3 Circular food systems: waste reduction, bioenergy, and nutrient recycling

Circular food systems in Africa offer promising solutions for waste reduction, bioenergy production, and nutrient recycling. These systems minimize resource use, decrease chemical fertilizer dependency, and utilize bio-based materials (Andeweg et al., 2023). Africa's biodiversity and natural resources provide potential for

TABLE 2 Regenerative agriculture and carbon sequestration strategies.

References	Practices	Impact
Govaerts et al. (2009)	No-till farming, cover cropping, crop rotations.	Improving soil organic carbon (SOC) content and increasing carbon sequestration rates.
Ma et al. (2025)	Agroforestry with deep-rooted trees and diversified cropping.	Enhancing carbon storage in soil and biomass.
Powlson et al. (2011)	Soil organic matter (SOM) accumulation based on climate, soil texture, and land management.	Developing site-specific carbon sequestration strategies.
Tuomisto et al. (2015)	Farm-level carbon footprint calculator for assessing and implementing carbon sequestration.	Providing tools for farmers to measure and implement carbon sequestration.
Baker et al. (2007)	Reducing tillage operations and maintaining soil carbon levels.	Aligning soil carbon conservation with sustainable development and climate resilience.

bioenergy development, though policy, infrastructure, and financing challenges persist (Leela et al., 2024). Existing circular bioeconomy practices, such as composting, are present in countries like Rwanda, DRC, and Ethiopia, with generally positive public attitudes towards circular bioeconomy foods (Sekabira et al., 2022). South Africa emphasizes composting and anaerobic digestion for organic waste diversion, aligning with national priorities (Chitaka and Schenck, 2023). Implementing circularity principles in food systems can significantly reduce land use and greenhouse gas emissions. Traditional African agricultural practices already incorporate many circular principles, offering potential lessons for global sustainable food production (Tindwa et al., 2024). Table 3 summarizes key insights from the literature on circular food systems, focusing on strategies that reduce waste, promote bioenergy, and enhance sustainability. By integrating waste reduction, bioenergy, and nutrient cycling, circular food systems help close the loop on resource flows, making agriculture less wasteful and more climate-friendly.

4 Interconnectedness of policies with climate-smart agriculture

Climate-smart agriculture (CSA) is increasingly recognized as a crucial approach for addressing climate change impacts on food security in Africa, particularly in Southern Africa (Branca and Perelli, 2020). However, the adoption of CSA practices among smallholder farmers remains limited due to various challenges, including a lack of awareness, poor access to resources, and inadequate policy implementation (Kubanza and Oladele, 2024; Khwidzhili and Worth, 2017). To enhance CSA adoption, there is a need for improved policy coherence, stakeholder engagement, and institutional coordination at

TABLE 3 Circular food systems practices.

References	Practices	Impact
Garibaldi et al. (2016)	Linking marine and terrestrial food production into a circular bioeconomy.	Enhancing sustainability in food production by integrating land and ocean resources.
Koppelmäki et al. (2021)	Quantifying biomass, nutrient, and energy flows to enable circular food system transitions.	Facilitating circular economy principles through better resource flow analysis.
Girotto et al. (2015)	Utilizing food waste for waste-to-energy technologies.	Reducing emissions and creating economic value through waste-to-energy technologies.
Zhou et al. (2022)	Community-based food waste recycling through composting, biogas production, and resource recovery.	Promoting community-driven sustainability and reducing food waste.
Sharma et al. (2021)	Bioconversion techniques such as anaerobic fermentation and oleaginous metabolism to turn food waste into bio-products.	Transforming food waste into valuable bio-products for sustainability.
Bayu (2020) and Hou et al. (2015)	Integrated manure management to process livestock waste into biofertilizers.	Reducing methane emissions and improving soil health through livestock waste management.

multiple levels (Chevallier, 2023; Hlahla et al., 2023). Integrating nutrition into CSA policies is crucial for sustainable food security (Beattie and Sallu, 2021). Overcoming these challenges requires a multistakeholder, bottom-up approach, and top-down frameworks prioritizing agriculture in climate debates (Knaepen et al., 2015). Additionally, creating an enabling environment for private sector involvement, particularly SMEs, can promote sustainable CSA practices and local market adaptation (Knaepen et al., 2015; Branca and Perelli, 2020).

South Africa's sustainable agriculture policies (Table 4) are deeply interconnected with the principles of climate-smart agriculture (CSA), which integrates adaptation, mitigation, and governance to enhance food security while addressing climate change challenges. These policies align with the Conceptual Framework for Climate-Smart Food Systems (Figure 1) by establishing regulatory and institutional frameworks that promote climate resilience, emissions reduction, and sustainable resource use. The interconnectedness of these policies ensures that agricultural sustainability is not pursued in isolation but rather as part of a holistic approach that incorporates environmental, economic, and social dimensions.

One of the key aspects of climate adaptation in agriculture is ensuring that farmers can adjust to climate variability, extreme weather events, and changing environmental conditions. The National Climate Change Adaptation Strategy (NCCAS) provides a comprehensive framework for building resilience in agriculture, with a focus on improving water management, promoting drought-resistant crops, and strengthening early warning systems (Department of Environment, Forestry and Fisheries, 2020). In addition, the National Policy on Sustainable Agriculture promotes agroecological approaches that emphasize soil conservation, biodiversity enhancement, and sustainable farming techniques, which are essential for long-term adaptation to climate change (Altieri, 2019).

At the same time, mitigation policies are crucial for reducing greenhouse gas (GHG) emissions from agriculture. The National Policy on Climate Change outlines specific strategies for lowering emissions in the agricultural sector, particularly through carbon sequestration, improved soil management, and reduced methane emissions from livestock (Cassandro, 2020). Policies such as the National Policy on Sustainable Livestock Production and the National Policy on Sustainable Land Use complement mitigation efforts by encouraging the adoption of low-emission farming practices, conservation tillage, and responsible land-use management (Govaerts et al., 2009). These measures align with the Paris Agreement and South Africa's Nationally Determined Contributions (NDCs), which emphasize the importance of integrating mitigation strategies within agriculture to meet emission reduction targets (South African Department of Agriculture, Land Reform and Rural Development, 2021).

Furthermore, the governance aspect of climate-smart agriculture is supported by policies that facilitate institutional collaboration, financial support, and knowledge-sharing among stakeholders. The National Agricultural Research and Development Strategy plays a crucial role in driving innovation and technological advancements that enhance precision agriculture, climate-resilient crop breeding, and smart irrigation technologies (Roncoli et al., 2022). Additionally, policies such as the National Strategy for Sustainable Development and the National Rural Development Framework provide the necessary institutional and financial mechanisms to ensure that climate-smart practices are accessible to smallholder farmers and rural communities (Department of Agriculture, Forestry and Fisheries, 2017).

The circular food system approach, which promotes waste reduction, bioenergy production, and nutrient recycling, is also embedded in South Africa's sustainable agriculture policies. The National Policy on Agroecology encourages closed-loop farming systems that emphasize organic waste management and sustainable nutrient cycles, reducing agriculture's overall carbon footprint (Kubanza and Oladele, 2024). Similarly, the National Policy on Agricultural Cooperatives supports community-driven approaches to sustainable food production, fostering collaborative resource management and equitable access to agricultural inputs (Koppelmäki et al., 2021).

The interconnectedness of these policies ensures that adaptation and mitigation efforts reinforce each other rather than functioning as separate initiatives. By integrating climate resilience, emissions reduction, and sustainable governance, South Africa's agricultural policies create a coherent framework that supports long-term food security and environmental sustainability. However, successful implementation remains a challenge, requiring stronger enforcement mechanisms, greater financial investment, and enhanced stakeholder coordination (Mthembu et al., 2021). Bridging these gaps will be essential for ensuring that climate-smart agriculture becomes a cornerstone of South Africa's food system, ultimately enhancing resilience, productivity, and sustainability in the face of climate change.

TABLE 4 Key national policies for sustainable agriculture in South Africa.

Policy/Framework	Key focus	Source
National Climate Change Strategy	Integrates climate adaptation and mitigation strategies in agriculture to enhance resilience and reduce greenhouse gas emissions.	Department of Environmental Affairs (2011a)
Sustainable Agricultural Practices Framework	Encourages sustainable farming methods to improve productivity, ecosystem health, and climate resilience.	Department of Agriculture, Forestry and Fisheries (2017)
National Climate Change Adaptation Strategy	Provides a framework for addressing climate variability, including water management, drought-resistant crops, and early warning systems.	Department of Environment, Forestry and Fisheries (2020)
National Agricultural Research and Development Strategy	Supports research and innovation in sustainable farming technologies, precision agriculture, and climate-resilient crop breeding.	Department of Science and Innovation (2018)
National Policy on Sustainable Agriculture	Establishes principles for eco-friendly, resource-efficient, and climate-resilient farming systems.	Department of Agriculture, Forestry and Fisheries (2017)
National Strategy for the Conservation of Agricultural Biodiversity	Protects genetic resources and promotes biodiversity to strengthen food production and ecosystem services.	Department of Environmental Affairs (2013)
National Strategy for Sustainable Development	Links sustainable agriculture with national development goals, ensuring policy coherence and environmental sustainability.	Department of Environmental Affairs (2011b)
National Policy on Climate Change	Guides to emissions reduction, climate-smart agricultural practices, and sustainable land-use management.	Department of Environmental Affairs (2018)
National Policy on Sustainable Land Use	Focuses on preventing land degradation, promoting conservation agriculture, and ensuring long-term soil health.	Department of Rural Development and Land Reform (2015)
National Rural Development Framework	Enhances rural resilience, supports smallholder farmers, and improves access to sustainable farming inputs and markets.	Department of Rural Development and Land Reform (2013)
National Policy on Sustainable Livestock Production	Reduces the environmental footprint of livestock farming, emphasizing low-emission production and sustainable feeding practices.	Department of Agriculture, Land Reform and Rural Development (2019)
National Policy on Sustainable Fisheries	Ensures responsible fisheries management, marine biodiversity conservation, and climate-adaptive fishing practices.	Department of Environment, Forestry and Fisheries (2014)
National Policy on Agricultural Cooperatives	Strengthens cooperative models for sustainable agriculture, providing financial and technical support to farmer organizations.	Department of Agriculture, Forestry and Fisheries (2016)
National Policy on Food and Nutrition Security	Addresses food security and malnutrition through climate-resilient food systems and nutrition-sensitive agriculture.	Department of Agriculture, Land Reform and Rural Development (2018)
National Policy on Agroecology	Promotes agroecological approaches such as organic farming, permaculture, and regenerative agriculture to enhance sustainability.	Department of Agriculture, Land Reform and Rural Development (2021)

4.1 Challenges and gaps in policy implementation

The implementation of climate-smart agriculture (CSA) policies in South Africa is frequently constrained by entrenched power asymmetries. Dominant political and economic interests most notably those of coal-related industries have effectively delayed the enactment of critical climate policy instruments, such as carbon pricing mechanisms, thereby undermining CSA advancement (Rennkamp, 2019). Concurrently, the limited awareness and comprehension of CSA concepts among key stakeholders further inhibit effective policy dissemination and uptake (Kubanza and Oladele, 2024). Smallholder farmers, who are particularly susceptible to climate-induced shocks, encounter multiple structural barriers including insecure land tenure, pervasive poverty, insufficient extension and advisory services, and restricted access to agricultural inputs and financial credit (Olabanji and Chitakira, 2025; Mutengwa et al., 2023).

Institutional impediments characterized by fragmented support systems and inadequate inter-agency coordination further complicate CSA policy implementation across various administrative scales. Local municipalities, in particular, grapple with overlapping socio-economic, ecological, and cognitive challenges, often resulting in reactive rather than anticipatory adaptation responses (Olabanji and Chitakira, 2025). Addressing these complexities necessitates an integrated and multidimensional policy framework, one that fosters institutional synergies, ensures coherence across policy domains, enhances market accessibility, and facilitates the empowerment of grassroots actors, particularly women (Olabanji and Chitakira, 2025; Mutengwa et al., 2023).

Critical enablers of CSA adoption include the establishment of secure land rights, improved understanding of climate change dynamics, and increased availability of context-appropriate agricultural technologies (Antwi-Agyei et al., 2021). Nevertheless, the persistent socio-economic marginalization of smallholder farmers significantly constrains the intensity and scale of CSA adoption. This underscores the imperative for targeted incentive structures and governance systems that are inclusive and participatory (Branca and Perelli, 2020). Strengthening farmer agency through participatory governance mechanisms particularly those that amplify the voices and decision-making power of women can contribute to rectifying prevailing power disparities (Kubanza and Oladele, 2024).

Furthermore, the successful implementation of CSA initiatives is closely tied to the institutional readiness and leadership capacity of government entities. In contexts where organizational culture is conducive and collaborative partnerships are actively promoted, CSA projects are more likely to achieve their objectives and yield co-benefits, including enhanced food security and ecological sustainability (Olabanji and Chitakira, 2025). In light of the escalating impacts of climate change on agricultural systems, CSA constitutes a critical policy instrument for fostering resilience and sustainability in South Africa and the broader sub-Saharan region. However, overcoming the existing policy implementation deficits necessitates strategic investment in institutional capacity building, enhanced policy coherence, and the development of inclusive frameworks that prioritize the needs and voices of historically marginalized agricultural communities.

5 Discussion

5.1 Barriers to climate-smart agriculture: challenges and constraints in adoption

Climate-smart agriculture (CSA) offers promising solutions for increasing agricultural productivity while addressing climate change challenges, but its adoption faces significant barriers, particularly among smallholder farmers in developing regions. Key obstacles include financial constraints, lack of knowledge and awareness, weak institutional frameworks, and socio-economic inequalities (Wakweya, 2023). Limited access to credit, insufficient policy support, and land tenure issues further hinder CSA implementation (Zerssa et al., 2021; Finizola e Silva et al., 2024). However, CSA practices like agroforestry, conservation agriculture, and crop diversification have shown potential to improve yields, increase resilience, and enhance food security (Finizola e Silva et al., 2024). Factors positively influencing CSA adoption include education, farming experience, and access to extension services (Finizola e Silva et al., 2024). To overcome these barriers, location-specific solutions, inclusive national planning, international financing, and cooperation among stakeholders are essential (Zerssa et al., 2021).

Climate-smart agriculture (CSA) offers promising solutions to address climate change challenges in agriculture, particularly for smallholder farmers (Vasavi et al., 2025). However, its adoption faces significant barriers, including financial constraints, lack of knowledge, and institutional limitations (Wakweya, 2023; Olabanji and Chitakira, 2025). Key CSA practices like agroforestry, conservation agriculture, and improved water management can enhance productivity and resilience (McCarthy et al., 2011; Vasavi et al., 2025). To overcome adoption barriers, studies emphasize the importance of secure land rights, effective extension services, access to credit, and tailored policy frameworks (Olabanji and Chitakira, 2025; Wakweya, 2023). Digital tools and gender-sensitive interventions can facilitate knowledge dissemination and inclusivity (Vasavi et al., 2025). Scaling CSA requires a holistic approach involving institutional coordination, policy coherence, and market integration (Olabanji and Chitakira, 2025). Addressing these multidimensional challenges is crucial for promoting sustainable agricultural systems and ensuring food security in the face of climate change (Vasavi et al., 2025; Wakweya, 2023).

Another major challenge to CSA adoption is the lack of technical knowledge and training among smallholder farmers. Many farmers are unaware of the benefits and practical applications of CSA technologies, leading to hesitation and resistance to change. Additionally, there is a disconnect between scientific research and farmer knowledge systems, with indigenous and local knowledge often overlooked in formal CSA frameworks (Ogunyiola et al., 2022). The absence of adequate agricultural extension services further limits CSA uptake. Many rural farmers lack access to expert guidance, training programs, and digital advisory platforms that could help them implement climate-smart practices effectively (Autio et al., 2021). Moreover, digital illiteracy and infrastructural deficiencies in many developing countries hinder farmers' ability to leverage emerging digital tools for CSA, such as remote sensing, precision farming, and climate forecasting applications (Vasavi et al., 2025; Zerssa et al., 2021). To bridge this gap, translational research and participatory extension programs should be prioritized to ensure that CSA knowledge is accessible, context-specific, and farmer-friendly.

Weak policy frameworks and institutional inefficiencies pose significant obstacles to CSA adoption. Many national agricultural policies fail to integrate climate adaptation and mitigation strategies, resulting in fragmented governance and ineffective implementation of CSA programs (Ma and Rahut, 2024). Additionally, land tenure insecurity discourages farmers from investing in long-term climate-smart solutions, as they lack legal assurance over land ownership and resource access (Regmi and Paudel, 2024). Strengthening land tenure policies, facilitating credit access, and ensuring inclusive governance mechanisms are essential to promoting widespread CSA adoption (Ma and Rahut, 2024).

Beyond financial and policy-related constraints, CSA implementation is also hindered by social and cultural barriers. Many farmers, especially in marginalized communities, face gender disparities, social isolation, and limited representation in decision-making processes (Tsige et al., 2020). Women, who constitute a large percentage of agricultural labour in many developing regions, often lack access to CSA training, credit facilities, and land rights, further limiting their participation in sustainable agriculture (Vasavi et al., 2025). Additionally, top-down agricultural policies and weak community engagement reduce local ownership of CSA initiatives, leading to low participation and poor sustainability of projects (Huyer et al., 2024). To overcome these socio-economic barriers, CSA interventions should adopt inclusive, participatory approaches that empower smallholder farmers and marginalized groups while fostering stronger community-based agricultural networks (Huyer et al., 2024).

5.2 Emerging innovations for sustainable agriculture

Agriculture faces the dual challenge of increasing productivity to meet the demands of a growing global population while ensuring environmental sustainability. To address this, innovative approaches such as microbial technologies, bio-based solutions, precision farming, integrated plant management, conservation agriculture, circular food systems, and reduced chemical usage are being explored and implemented.

5.2.1 Microbial technologies

Microbial technologies, particularly those involving plant growth-promoting bacteria (PGPB), such as biofertilizers and microbial inoculants, have shown promise in enhancing nutrient uptake, stimulating plant growth, and improving resistance to pathogens. These microbes contribute to sustainable agriculture by reducing the need for chemical fertilizers and pesticides, thus minimizing environmental impact (Kumari et al., 2023). Recent literature, including research by Amari (2023), shows significant yield improvements using microbial biofertilizers under drought conditions in South Africa.

5.2.2 Bio-based solutions

The advancement of bio-based agricultural inputs, including bio stimulants and biofertilizers, presents a sustainable and environmentally friendly alternative to conventional agrochemicals. Derived from natural and renewable sources, these products contribute to improved soil fertility and enhanced crop performance, while also promoting the transition toward a circular agricultural economy (Priya et al., 2023). Among these innovations, biochar a carbon-rich material produced through the pyrolysis of organic biomass has emerged as a promising solution for sustainable agricultural practices and environmental restoration. Biochar has demonstrated considerable potential in improving key soil properties such as water retention, nutrient availability, and microbial activity, thereby fostering increased crop resilience (Khan et al., 2024). In addition, biochar functions as a slow-release fertilizer, enhancing soil nutrient retention and availability over time.

The efficacy of biochar in immobilizing agricultural pollutants, including pesticides and heavy metals, is influenced by a range of factors such as the pyrolysis temperature, the type of feedstock used, and the mode of application (Ogura et al., 2021). Recent developments in the field have enabled the engineering of modified biochar's with enhanced surface area and adsorption capacities, significantly improving the removal of pollutants like antibiotics, pesticides, and polycyclic aromatic hydrocarbons from soils (Qiu et al., 2022). Empirical evidence supports biochar's agronomic benefits. For instance, a study conducted by Mokgolo et al. (2024) in Limpopo province, South Africa, found that biochar application significantly improved soil moisture retention and fertility, thereby mitigating drought stress in maize cultivation. Additionally, biochar contributes to climate change mitigation through carbon sequestration and reduction of greenhouse gas emissions (Gwenzi et al., 2015; Brassard et al., 2016).

However, the performance of biochar is highly context-specific. Its effectiveness is shaped by production technology, biomass type, climatic conditions, soil characteristics, and crop species (Wang et al., 2020). In sub-Saharan Africa, biochar holds significant potential to address widespread soil degradation and energy access challenges. Yet, barriers such as limited financial resources, negative stakeholder perceptions, and inconsistent access to raw materials inhibit its broader adoption (Gwenzi et al., 2015).

Moreover, while biochar generally enhances soil quality, it can have unintended effects, particularly in temperate environments where excessive liming and nutrient immobilization may suppress crop yields (Kavitha et al., 2018; Kuppusamy et al., 2016). To optimise its agricultural benefits, biochar should be applied in combination with other organic or inorganic fertilizers or enriched to form composite biochar-based fertilizers (Kavitha et al., 2018). Although biochar offers numerous agronomic and environmental advantages, its wider adoption remains constrained by production costs, site-specific variability in performance, and potential risks such as pH imbalances and nutrient lock-up in certain soil types. Continued research and development are essential to refine biochar formulations, adapt application methods to local contexts, and promote policy and financial support mechanisms for its sustainable integration into agricultural systems.

5.2.3 Precision farming

Precision agriculture technologies (PATs) are transforming crop production by optimizing resource management and enhancing environmental sustainability (Getahun et al., 2024). Key components include remote sensing, GPS-guided equipment, variable rate technology (VRT), and IoT devices, which enable precise monitoring and application of inputs like water, fertilizers, and pesticides (Getahun et al., 2024; Hatfield and Dold, 2019). These technologies promote eco-friendly practices by minimizing waste and reducing environmental impact through targeted resource use (Gawande et al., 2023). PATs incorporate advanced data analytics for informed decision-making, leading to improved crop management and increased productivity (Hatfield and Dold, 2019). While precision agriculture offers significant benefits, challenges related to cost, accessibility, data management, and adoption need to be addressed (Hatfield and Dold, 2019). Ongoing research and cooperation are necessary to fully unlock the potential of precision agriculture in addressing global food security and sustainability challenges (Singh, 2024).

5.2.4 Integrated plant management

Integrated pest management (IPM) and integrated soil fertility management (ISFM) are key components of sustainable agriculture. The IPM combines cultural practices, biological control, genetic pest control, and targeted pesticide application to reduce reliance on chemicals while improving crop productivity and ecosystem health (Zhou et al., 2024). Farmer Field Schools have been established in over 40 countries to train farmers in environmentally friendly plant protection and soil fertility management methods (Gallagher, 2000). The ISFM, defined as a set of practices including fertilizer use, organic inputs, and improved germplasm, aims to maximize agronomic efficiency and crop productivity (Vanlauwe and Zingore, 2011). Recent advancements in IPM include the development of novel biopesticides and targeted pesticide delivery systems (Zhou et al., 2024). Successful implementation of these integrated approaches requires adaptation to local conditions, participatory approaches, and effective knowledge exchange among stakeholders (Zhou et al., 2024; Vanlauwe and Zingore, 2011).

5.2.5 Conservation agriculture

Conservation agriculture, characterized by minimal soil disturbance, permanent soil cover, and crop rotations, has been promoted in Southern Africa to combat land degradation and improve food security (Thierfelder et al., 2015). Conservation agriculture practices have shown significant benefits for soil health and carbon sequestration in the Eastern Cape, South Africa. No-till systems, combined with crop rotations including maize, wheat, and soybean, and residue retention, demonstrated increased soil organic carbon, particulate organic matter, and microbial biomass carbon compared to conventional tillage and residue removal (Muzangwa et al., 2021; Muzangwa et al., 2022). These practices also reduced CO_2 emissions by 20% (Muzangwa et al., 2021). Crop rotations, particularly those including oats, improved soil aggregate stability and carbon sequestration more effectively than tillage alone (Njaimwe et al., 2016). The inclusion of legumes in rotations and residue retention significantly enhanced soil enzyme activities and earthworm biomass (Muzangwa et al., 2022). Conservation agriculture practices also increased total carbon and nitrogen concentrations compared to conventional methods (Nyambo et al., 2021). These findings highlight the potential of conservation agriculture to improve soil health and mitigate climate change in semi-arid regions. Despite its benefits, adoption among smallholder farmers remains limited due to various socio-economic factors (Thierfelder et al., 2015).

5.2.6 Circular food systems, including urban farming techniques

Circular food systems in urban environments are gaining attention as a sustainable approach to address environmental challenges associated with traditional linear food production and consumption (Erälinna and Szymoniuk, 2021). These systems aim to reduce resource use, minimize waste, and optimize nutrient recycling through innovative techniques such as rainwater harvesting, composting, and precision agriculture (Ioannides et al., 2025). Urban farming plays a crucial role in circular food systems by shortening supply chains and enhancing urban resilience (Pascucci, 2020). Implementing circular economy principles across the food value chain offers opportunities to address sustainability issues in urban food systems (Zou et al., 2022). Practical examples include urban farming examples from Johannesburg and Cape Town in South Africa, where rooftop and community gardens have successfully implemented nutrient recycling and waste management (Chitaka and Schenck, 2023).

5.2.7 Reduced chemical usage in agriculture

Reducing chemical inputs in agriculture is essential for environmental health and sustainability. However, achieving this requires systemic changes, including policy reforms, farmer education, and the adoption of alternative practices such as organic farming and the use of biopesticides (Brunelle et al., 2024). Recent studies highlight strategies to reduce chemical inputs in agriculture while maintaining productivity and improving soil health. Organic substitution of chemical fertilizers has been shown to increase wheat yields, enhance soil quality, and promote microbial diversity (He et al., 2024). Similarly, organic fertilizers like poultry manure and vermicompost can improve soil nutrients and microbial activity in rice production (Durán-Lara et al., 2020). Natural organic compounds, including plant-based pesticides and fertilizers, offer environmentally friendly alternatives to synthetic agrochemicals, though commercialization faces challenges (Durán-Lara et al., 2020). Effective reduction of chemical inputs requires systemic changes involving all stakeholders in the agri-food system and combining policy instruments such as standards, taxes, and subsidies (Brunelle et al., 2024). While organic substitution strategies show promise for sustainable agriculture, long-term monitoring of soil heavy metals is necessary (He et al., 2024). Overall, these studies demonstrate the potential for reducing chemical usage through organic farming practices. Integrating these innovative approaches is crucial for developing resilient and sustainable agricultural systems that can meet current and future challenges (Brunelle et al., 2024).

5.3 Interdisciplinary research for climate-smart agriculture: the necessity of collaborative, cross-disciplinary approaches

Climate-smart agriculture (CSA) is an interdisciplinary approach addressing the challenges of food security, climate change adaptation, and mitigation (Steenwerth et al., 2014). It requires collaboration across various disciplines, including crop physiology, genetics, climate risk management, and socioeconomics (Steenwerth et al., 2014; Torquebiau et al., 2018). Research gaps exist in theoretical foundations, implementation practices, and policy tools (Torquebiau et al., 2018; Chandra et al., 2018). The effectiveness of CSA measures depends on site-specific factors and consumer behavior (Chandra et al., 2018). Despite positive biophysical results, adoption rates remain low, necessitating a better understanding of farmer decision-making (Hermans et al., 2020). Integrating different forms of knowledge and bridging disciplinary gaps are crucial for addressing complex agricultural challenges (Hermans et al., 2020).

Given the complex and multi-dimensional nature of CSA, interdisciplinary collaboration is essential for designing effective, scalable, and sustainable solutions. A systems-thinking approach that integrates knowledge from agriculture, environmental science, economics, social sciences, and digital technology can enhance the effectiveness of CSA interventions. Climate-smart agriculture research must move beyond traditional disciplinary boundaries and adopt transdisciplinary approaches that engage farmers, policymakers, and industry stakeholders in knowledge co-production (Torquebiau et al., 2018). Indigenous and local knowledge should be recognized as valuable sources of insight for CSA adaptation, ensuring that scientific research practically applies to diverse agricultural contexts (Ogunyiola et al., 2022). Advancements in precision agriculture, climate data analytics, and IoT-based monitoring present opportunities for enhancing CSA implementation. However, ensuring equitable access to these technologies requires interdisciplinary research efforts to address the digital divide, improve infrastructure, and develop farmer-friendly digital tools (Mehrabi et al., 2021).

For CSA to be effectively scaled, research must inform national agricultural policies by integrating scientific evidence into institutional frameworks. Governments, research institutions, and development partners must collaborate to prioritize capacity-building initiatives, invest in CSA research infrastructure, and establish multi-stakeholder partnerships (Negra et al., 2014). Climate-smart agriculture (CSA) is a transformative approach that aligns agricultural development with global sustainability objectives. As an integrated framework, CSA aims to enhance food security, build resilience to climate change, and contribute to climate change mitigation, making it a critical strategy in advancing the United Nations Sustainable Development Goals (SDGs) (Ogunyiola et al., 2022). The successful scaling and implementation of CSA practices can directly support SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land), while indirectly influencing other goals related to poverty reduction, economic growth, and environmental conservation.

5.3.1 Enhancing food security through CSA

At the core of CSA is the principle of sustainable agricultural intensification, which seeks to increase food production while maintaining ecosystem integrity. Given the projected rise in global food demand, CSA offers a means to improve agricultural productivity without exacerbating environmental degradation (Regmi and Paudel, 2024). By adopting climate-resilient crop varieties, precision irrigation techniques, and improved soil management practices, farmers can mitigate risks associated with climate variability, droughts, and extreme weather events, ensuring stable food supplies for both rural and urban populations (Kabato et al., 2025). Furthermore, CSA enables smallholder farmers to diversify their production systems, enhancing dietary diversity and improving nutrition security (Kabato et al., 2025). CSA practices such as agroforestry, intercropping, and conservation agriculture contribute to improved soil fertility, higher crop yields, and increased farm income, ensuring that food security is not only achieved in the present but sustained for future generations (Ma and Rahut, 2024).

5.3.2 Building resilience to climate change and environmental sustainability

One of the key contributions of CSA to the SDGs is its role in enhancing the adaptive capacity of farming communities. Given the increasing unpredictability of climate patterns, CSA interventions focus on empowering farmers to cope with climate-related shocks while minimizing losses in agricultural production (Ma and Rahut, 2024). The integration of climate-smart technologies, such as digital monitoring systems, weather forecasting tools, and the Internet of Things (IoT)-enabled precision farming, allowing farmers to make informed decisions, improving resource efficiency, and reducing vulnerability to climate extremes (Regmi and Paudel, 2024).

CSA also plays a vital role in conserving natural resources and protecting biodiversity. Sustainable land and water management practices, including minimum tillage, organic composting, and efficient water-use strategies, help mitigate soil degradation and enhance carbon sequestration, aligning with SDG 15 (Life on Land) and SDG 6 (Clean Water and Sanitation) (Nandeha et al., 2025; Mwongera et al., 2020). By promoting land restoration, afforestation, and ecosystem-based adaptation, CSA fosters holistic environmental stewardship, ensuring that agricultural expansion does not lead to deforestation, biodiversity loss, or water scarcity (Nandeha et al., 2025; Mwongera et al., 2020).

5.3.3 Mitigating climate change through CSA practices

A defining aspect of CSA is its potential to contribute to climate change mitigation by reducing greenhouse gas (GHG) emissions from the agricultural sector (Neupane et al., 2024). Agriculture is a major contributor to global GHG emissions, primarily through livestock production, synthetic fertilizer use, and land-use changes. CSA addresses these challenges by integrating low-emission farming systems that reduce carbon footprints while maintaining productivity (Neupane et al., 2024). Key CSA strategies for climate mitigation include improved livestock management to reduce methane emissions, agroforestry and soil carbon sequestration to enhance carbon storage in agricultural landscapes, and nutrient management and organic farming practices that minimize nitrogen oxide emissions (Kabato et al., 2025). Additionally, the circular economy approach within CSA, such as waste recycling, bioenergy production, and regenerative agricultural techniques, fosters low-carbon development pathways, making agriculture a key driver of sustainability transitions (Nandeha et al., 2025; Mwongera et al., 2020). By integrating mitigation strategies with adaptation measures, CSA contributes to achieving SDG 13 (Climate Action) by ensuring that farming communities adapt to climate change and become active agents in reducing its long-term impact (Nandeha et al., 2025; Mwongera et al., 2020).

5.3.4 Policy and institutional support for scaling CSA

For CSA to achieve its full potential, policy coherence, institutional support, and strategic investments are required. Governments, international organizations, and financial institutions must collaborate to design policies that facilitate CSA adoption and incentivize sustainable farming practices (Olabanji and Chitakira, 2025). Evidence suggests that strengthening local institutions, integrating indigenous knowledge, and promoting participatory governance can enhance the adoption of CSA innovations, leading to more inclusive and community-driven climate adaptation strategies (Olabanji and Chitakira, 2025; Mutengwa et al., 2023).

The role of financial mechanisms in CSA adoption cannot be overstated. Limited access to capital remains a significant barrier for smallholder farmers, preventing them from investing in climate-resilient practices (Ogunyiola et al., 2022). Financial solutions such as microfinance, climate insurance, and carbon credit schemes can provide economic incentives, ensuring that CSA technologies are not only accessible but also economically viable (Ogunyiola et al., 2022).

Moreover, integrating CSA into national and regional development frameworks can accelerate its adoption at scale. Policies should focus on (Bhattacharyya et al., 2020; Branca and Perelli, 2020; Totin et al., 2018; Dany, 2016):

i) Investing in CSA research and innovation to develop locally adapted solutions.
ii) Strengthening agricultural extension services to enhance farmer training and capacity building.
iii) Leveraging digital technologies to improve access to real-time climate and market information.
iv) Developing public-private partnerships (PPPs) to mobilize investments in CSA infrastructure and supply chains.

Aligning CSA policies with broader sustainability goals can bridge the gap between climate action and agricultural development, ensuring that CSA transitions from a niche intervention to a mainstream agricultural paradigm (Bhattacharyya et al., 2020; Totin et al., 2018).

6 Conclusion

This review underscores the critical importance of climate-smart food systems (CSFS) for advancing sustainable agriculture in South Africa amidst growing climate challenges. It highlights that adaptation and mitigation strategies such as drought-resilient crops, agroecological practices, precision agriculture, carbon sequestration, and circular food systems must be integrated and supported by enabling policy frameworks, financial incentives, and inclusive knowledge-sharing platforms. The success of CSFS depends on coordinated multi-stakeholder efforts that align technical innovation with socio-economic realities.

Despite significant progress, the literature reveals persistent knowledge gaps and implementation challenges. First, empirical evidence on the long-term impacts of CSA practices, particularly under diverse agroecological zones in South Africa is limited. There is a need for longitudinal and region-specific studies that assess how CSA interventions affect productivity, resilience, and ecosystem health over time. Second, methodological limitations are evident in many studies, which often lack comparative or interdisciplinary approaches that capture the complexity of food systems. Few studies integrate climate models, economic analyses, and socio-cultural dynamics into a unified assessment of CSA effectiveness.

Moreover, the role of emerging digital technologies such as artificial intelligence, remote sensing, and blockchain in optimizing climate-smart interventions remains underexplored, particularly in low-resource smallholder contexts. Research should focus on how these innovations can be tailored to local conditions, enhance decision-making, and bridge information gaps for marginalized farmers. Additionally, more robust research is needed on gender-differentiated impacts and the integration of indigenous knowledge systems to ensure equity and cultural relevance in CSA interventions.

Future interdisciplinary research should prioritize the co-production of knowledge across scientific disciplines and stakeholder groups, particularly integrating farmer-led innovations with formal scientific inquiry. This entails participatory research designs, transdisciplinary collaboration, and iterative policy learning frameworks. Policy innovation should also focus on enabling environments for CSA adoption particularly securing land tenure, de-risking private sector investment, and establishing context-specific financing models that lower barriers to entry for smallholder farmers.

Ultimately, building resilient food systems in South Africa requires a transformative research and policy agenda that is systemic, inclusive, and forward-looking. By identifying these knowledge gaps and methodological limitations, this review offers a roadmap for future scholarship and action aimed at embedding climate-smart agriculture within the broader goals of food security, sustainability, and climate resilience.

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