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Review

Integrating Sustainable Agricultural Practices to Enhance Climate Resilience and Food Security in Sub-Saharan Africa: A Multidisciplinary Perspective

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Abstract

Sub-Saharan Africa (SSA) is experiencing escalating climate variability, land degradation, and food insecurity, which threaten livelihoods and economic stability. Sustainable agricultural practices (SAPs), including climate-smart agriculture, conservation agriculture, and agroecology, offer promising strategies to boost productivity while enhancing ecological stability. This review proposes that multidisciplinary integration of SAPs, encompassing agronomy, socioeconomics, and governance, is the most promising route to achieving climate-resilient food systems in SSA by 2030. Despite its proven benefits, the use of SAPs remains limited. This is largely because of financial constraints, weak institutional frameworks, and inadequate infrastructure. To address these challenges, this review evaluates the role of SAPs in mitigating climate risk, improving soil health, and enhancing food security. It also identifies systemic adoption barriers and examines the effectiveness of policy and financing frameworks. Drawing on evidence from across SSA, including Ethiopia's agroforestry success and Senegal's millet resilience, this review highlights how integrating sustainable practices with postharvest innovation and community-driven approaches can strengthen food systems. Ultimately, the findings underscore that weaving science, policy, and grassroots action is essential for building a resilient and food-secure SSA, particularly within the context of the 2025 global adaptation agenda.

Keywords: climate change; sustainable agriculture; sub-Saharan Africa; food security; agricultural productivity; climate resilience

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Academic Editors: Laura Meno, M. Carmen Seijo and Olga Escuredo

Received: 17 May 2025
Revised: 20 June 2025
Accepted: 2 July 2025
Published: 8 July 2025

Citation: Olarewaju, O.O.; Fawole, O.A.; Baiyegunhi, L.J.S.; Mabhaudhi, T. Integrating Sustainable Agricultural Practices to Enhance Climate Resilience and Food Security in Sub-Saharan Africa: A Multidisciplinary Perspective. *Sustainability* **2025**, *17*, 6259. https://doi.org/10.3390/su17146259

1. Introduction

Agriculture is a key component of Sub-Saharan African (SSA) economies, contributing approximately 23% of the regional GDP and providing livelihoods for over 60% of the population, particularly in rural areas [1,2]. However, the region is increasingly vulnerable to climate change, with rising temperatures, erratic rainfall, and extreme weather leading to land degradation, reduced crop productivity, and food insecurity [3,4], driven by unsustainable farming practices and limited uptake of sustainable agricultural practices (SAPs). This issue is compounded by the lack of a cohesive support system that enables farmers to adopt and sustain improved practices over time [5,6]. The urgency for action is underscored by data that suggest that climate variability has reduced yields by up to 30% in arid and semi-arid zones [7], while postharvest losses in some SSA countries reach 30–40% annually [8]. In regions such as Tigray, Ethiopia, recent climate extremes, such as the 2023 heatwave, have devastated maize harvests. However, localized interventions, such as agroforestry and minimum tillage, can reduce soil erosion by up to 50% and enhance soil water retention [9–11]. In the Central Kenya highlands, Guto et al. (2012) [6] demonstrated that combining minimum tillage with vegetative barriers, particularly leguminous *Leucaena trichandra*, significantly improved soil water content and mitigated yield suppression compared to conventional tillage without barriers. While Napier grass barriers captured more rainwater, they also introduced stronger competition with companion crops, especially under minimum tillage. In contrast, *Leucaena* barriers showed complementary water uptake patterns, preserving crop performance and stabilizing yields even during dry spells [6]. These practices, when combined with solar drying or postharvest technologies, also contribute to reducing crop losses and stabilizing food production in vulnerable highlands [12]. To address these challenges, this review critically examines the integration of SAP as a pathway toward climate-resilient and food-secure systems in SSA. This study explores how SAPs can be scaled using interdisciplinary innovation and inclusive governance, by blending evidence from agronomy, environmental science, economics, and policy.

Given this backdrop, integrating SAPs, including climate-smart agriculture (CSA), conservation agriculture (CA), agroecology, and organic farming, has emerged as a pivotal pathway toward building resilient food systems in SSA. Sustainable agricultural practices offer multiple benefits, including enhancing soil fertility, increasing water retention, boosting biodiversity, and reducing dependency on synthetic inputs [12]. However, widespread adoption is hindered by systemic constraints such as limited access to credit, weak extension services, insecure land tenure, and inadequate policy alignment [13,14]. For the purposes of this review, we use ‘SAPs’ as an inclusive term encompassing principles of sustainable agriculture and CSA, recognizing their shared emphasis on resilience, resource efficiency, and environmental integrity.

The persistence of these adoption constraints is closely tied to structural and institutional factors that inhibit the operationalization and scaling of SAPs across SSA. Inadequate infrastructure, such as poor road networks, limited irrigation, and lack of postharvest storage, constrain market participation and elevate transaction costs for rural farmers [8,15]. Without access to affordable and reliable infrastructure, farmers struggle to commercialize outputs, adopt technologies, or invest in soil and water conservation measures. Moreover, the absence of inclusive financial mechanisms restricts farmers’ access to capital, insurance, and subsidized inputs, creating entry barriers for innovations such as precision irrigation or improved drought-resilient seed systems [16,17]. A diagnostic study of Sudan’s agriculture finance sector [18] highlights how government-directed credit allocation and over-reliance on state-owned banks like the Agricultural Bank of Sudan (ABS) have distorted lending priorities and constrained financial innovation. While agriculture receives a relatively large share of total private sector credit (14.5% in 2018), this financing is disproportionately allocated to irrigated and mechanized sectors, excluding the traditional rainfed systems that dominate smallholder farming. Furthermore, the credit appraisal criteria often neglect farmer productivity in favor of rigid input absorption formulas tied to government priorities, which limits the sector's ability to evolve into a high-value, market-responsive contributor to food security and export growth. Commercial banks and insurers also avoid lending to high-risk segments such as livestock producers and dryland farmers due to a lack of collateral systems and weather-indexed risk tools [18]. According to the 2017 Global Findex Database, only 17% of farmers in SSA reported saving formally, and a mere 10% borrowed from formal financial institutions. These figures underscore the persistent exclusion of smallholders from mainstream financial systems, especially women and marginalized groups, whose access is further constrained by socio-economic and cultural factors [19]. Therefore, structural reforms, including the transformation of the ABS into a market-oriented institution, enhanced crop insurance coverage, and the expansion of digital finance, are necessary to break the financial exclusion cycle in SSA's agricultural systems.

Institutional fragmentation, under-resourced extension programs, and insecure land tenure further undermine confidence and continuity in SAP investments [5,20]. These issues are logistical and deeply political, as fragmented governance and short-term policy cycles often deprioritize long-term sustainability goals [5,20]. Without a coherent enabling environment, anchored in strong governance, financing structures, and inclusive land policies, the potential of SAPs remains largely unrealized in many subregions of SSA.

Although agronomic solutions are critical, coordinated efforts across economics, governance, and institutional design are equally important for unlocking the full potential of sustainable agricultural practices and achieving lasting climate resilience [21,22]. For instance, financial innovations such as climate-smart subsidies and risk insurance, combined with gender-responsive governance, can significantly enhance the scale and sustainability of SAP interventions. Moreover, regional disparities persist in the adoption of SAP. While countries such as Kenya and Malawi have demonstrated progress in scaling CSA technologies, particularly through minimum tillage, integrated fertility management and smallholder financing [23], other countries in West and Central Africa remain underrepresented in terms of both policy focus and empirical evidence [24]. Similarly, climate-resilient crops such as millets, cassava, and orphan legumes continue to receive less attention than maize and rice, despite their robustness in marginal agroecology [12,25]

Recent research has deepened our understanding of how climate variability and institutional weaknesses together impede agricultural transformation in SSA. For instance, although climate-smart technologies are available, their adoption remains uneven due to economic marginalization and fragmented extension systems [26,27]. Additionally, Ref. [28] highlights the importance of indigenous knowledge systems in shaping locally appropriate adaptation strategies but notes that national policies often overlook or fail to integrate these practices into formal planning processes. Comparative studies across West and East Africa further revealed significant differences in the adoption of sustainable practices, shaped by factors such as gender, land tenure, and agroecological conditions [29,30]. These insights point to the need for a regionally nuanced and institutionally grounded analysis, an approach that this study seeks to advance.

In 2025, with global platforms such as the 29th conference of the parties (also known as COP29) advancing climate adaptation agendas and SSA's population projected to surpass 1.5 billion [31], the stakes for transformational agricultural change have never been higher. Hence, this study aims to critically explore how the integration of SAPs can enhance climate resilience and food security in SSA. The objectives of this study were as follows:

1. Evaluation of the role of SAPs in mitigating climate risk, improving soil health, and increasing food productivity.
2. Identify and critically examine the key economic, institutional, and knowledge-based barriers that hinder SAP adoption.

3. Assess the effectiveness of existing policy frameworks and financing mechanisms that support sustainable agriculture.
4. Compare adoption trends and implementation outcomes across SSA subregions with a focus on underrepresented areas.
5. Propose actionable, region-specific strategies that leverage governance, extension systems, and innovative finance to scale up SAPs.

By combining insights from agronomy, environmental science, economics, and development policies, this review offers a data-driven and multidisciplinary perspective on accelerating sustainable agriculture in SSA.

Although the objectives are presented separately, this study adopts a thematic approach that promotes analytical depth and coherence across interconnected issues. Section 2 outlines the conceptual foundations and methodological framework. Sections 3–5 synthesize empirical and policy evidence on the role of SAPs in enhancing climate resilience. Section 6 explores the institutional and socioeconomic barriers to their adoption. Policy and financing mechanisms are analyzed in Section 7, followed by a discussion in Section 8 that integrates cross-cutting insights. Finally, Section 9 concludes with regionally grounded policy implications. This structure enables this study to address all stated objectives while maintaining a cohesive narrative that captures the multi-dimensional nature of sustainable agriculture in SSA.

2. Methodology

This review adopts a narrative-based, multidisciplinary literature review approach to explore the integration and effectiveness of SAPs in enhancing climate resilience and food security in SSA. This review presents findings from a wide range of empirical studies, policy reports, and theoretical frameworks drawn from agricultural sciences, environmental policy, development economics, and rural sociology. To inform this review, targeted searches were conducted across multiple academic databases, including Google Scholar, Scopus, Web of Science, ScienceDirect, AGORA, and PubMed. Gray literature sources, such as development agency reports, policy briefs, and institutional publications, were also consulted to capture non-academic but contextually rich insights, particularly from regional organizations working in SSA. The search strategy focused on a combination of key terms and Boolean operators, including but not limited to “sustainable agricultural practices” AND “climate change” AND “food security” AND “Sub-Saharan Africa”; “climate-smart agriculture” OR “agroecology” OR “conservation agriculture”; “drought-resistant crops” AND “SSA adoption challenges”; and “policy framework” AND “agricultural finance” AND “climate resilience”. The inclusion criteria emphasized empirical studies or reviews published between 2000 and 2025, geographic focus on SSA, general studies offering transferable insights applicable to the region, and content addressing policy, financial, technological, or institutional dimensions of SAPs. Studies were excluded if they (1) focused solely on agronomic experiments without relevance to sustainability or climate adaptation; (2) lacked a direct focus on SSA or transferable global contexts; and (3) were preprints without peer review, duplicates, or commentary articles lacking empirical depth.

Although this review does not follow a formal systematic review framework such as PRISMA, structured screening steps have been applied to enhance transparency. This included initial database identification, duplicate removal, title/abstract screening, and full-text assessment based on thematic alignment and methodological quality. A summary of this screening process is presented in Figure S1, the inclusion/exclusion logic is outlined in Supplementary Table S1, and a representative appraisal of key sources is provided in Table S2.

Approximately 150 peer-reviewed publications and gray literature sources were selected for the full-text review. This process focused on extracting both qualitative themes and quantitative metrics, including adoption trends, yield performance, water use efficiency, and institutional constraints. Emphasis was placed on high-quality region-specific studies, especially those featured in recent climate resilience assessments in SSA. The integrative nature of this review facilitates a comparative synthesis of SAPs and informs the development of evidence-based recommendations. These recommendations are grounded in interdisciplinary insights that span agronomy, environmental science, economics, and policy.

3. Results and Discussion

3.1. Climate Impacts and Regional Responses in SSA

Sub-Saharan Africa is increasingly threatened by climate change, with agriculture (the most vital sector) experiencing some of the most severe impacts. Rising temperatures, erratic rainfall, and intensifying extreme weather events are reshaping the region's growing conditions and reducing the productivity of staple crops, such as maize, sorghum, and millet [2,3]. These disruptions are further compounded by pests and diseases, often triggered by climatic shifts, and worsen under-resourced farming systems with limited adaptive capacities [32].

Extreme weather events, particularly droughts, heat waves, and floods, exacerbate existing vulnerabilities. Drought alone accounts for a yield decline of up to 30% in many regions, along with livestock deaths and increased food insecurity [33,34]. Heatwaves reduce crop viability, escalate pest pressure, and lower livestock productivity [35], whereas flooding causes nutrient loss, soil erosion, and crop damage [36]. The projected crop yield declines due to these stressors are highlighted in Figure 1, which illustrates the compounding effects of climatic extremes on staple crops in SSA.

Region-specific vulnerabilities across SSA require tailored responses. In Eastern Africa, recurrent droughts have disrupted maize and sorghum yields in Ethiopia and Kenya [23,37], underscoring the urgency for region-specific SAP scaling strategies. Southern Africa faces heat and drought convergence, particularly in South Africa and Malawi, with economic and nutritional consequences [38]. In West Africa, intensifying heat reduces yields and affects livestock health in Ghana and Nigeria [39–41], while Central Africa, including Cameroon, is increasingly susceptible to flood-related erosion and disease outbreaks [42–44].

These regional experiences, synthesized in Table 1, underscore the crosscutting impacts of climate hazards and the shared need for adaptation. In response, many countries are scaling up SAPs, including CSA, agroforestry, and drought-tolerant crops [45]. While adoption varies, case-specific interventions have helped communities stabilize yields and adapt to growing climate risks.

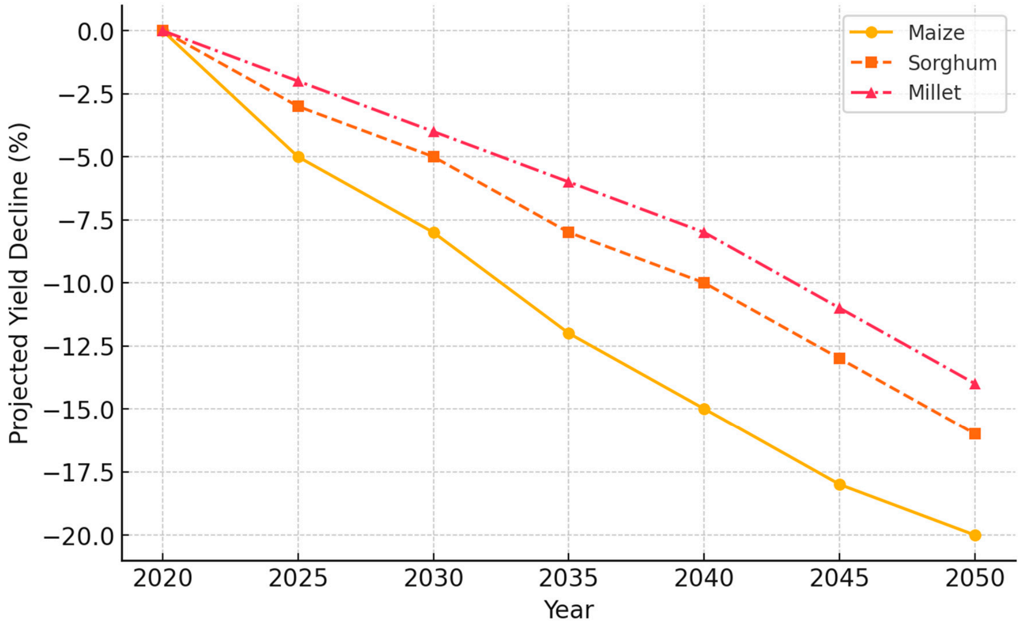

Figure 1. Projected impact of climate change on staple crop yields in SSA under mid-range climate change scenarios (2020–2050). Values reflect synthesized trends from key regional studies, highlighting average yield declines of 10–30% under warming and rainfall variability scenarios. Data were sourced from Refs. [34,46–48] and IPCC regional summaries. These values are illustrative and are intended to reflect recurring patterns in multi-country projections, emphasizing the need for adaptive responses across agroecological zones.

Table 1. Impact of climate change on agricultural systems across Sub-Saharan Africa.

SN	Impact	Description	Citation
1	Reduced crop yields	Changes in temperature and rainfall patterns affected crop growth and productivity.	[49]
2	Decreased food security	Climate change impacted agriculture, leading to reduced food availability and access.	[2]
3	Water scarcity	Changes in rainfall patterns and increased evapotranspiration led to water scarcity.	[50,51]
4	Extreme weather events	Increased frequency and intensity of droughts, heatwaves, and floods affected agricultural productivity.	[46]
5	Drought impacts	Droughts led to reduced crop yields, increased food insecurity, and decreased livestock productivity.	[34]
6	Heatwave impacts	Heatwaves led to reduced crop yields, increased pest and disease pressure, and decreased livestock productivity.	[39,40,52]
7	Flood impacts	Floods led to soil erosion, nutrient depletion, and increased pest and disease pressure, reducing agricultural productivity.	[44]

3.2. Sustainable Agricultural Practices

Sustainable agricultural practices are central to transforming food systems in SSA amid worsening climate risks. These practices, including agroforestry, CA, CSA, and organic farming, aim to improve productivity, enhance resilience, and promote long-term environmental sustainability [21,53].

Agroforestry, which integrates trees into farming landscapes, addresses critical challenges such as soil degradation, biodiversity loss, and temperature stress. It enhances soil structure and fertility, while offering income diversification through timber, fruits, and shade-tolerant crops [53]. Conservation agriculture, anchored on minimal tillage, permanent soil cover, and crop rotation, improves water retention, reduces erosion, and boosts soil organic matter, thus contributing to sustainable soil health [54–56].

Climate-smart agriculture offers a system-based approach that integrates several SAPs to achieve three goals: productivity, adaptation, and mitigation. Its application across the SSA has demonstrated multiple benefits. For example, CSA practices such as conservation tillage and early warning systems in Kenya have been associated with yield increases and greater climate resilience. In Machakos County, combining conservation tillage with integrated fertility management resulted in maize yield increases of up to 379% and soil moisture improvements of 15–18% [23], confirming the multi-dimensional benefits of CSA systems. In Zambia, cover cropping and minimal tillage have enhanced soil fertility and crop yields [57], whereas drought-tolerant millet and agroforestry in Senegal and Malawi have improved climate resilience and soil health [8]. Figure 2 summarizes the yield improvements attributed to different SAPs across the region [34,58].

Key constraints include high initial investment costs, limited access to quality seeds, poor extension services, and weak institutional and policy frameworks [13,32,58]. Furthermore, farmers often face systemic challenges in accessing financing, climate forecasts, and reliable market linkages [15,59].

Table 2 presents a comparative analysis of SAPs and illustrates their benefits and limitations. Although agroforestry and CA provide long-term ecological gains, they require technical capacity and time. Drought-resistant crops enhance yields under stress but are underutilized because of their weak seed systems. Similarly, organic farming and integrated pest management (IPM) reduce chemical dependency but face adoption challenges stemming from certification barriers and knowledge gaps. Precision agriculture offers high potential but remains financially inaccessible to most smallholders.

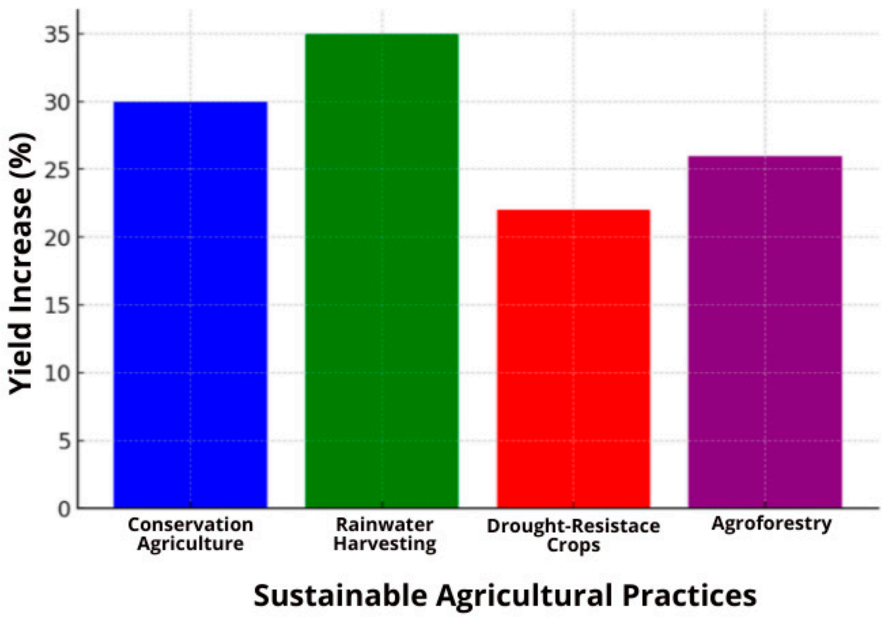

Figure 2. Estimated yield improvements from selected sustainable agricultural practices in Sub-Saharan Africa. Values reflect average gains reported in studies on agroforestry (5–20%), conservation agriculture (8–25%), rainwater harvesting (10–30%), and drought-tolerant crops (up to 20%). These values were derived from previous reports [8,10,34,37,58,60]. The results are illustrative and are meant to convey general regional trends, not country-specific estimates.

Table 2. Comparative evaluation of selected sustainable agricultural practices in Sub-Saharan Africa, including agroforestry, conservation agriculture, drought-tolerant crops, integrated pest management, and organic farming.

S/N	Sustainable Agricultural Practice	Benefits	Limitations	Citation
1	Agroforestry	Enhances soil fertility, improves biodiversity, provides additional income from tree products.	Requires long-term investment, trees may compete with crops for water and nutrients.	[21,53]
2	Conservation Agriculture (CA)	Reduces soil erosion, improves soil moisture retention, enhances carbon sequestration.	Initial transition period may lead to lower yields, require specialized equipment.	[1,15]
3	Climate-Smart Agriculture (CSA)	Enhance climate resilience, improve yields, support sustainable intensification.	High cost of implementation, need for training and extension services.	[45]
4	Organic Farming	Improves soil health, reduces reliance on synthetic inputs, promotes biodiversity.	Lower initial yields compared to conventional farming require more labor.	[22]
5	Integrated Pest Management	Reduces chemical pesticide use, minimizes environmental impact, enhances ecosystem balance.	Requires knowledge of pest ecology, potential yield losses in early adoption phase.	[12]
6	Drought-Resistant Crop Varieties	Ensures food security in arid regions, improves resilience to climate change, stabilizes yields.	May require additional breeding programs, initial adoption challenges.	[32]
7	Precision Agriculture	Increases resource efficiency (water, fertilizers), reduces input costs, enhances productivity.	High initial cost, requires digital literacy, data management challenges.	[13]
8	Push-Pull Technology	Effective for controlling pests, improves soil fertility, increases yields in smallholder farms.	Requires knowledge and proper implementation, needs specific crop varieties.	[34]
9	Water Harvesting Techniques	Reduces reliance on groundwater, improves water availability in dry regions, enhances irrigation efficiency.	Requires storage infrastructure, dependent on rainfall availability.	[1]

Scaling SAPs across SSA requires an integrated approach. Priority actions include capacity-building for farmers, expansion of access to credit and climate information, land tenure reform, and strengthening linkages between research, extension services, and markets. Collaboration among governments, development agencies, researchers, and the private sector is critical for catalyzing context-specific innovations and ensuring equitable and widespread adoption.

3.3. Innovations and Technological Interventions

The sustainable transformation of agriculture in SSA relies on both traditional knowledge systems and context-specific innovations. Core SAPs, including CA, agroforestry, IPM, and organic farming, serve as pillars for building climate resilience, ecological regeneration, and food security in the region.

3.3.1. Conservation Agriculture

Conservation agriculture focuses on minimizing soil disturbance, permanent soil cover, and crop rotation. These practices have been shown to improve soil structure, reduce erosion, and increase water-use efficiency, which are key climate outcome variables in SSA [61,62]. Techniques such as mulching and intercropping reduce evapotranspiration and improve moisture retention, whereas legumes in rotation enhance nitrogen fixation and yield stability [63,64]. Moreover, CA reduces dependency on synthetic inputs, lowers production costs, and enhances carbon sequestration [63]. However, its adoption is often constrained by labor intensity, limited mechanization, and knowledge gaps, necessitating targeted farmer training and supportive policies for scale-up.

3.3.2. Agroforestry

Agroforestry systems, which integrate trees with crops and/or livestock, improve soil fertility through litter deposition and nitrogen fixation, buffer farms against climatic extremes, and diversify smallholder incomes through timber, fruit, and fodder [53,65]. Models such as agrosilvicultural, silvopastoral, and agrosilvopastoral systems also support biodiversity conservation [66]. However, insecure land tenure and the time required to realize returns present significant adoption barriers. Addressing these requires strengthened farmer support systems and land policy reforms that secure rights and incentivize long-term investments.

3.3.3. Integrated Pest Management

Integrated pest management combines biological, physical, cultural, and chemical tools to reduce pest pressure while minimizing environmental and health risks. In SSA, biological control using natural enemies such as predators and parasitoids is a cost-effective and eco-friendly strategy [67]. A notable example is the use of the parasitoid *Cotesia icipe* to manage *Spodoptera frugiperda* (fall armyworm), a major maize pest [68]. Complementary approaches, such as neem-based biopesticides and resistant crop varieties, further reduce the reliance on synthetic pesticides. However, poor extension services and limited access to biocontrol inputs continue to constrain their widespread adoption [69].

3.3.4. Organic Farming Practices

Organic farming promotes ecosystem health by avoiding synthetic inputs and relies on natural soil fertility, composting, and biological pest control. It is often rooted in indigenous knowledge, making it well-suited to SSA's cultural and agroecological contexts [70,71]. Practices such as compost application, intercropping with legumes, and crop residue retention enhance soil organic matter content, nutrient cycling, and microbial activity, thereby improving yield resilience under stress [72,73].

The use of traditional inputs, such as ash and manure, further reinforces local adaptation [74,75]. However, organic agriculture faces constraints, such as limited certification infrastructure, weak regulations, and insufficient extension support. A blend of participatory training, local certification models, and policy incentives is required to unlock its full potential [76].

3.3.5. Case Study: Integrating SAPs and Postharvest Innovations in Kenya and Nigeria

Case studies from Kenya and Nigeria have demonstrated the synergistic benefits of combining SAPs with postharvest innovations. In Kenya's Machakos County, integrating drought-tolerant maize and conservation tillage with solar-powered cold storage reduced postharvest losses by 25% and increased smallholder income by 18% [23,77]. Similarly, in parts of Nigeria, combining agroforestry with mobile-based market platforms has improved buyer access and reduced fruit spoilage [78]. These examples highlight the value of bundling agronomic practices with digital and postharvest technologies to maximize food security gains [78]. These innovations reflect the convergence of scientific advancement and local knowledge and offer robust strategies for sustainable agriculture in SSA. However, their wider adoption depends on investments in farmer training, institutional capacity, inclusive policies, and targeted financial mechanisms that prioritize smallholder realities.

4. Postharvest Preservation Techniques

Postharvest preservation techniques are vital to ensure food security by minimizing food loss and enhancing the quality of agricultural products. This is particularly important in SSA, where food insecurity remains a persistent issue due to high postharvest losses.

4.1. The Role of Postharvest Innovations in Food Security

Postharvest losses constitute a critical bottleneck in achieving agricultural sustainability and food security in SSA. It is estimated that between 30% and 40% of the food produced in the region is lost between the harvest and consumption stages, predominantly because of inadequate storage, poor transport infrastructure, and limited market access [8,79]. These losses not only undermine the availability and accessibility of food but also erode smallholder farmers' incomes, discourage surplus production, and weaken overall supply chain resilience [80,81].

The impact of postharvest losses is particularly severe among smallholder farmers who typically operate in fragmented markets with minimal access to cold storage, value-added processing, or preservation technologies. Without reliable postharvest systems, these farmers face high perishability risks, reduced bargaining power, and volatile prices, particularly for fruits, vegetables, and dairy products [82]. Climate variability compounds temperature extremes, and erratic rainfall exacerbates spoilage rates, increases microbial contamination, and disrupts transportation, making the development of adaptive postharvest strategies a central concern in agricultural planning [83,84].

In response, a range of technological and organizational innovations is emerging to address SSA's unique infrastructural and energy constraints. Solar-powered cold storage systems are among the most promising solutions for off-grid rural areas. These units help preserve the quality of perishable goods, extend shelf life, and reduce microbial spoilage. In Ghana, the adoption of solar-powered cold storage systems by smallholder cooperatives has emerged as a viable postharvest solution. Ref. [85] showed that these off-grid units, used predominantly for perishable crops such as tomatoes, reduced spoilage rates by up to 30–40%, thereby improving farmer income and food security outcomes. In Senegal, pilot programs deploying community-based mobile cooling units demonstrated an increase of up to 50% in the shelf life of leafy vegetables, thereby providing scalable low-energy interventions for vulnerable farmers [86].

In addition to cooling technologies, digital innovations are transforming the postharvest logistics. Mobile-based platforms and blockchain-enabled traceability systems help farmers access real-time market information, establish linkages with buyers, and reduce transaction costs. In Ethiopia, digital traceability solutions such as blockchain-enabled logistics have shown potential for reducing postharvest losses and improving supply chains. Ref. [87] highlighted how agro-processing and digital platforms optimize market linkages and reduce spoilage through real-time coordination. Digital platforms in SSA have proven to be effective in enabling farmers to avoid distress sales and spoilage by facilitating faster, demand-driven transactions. These innovations are especially valuable to smallholder farmers who have limited access to structured markets [88].

Cooperative-based storage systems are increasingly recognized as effective tools for reducing postharvest losses and enhancing smallholder market participation. Shared aggregation centers and warehouses, often facilitated by non-governmental organizations (NGOs) or public-private partnerships, provide controlled storage conditions that reduce spoilage and enable collective bargaining [89]. The integration of SAPs with postharvest innovations enhances smallholder resilience in SSA. These approaches extend beyond productivity to improve climate resilience, market access, and livelihood security by linking CA with solar-powered storage or agroecological systems with digital platforms such as blockchain. Postharvest interventions should be viewed as integral components of sustainable food systems that are critical for addressing climate variability and food insecurity [90].

4.2. Techniques for Horticultural Crop Preservation

Horticultural crops such as tomatoes, leafy greens, mangoes, and berries are among the most vulnerable to postharvest deterioration owing to their high moisture content and delicate physiology. Effective preservation strategies are essential to reduce losses and maintain harvest quality through market delivery.

4.2.1. Cold Storage and Refrigeration

Refrigeration remains a cornerstone in postharvest management by reducing metabolic rates and microbial growth, thereby preventing spoilage and extending the shelf life of perishables. In SSA, the emergence of solar-powered cold storage solutions offers a decentralized and sustainable alternative suited to rural agricultural settings. These systems enable smallholders to preserve unsold produce, access broader markets, and reduce economic loss and food waste. Empirical studies have shown that solar-powered cold storage can reduce postharvest spoilage by up to 50%, particularly in off-grid rural communities [91].

4.2.2. Modified Atmosphere Packaging (MAP)

Modified atmosphere packaging is an advanced postharvest technique that involves the regulation of internal gas composition, typically by lowering oxygen and increasing carbon dioxide levels to slow down physiological and microbial spoilage. This method is particularly effective for fresh-cut produce, herbs, and leafy vegetables, as it helps maintain textural integrity, color, and nutritional quality throughout storage and transportation. By extending shelf life, MAP enables longer distribution chains without compromising product quality, thereby improving market access for smallholder farmers targeting urban centers and export destinations. Its adoption in SSA, while still emerging, holds significant potential for enhancing food security by reducing postharvest losses [92,93].

4.2.3. Use of Natural Preservatives and Edible Coatings

Natural and biodegradable preservation agents are gaining attention because of their compatibility with organic and agroecological systems. Edible coatings made from aloe vera gel, chitosan, or essential oils serve as protective barriers that reduce moisture loss and suppress microbial growth. These approaches offer an alternative to chemical preservatives, improving the shelf life of produce while maintaining food safety and aligning with consumer demand for chemical-free foods. The low cost and ecological compatibility of these methods make them particularly relevant for smallholder farmers operating in resource-limited settings. Hence, strengthening postharvest preservation is fundamental to sustainable agriculture in SSA. This is directly linked to reducing food loss, enhancing economic returns, and building more resilient food systems. Policies that support the diffusion of these technologies, alongside farmer training, value chain integration, and inclusive innovation financing, are essential for translating potential into long-term impacts.

4.2.4. Blockchain and Biodegradable Packaging

Blockchain technology has emerged as a promising innovation to enhance agricultural supply chain transparency in postharvest systems. By providing real-time tracking and traceability from the farm to the market, blockchain can reduce delays and losses. Although specific pilot data from Uganda remain unpublished, earlier interventions have shown that blockchain systems combined with logistics coordination can reduce fruit losses by 10–20% in similar contexts [94,95]. These outcomes are especially relevant for perishable commodities such as mangoes. Biodegradable packaging technologies are gaining traction for sustainable postharvest interventions. Cassava starch-based films are biodegradable, cost-effective, and suitable for use in tropical climates. Trials have shown that these films can extend fruit shelf life by 25–30% while meeting consumer demand for eco-friendly packaging [96]. These innovations reduce spoilage and align with the circular economic principles across the food value chain. Technologies such as blockchain for logistics and biodegradable materials for packaging offer synergies when integrated into sustainable agriculture strategies. For smallholder farmers in SSA, such interventions can enhance market access, reduce losses, improve income security, and support climate resilience and food system transformation.

5. Water Management Strategies

Water availability is a foundational determinant of agricultural productivity, especially in SSA, where rainfall variability, drought, and land degradation threaten crop yields and food security. Therefore, the adoption of efficient water management strategies is critical to ensure the resilience and sustainability of farming systems. These strategies include precision irrigation systems, rainwater harvesting, and soil moisture conservation practices, all of which aim to optimize water use while reducing environmental degradation.

5.1. Efficient Irrigation Systems

Drip and sprinkler irrigation systems are among the most transformative innovations in water use efficiency. Drip irrigation delivers water directly to the root zones of plants, significantly minimizing evaporation and surface runoff. It has been found to reduce water consumption by up to 50% compared to traditional flood irrigation methods [97]. For instance, Ref. [98] reported a 45% reduction in water use and 25% increase in crop yield with drip irrigation in vegetable farming. Sprinkler systems, which distribute water through a network of pressurized pipes and nozzles, offer an alternative that is especially suitable for large-scale or diversified farms. Sprinkler systems that distribute water via pressurized nozzles are suitable for large-scale or diversified farming. These systems can be optimized using pressure regulators, timers, and moisture sensors. Studies in semi-arid regions have shown that sprinkler irrigation can reduce water use by 20–30% while maintaining or improving crop yields compared to conventional surface irrigation [99].

5.2. Rainwater Harvesting

Rainwater harvesting is a highly relevant strategy for both high- and low-rainfall regions of SSA. By capturing and storing rainwater during peak seasons, farmers can reduce their reliance on increasingly stressed groundwater and surface-water sources. According to Ref. [51], rainwater harvesting systems in Kenya increase crop yields by 20% and reduce water costs by 15%. These systems can be constructed using local materials and maintained at minimal cost, making them ideal for smallholder farming systems. Beyond yield improvements, rainwater harvesting enhances resilience by providing a reliable water source during dry spells or seasonal droughts.

5.3. Soil Moisture Conservation Techniques

Conserving moisture in the root zone is equally important for external water supply. Techniques such as mulching, cover cropping, and conservation tillage play a significant role in maintaining the soil water content and reducing erosion. Organic mulches made from straw, leaves, or compost can create a barrier that minimizes evaporation, regulates soil temperature, and improves microbial activity. Cover crops protect the soil during fallow periods and add organic matter, whereas conservation tillage minimizes the disruption of soil structure, helping retain water and reduce runoff. Empirical studies in Ethiopia indicate that conservation tillage and mulching can reduce runoff by 48%, soil erosion by up to 27%, and modestly increase barley and teff yields [10,60]. These practices contribute to long-term land productivity and enhance soil moisture conservation, which are critical for dry season resilience. The combined benefits of these practices contribute to long-term land productivity, climate resilience, and reduced irrigation needs, making them crucial components of sustainable water-management strategies in SSA.

Therefore, the integration of modern irrigation systems, traditional rainwater harvesting, and ecological soil management techniques is a comprehensive approach to optimizing water use in agriculture. Scaling up these interventions requires supportive policies, farmer education, investment in infrastructure, and local adaptation strategies tailored to the agro-ecological context.

6. Development and Adoption of Climate-Resilient Crop Varieties

6.1. Breeding for Drought and Heat Tolerance

Breeding climate-resilient crops is essential for stabilizing yields under increasingly variable weather conditions. Traditional breeding methods, including selection and hybridization, have led to the development of drought-tolerant maize, which has improved yields by up to 20% in parts of SSA [100]. Heat-tolerant crop lines have been introduced to maintain reproductive performance and ensure grain filling under extreme temperature conditions, which is a key adaptation for yield stability in SSA warming climates [101]. In parallel, advances in molecular breeding have accelerated the development of climate-resilient cultivars. Marker-assisted selection enables the precise identification and introgression of drought- and heat-tolerant traits, significantly improving breeding efficiency and trait targeting [102].

6.2. Role of Biotechnology in Crop Improvement

Biotechnology complements conventional breeding by accelerating the development of stress-resilient and nutritionally enhanced crops. Genetic engineering has facilitated the creation of transgenic varieties with drought and pest resistance, leading to yield improvements of up to 15% under water-limited conditions [103]. In addition to abiotic stress management, attempts have been made to use biotechnology to address micronutrient deficiencies through biofortification. For example, vitamin A-fortified maize and cassava are disseminated across SSA to combat hidden hunger [104].

6.3. Selected Case Studies on Successful Crop Varieties in SSA

The practical success of the climate-resilient varieties is best illustrated using region-specific case studies (Table 3). These examples highlight the critical roles of breeding programs and crop diversification in addressing climate-related challenges.

Cowpea (*Vigna unguiculata*)

Cowpeas are staple legumes that are widely cultivated across West and Central Africa for their drought tolerance, high protein content, and soil-enriching properties. Breeding programs that focus on yield stability, pest resistance, and nutritional quality have led to the adoption of improved varieties with considerable gains in food security and market value [105,106].

Sorghum (*Sorghum bicolor*)

Sorghum, the second most cultivated cereal in SSA, is highly resilient to drought and has poor soil quality. In rainfed systems, particularly in the Sahel and Eastern Africa, sorghum yields have been enhanced using soil amendments, such as biochar and compost, which improve water retention and nutrient availability [107,108].

Other Emerging Crops

Millets, chickpeas, cassava, and orphan legumes such as Bambara groundnut and pigeon pea have gained prominence in SSA because of their adaptability to harsh conditions and nutrition. These crops are tolerant to heat and water stress, which makes them ideal for climate-resilient agriculture. Recent advances in breeding and biotechnology have enhanced stress performance. Genomic studies have revealed the high adaptability and regional vulnerability of pearl millet to climate change, which requires targeted breeding [109]. Chickpeas have been improved using integrated genomic approaches to boost their productivity under drought conditions [110]. Cassava improvement in SSA has focused on biofortification and stress resistance [111]. The resilience of Bambara groundnut to drought and poor soils has made it central to genetic improvement programs [112]. Pigeon pea breeding has advanced with hybrid varieties that enhance yield stability and disease resistance [113].

A combination of breeding, biotechnology, and local knowledge has enabled the development of climate-resilient crop varieties. However, adoption faces constraints such as limited seed access, weak extension services, and inadequate policy frameworks. Scaling requires investments in seed systems, participatory breeding, and context-specific extension models that align with the local conditions.

Table 3. Key studies on successful crop varieties for enhancing food security and climate resilience in SSA.

S/N	Study Title	Crop/Practice	Scientific Name	Key Findings	Reference
1	Breeding elite cowpea [*Vigna unguiculata* (L.) Walp] varieties for improved food security and income in Africa: opportunities and challenges	Cowpea	*Vigna unguiculata*	Enhanced breeding programs have improved cowpea's drought tolerance, boosting food security and income generation for smallholder farmers.	[106]
2	Production constraints and improvement strategies of cowpea (*Vigna unguiculata* L. Walp.) genotypes for drought tolerance	Cowpea	*Vigna unguiculata*	Cowpea genotypes selected for drought tolerance are increasingly adopted by farmers in SSA, leading to improved crop productivity under water stress.	[105]
3	Drought tolerance and water use of cereal crops: A focus on sorghum as a food security crop in Sub-Saharan Africa	Sorghum	*Sorghum bicolor*	Sorghum has proven drought tolerance and water use efficiency, making it a vital crop for food security in arid regions.	[108]
4	Aquacrop-simulated response of sorghum biomass and grain yield to biochar amendment in South Sudan	Sorghum	*Sorghum bicolor*	Biochar amendments significantly boost sorghum yields in rainfed systems, aligning with sustainable soil management practices.	[107]
7	Crops diversification and the role of orphan legumes to improve the SSA farming systems	Orphan Legumes	Various	Underutilized legumes require fewer inputs and can thrive in marginal conditions, making them key for sustainable diversification in SSA farming.	[114]
10	Impact of training on the intensification of rice farming: Evidence from rainfed areas in Tanzania	Rice	*Oryza sativa*	Training programs on rice farming have improved farmers' crop management skills and increased adoption of climate-resilient rice varieties.	[115]
11	Adapting maize production to climate change in SSA	Maize	*Zea mays*	Drought-resistant maize varieties improve yields and food security in regions with increasing rainfall variability.	[116]

Table 3. *Cont.*

S/N	Study Title	Crop/Practice	Scientific Name	Key Findings	Reference
12	Consequences of dryland maize planting decisions under increased seasonal rainfall variability	Maize	*Zea mays*	Efficient planting strategies for maize in response to rainfall variability are essential for maintaining yields under climate change pressures.	[117]
13	Impact of solar cold storage on postharvest loss reduction in Kenya	Maize + cold Storage	*Zea mays*	Reduced postharvest loss, increased farmer revenue	[118]

7. Socio-Economic Aspects and Policy Frameworks

7.1. Role of Government Policies in Promoting Sustainable Practices

Government policies are pivotal in steering agricultural systems toward sustainability, particularly in SSA, where resource limitations and climate stressors challenge the widespread adoption of SAPs. Supportive policy frameworks, such as subsidies for organic inputs, tax incentives for conservation farming, and regulatory backing for sustainable land use, serve as critical enablers for smallholder farmers to transition to eco-friendly practices. In Rwanda, targeted government programs promoting the use of organic fertilizers have led to increased adoption among smallholders, facilitated by supportive institutional and financial incentives [119,120]. Similarly, Kenya's policy thrust toward CA has demonstrated tangible benefits, including improved soil structure and reduced erosion, thereby enhancing long-term agricultural productivity [121]. Evidence suggests that supportive and targeted land management policies have substantially increased SAP adoption rates, particularly in dryland regions of SSA [122].

7.2. Financial Incentives and Support for Farmers

Access to financial support remains a key determinant of SAP adoption, particularly for smallholder farmers, who often face high upfront costs and market uncertainties. Governments, microfinance institutions, and international donors play a central role in offering subsidies, grants, and concessional loans to mitigate financial risks. For instance, the African Development Bank has supported the implementation of climate-smart practices through targeted funding instruments and policy lending [123]. Microfinance innovations and fintech tools are increasingly enabling farmers access to capital, whereas digital solutions streamline access to affordable credit [124]. Ref. [16] further emphasized the need for sustainable finance strategies linked to adaptive policies to facilitate inclusive and scalable SAP adoption across urban and rural farming systems in SSA.

7.3. Community Engagement and Education

Community-level engagement is crucial in translating policies and technologies into practice. Farmer field schools, peer-to-peer training, and participatory research initiatives empower communities with the skills and knowledge required to effectively implement SAPs [125–128]. These models foster collective learning, increase the relevance of interventions, and build trust in sustainable solutions. Community engagement also supports the cultural adaptation of climate-resilient crops, contributing to dietary diversity and food sovereignty.

7.4. International Collaborations and Partnerships

International collaboration offers critical avenues for knowledge transfer, technology diffusion, and financial investment in sustainable agriculture. Initiatives such as the Alliance for a Green Revolution in Africa (AGRA) and the International Fund for Agricultural Development (IFAD) have played instrumental roles in fostering climate-resilient farming systems through partnerships with national governments, research organizations, and local communities. These collaborations have facilitated the diffusion of sustainable innovation, coordinated policy development, and expanded access to funding mechanisms [129,130]. Studies indicate that partnerships with international organizations such as AGRA and IFAD can increase SAP adoption by up to 50%, particularly when embedded within national agricultural transformation agendas and aligned with farmers' needs [131].

8. Challenges and Limitations

8.1. Barriers to Adoption of Sustainable Practices

The uptake of SAPs in SSA is constrained by multiple systemic and environmental factors. Degraded soils, erosion, and nutrient depletion, compounded by intensified climate stress, continue to undermine agricultural productivity and reduce the effectiveness of sustainable interventions [132]. Most smallholder farmers operate on marginal lands with limited access to soil fertility inputs, irrigation, or agronomic support [133]. Socioeconomic constraints such as gender inequality, credit inaccessibility, and high input costs form a web of structural limitations that hinder SAP adoption [134].

8.2. Economic and Technological Constraints

Economic fragility across many SSA nations is a major impediment to sustainable agriculture. Inadequate investment in rural infrastructure, limited research funding, and underdeveloped irrigation systems restrict innovation and adaptive capacity [135]. High inflation, currency volatility, and underperforming credit markets further hinder access to financial services and essential technologies. However, technological barriers are significant obstacles. For example, precision agriculture tools, solar irrigation systems, and hybrid renewable energy technologies remain inaccessible to most smallholders owing to their high costs and poor extension services [17]. Moreover, declining per capita landholdings and insufficient mechanization make it difficult for farmers to implement labor-saving or large-scale SAPs [5]. These technological deficits, combined with economic limitations, significantly constrain the scalability of innovative solutions across the region.

8.3. Policy and Institutional Challenges

Policy and governance remain central to shaping the transition toward sustainable agriculture in SSA. Weak institutional capacity, fragmented mandates, and inadequate stakeholder coordination significantly constrain the adoption and scaling of SAPs. For instance, many national agricultural strategies lack effective implementation pathways or fail to cater to the localized needs of smallholder farmers [136,137]. Inadequate agricultural research support, underfunded extension systems, and insufficient infrastructure have further undermined the spread of smart climate innovation. These structural limitations also affect the longevity of donor-funded projects and the institutionalization of best practices [58]. Moreover, misaligned policies and bureaucratic inertia can stall urban-rural linkages, widen equity gaps, and stifle grassroots innovation [138].

Comprehensive reforms are required to overcome these institutional challenges. Evidence-based policymaking, capacity building for agricultural institutions, and inclusive governance structures can help align SAP implementations with broader developmental goals. Strategic public investments and partnerships with civil society and the private sector are also essential to build trust, scale innovations, and deliver benefits equitably. The constraints affecting SAP adoption in SSA are deeply interconnected, cutting across ecological, economic, technological, and institutional domains. Addressing these challenges requires a system-oriented approach that integrates policy reforms, targeted investment, and inclusive innovation tailored to smallholder farmers.

8.4. Socio-Economic Dimensions Influencing SAP Adoption

The implementation of SAPs in SSA depends on agro-ecological viability and socio-economic disparities. Although policies promote technical adoption, evidence shows that household decisions are influenced by factors such as land tenure insecurity, access to financial services, and educational attainment [139]. The authors [139] indicated that although crop rotation and intercropping are widely adopted, labor-intensive techniques such as agroforestry and conservation tillage remain underutilized in rural SSA communities. This underutilization stems from constraints on household labor, market accessibility, and technical expertise. Social risk factors, including fear of crop failure and uncertain land ownership, discourage investment in long-term land-enhancing SAPs. A regional synthesis of empirical evidence on the SAP yield impacts is provided in Table S3.

Furthermore, SAP adoption is affected by gendered labor burdens, wherein women, despite their central role in agriculture, are frequently excluded from extension services and credit [140]. This exclusion limits their capacity to implement SAPs. Addressing these disparities through targeted financial instruments, cooperative training, and tenure-norm reform could transform adoption from an elite-driven initiative to a community-wide resilience strategy. The systemic linkages among SAP, water resource management, and postharvest strategies are summarized in Figure 3, which illustrates the key feedback loops and enabling conditions relevant for scaling adoption across the region.

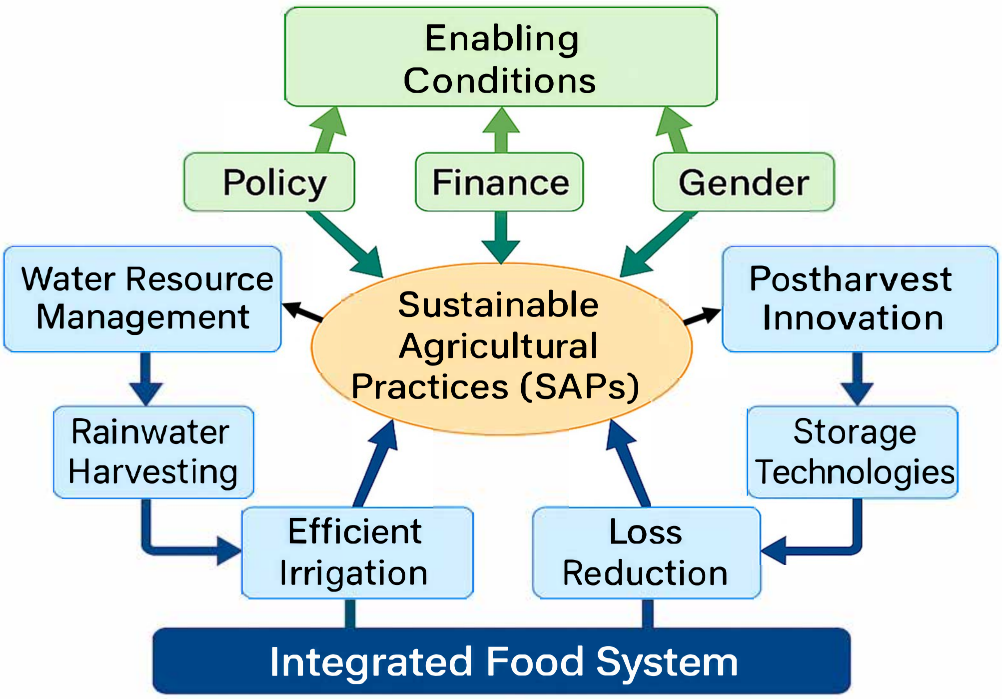

Figure 3. Conceptual linkages among sustainable agricultural practices, water resource management, and postharvest strategies in Sub-Saharan Africa. This figure illustrates how SAPs interact with water and postharvest systems through feedback loops and enabling mechanisms, such as finance, policy, and social inclusion. These connections reflect a systems-based approach to scaling sustainability across agricultural value chains.

9. Future Directions and Recommendations

9.1. Research Gaps and Priorities

Despite significant progress, crucial knowledge gaps remain. There is an urgent need to understand how SAPs affect yield, resilience, and long-term ecological health across the diverse agroecological zones of SSA. Further investigation is warranted into the scalability and long-term impact of conservation agriculture, agroforestry, and integrated crop-livestock systems on soil health, biodiversity, and farm productivity [141]. There is a growing need to enhance the breeding programs for drought-tolerant, heat-resilient, and nutrient-rich crop varieties. These include indigenous and underutilized species that have untapped potential for climate resilience and food security [62]. Moreover, land tenure systems, farmer behavior under climate stress, and the socio-cultural dimensions of sustainability remain underexplored. Ongoing research on how climate variability affects productivity and adaptation responses is essential for building resilient food systems [46].

9.2. Innovations in Sustainable Agricultural Technologies

Innovation remains pivotal for transforming agricultural systems in SSA, particularly under intensified climate stress. Climate-resilient technologies, such as conservation tillage, drought-tolerant crop varieties, and improved water-use systems, are increasingly being adopted to address soil degradation and erratic weather conditions. For instance, conservation tillage and drought management practices have shown substantial potential in enhancing soil moisture retention and crop resilience across semi-arid tropics [142]. In South Africa, indigenous climate-resilient crops such as millet and cowpea have demonstrated notable success in maintaining yields under water-scarce conditions, thereby contributing to both food security and ecological stability [143].

Agroforestry also continues to offer a sustainable pathway for intensification, delivering multiple benefits including improved soil fertility, enhanced microclimates, and diversified income streams. Its adoption in SSA has been linked to improved rural livelihoods and landscape restoration, particularly in smallholder systems [144]. Integrated crop-livestock systems are similarly central to sustainable farming in SSA. These systems support nutrient recycling, minimize external input dependence, and increase resilience by diversifying food and income sources. As Ref. [20] highlighted, crop-livestock integration enhances agro-ecosystem services and contributes to long-term food system sustainability under changing climatic conditions.

Equally transformative is the growing use of digital and climate-smart technologies to monitor soil and water use, optimize irrigation, and guide adaptive responses. Innovations such as remote sensing, digital weather advisories, and localized water-saving systems have proven to be effective in increasing water productivity and climate resilience among smallholder farmers in SSA [145]. In Ethiopia, the integration of climate-smart practices into key agricultural value chains helps de-risk investments and boosts adaptive capacity in both lowland and highland farming systems [11,146,147]. These examples collectively underscore that sustainable agricultural innovation in SSA must integrate ecological, technological, and institutional elements to build systems that are productive, resilient, and inclusive.

9.3. Recommendations for Policy Makers, Researchers, and Practitioners

A successful transition toward climate-resilient and sustainable agriculture in SSA necessitates coordinated action across policy, research, and practitioner domains. Policymakers must prioritize inclusive, context-sensitive policies that secure land tenure, reform input subsidies to favor sustainable practices, and expand access to climate information, extension, and finance. These actions are essential for addressing intersecting challenges related to climate vulnerability, socioeconomic marginalization, and institutional inertia [124,148,149].

Researchers play a pivotal role in producing and translating robust context-specific knowledge into actionable policy and practice. Participatory and interdisciplinary approaches, engaging agronomists, economists, climate scientists, and sociologists, are critical for co-designing adaptive solutions with farmers, especially women and youth. Research indicates that integrating these elements boosts the adoption of SAP and strengthens system resilience [20,129,150]. Practitioners, including extension agents, NGOs, and community-based organizations, must operationalize these policies by delivering inclusive training, on-farm demonstrations, and peer-to-peer learning platforms. Their grassroots proximity makes them uniquely positioned to institutionalize sustainable practices while ensuring gender equity and local relevance [151].

Development partners such as the Food and Agriculture Organization, IFAD, and World Bank must support multilevel strategies through concessional finance, infrastructure investment, and regional knowledge exchange. High-impact innovations such as farmer-led seed systems, decentralized solar storage, and adaptive farmer field schools should be prioritized for scaling [124,152]. Ultimately, building resilient food systems in SSA hinges on the alignment of science, policy, and practice. The future of agriculture lies not in fragmented interventions but in synergistic, inclusive systems that empower smallholders while addressing ecological limits.

9.4. Phased Implementation Pathway for SAP Scaling

To operationalize the policy recommendations, a sequenced implementation pathway is proposed, grounded in Africa's existing agricultural development frameworks, including the Comprehensive Africa Agriculture Development Programme (CAADP), Agenda 2063 [153], and the Food and Agriculture's Climate-smart Agriculture Sourcebook. This phased approach is designed to accommodate varying institutional capacities across the SSA.

Short-Term Goals (1–3 years)

- Train decentralized SAP facilitators and utilize digital platforms to deliver localized climate-smart advisories.
- Roll-out input voucher schemes, climate-risk insurance, and blended finance models tailored to smallholders.
- Integrate SAP objectives into the revised National Agricultural Investment Plans (NAIPs) under CAADP.

Medium-Term Goals (4–7 years)

- Implement regional agro-zoning and SAP suitability mapping for data-driven planning.
- Scale gender-sensitive and youth-responsive SAP incentives aligned with regional economic community (REC) adaptation priorities.
- Develop district-level SAP performance metrics embedded within existing agricultural monitoring and evaluation systems.

Long-Term Goals (8–15 years)

- Incorporate SAP resilience targets into pillar 1 (inclusive growth) and pillar 3 (environmental sustainability) of the African Union Agenda 2063.
- Establish region-wide carbon markets and climate-smart finance hubs through RECs.
- Operationalize a pan-African SAP observatory to harmonize reporting, track impact, and foster cross-country learning.

This phased structure offers a pragmatic, evidence-informed roadmap for scalable and inclusive SAP adoption across SSA.

9.5. Limitations

This review integrates various strands of evidence on SAPs. However, this study has some limitations. First, the narrative and integrative design of the review may be prone to publication bias, particularly due to the underreporting of unsuccessful pilot programs or null results in the gray literature. Second, the heterogeneity of data across different agroecological zones, languages, and research designs limits comparability, particularly in terms of yield response estimates and socioeconomic outcomes. Third, despite attempts to achieve regional balance, empirical gaps remain in Central Africa and the lowland agro-pastoral zones. Lastly, the projected claims regarding climate adaptation, scalability, and resilience are shaped by model assumptions that may not fully account for dynamic farmer behavior, institutional fragility, or future climatic volatility. These limitations highlight the necessity for longitudinal, gender-disaggregated, and system-level studies to improve the quality and applicability of evidence.

10. Conclusions

This review demonstrated that SAPs offer a transformative pathway toward climate-resilient and food-secure systems in SSA. Approaches such as CA, agroforestry, integrated crop-livestock systems, organic farming, and improved postharvest strategies can enhance soil fertility, water use efficiency, and agricultural productivity under variable climatic conditions. These practices mitigate climate impacts while contributing to biodiversity conservation, carbon sequestration, and agroecosystem resilience. Although the technical benefits of SAPs have been established, their adoption remains constrained by limited institutional capacity, inadequate credit access, weak extension services, knowledge gaps, and insecure land tenure. The exclusion of women, youth, and marginalized groups in agricultural planning hinders equitable participation and sustainability.

The development of climate-resilient crop varieties is critical for building adaptive capacity among smallholders and requires context-appropriate implementation strategies supported by participatory research and strong institutional frameworks. Future research should evaluate SAPs across diverse agroecological settings and assess ecological trade-offs using longitudinal studies. Innovations in crop breeding and integrated systems must align with local realities and incorporate social dimensions, such as land rights and gender roles, to ensure adoption.

A transdisciplinary approach is vital for systemic changes. Researchers should generate local evidence, whereas practitioners should facilitate technology transfer. Policymakers should create an enabling environment through regulations, subsidies, and tenure reform. International partners should complement these efforts through financing and policy support. Regional integration and multilevel capacity development are crucial.

To drive the real impact, SSA must focus on addressing implementation gaps. Integrating SAPs at a scale requires bold policy actions, farmer-led innovation, inclusive financing, and continuous monitoring. Stakeholders (governments, researchers, practitioners, and donors) must act in concert to dismantle systemic barriers and invest in scalable and locally grounded solutions. The region is at a crucial moment. Hence, with collective action, collaboration, and coordination, SSA can lead the global shift toward climate-resilient agri-food systems. The time to act is now.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17146259/s1, Figure S1: Structured summary of the literature screening process; Table S1: Inclusion and exclusion criteria used in the literature screening process; Table S2: Representative quality appraisal of key sources cited in the review. Entries include peer-reviewed, institutional, and gray literature sources categorized by design robustness, policy relevance, and regional applicability; Table S3: Directional evidence summary of selected studies evaluating SAP across SSA. The table summarizes reported yield and resilience outcomes, effect direction, and approximate magnitude. Reference [154] is cited in the Supplementary Materials.

Author Contributions: With the submission of this manuscript, we would like to state that this work is original and has been compiled by the authors. No part of this manuscript has been submitted or published elsewhere. O.O.O. conceived the idea, designed and wrote the first draft. O.O.O., O.A.F., L.J.S.B. and T.M. edited the article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partly funded by the Wellcome Trust through the Sustainable and Healthy Food Systems Project [Grant number: 205200/Z/16/Z]. For the purpose of Open Access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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