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Review

Unpacking Water Scarcity Adaptation Strategies for Sustainable Food Production Systems in Sub-Saharan Africa

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Abstract

Building resilient and sustainable food production systems is a major challenge in Sub-Saharan Africa (SSA) due to environmental, climatic, and economic pressures. Farmers in the region must adopt effective adaptation strategies to maintain productivity and contribute toward achieving the United Nations' Sustainable Development Goal 2, "Zero Hunger." Among these, water scarcity adaptation strategies are critical for building resilient food systems that also address poverty reduction. However, various obstacles hinder their widespread adoption, and documentation on these strategies remains fragmented. This paper examines available water scarcity adaptation strategies, the opportunities and challenges faced by farmers, and the policy and infrastructure implications for sustainable food production. The findings highlight the essential role of Indigenous Knowledge Systems (IKS) in adopting these strategies. IKS supports natural resource conservation, promotes inclusive market participation, strengthens institutional frameworks, and improves resource-use efficiency under climate stress. The paper recommends further research on transferring Indigenous Knowledge to future generations and exploring the role of policy in preserving and promoting IKS, especially within the SSA context. Emphasizing Indigenous Knowledge is crucial for creating sustainable, resilient agricultural systems that can thrive amid the region's growing environmental challenges.

Keywords: climate resilience; natural resource conservation; indigenous knowledge transfer; institutional frameworks; smallholder agriculture

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1. Introduction

Agricultural production in the SSA is increasingly constrained by water scarcity, which undermines yields, livelihoods, and progress toward Sustainable Development Goal 2 (Zero Hunger) [1–4]. Climatic variability, land degradation, and limited access to reliable irrigation combine to make water the single most binding constraint for many smallholder farming systems [5,6]. Although many studies [3,7,8] discuss technical solutions such as small-scale irrigation and rainwater harvesting, as well as various policy approaches, the contribution of locally embedded responses, especially IKS, has not yet been adequately synthesized across different contexts.

The review synthesizes empirical and policy literature from 2010 to 2025 to map the full spectrum of water scarcity adaptation strategies used by farmers in SSA; to identify the enabling conditions and barriers to uptake; and highlight policy and research priorities for scaling context-appropriate solutions. Unlike prior reviews [9,10] that focus narrowly on technological interventions or single countries, this paper integrates technological, biophysical and sociocultural adaptation practices with particular attention on IKS to offer a more holistic view of how smallholder systems adapt to water scarcity. Doing so highlights under-recognized complementarities among low-cost, locally adapted practices, and modern innovations, and identifies where policy or research support can unlock greater resilience.

And thus, the paper's novelty lies in gathering evidence on IKS, small-scale irrigation, digital climate services and institutional frameworks into a unified synthesis that explicitly examines interactions across these categories and their implications for inclusive, scalable water scarcity adaptation in SSA.

2. Water Scarcity Adaptation: Theory of Change (ToC)

This review is guided by the Theory of Change (ToC) approach to climate adaptation. The ToC provides a structured way of linking interventions to outcomes by making explicit the pathways, assumptions, and feedback through which adaptation strategies are expected to deliver resilience and long-term impact [11]. Applied to the context of agricultural water scarcity in SSA, the framework situates adaptation practices (ranging from IKS and small-scale irrigation to digital tools and institutional reforms) as the inputs or activities that initiate change. These inputs generate immediate outputs such as improved access to water, strengthened farmer knowledge, and/or the formation of water user associations, which in turn contribute to intermediate outcomes like reduced vulnerability, enhanced adaptive capacity, and strengthened governance systems.

The framework also highlights the importance of tracing these outcomes to their intended long-term impacts [12]. Ultimately, adaptation interventions are expected to improve household well-being, stabilize agricultural productivity, reduce losses from climate shocks, and promote equitable and sustainable resource use. However, the ToC outlook reminds researchers, farmers, and agricultural stakeholders that these causal chains are not automatic as they rest on specific assumptions and are subject to contextual risks. For instance, the effectiveness of irrigation assumes the availability of reliable water sources and functioning maintenance systems, while the success of digital advisory services depends on connectivity, literacy, and trust [13,14]. Similarly, the adoption of drought-tolerant crops presumes functioning seed systems and supportive markets. Through the explicit identification of these assumptions, the framework underscores the need for critical appraisal of both the evidence base and the contextual conditions that shape adaptation outcomes.

Using this theoretical framing, the review evaluates not only whether strategies exist but also how well they align with resilience theory and broader adaptation debates. Practices can be located along a range of resilience capacities which are, namely, absorptive (buffering immediate shocks), adaptive (enabling flexible responses to variability), and transformative (driving structural change in systems and institutions). Positioning strategies within this framework allows for a deeper scientific and scholarly contribution, as it shows how interventions interact across scales and where they fall short of delivering durable resilience. This theoretical grounding strengthens the analysis by linking descriptive evidence on adaptation practices to broader conceptual debates on climate resilience, while also providing a basis for identifying gaps, limitations, and priorities for future research and policy action.

3. Review of Literature

Water scarcity is a critical threat to sustainable agriculture and food systems in SSA, where farmers remain among the most vulnerable actors in the agricultural value chain. In response, farmers employ a wide range of adaptation strategies that include IKS, small-scale irrigation, rainwater harvesting, soil moisture conservation, and the cultivation of drought-resistant and indigenous crops. These strategies are reinforced by government interventions through policy frameworks, extension services, infrastructure, and the digitalization of agriculture, creating a mosaic of responses shaped by both local realities and institutional support.

Rainwater harvesting and soil moisture conservation have become indispensable in regions with sporadic rainfall. Practices such as water pans, rock catchments, and rooftop tanks are common in Kenya and Ethiopia [15,16], supported by mulching, tied ridges, and contour bunds that improve infiltration, reduce runoff, and retain soil moisture [17]. These methods offer dual benefits by enhancing crop productivity and restoring degraded ecosystems, although adoption remains uneven. Many farmers prioritize short-term food needs over long-term ecological gains [18,19], yet evidence shows that farmer-led innovation and extension support significantly increase uptake. Similarly, drought-resistant and indigenous crops such as sorghum, millet, cowpea, and amaranth offer resilience under low-water conditions [20,21] while also providing nutritional advantages [22]. Their cultural embeddedness lowers behavioral barriers to adoption, but marginalization in seed systems and markets has constrained their potential [23]. Expanding their use requires stronger seed systems, nutrition education, and market development [24].

Policy and institutional frameworks are equally vital. Kenya's Water Act and Ethiopia's Climate Resilient Green Economy framework illustrate national efforts to embed water security into development planning [25,26]. Regional collaborations, such as those under the Southern African Development Community (SADC), demonstrate recognition that water management must transcend political borders [27]. However, fragmented institutions, weak enforcement, and parallel statutory and customary systems undermine effective governance [28–30]. Without coherence and participatory governance, well-designed policies risk failing at the point of implementation.

Adaptation strategies are therefore diverse, complex, and interconnected. Their strength lies less in isolated interventions than in their complementarity, where indigenous practices, modern technologies, and institutional frameworks reinforce one another. Yet several challenges persist. Fragmented governance remains a key barrier, with overlapping mandates across government levels creating regulatory confusion and mismatched priorities [31,32]. Disconnection between statutory laws and customary rights further complicates water governance [33–35]. Technical and infrastructural limitations also constrain adaptation: many extension officers lack specialized training [36–39], and rural communities often lack roads, electricity, or storage facilities [40,41]. Imported technologies are sometimes poorly adapted to local contexts, leading to abandonment [42].

Financial constraints add another obstacle. Smallholders rarely afford upfront costs for water infrastructure or improved seeds [42,43], while credit facilities carry high interest rates and are poorly tailored to seasonal incomes. Markets often fail to reward climate-resilient crops [44], as staples such as maize and wheat dominate [10]. Sociocultural barriers also play a role: crops like millet and cowpea are still stigmatized as "poor man's food" [45,46], while youth may dismiss indigenous practices as outdated [47]. Behavioral inertia further reduces willingness to adopt unfamiliar methods [48]. Climate uncertainty and environmental degradation compound these barriers, with increasingly unpredictable rainfall, droughts, and degraded ecosystems undermining adaptation measures [10,49,50].

Despite these challenges, important opportunities exist. Revitalizing indigenous knowledge and agroecological practices has gained momentum, supported by research and policy integration [51,52]. Scaling up Zai pits, mulching, and intercropping demonstrates the potential of locally adapted low-cost approaches [53]. At the same time, technological innovation and digital tools offer new opportunities. Mobile platforms provide farmers with weather forecasts, irrigation schedules, and market prices [34,54,55], while advances in solar energy, precision agriculture, and remote sensing improve water-use efficiency and monitoring [56]. Policy reform and investment momentum are also significant. Initiatives such as the Comprehensive Africa Agriculture Development Programme (CAADP) and global climate funds increasingly channel resources into water-smart agriculture [57–63]. Youth engagement further enhances long-term sustainability, as younger generations are more receptive to digital technologies and climate-resilient practices [1,64–66]. Finally, community-based adaptation, including farmer field schools and watershed committees, strengthens ownership, accountability, and social cohesion [67–69].

In sum, adaptation in SSA is not a one-size-fits-all process but a dynamic, evolving set of strategies that draw on local knowledge, modern innovations, and supportive policies. The literature shows that while technical, financial, and institutional barriers persist, the opportunities created by agroecology, digital transformation, policy reforms, youth engagement, and participatory governance provide a strong foundation for building climate-resilient and equitable food systems across the region.

4. Methodology

This study made use of a systematic review guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework [70,71] to identify, select, and synthesize adaptation strategies to water scarcity in the SSA agriculture. The aim was to comprehensively map peer-reviewed and high-quality gray literature that explores both technological and indigenous adaptation approaches, their implementation contexts, and effectiveness. A systematic review was deemed appropriate due to the growing and fragmented body of literature on climate adaptation, which requires consolidation to inform policy, practice, and future research. The review adhered to the four PRISMA phases: identification, screening, eligibility, and inclusion [72]. The protocol for this review was designed prior to the literature search, outlining the review objectives, inclusion/exclusion criteria, databases, and data extraction strategy to enhance transparency and reproducibility (see Figure 1 below).

A structured and comprehensive search was conducted across six electronic databases: Scopus, Web of Science, Google Scholar, JSTOR, FAO's Open Knowledge Repository, and CGSpace (a repository of the Consultative Group on International Agricultural Research (CGIAR)). The search string included keywords and Boolean operators such as water scarcity, drought, adaptation, resilience, agriculture, farming systems, and SSA. Literature published between January 2010, and April 2025 was included to capture both historical and contemporary adaptation insights. After removing duplicates, a total of 419 records were retrieved. Titles and abstracts were screened for relevance, after which full-text articles and reports were assessed against predefined inclusion criteria: (1) relevance to agricultural water scarcity adaptation in SSA; (2) description of adaptation strategies or enabling frameworks; and (3) empirical, theoretical, or policy-driven orientation. The studies/articles or publications reviewed in the study were broken down into theme to streamline the results as highlighted in Table 1.

Table 1. Summary of studies included per theme and their total.

Theme	Number of Articles Reviewed
Rainwater harvesting and soil moisture conservation	22
Drought-resistant and indigenous crops	20
Policy and institutional frameworks	27
Indigenous Knowledge Systems (IKS)	17

Table 1. *Cont.*

Theme	Number of Articles Reviewed
Digital tools and technological innovations	18
Challenges of adaption	38
Opportunities for adaption	28

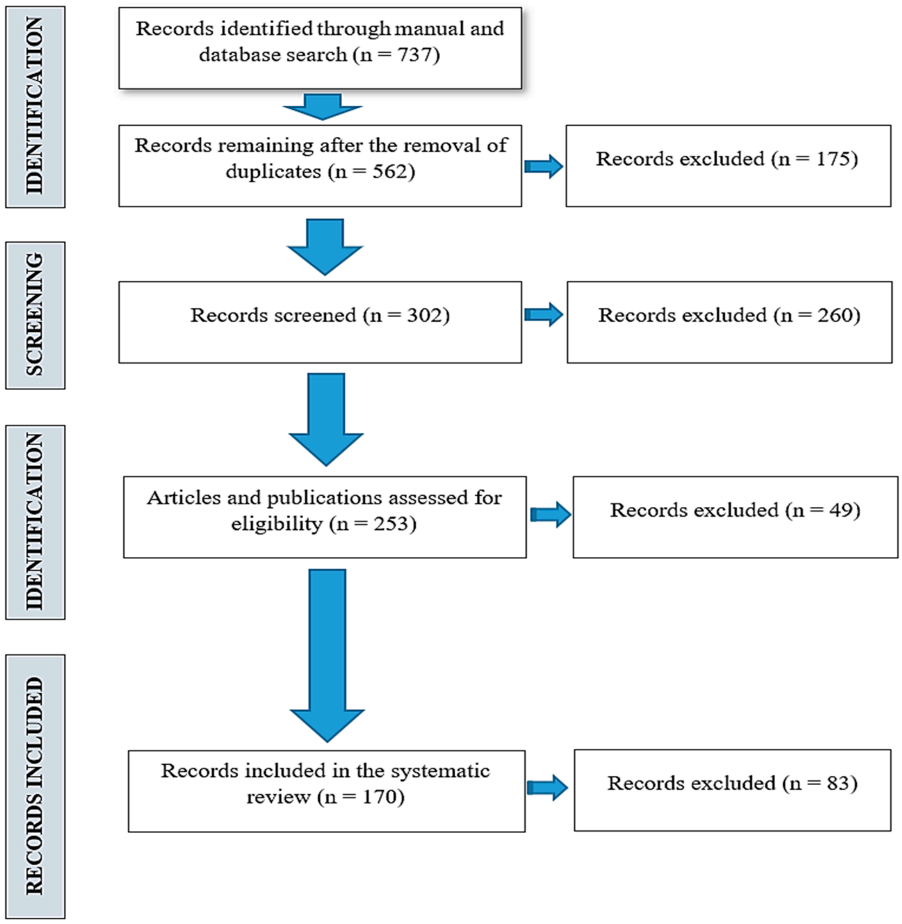

Figure 1. Flowchart indicating the inclusion criteria.

Studies focusing solely on urban or industrial water use or lacking methodological clarity were excluded to maintain a targeted synthesis of farm-level and rural community adaptation relevant to food production. This exclusion of urban or industrial water use was motivated by looking at urban water governance, infrastructure financing and demand management dynamics (such as municipal utilities, piped networks, industrial allocation) differ qualitatively from rural smallholder contexts. As such, the inclusion of urban literature would have conflated governance and technological solutions tailored to cities with those applicable to dispersed or marginalized agricultural households, weakening the review's practical relevance to agricultural policy and extension.

However, this exclusion narrows the review's scope and creates limitations by reducing the coverage of peri-urban cropping systems and urban agriculture (which may share hybrid features), and it omits lessons from urban water management innovations (such as large-scale stormwater capture) that could be adapted for community-level water banking.

Moreover, the data extraction was conducted using a standardized matrix capturing publication year, country or region, the type of adaptation (for example, indigenous, institutional, technological), stakeholder involvement, reported outcomes, and challenges or enablers. The final synthesis was performed using narrative and thematic analysis, with strategies grouped under six emergent categories: IKS, Small-Scale Irrigation, Rainwater Harvesting and Soil Moisture Conservation, Drought-Tolerant and Indigenous Crops, Policy and Institutional Frameworks, and Digital Tools for Climate Information Services. Cross-cutting themes such as institutional coordination, capacity constraints, and gender inclusivity were also identified. This approach ensured that both converging and diverging perspectives across the selected studies were preserved, enhancing the robustness of the findings.

5. Results and Discussion

5.1. Unpacking the Water Scarcity Adaptation Strategies in Sub-Saharan Africa

Sub-Saharan Africa (SSA) faces growing water stress driven by climate change, environmental degradation, and socioeconomic pressures as mentioned in the previous sections. As rainfall patterns become more erratic and dry seasons lengthen, farming communities are turning to a range of adaptation strategies to sustain their livelihoods and food systems. Among these, locally grounded approaches rooted in IKS are emerging as essential tools for resilience. These include time-tested practices such as zai pits in Burkina Faso and the matengo system in Tanzania, which conserve water, improve soil health, and foster social cohesion [73]. However, such practices often remain overlooked in policy and development agendas.

In parallel, small-scale irrigation systems are gaining traction as affordable, decentralized alternatives to large infrastructure projects. Technologies like treadle pumps and solar kits enable farmers to extend growing seasons and diversify crops, although maintenance and water governance remain ongoing challenges [74]. Complementary strategies discussed below such as rainwater harvesting, soil moisture conservation, and conservation agriculture further enhance water use efficiency and drought preparedness. Promoting drought-tolerant and indigenous crops also reduces the water footprint of agriculture while boosting nutrition. Despite clear benefits, these approaches face barriers including labor demands, limited support, and cultural biases.

5.1.1. Indigenous Knowledge Systems an Anchor for Farmer Resilience

Indigenous Knowledge Systems are widely recognized as an important foundation for water scarcity adaptation in SSA. Practices such as Zai pits in Burkina Faso and the Matengo pits of Tanzania exemplify low-cost, context-specific techniques that enhance soil fertility, improve water infiltration, and sustain productivity in marginal environments [73]. These systems are notable for their participatory and locally embedded nature as they are often transmitted intergenerationally and require little external investment [75]. This makes them attractive for smallholders who lack access to formal irrigation or modern technologies.

Despite these strengths, the evidence base remains uneven. Much of the literature provides rich descriptive accounts of these practices but rarely evaluates outcomes with rigorous, quantitative methodologies [76–78]. Systematic yield measurements, cost-effectiveness comparisons, or long-term sustainability data across multiple agroecological zones is less reported. As a result, while the effectiveness of IKS is widely asserted, the quality of the supporting evidence is often anecdotal or case-specific, which limits the ability to generalize findings across the region [79].

A further limitation is the vulnerability of IKS under conditions of rapid environmental and social change [80]. Climate non-stationarity means that ecological cues historically used to forecast rainfall may no longer hold, and intergenerational knowledge transfer is weakening as younger generations migrate or adopt different livelihood strategies [81]. Moreover, IKS often remain marginalized in formal policy and extension systems, reducing their recognition and scalability. To strengthen this area, future research should employ mixed-methods evaluations that quantify agronomic outcomes while also documenting the sociocultural processes that support knowledge transmission.

5.1.2. Small-Scale Irrigation as a Decentralized Water Security Strategy

Small-scale irrigation, including treadle pumps, solar-powered drip systems, and community-managed schemes, is often highlighted as a transformative strategy for mitigating water scarcity [82]. Evidence from pilot projects and country-specific initiatives demonstrates that irrigation can extend growing seasons, enable crop diversification, and increase household income [83,84]. For many farmers, access to reliable water supply translates directly into reduced vulnerability to rainfall variability and improved food security.

However, the evidence base in the reviewed studies included in this paper is not consistently robust. While some evaluations show yield improvements and income gains, these are frequently based on small samples, case studies, or project reports with limited external validity. Few studies provide longitudinal data on system sustainability or measure potential trade-offs, such as the impact on groundwater levels or downstream water availability [85]. As a result, while irrigation appears effective in the short term, its broader environmental and social consequences remain insufficiently examined.

Contextual barriers further limit widespread adoption. The high upfront costs of pumps and drip systems often exclude the poorest households, while inadequate maintenance services and lack of spare parts lead to frequent system abandonment [86]. There is also an equity dimension as better-off farmers are typically the first to benefit, which risks widening existing socio-economic gaps. Moreover, poorly managed irrigation can result in salinization, waterlogging, or unsustainable extraction [87]. Addressing these challenges requires integrated studies that assess not only productivity but also equity and environmental sustainability, coupled with governance mechanisms to ensure fair access and long-term viability.

5.1.3. Rainwater Harvesting and Soil Moisture Conservation as Water Banking Tools

Rainwater harvesting and soil-moisture conservation techniques, such as contour bunds, rock catchments, mulching, and tied ridges, are promoted as low-cost and widely accessible solutions for managing scarce rainfall [75]. When implemented effectively, these methods improve infiltration, enhance soil water retention, and provide critical buffers during dry spells. The reviewed literature presents several examples where these interventions have led to improved crop performance and greater resilience to seasonal variability [88].

Nevertheless, the strength of the supporting evidence is variable. Much of it derives from localized case studies or programmatic reports rather than comparative, peer-reviewed evaluations [89–91]. In many instances, outcomes are described in general terms, such as “improved yields” or “greater resilience” without providing detailed metrics or counterfactual analyses [92,93]. This weakens the empirical basis for claiming effectiveness, especially when attempting to generalize across highly diverse agroecological contexts.

Adoption of rainwater harvesting also faces significant challenges. These practices are labor-intensive and require upfront investment, which may discourage resource-constrained households. Furthermore, their success is highly dependent on rainfall timing and distribution: if rain is delayed or fails, constructed pans and bunds provide little benefit. Long-term sustainability is also uncertain, as structures require ongoing maintenance that is not always feasible for smallholders. To address these gaps, future work should establish standardized monitoring protocols that assess water capture efficiency, cost-effectiveness, and crop yield responses under different climate scenarios.

5.1.4. Drought-Resistant and Indigenous Crops for Climate-Smart Nutrition

The promotion of drought-tolerant crops such as sorghum, millet, cowpea, and indigenous leafy vegetables has been identified as a promising strategy for coping with water scarcity [10]. These crops require less water than maize or rice, and many offers nutritional advantages that can strengthen household food security as presented in Table 2 below [25]. Studies reviewed highlight cases where smallholders who adopted these crops were less vulnerable to rainfall variability and experienced more stable production in dry years [94–96].

Table 2. Nutritional benefits of indigenous and drought-tolerant African crops.

Crop	Energy (Kcal)	Protein (g)	Iron (mg)	Calcium (mg)	Fiber (g)
Sorghum	329	11.3	4.4	28	6.3
Pearl Millet	378	11.8	8.0	42	8.5
Finger Millet	336	7.3	3.9	350	11.0
Cowpea (seeds)	343	24.1	8.3	110	10.7
Amaranth (leaves)	23	2.5	2.3	215	2.1
African Yam Bean	338	19.0	6.0	130	5.0

The agronomic evidence supporting drought tolerance is generally solid, but the literature reviewed often neglects the socio-economic dimensions [97–99]. There is limited analysis of market demand, price stability, and consumer acceptance, which are factors that strongly influence whether farmers adopt these crops beyond subsistence purposes [100]. While some projects report yields' benefits [101,102], few assess profitability in relation to input costs, or compare returns to those of other crops under real market conditions [103,104]. Without addressing these gaps, the long-term economic viability of drought-tolerant crops remains uncertain.

Adoption is further constrained by systemic challenges as formal seed systems for indigenous crops remain underdeveloped, and many farmers rely on informal seed exchange networks, which can limit access to high-quality or improved varieties [105]. Cultural perceptions also play a role as in some communities, indigenous foods are stigmatized as "poor people's food," reducing market incentives [106]. Expanding adoption will therefore require not only agronomic research but also interventions along the value chain, including seed system development, consumer education, and efforts to create sustainable markets for these crops.

5.1.5. The Use of Digital Tools in Combating Water Scarcity in SSA

Digital technologies are increasingly recognized as critical enablers of agricultural adaptation in SSA, particularly in response to water scarcity [107]. Mobile phones, remote sensing platforms, and internet-based applications provide farmers with timely climate and water information that was previously inaccessible. Services such as SMS-based weather advisories and market updates (for example, Esoko in Ghana and M-Farm in Kenya) allow farmers to make informed decisions about planting dates, crop selection, and the allocation of scarce water resources [108]. Remote sensing technologies and geographic information systems (GIS) further enhance the monitoring of rainfall variability, soil moisture, and water availability at scales relevant to smallholder decision-making, offering opportunities for early warning and proactive risk management [109].

The value of these tools lies in their capacity to reduce uncertainty. Accurate short-term forecasts, combined with seasonal climate outlooks, enable farmers to adjust planting schedules and adopt water-efficient practices before water stress becomes critical. In many cases, digital tools complement IKS by combining local experiential insights with scientific data. This integration improves both the precision and the acceptance of adaptation measures. Furthermore, digital innovations can be scaled efficiently; once the necessary infrastructure is established, services can be delivered to large numbers of farmers at relatively low marginal cost [110].

Despite these advantages, the adoption and impact of digital tools remain uneven across the region. Structural barriers such as limited network coverage, low levels of digital literacy, affordability constraints, and gendered access to mobile technology often exclude the most vulnerable populations [111]. Research also shows that farmers may receive weather information but do not consistently act on it unless the information is locally relevant, easy to interpret, and provided in a trusted format [112,113]. This suggests that information provision alone is insufficient to drive behavioral change. Effective use of digital tools requires parallel investments in agricultural extension, training, and mechanisms that translate forecasts into actionable advice at the farm level.

Maximizing the contribution of digital tools to water scarcity adaptation will require deliberate attention to inclusivity and integration. Programs must be designed to accommodate linguistic, cultural, and literacy differences in order to reach diverse farming populations. Strong partnerships between governments, private providers, and local institutions are also needed to ensure trust, data reliability, and equitable access. In addition, rigorous impact evaluations are necessary to move beyond anecdotal reports and establish clear evidence of how digital services influence yields, household incomes, and water-use efficiency. Addressing these challenges will allow digital tools to progress from promising innovations to established components of climate-resilient agriculture in SSA.

5.1.6. Legislative Framework on Agricultural Water Use in SSA

- West Africa

In West Africa, the management of agricultural water resources is primarily guided by the West Africa Water Resources Policy (WAWRP), developed by Economic Community of West African States (ECOWAS) in collaboration with West African Economic and Monetary Union (UEMOA) and Permanent Interstate Committee for Drought Control in the Sahel (CILSS) [114,115]. Adopted in 2008, this policy emphasizes integrated water resources management (IWRM) to ensure equitable access, enhance agricultural productivity, and protect ecosystems [116]. It serves as a foundational document for harmonizing national policies and promoting regional cooperation in water management.

Complementing the WAWRP, the ECOWAS Agricultural Policy (ECOWAP) addresses the challenges of food security and agricultural development in the region [117]. Revised in 2016, ECOWAP incorporates climate change considerations and aims to improve agricultural productivity through sustainable water use practices [118]. The policy framework encourages member states to adopt strategies that integrate water management with agricultural development.

At the national level, countries like Ghana and Côte d'Ivoire have enacted specific laws to regulate water use in agriculture [119,120]. These laws typically require farmers to obtain permits for irrigation and impose restrictions to prevent over-extraction of water resources. However, enforcement remains a challenge due to limited resources and capacity at the local level.

- East Africa

East Africa's approach to agricultural water management is characterized by a mix of regional cooperation and national legislation. The East African Community (EAC), comprising Kenya, Uganda, Tanzania, Rwanda, Burundi, and South Sudan, has developed a regional framework to promote sustainable water use in agriculture [121]. This framework encourages member states to harmonize their water policies and share best practices in water management.

Nationally, countries have enacted specific laws to govern agricultural water use. For instance, Kenya's Water Act of 2002 established the Water Resources Management Authority (WRMA) to regulate and manage water resources, including those used for irrigation [122]. Similarly, Uganda's Water Act (Cap 152) provides for the use, protection, and management of water resources, with provisions for licensing water use in agriculture [123,124]. These laws aim to ensure that water resources are used efficiently and equitably in the agricultural sector.

Despite these legal frameworks, challenges persist in enforcement and capacity building. Inadequate infrastructure, limited technical expertise, and competing demands for water resources often hinder effective implementation of water management policies. Addressing these challenges requires strengthening institutional frameworks, improving data collection and monitoring systems, and enhancing public awareness on sustainable water use practices.

- Central Africa

In Central Africa, the Economic Community of Central African States (ECCAS) adopted a Regional Water Policy in 2009 to promote integrated water resources management (IWRM) across member states [114]. This policy emphasizes the sustainable and equitable use of water resources, with a focus on agriculture as a key sector for development. It encourages countries to adopt national policies that align with regional objectives and to collaborate on transboundary water management.

To operationalize the regional policy, ECCAS developed the Regional Action Plan for Integrated Water Resources Management in 2014 [125]. This plan outlines strategic orientations and actions to address water-related challenges in the region, including those affecting agricultural water use [126]. It aims to enhance cooperation among member states, improve infrastructure, and promote sustainable agricultural practices.

At the national level, countries like Cameroon and the Central African Republic have established laws and institutions to manage water resources. For example, Cameroon has a Water Law that regulates the use of water resources, including for irrigation, and establishes the National Water Board to oversee water management [127]. However, implementation remains uneven, and capacity constraints at the local level impede effective management of agricultural water use.

- Southern Africa

The SADC has established a comprehensive Regional Water Policy (RWP) to guide the sustainable and equitable use of water resources across its member states [128]. Adopted in 2002, the RWP emphasizes integrated water resources management (IWRM) and highlights water as a social good essential to human dignity and well-being. It underscores the importance of prioritizing water allocation for basic human needs before considering its use for productive purposes, including agriculture.

Complementing the RWP, SADC's Revised Protocol on Shared Watercourses (2000) provides a legal framework for the equitable and reasonable utilization of transboundary water resources [129]. This protocol is particularly pertinent in Southern Africa, where many countries share river basins such as the Zambezi, Limpopo, and Orange-Senqu [130]. The protocol facilitates cooperation among member states to manage these shared resources effectively, ensuring that agricultural water use does not compromise the needs of other sectors or countries.

At the national level, countries within the SADC region have enacted various laws and policies to regulate agricultural water use. For instance, Zimbabwe's Water Act (1998) governs the allocation and use of water resources, including those for irrigation [131]. Similarly, Zambia's Water Resources Management Act (2011) establishes a framework for the sustainable management of water resources, with provisions for agricultural water use [132]. These national laws are designed to align with regional frameworks, promoting consistency and cooperation in managing water resources for agriculture across the Southern African region.

5.2. Implications for Sustainable Food Production Systems in SSA

Rising temperatures, erratic rainfall, and ongoing environmental degradation are making it increasingly difficult for farmers in SSA to sustain their livelihoods. Conventional agricultural models, which depend on costly inputs and imported technologies, are proving less effective and less accessible for smallholder farmers. In response, more locally grounded and environmentally sustainable strategies are gaining traction. Adaptation approaches rooted in indigenous knowledge, which improve soil health, conserve water, and reduce reliance on external inputs, are helping farming communities become more resilient, inclusive, and productive [133].

This discussion explores four key areas where such strategies are shaping more sustainable and climate-resilient food systems. These include improving agroecological resilience, supporting inclusive economic growth, strengthening institutional support, and enhancing food and nutrition security. Collectively, these approaches offer a promising pathway for building food systems that can adapt to climate challenges while remaining rooted in local knowledge and ecological sustainability.

5.2.1. Enhancing Agroecological Resilience and Resource Efficiency

One of the most immediate implications is the strengthening of agroecological resilience. Indigenous practices, drought-tolerant crops, and soil moisture conservation techniques promote farming systems better adapted to water stress and climate variability [10]. These approaches lessen the reliance on external inputs like synthetic fertilizers and heavy irrigation resources, which are often out of reach for the majority if smallholder farmers and not always environmentally sustainable. Instead, they draw on local knowledge and available materials, which helps cut costs and minimize environmental harm. Improving soil health, encouraging biodiversity, and enhancing water retention create a strong foundation for regenerative farming systems [134]. Soils in better condition retain more moisture and nutrients, foster richer microbial life, and provide greater resilience against climate-related stress [135].

This further enables continuous cropping with less yield volatility, which is vital for communities living in chronically food-insecure regions. By improving water-use efficiency, these systems also contribute to conserving groundwater and reducing the stress on already overburdened water catchments [6]. Over time, this helps build a more stable and self-sufficient farming system less exposed to outside disruptions. Just as important, bringing indigenous knowledge back into practice restores a more profound sense of environmental responsibility [136]. When farmers rely on methods that reflect their cultural and spiritual values, they are more inclined to care for and preserve natural resources. This behavioral side of adaptation often gets overlooked, yet ensuring interventions last and truly take root is vital. Therefore, a sustainable food system is defined not only by what is produced or consumed but also by how production interacts with a place's cultural and ecological integrity [137].

5.2.2. Promoting Inclusive Economic Growth and Market Integration

Water scarcity adaptation strategies also significantly affect rural livelihoods and inclusive economic development [135]. Small-scale irrigation and climate-resilient crops provide pathways for diversification and income generation [136]. When farmers can produce vegetables, fruits, or indigenous grains during the dry season or in water-scarce areas, they open new marketing windows and price premiums that were previously inaccessible. This seasonal production shift helps to stabilize household incomes and reduce vulnerability to food price volatility.

More importantly, these strategies directly support marginalized groups, especially women and young people. Women (who are often responsible for home gardens and small plots) gain from crops and techniques that reduce water use and lighten labor demands [137]. Likewise, many drought-tolerant crops have shorter growing seasons, making it easier to stagger planting and harvesting in ways that fit household duties or off-farm work [138]. When adaptation strategies are designed with these groups in mind, food systems become more resilient, inclusive, and productive.

Still, one of the key hurdles that remains is access to markets. The economic benefits of sustainable adaptation strategies can only be realized if enabling conditions such as transport infrastructure, market information systems, and supportive policies for local value chain development [139]. Farmers risk staying locked in subsistence farming without these supports, with little opportunity to sell their surplus or scale up. That is why sustainable food production should not be viewed in isolation as it is part of a broader development system that depends on infrastructure, access to finance, and strong institutional backing.

5.2.3. Strengthening Institutional Legitimacy and Adaptive Governance

A third point is how governance and institutional strength shape the path toward sustainable food systems [140]. When adaptation strategies are included in national policies, like agriculture, water management, or extension services, it helps to legitimize those efforts and makes it easier to scale them up. If governments recognize the importance of indigenous knowledge or put money into smallholder irrigation, it shows they are serious about inclusive, climate-resilient development [141]. That commitment builds trust and encourages more farmers to get on board.

Strong governance also helps prevent conflict. Water shortages in many parts of SSA can lead to disputes between groups, like upstream and downstream users, farmers and herders, or even neighboring villages [142]. Setting up local systems like water user groups or catchment committees creates a space for people to talk, settle disputes, and manage resources together [143]. These platforms give communities a voice, help set fair rules, and allow people to work together in managing shared water sources. It strengthens both social ties and environmental stewardship.

At the same time, digital tools and climate services are changing how people access and act on information. When farmers can get accurate weather forecasts, early warnings, or advice through mobile platforms, they can plan better and avoid some of the risks [144]. The institutions that provide these tools become more connected to the people they serve and can step in more quickly when things go wrong. Over time, these efforts do not build stronger farming systems and create institutions that can learn, adapt, and respond to the changing climate.

5.2.4. Advancing Food and Nutrition Security Under Climate Stress

The final and arguably most important point is how these adaptation strategies help ensure food and nutritional security as the climate becomes more unpredictable. By encouraging more diverse cropping systems, especially ones that include indigenous and less commonly grown crops, SSA can simultaneously tackle different aspects of malnutrition [145]. Many of these crops have higher levels of protein, vitamins, and minerals than the major staples, and they tend to fit better with local diets and food cultures [146].

Better water management through harvesting and conservation also plays a key role. It supports the growth of perishable but highly nutritious foods like leafy greens, legumes, and fruits [147]. These are often the first to disappear from household diets during dry spells simply because they require more water. Nevertheless, when water is more reliably available, families can grow and eat various foods year-round, improving nutrition and health. This has lasting effects, not just on physical growth in children but also on maternal health, brain development, and people's ability to work productively [148].

There is also a deeper issue at play. Food security is not only about calories but about dignity and self-reliance [149–154]. When communities adapt in ways that reduce their dependence on food aid or imports, they regain some control over how they feed themselves [155]. In a region where hunger and marginalization in agriculture have been long-standing problems, bringing back traditional crops, practices, and knowledge is more than just a strategy, it is a statement. It shows that sustainability is not just about weathering the next drought. It is about restoring the ability to grow food with confidence, resilience, and pride.

5.2.5. Digital Tools and Their Effects on Improved Food Systems in SSA

The integration of digital tools into agricultural adaptation strategies has several important implications for food systems in SSA. At the production level, access to timely and localized climate and water information enables farmers to make more precise decisions about planting schedules, irrigation, and crop choices [156]. This reduces the risk of crop failure during periods of rainfall variability and promotes more efficient use of scarce water resources. Over time, such improvements in decision-making can enhance productivity and stabilize yields, which are critical foundations for food system resilience.

At the systems level, digital platforms contribute to greater connectivity between producers, markets, and institutions [157]. Mobile applications that provide price information or link farmers to buyers can strengthen value chains and reduce information asymmetries, thereby improving farm incomes and incentivizing the adoption of climate-resilient practices. In addition, digital monitoring tools support policymakers and extension agents by supplying real-time data on weather patterns, soil moisture, and water availability [158]. This strengthens institutional capacity to anticipate shocks, coordinate responses, and design evidence-based interventions.

However, the benefits of digital tools are not automatically distributed across all groups as highlighted in Figure 2 that not the entire population of SSA makes full use of digital technology. Inequalities in access to mobile technologies and digital literacy mean that women, youth, and the poorest farmers are at risk of exclusion [159]. If these disparities are not addressed, digital innovations could reinforce existing structural inequalities within food systems. Furthermore, the reliability of information and trust in its accuracy are essential for behavioral change. Without careful tailoring to local contexts, the information provided may remain underutilized, limiting the potential impact on food security.

Taken together, the implications of digital tools for food systems in SSA are twofold. On one hand, they present a significant opportunity to enhance productivity, strengthen value chains, and support adaptive governance, thereby advancing progress toward resilient and sustainable food systems. On the other hand, their effectiveness depends on addressing barriers of access, inclusivity, and institutional integration. Future strategies should therefore prioritize not only the technological dimension but also the social and policy frameworks that ensure digital tools contribute to equitable and climate-resilient food systems in the region.

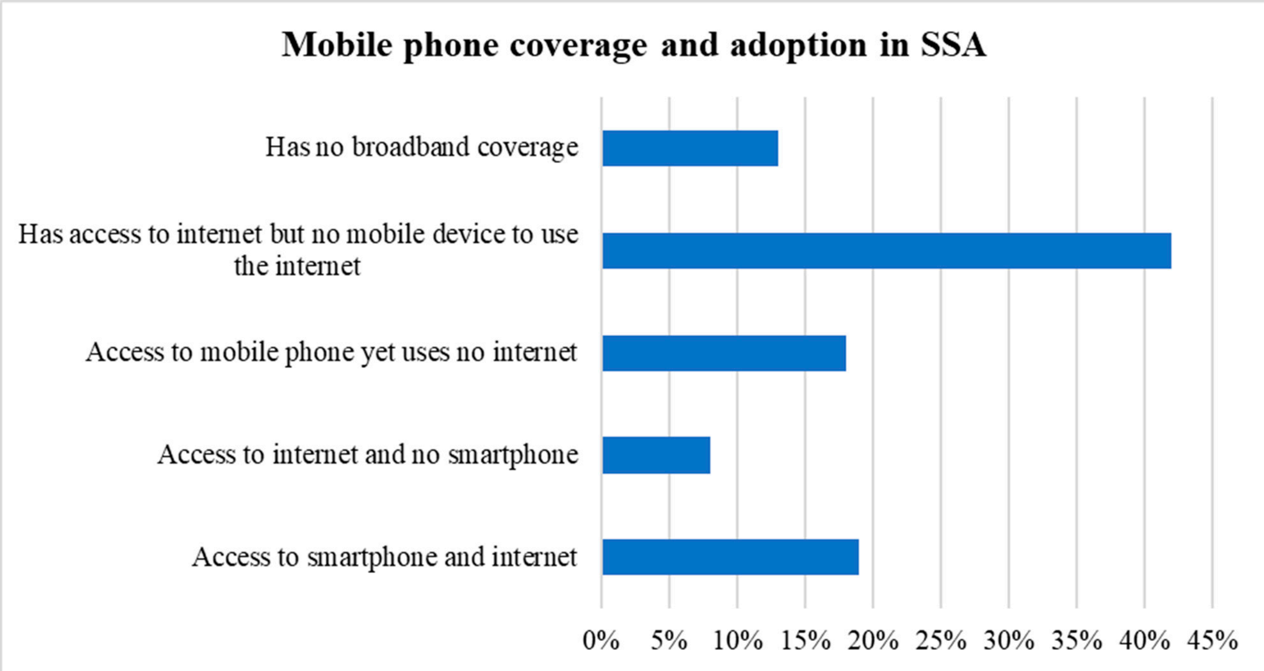

Figure 2. Access and use of the internet and smartphones in SSA (adapted from [160]).

5.2.6. Summary

While this review identified a wide range of adaptation strategies ranging from IKS to small-scale irrigation and emerging digital tools, it is equally important to interrogate their effectiveness and constraints. Evidence [91,161,162] suggests that rainwater harvesting, and small-scale irrigation can improve yields and buffer seasonal variability, but their success is contingent on sustained maintenance, capital investment, and access to local markets. Studies often highlight positive yield gains yet under-report issues of equity in the context of wealthier households being more likely to afford pumps or storage tanks, while poorer farmers may be excluded from such benefits [163,164].

Similarly, IKS offer context-appropriate, low-cost practices such as early warning through ecological indicators or seed preservation, but their effectiveness can be undermined by rapid environmental change, erosion of intergenerational knowledge transfer, and limited formal recognition in policy frameworks. Conversely, digital climate services are celebrated for their potential to democratize access to timely weather information, yet their adoption remains uneven due to digital divides in literacy, affordability, and infrastructure.

This highlights a critical gap in literature because while strategies are well documented, systematic evaluations of outcomes, cost-effectiveness, and scalability across diverse agro-ecologies are limited. Few studies [165–169] compare interventions head-to-head, and many rely on case studies with small samples. This constrains our ability to generalize which strategies are most resilient or cost-effective under specific contexts.

6. Conclusions

In conclusion, this review demonstrates that farmers across Sub-Saharan Africa employ a diverse portfolio of strategies to cope with water scarcity, ranging from long-standing indigenous knowledge practices to emerging digital innovations. The study's originality lies in synthesizing these responses into a unified framework that cuts across technological, sociocultural, and institutional domains, while explicitly linking them to adaptation theory.

Despite the breadth of strategies, evidence quality remains uneven and often based on small-scale case studies without the rigorous evaluation of effectiveness. This limits the ability of policymakers to prioritize interventions. As such, the review identifies three critical gaps: (i) insufficient comparative analysis of costs, scalability, and long-term outcomes; (ii) under-exploration of digital and institutional innovations compared to traditional practices; and (iii) weak integration of adaptation practices into national policy frameworks.

Actionable recommendations emerge from this synthesis:

- Research should invest in longitudinal studies and comparative evaluations that measure both technical outcomes and social equity impacts.
- Policy should create enabling environments that validate and integrate Indigenous Knowledge alongside modern technologies, with attention to gender and youth inclusivity.
- For the practical application of water adaptation strategies, blended approaches that combine low-cost, farmer-driven adaptations with institutional support and digital innovations should be implemented.

Thus, through the articulation of these contributions, this review not only consolidates existing knowledge but also charts clear pathways for future inquiry and policy action toward resilient, water-secure agriculture in SSA.

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Abbreviations

The following abbreviations are used in this manuscript:

SSA	Sub-Saharan Africa
IKS	Indigenous Knowledge Systems
AVC	Agricultural Value Chain
SADC	Southern African Development Community
CAADP	African Union's Comprehensive Africa Agriculture Development Programme
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
JSTOR	Journal Storage
FAO	Food and Agriculture Organization of the United Nations
CGspace	Digital Library of the Consultative Group on International Agricultural Research
CGIAR	Consultative Group on International Agricultural Research
WAWRP	West Africa Water Resources Policy
ECOWAS	Economic Community of West African States
IWRM	Integrated Water Resources Management
UEMOA	West African Economic and Monetary Union

CILSS	Permanent Interstate Committee for Drought Control in the Sahel
ECOWAP	Economic Community of West African States Agricultural Policy
EAC	East African Community
WRMA	Water Resources Management Authority
ECCAS	Economic Community of Central African States
RWP	Regional Water Policy

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