

Review

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Review

A Review of Land- and Water- Management Technologies for Resilient Agriculture in the Sahel: Insights from Climate Analogues in Sub-Saharan Africa

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Abstract

In sub-Saharan Africa, land degradation and climate change threaten food security by reducing soil productivity and water availability. Soil and water conservation (SWC) technologies can restore soil health, enhance moisture retention, and support crop growth under adverse conditions. This review identifies SWC technologies applied in climatically similar African regions with the aim of informing adoption in Senegal, particularly in Sédhiou and Tambacounda regions. Using K-means clustering on 19 WorldClim bioclimatic variables, 35 comparable countries were identified, of which 17 met inclusion criteria based on data availability and $\geq 60\%$ climatic similarity. Around 85 technologies were reviewed, including water harvesting, soil-moisture conservation, and erosion control, assessed for their compatibility across rainfall patterns, and land gradients and uses. The review highlights 12 successful technologies across Africa with high potential for cross-border transfer and upscaling in Senegal's agroecological context. While countries such as Burkina Faso, Kenya, and Malawi lead in technology adoption and diversity, Senegal lags behind due to institutional gaps, limited funding, and weak extension systems. The findings highlight the importance of site-specific water management for improving soil conservation, biodiversity protection, climate adaptation, and food security, and emphasize the need for policy integration, stakeholder empowerment, private-sector engagement, and cross-border learning to accelerate adoption.

Keywords: climate resilience; sustainable intensification; soil conservation; water-management technology; climate analogues; k-means clustering; sub-Saharan Africa

1. Introduction

Soil and water are the most important agriculture resources, serving as the foundation for food production and environmental sustainability [1]. However, global transformations have caused climate change, population expansion, deforestation, urbanization, intensified agricultural practices, and the migration of subsistence farming to less fertile lands. These challenges underscore an urgent need to preserve these resources [2] along with a need for robust soil and water conservation (SWC) efforts within the larger framework of ensuring food security. The United Nations' 2023 World Water Development Report [3] highlights a concerning trajectory: the number of urban populations affected by water shortage is projected to rise from 933 million in 2016 to between 1.7 and 2.4 billion people by 2050 [3]. This projected escalation in water stress necessitates both rigorous scientific research and the implementation of adaptive, evidence-based management practices. The urgency is particularly

concerning for small-scale farmers in Africa, who are disproportionately affected by the multifaceted impacts of climate change and land degradation [4].

Understanding the biophysical roles of soil and water is essential for formulating effective conservation strategies. Soil provides a medium for plant growth, carbon sequestration, nutrient cycling, water retention and root growth, making its quality a critical determinant of crop productivity [5,6]. On the other hand, water acts as a vital carrier of nutrients and a key driver of metabolic processes crucial for plant growth [7]. The intricate relationship between soil and water management is central to optimizing agricultural productivity and ensuring food security [8]. The degradation of these two pillars—through erosion, nutrient depletion, salinization, and erratic rainfall—threatens food systems and livelihoods, particularly in sub-Saharan Africa.

Sub-Saharan Africa exemplifies the urgency of this challenge, as land degradation continues to undermine agricultural systems and environmental sustainability [8]. The African Union Commission estimates that 65% of African arable land is affected by degradation, contributing to declining soil fertility and agricultural productivity [9]. The United Nations Environment Programme (UNEP) reports that desertification affects around 45% of Africa's land area, with 55% of this area at high or very high risk of further degradation [10]. A study by the Food and Agriculture Organization (FAO) highlights that soil erosion alone impacts roughly 43% of agricultural land across the continent [11]. These statistics reveal the crises and reinforce the need for comprehensive strategies to combat land degradation, enhance climate resilience, and ensure long-term food security for the region's growing populations.

Land degradation, soil-water scarcity, and climate change are intricately interconnected, collectively posing serious threats to agricultural sustainability and food security [12,13]. As climate change intensifies, shifting precipitation patterns and rising temperatures heighten the risk of land degradation. Intensive agricultural practices exacerbate this issue by contributing to soil erosion and nutrient depletion, accelerating degradation [14]. Simultaneously, land degradation reduces the soil's water retention capacity, exacerbating soil-water scarcity [15]. These interconnected challenges form a negative feedback loop, where degraded land becomes increasingly incapable of withstanding climate impacts, leading to a downward spiral of declining agricultural productivity. Breaking this cycle requires widespread adoption of sustainable land-management (SLM) practices. Through measures such as erosion control, water conservation, afforestation, conservation tillage, and watershed management, farmers can maintain soil health and improve water retention. Maintaining soil organic matter, coupled with installing SWC structures enhances overall ecosystem resilience. Education and extension services further ensure the widespread adoption of sustainable practices. By addressing the interconnected challenges of soil erosion, water scarcity, and climate change, these management strategies create a foundation for sustainable agriculture, fostering resilience, enhancing biodiversity, and securing long-term ecosystem viability [16].

Senegal, situated in West Africa, experiences a predominantly arid to semi-arid climate, posing significant challenges to agriculture. The population has grown steadily, with a current estimate of over 18 million people in 2023 with a density of 92 people per km² [17]. Agriculture is mostly rainfed, where less than 5% of cultivated land is irrigated [18]. The agricultural economy is dominated by smallholder farmers cultivating maize, millet, rice, and sorghum for subsistence purposes [19]. Recurrent droughts, periodic flooding, and land degradation driven by climate change are major factors contributing to stagnating farm productivity [20]. Adoption of land and water management technologies among small-scale farmers in Senegal remains low [21] compared to other African countries [35], especially the neighboring countries of Burkina Faso and Niger. This is mainly due to weak institutional and policy frameworks, inadequate land tenure incentives, and fragmented, project-based implementation approaches [22]. Many farmers still rely on harmful practices like bush burning, which degrades the soil, depletes organic matter, and increases erosion risks [23]. Despite these impacts, traditional methods persist due to limited awareness of sustainable alternatives [24]. Effective awareness campaigns, training, and supportive policies are essential for driving this transition [25].

This review examines existing literature to identify effective soil and water management practices adopted across 17 selected sub-Saharan African countries, particularly in arid and semi-arid regions with climatic and agricultural conditions similar to those in Senegal and the broader Sahel. The objective is to highlight successful technologies that have been effectively implemented in these climate-analogous regions but remain underutilized in Senegal. The documented practices will be recorded and those that fit the Senegalese landscape and climate of Sédhiou and Tambacounda regions will be selected and recommended for adoption. By synthesizing regionally tested practices and aligning them with local needs, this review contributes to a deeper understanding of sustainable water resource management and their potential to transform agriculture in the region. Ultimately, it supports the development of resilient agricultural systems and a more secure future for communities in water-stressed environments. It informs technology transfer and adoption in the Sahel, with a focus on Senegal.

2. Materials and Methods

The review process followed a structured and replicable methodology which first employed K-means clustering to identify regions across Africa that exhibit similar climatic conditions to the Sahel areas of Sédhiou and Tambacounda. This analysis utilized bioclimatic variables obtained from WorldClim historical data [26] to categorize regions based on climate similarity.

Following Rockström et al. [27], the identified water-management technologies were classified into three categories of systems that: (i) Prolong the duration of soil-moisture availability in the soil, for example mulching practices; (ii) Promote infiltration of rainwater into the soil. These techniques include pitting, ridging/furrowing and terracing, or (iii) Store surface and sub-surface runoff water for later use, for example, rainwater harvesting systems with storage for supplementary irrigation [28].

2.1. Clustering Approach and Justification

The study applied the widely used **K-means clustering algorithm** to categorize regions across Africa exhibiting climatic conditions akin to the targeted Sahel areas and specifically Sédhiou and Tambacounda, due to its efficiency in handling large datasets and its ability to identify distinct groups based on proximity to cluster centroids [29]. This method was deemed appropriate for:

- **Scalability:** It effectively processes high-dimensional climatic data across Africa. K-means' straightforward iterative structure makes scaling to large amounts of data comparatively simple [30].
- **Flexibility:** The iterative process refines clusters based on climatic homogeneity [29].
- **Interpretability:** The clusters provide insights into identifying comparable regions and informing land and water management strategies.

The algorithm works by iteratively assigning data points to clusters based on their proximity to cluster centers and updating these centers [31]. In this context, it helped identify areas in other countries that share similar climatic characteristics with the study areas, forming clusters of analogous conditions. To determine the **optimal number of clusters (k)**, the **Elbow Method** was applied, evaluating within-cluster variance across different values of k . The final model adopted a 60% **climate similarity threshold**, determined via Geometric Interval classification, to account for non-normal distributions in bioclimatic variables, thus ensuring that only significantly comparable regions were selected.

K-means clustering facilitated a preliminary systematic exploration of sustainable land and water management practices, providing valuable insights into strategies for on-farm or off-farm rainwater harvesting and storage, which is particularly crucial during periods of drought and intense, short-duration rainfall that are associated with climate change.

2.2. Bioclimatic Variables

Table 1 presents the statistics of **bioclimatic variables** used in clustering. These variables capture temperature and precipitation patterns, which are critical for assessing climatic similarity and rainwater management potential. The selection of bioclimatic variables (such as temperature seasonality (BIO4) and precipitation of the driest month (BIO14)) was guided by their relevance to water management in semi-arid regions. These variables capture critical aspects of climate variability that influence soil-moisture availability and rainwater-harvesting potential.

Table 1. Bio-climatic variables as used in the k-means clustering.

Variable	Description	MIN	MAX	MEAN	STD
BIO1	Annual Mean Temperature	-3.2	31.1	23.9	3.6
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	1	19.6	13.36	2.3
BIO3	Isothermality (BIO2/BIO7) ($\times 100$)	27.1	100	58.9	12.5
BIO4	Temperature Seasonality (standard deviation $\times 100$)	0	931.0	359.0	244.6
BIO5	Max Temperature of Warmest Month	0.5	48.6	35.5	4.9
BIO6	Min Temperature of Coldest Month	-12.5	24.8	11.4	5.64
BIO7	Temperature Annual Range (BIO5-BIO6)	1	41.5	24.1	7.73
BIO8	Mean Temperature of Wettest Quarter	-4.1	38.0	24.3	5.6
BIO9	Mean Temperature of Driest Quarter	-4.4	36.3	22.8	5.0
BIO10	Mean Temperature of Warmest Quarter	-2.4	38.5	28.1	4.3
BIO11	Mean Temperature of Coldest Quarter	-7.6	29.3	19.2	5.0
BIO12	Annual Precipitation	0	4566	647.7	622.1
BIO13	Precipitation of Wettest Month	0	1119	130.3	113.1
BIO14	Precipitation of Driest Month	0	196	6.0	15.1
BIO15	Precipitation Seasonality (Coefficient of Variation)	0	224.8	87.8	37.3
BIO16	Precipitation of Wettest Quarter	0	2736	334.3	297.0
BIO17	Precipitation of Driest Quarter	0	602	26.4	58.0
BIO18	Precipitation of Warmest Quarter	0	1291	160.4	178.0
BIO19	Precipitation of Coldest Quarter	0	2736	111.3	230.1

2.3. Regional Selection and Literature Review

This approach enabled researchers to pinpoint regions with analogous conditions, subsequently facilitating a comprehensive literature review on water-management technologies. The goal was to explore strategies for rainwater storage in the soil and rainwater harvesting that support crop growth through to maturity, particularly during droughts and intense, short-duration rainfall associated with climate change. By pinpointing regions with analogous climatic conditions, this study contributes to international research on climate adaptation and water-resource management. The findings offer a transferable framework for identifying areas where successful water-management strategies could be replicated, making them valuable for development organizations, farmers, policymakers, and researchers.

The clustering process identified **35 African countries** with comparable climatic conditions (Figure 1). However, only **17 countries** (bolded in the list below), were included in the literature review due to lack of adequate literature (as shown in Table 2, at the end of the results section). The countries encompassed, **Botswana, Burkina Faso, Ethiopia, Guinea, Kenya, Malawi, Mali, Namibia, Niger, Nigeria, Senegal, Somalia, South Africa, Sudan, Tanzania, Zambia, Zimbabwe**, Angola, Benin, Cameroon, Central African Republic, Chad, Côte d'Ivoire, Eritrea, Egypt, Gambia, Ghana, Guinea Bissau, Libya, Mauritania, Mozambique, Morocco, South Sudan, Togo, and Tunisia.

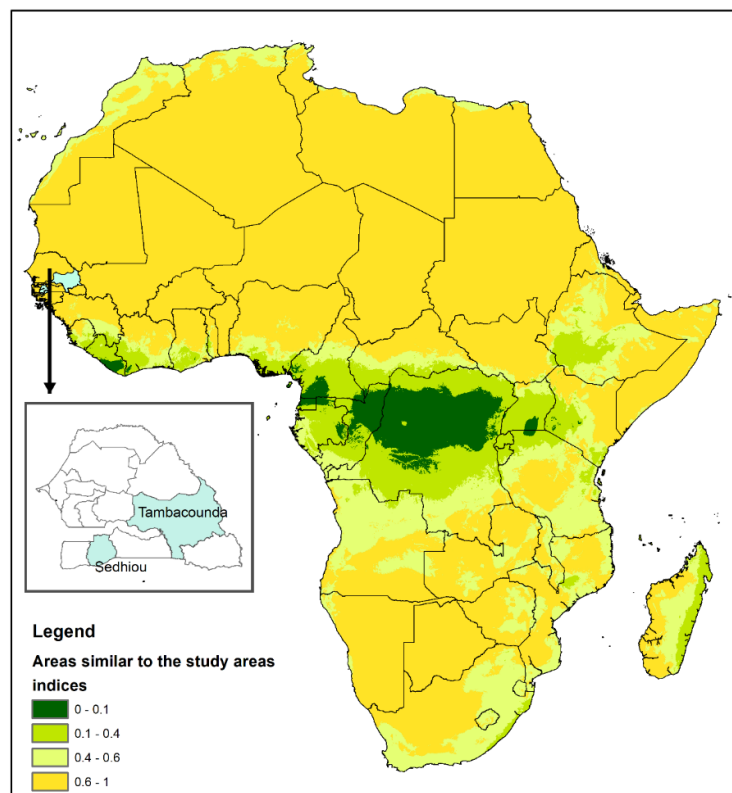


Figure 1. A map of Africa showing areas climatically analogous to the Sédhiou and Tambacounda regions of Senegal.

2.4. Review Methodology

To achieve the research objective, we conducted a systematic analysis of peer-reviewed and published articles, technical reports, and working papers. The review followed the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol** as outlined by Moher et al. [32] and Page et al. [33] (Fig. 2). A comprehensive search was carried out across multiple platforms, including **Google Scholar, Web of Science, Scopus, and Google**, using search strings that combined terms such as “water management,” “soil and water management,” “sustainable land management,” “rainwater harvesting” with additional keywords like “technologies,” “practices,” “arid regions,” “semi-arid Africa,” and country-specific identifiers (e.g., “Ethiopia,” “Kenya,” “Sahel”).

From an initial pool of approximately **520 documents**, **200** documents were excluded because they contained research from countries that had not been selected from the pool of 17 after the country clustering process. From the remaining 320 documents, duplicates, book chapters, reviews, and irrelevant grey literature were removed ($n = 108$). The remaining **212 documents** were screened based on title and abstract for relevance to water management technology adoption in semi-arid regions. At this stage, **140 studies** were excluded as irrelevant. A final set of **72 articles** were selected for detailed assessment (Figure 2), and a total of 136 articles are cited in this paper.

Each study was analyzed to document the **type of technology** (e.g., in-situ/ex-situ water harvesting, soil-moisture conservation, efficient irrigation), its **agroecological suitability** (e.g., slope, rainfall, temperature), and the **context and challenges of implementation**. The review covered the period **2005–2023**, ensuring that findings reflect current climatic realities and technological advances.

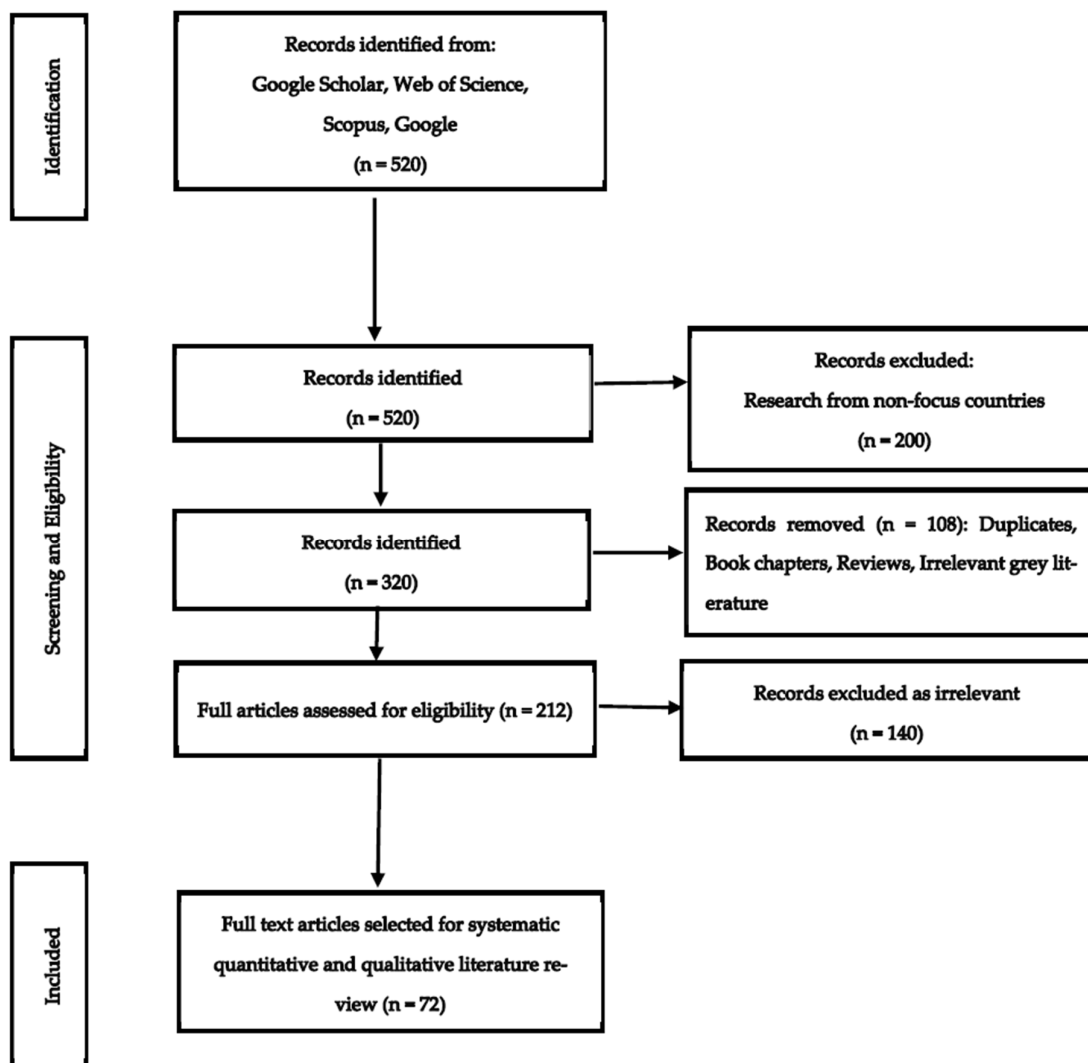


Figure 2. PRISMA statement describing the steps for systematic literature review.

While this review focuses on the Sahel regions of Sédhiou and Tambacounda, the methodology is designed to be replicable in other semi-arid regions globally. For instance, the bioclimatic variables used in this analysis are universally applicable, and the clustering approach can be adapted to identify regions with similar climatic challenges in other parts of the world as any area of study. The water management strategies identified, such as rainwater harvesting and mulching, have been successfully implemented in semi-arid regions of Africa and could be adapted to other regions facing similar climatic pressures.

This methodology provides **broader applicability** beyond Sédhiou and Tambacounda by:

- **Identifying transferable water management strategies** applicable to regions with similar climate profiles.
- **Enhancing climate adaptation frameworks** by linking findings to global agricultural resilience policies (FAO, UNDP).
- **Providing a replicable model** for future studies assessing climate-adaptation-based agricultural interventions in semi-arid regions worldwide.

This study contributes to advancing the field by addressing the critical gap in the adoption of land and water management technologies in Senegal. By leveraging K-means clustering to identify comparable climatic regions and conducting a systematic literature review, this study introduces a

data-driven approach to technology transfer. The findings provide a scientifically grounded framework for farmers, policymakers and development practitioners to adopt proven water management strategies, ensuring that innovations are tailored to the specific needs of Senegalese farmers. In doing so, this study aligns with international research efforts on climate adaptation, land management, and sustainable agriculture, reinforcing the global discourse on improving agricultural resilience in semi-arid regions.

Compiling Water Management and Conservation Technologies Across the Selected Countries

A comprehensive collection of water conservation and management technologies as implemented in various African countries, was compiled and organized on a country-by-country basis into tables after sorting them into, in-situ and ex-situ water harvesting, soil-moisture management and efficient irrigation techniques (Tables A1–A5, fully listed in the supplementary material in the Appendix).

The technologies were further analyzed in the context of Senegal's land gradient (Table 3). This assessment was crucial to prioritizing feasible technologies, by identifying the best-suited technologies for Senegal's topography and to ensure that the technologies align with local farming practices and socio-economic conditions, increasing their practicality and acceptance by farmers. Slope suitability is a critical factor for successfully implementing most soil and water conservation measures. Each technology has specific slope thresholds, influencing its effectiveness and minimizing risks like erosion or inefficiency.

3. Results

3.1. Water Conservation and Management

Water conservation and management involve the following measures: (i) in-situ and ex-situ water harvesting; (ii) soil-moisture management which adopts technologies that help retain soil moisture, reducing the need for irrigation; (iii) using efficient irrigation techniques; (iv) suitable crop selection; (v) applying precision agriculture, and (vi) planting drought resistant/tolerant varieties [34]. In this review we focus on i–iii, in-situ and ex-situ water harvesting, soil-moisture management and efficient irrigation techniques. This is because the review prioritizes practices that are cost-effective and accessible to Senegalese smallholder farmers, as we focus on the goal of evaluating water-management strategies that directly address soil and water dynamics, such as capturing, storing, and efficiently utilizing water. Future studies can complement this work by exploring agronomic practices and technological advancements such as crop selection, precision agriculture, and drought-tolerant varieties.

3.2. Ex-Situ Water Harvesting Practices

Ex-situ water harvesting is a technique that involves collecting water in an area external to where it falls, storing it for future use. Examples of ex-situ water harvesting techniques include the capture and storage of water in dams, wells, ponds, and cisterns. This approach helps to effectively manage water resources, hence addressing water-scarcity challenges [35].

Small earthen dams are intended to store upstream water that can be later used for irrigation. Generally, constructing small earthen dams provides water for domestic use, provides a water storage system for livestock, and supports crop growth.

Similarly, sand dams are simple, low cost and low maintenance structures that provide an improved, year-round local water supply for domestic and agricultural uses. Structurally, they comprise stone masonry barriers placed across a seasonal sandy riverbed that traps rainwater and sand flowing down the catchment. Sand dams are applicable in drylands with seasonal rivers with sandy sediments and accessible bedrock.

3.3. In-Situ Water Harvesting

In-situ rainwater harvesting is a technique designed to enhance soil-water retention, effectively collecting water at its point of origin. This method ensures that rainwater is captured and utilized with minimal distance between the collection and usage areas. For example, practices like terracing, pitting, and conservation tillage are employed as in-situ water-harvesting methods. These measures are also used for soil conservation [36].

In-situ water-harvesting structures include *Zai* pits in Burkina Faso, and *tassa* pits in Niger constructed in soil-capped/crusted or degraded croplands with the aim of optimizing both the rainfall and runoff capture and increasing water infiltration for millet and sorghum cultivation. Others include stone lines laid on gently sloping fields in West Africa (Burkina Faso, Mali, Niger), and terraces that are locally known as *fanya juu* and *fanya chini* in East Africa (Ethiopia, Kenya, Tanzania, and Uganda). These terraces are constructed through excavation of trenches and ditches along the contour. Soil is piled uphill to generate bench terraces, preventing soil and water loss thereby improving plant growth conditions.

3.3.1. Soil-Moisture Management

Soil-moisture management techniques are practices designed to optimize the amount of water retained in the soil to support crop growth and improve water-use efficiency. These techniques are especially important in regions with irregular rainfall, such as arid and semi-arid areas. Some key soil-moisture management techniques include agroforestry; applying soil amendments; conservation tillage; contour farming and terracing; cover cropping, and mulching.

3.3.2. Efficient Irrigation Techniques

Efficient irrigation techniques minimize water wastage and maximize water delivery to crops, improving water-use efficiency and reducing environmental impacts. These techniques are particularly important in areas where water is scarce, for reduced water consumption. These techniques include drip-, flood-, sprinkler-, pivot-, or surface irrigation.

3.4. Studies and Innovations on Water Conservation and Management Technologies in Selected African Countries

This section presents a comprehensive collection of water conservation and management technologies as implemented in various African countries, organized on a country-by-country basis. Around 85 technologies were identified (some similar in practice) across the 17 countries, with Malawi adopting 22, Kenya 17 and South Africa, 13 (see table 2 and table A1 in the appendix). Additionally, detailed definitions and explanations of key technical terms related to soil and water management have been provided in the Appendix Tables A2–A5.

3.4.1. Botswana

Double ploughing is effective for weed control and boosting crop yields, while deep tillage and single moldboard ploughing of loamy and clod-forming soils increases water infiltration and crop yields. Surface-residue management and minimum tillage also enhance soil moisture [37]. There is extensive use of compacted ridges, strip tillage, and reservoir tillage [38] while ponds and small dams are being used to capture runoff [37]. Compacted ridges use plastic-covered ridging, compacted ridges/furrows, and loose ridges/furrows. The bottoms of the furrows are left loose. This type is very effective in harvesting water in events of low intensity rainfalls ($\leq 10\text{mm/hr.}$). Reservoir tillage consists of a series of regular pits, traditionally 1.5m square by 0.1 – 0.5m deep with the crops grown on the ridges around the pits. Strip tillage involves cultivating only narrow seed rows and leaving the rest of the soil undisturbed, combining the soil health benefits of no-till systems with the seedbed precision of conventional tillage.

3.4.2. Burkina Faso

In Burkina Faso, contour ploughing, earth bunds, grass strips, stone rows/strips, and *Zai* pits, have been extensively adopted [39,40]. Agroforestry, filter walls, half-moons and rock bunds are also widespread in Burkina Faso [41]. *Zai* involves dry-season digging of pits of 30–50cm in diameter and 10–20cm deep every 0.8–1.2m apart and piling the soil on the lower slope to form crescents [42]. Stone strips are anti-erosion structures constructed through judicious arrangements of stones along the contour line. They reduce the speed of running water, allowing it to percolate into the soil while properly draining the excess. Runoff water collection practices for complementary irrigation include 'boulis' reservoirs, *Geres* reservoirs, and micro-reservoirs [43]. Boulis are oval or circular structures 60m long and 4 to 6m deep for collecting runoff water for market-gardening, or agroforestry production during the dry season, and overwintering rice cultivation [44]. Other technologies include: i) the *Banka*, which is a runoff water catchment basin that allows runoff to be collected for additional irrigation during in-season droughts [45]; ii) a *filter bund*, which is built along a temporary flowing watercourse; iii) a *lowland or a drainage axis* using rubble stones of different sizes to reduce the velocity of runoff, control soil erosion and water infiltration [46]; iv) a *Tiarako bund*, which is an anti-erosion device composed of blocks of rubble or stones to break the force of runoff water while allowing excess water to pass in order to avoid concentrations of water upstream, or to cause a slower flow of water downstream; v) *permeable rock dams*, which are structures built in gullies using loose rocks and stones and sometimes reinforced with gabions used to fill in gullies and control water flow, spreading the water over adjacent land improving its infiltration [47]; vi) a *Vallerani system* which involves a special tractor-pulled plow that constructs micro-catchments combining the traditional techniques of rainwater harvesting with mechanization for large-scale land rehabilitation [48].; vii) *Ados* which are earth bunds arranged in contour lines that stops runoff water and allows infiltration, increasing soil water-retention and storage capacity [49], and viii) *permeable rock dikes* which are erosion-control structures built along the natural contours, and designed to reduce runoff [47].

3.4.3. Ethiopia

Use of *stone-faced soil bunds* results in higher soil moisture compared to other conservation measures [50]. Other technologies used to improve soil moisture include soil bunds, soil-faced, deep-trench bunds, grass strips and terraces (e.g., *fanya juu* terraces with grass). A terrace is a slope-controlling barrier made of earth, stone, or another suitable material. Each terrace retains water that can improve soil fertility and crop productivity. A soil bund on the other hand, is a structural measure that consists of a soil and/or stone embankment built along the contour and stabilized with vegetation such as grass and fodder trees. The height of bunds is determined by the quantity of stones available. These bunds slow the speed of runoff and control soil erosion by trapping water and enabling it to infiltrate. Additionally, they contribute to groundwater replenishment [50]. Trash lines [51], micro-catchments and ponds [52,53], ridge and basin [54], and runoff/floodwater farming [55,56] enhance soil and water conservation through residue management. In addition, water infiltrates slowly into the soil increasing soil moisture [52].

3.4.4. Guinea

Guinea uses improved wells, hill reservoirs and micro-dams [57]. Improved wells promote the use of groundwater to meet potable water needs and create pastoral water points. In Guinea, these are supplemented by the use of hill reservoirs and micro-dams for irrigation of plains and lowlands and for domestic and pastoral water needs.

3.4.5. Kenya

Soil and water conservation efforts in Kenya were first formally initiated by the colonial government in the early 1930s. These efforts have played a pivotal role in mitigating soil erosion and boosting agricultural yields. Kenya has implemented a range of water-management technologies,

especially in the lower eastern regions of the country, which receive less than 500mm of rainfall annually. These initiatives have been crucial in enhancing food production and agricultural sustainability. In Kenya, as outlined by Kimani et al. [58] a range of rainwater harvesting technologies (RWHTs) are actively employed in the lower eastern counties. Macro-catchment methods like earth dams; water pans and sand/sub-surface dams; micro-catchment practices such as *Zai* pits; strip catchment; conservation tillage; terracing; contour and semi-circular bunds; as well as rooftop rainwater harvesting techniques. Notably, rooftop catchment stands out as the most widely adopted approach among these methods.

The above-mentioned water conservation techniques encompass a range of methods employed to manage and harness rainwater efficiently. Earth dams refer to the construction of large reservoirs or embankments to store rainfall runoff. Sand and sub-surface dams involve the use of sand barriers and underground structures to trap and store rainwater. Water pans, often referred to as water pans or pans, are shallow excavated depressions designed to collect and store rainwater efficiently [59]. They usually have storage capacities that do not exceed 20,000m³ and have a shallow depth of less than 5m [60]. *Zai* pits are small pits dug into the ground to enhance soil-moisture retention and crop growth [61]. Strip catchments, tillage techniques, contour farming, and semi-circular bunds are key land and water management strategies designed to enhance water use efficiency and reduce soil degradation in water-scarce regions. Strip catchments involve constructing channels and physical structures to direct and capture rainwater, while tillage techniques improve soil infiltration and reduce surface runoff [60]. Contour farming aligns planting along the natural contours of the land, minimizing erosion and improving rainwater retention [62]. Semi-circular bunds—crescent-shaped earth barriers—trap rainfall and promote its gradual absorption into the soil [63]. Together, these techniques offer a sustainable approach to managing water resources, mitigating soil erosion, and improving agricultural productivity in arid and semi-arid environments.

Zai pits concentrate rainwater within a smaller area resulting in a higher soil water content per unit volume of soil, consequently elevating the water level in the soil [64]. This creates favorable conditions for crop nutrient uptake, ultimately contributing to increased crop yields. [65] documented *Negarims*, Grass strips, stone lines, and trash lines and added them to the list of technologies adopted in Kenyan dry areas. *Negarim*, a distinctive agricultural intervention, entails creating diamond-shaped, small runoff micro-basins enclosed by low earth bunds [66]. Primarily employed for cultivating trees and bushes in arid and semi-arid regions, *Negarim* simultaneously serves as a valuable measure against soil erosion. Meanwhile, grass strips, which involve linear plantings of grass or vegetation within agricultural fields, act as natural erosion barriers, slowing runoff, stabilizing soil, and promoting water infiltration [67]. Stone lines, characterized by stone or rock barriers across fields, effectively control soil erosion by capturing sediment and reducing surface runoff water velocity, allowing for enhanced rainwater infiltration [61]. Similarly, trash lines, formed from crop residues or organic materials arranged in fields, contribute to improved water infiltration, reduced runoff, and soil erosion prevention, reinforcing comprehensive soil and water management practices. These techniques collectively offer essential tools for sustainable agricultural and environmental management, emphasizing conservation, water harvesting, and erosion control while catering for various agricultural needs in arid and semi-arid areas.

Other technologies include Retention ditches (also known as infiltration ditches); Cut-off drains/diversion ditches; Artificial waterways; Bench terraces; Reverse sloping; Terraces with soil thrown upslope; channel terraces; grass strips; trash lines; road runoff; planting pits/nine maize pits; agroforestry and tree planting; woodlots; trees on boundary; irrigation; blue water structures; roof catchment into a surface tank (individual); communal water pans and earth dams [68]. Trash lines; stone lines; check dams; grassed waterways; grass strips; small earth dams and ponds, are very popular among farmers in selected highland water catchments of Kenya [69]. Others include open and tied ridges which are commonly adopted in lower eastern and coastal Kenya [70]. In addition, earthen bunds have been used for water harvesting in semiarid regions of Africa. These are various forms of earth-shaping, created for ponding runoff water [71]. The variations of earthen bunds

include contour bunds, semi-circular bunds and *Negarim* micro-catchments which have been used in arid and semi-arid regions where the seasonal rainfall can be as low as 150mm [72].

3.4.6. Malawi

The use above-ground tanks for domestic application have been the most popular technique for rainwater harvesting in Malawi [73]. Concrete lined underground tanks have mostly been built to collect runoff from ground surfaces, for example, in school grounds, on hill sides and as road runoff. Other measures include: i) compost manure making and application; ii) constructing earth dams for irrigation; iii) **in-situ or soil storage rainwater harvesting** by constructing box ridges, check dams, conservation agriculture, infiltration pits, marker ridges, percolation ponds, or swales; iv) mulching and crop-residue management, and v) planting grass strips/hedges along the contours [74]. Ponds and hand-dug wells store rainwater that is used productively in watering vegetables and fruit trees [73]. **Flood-based farming systems** include: i) *Flood-plain agriculture* (cultivation of flood plains using either receding or rising flood water); ii) *Inundation canals* (where cultivated fields are fed through a networks or canals by temporarily high water levels in perennial rivers); iii) Using *residual moisture* (as the moisture dries up farmers will use water from shallow wells using watering cans or treadle pumps to irrigate crops); and iv) Spate irrigation (diversion of short-term flood flows from seasonal rivers to field by means of small earth canals) [73].

There is also an extensive use of treadle pumps for irrigation [75]. The treadle pump is a simple, low-cost pump that was promoted for adoption by smallholder farmers owing to its simplicity, as farmers mostly repair and maintain them using locally available materials. The treadle pump is ideal for small areas (up to 0.4ha) which is appropriate for Malawian landholding sizes. This pump is appropriate where there are low pumping heads (<7m) with a nearby water source (<200m). The irrigation methods commonly used with treadle pumps in Malawi are basin and furrow irrigation.

3.4.7. Mali

In Mali, various soil-water management technologies are employed to address runoff and erosion issues. These include: i) non-permeable *dikes* used primarily in rice production but prone to waterlogging and requiring extensive maintenance; ii) *vegetative strips* planted with perennial grasses to combat wind and water erosion (though they can pose weeding challenges and provide cover for snakes); iii) half-moons [76], which are earthen ridges promoting water infiltration, often combined with using organic fertilizer; iv) *living hedges* planted on field boundaries and made of perennial species. They protect crops, improve soil quality, and offer additional benefits like forage and roofing materials; and v) *stone bunds* or *lines*, which reduce runoff, erosion, and waterlogging, while creating a micro-climate favoring natural vegetation growth. These diverse methods for managing soil and water effectively cater for the specific needs and conditions of different agricultural contexts in the region [77]. In addition, there are *check dams*, *contour ridges*, *grass strips*, *stone rows*, and *water evacuation dikes* [78]. *Contour bunding* is widely adopted in farmers' fields to improve land and water resource management [79], as well as *contour ridge tillage* [80].

3.4.8. Namibia

Namibians use contour ditches and bunds to trap rainwater and rehabilitate soil [81]. In addition, ripping, planting basins, composting and drip irrigation are being adopted [82]. The deep ripping method also known as "deep tillage" is a water conservation practice that involves the use of strong, deep working tines (spikes) that penetrate compacted soil and mechanically break up the hard sub-soil plough pan. *Nombete* (meaning 'beds') is a low-cost indigenous irrigation technique, involving the making of small irrigation beds for vegetable production that is practiced along the *Okavango* River [83]. Simple rainwater harvesting could easily be introduced, by creating tied ridges between the raised beds. Irrigation is done by watering cans using river water. Treadle/manual

pumps could reduce the labor requirement for irrigation, but would need to be easy to carry, since people walk significant distances to their gardens.

3.4.9. Niger

In Niger, *Zai* (locally called *tassa*) and half-moon catchment (*demi-lunes*) are the most promising, as both techniques are simply applicable, and use locally available materials that require little investment, making them affordable to small-scale subsistence farmers for boosting yields [84]. In addition to *Zai pits* [85], half-moons are also adopted. Fallow, mulching, stone strips, fallow and tree planting are also practiced [86]. There are also reports of an improved version of '*tassa*' and half-crescent-shaped earthen mounds which are the half-moons [87]. Planting pits / basins are commonly used in the sub-region with various modifications including *Zai pits (Tassa)* in Burkina Faso, Niger and in Mali, and half-moon (*demi-lunes*) in Niger.

A study in Niger reported higher yields on *Zai* treatments compared to flat planting [88]. This was attributed to a build-up in soil organic matter which may increase the soil's water-holding capacity in the *Zai* treatments. Additional conservation techniques include half-moons, promoting/protecting natural regeneration, riverbanks, rock dikes and stabilizing gullies and sand dunes [89].

3.4.10. Nigeria

There are two types of practices for soil and water conservation in Nigeria: **mechanical** (engineering, otherwise known as structural), and **biological measures** [90]. Mechanical measures include bunding, check dams, crib walls, gabion structures, loose/stone boulders, ridging, terracing, and trenching. Biological measures (otherwise known as agronomic or agricultural and agroforestry) are the vegetative measures which include agricultural/agronomic practices, agroforestry, forestry, and horticulture. Others include check dams [91], cut-off drains, diversion ditches, earth dams [92] and terraces.

3.4.11. Senegal

In Senegal, stone lines with live hedges combine physical structures and plant practices to slow the speed of flows (upstream) and reinforce the impact of gabions (downstream) in a watershed system. Anti-salt and runoff retention dikes retain runoff water and reduce land salinity. *Piterki* retention basins are used to retain runoff water longer during the dry season for use in irrigating crops during the dry season. These traditional ponds/water retention basins form part of a storage infrastructure to mobilize and recover runoff water [93]. Low pressure micro-irrigation uses drip irrigation and water reservoirs to limit the loss of topsoil through runoff and to encourage water-table replenishment [94].

3.4.12. Somalia

Soil bunds and grass strips are used in Somalia [95]. Several soil and water conservation measures have been used to conserve soil and water and extend the growing season such as soil bunding, terracing, and water storage (in dams and other reservoirs) [96].

3.4.13. South Africa

In South Africa, the adoption and application of contour ridges, mulching, rainwater harvesting, and terraces in Mpumalanga province has been widely documented (see below) [97]. Overall, the following 14 technologies are deployed in South Africa: **i)** *Ama-pitsi* or *homestead ponds* are hand-dug pits or small dams into which the surface runoff is diverted via small furrows and then stored for crops and domestic use ; **ii)** contouring; **iii)** diversion furrows; **iv)** granite dome water harvesting; **v)** *Gelesha* (a soil-turning method) *Gelesha* is the tilling of soil immediately after harvest. The practice ensures that any rain, dew or frost infiltrates the tilled soil, rather than ponding and evaporating or

running off, thus increasing water availability for the next crop.; **vi**) grass strips on the contour (grown between fields to act as traps for increased infiltration); **vii**) *klipplate* and *vanggate* (hardened surface and catchment tanks), where a natural hardened and impermeable surface is cleaned and compacted, and rainwater is channeled from this surface to an underground tank; **viii**) modified tied ridges (locally called in-field rainwater harvesting); **ix**) mulching; **x**) *ploegvoore* (mechanized pitting); **xi**) rock packs around individual maize plants that act as small basins intercepting and pooling overland runoff. These increase infiltration and seem to be a combination of micro-terracing and pitting. They consist of rocks packed into large crevices in granite and basalt domes, filled with soil and planted with maize and other crops. The cracks and crevices are the natural flow path of water running off the domes and this water is concentrated into the soil on the rock pack.; **xii**) *saaidamme* (floodwater harvesting) involves, fertile, silt-laden floodwater, usually from distant mountains (up to 150km away) being diverted by large weirs into a series of flat fields annually or biennially. Each field is between 1 and 100ha in size and is surrounded by a low earth wall 1–2m high. Together, the field and the wall form a flat, shallow dam, the floor of which is cultivated with crops—hence the name *saaidam* or ‘planting dam.’; **xiii**) terracing; and **xiv**) trench beds [98].

3.4.14. Sudan

The Sudanese use contour farming, half-moon basins, low-lying crescents, mulching, and ridging to ensure longer-term rainwater retention on the cropped area to ensure infiltration [99]. The use of ridge-furrow has proven highly effective in conserving water in the root zone in semi-arid to sub-humid regions, particularly when ridges have cross ties in the furrows (known as tied-ridging, furrow blocking, or basin tillage). Tied ridging is likely to reduce surface runoff and increase retained water within the field, if carefully designed across the slope or along the contour lines [99]. Also documented are the application of the low-lying crescents [76].

3.4.15. Tanzania

In Tanzania, the World Agroforestry Center introduced *Chololo* pits [100]. *Chololo* pits are a technology that helps conserve soil moisture and improve soil fertility, increasing crop production and mitigating drought effects [101]. *Tied ridges* are also used and are commonly adopted in maize and millet crops [102]. *Matengo* pits are another water management technology that combines the anti-erosion techniques of pits and ridges on steep slopes. They were introduced in the 19th century in *Mbinga* district and used in producing staple crops [103]. *Chaco dams* are used for harvesting runoff water for domestic, livestock and agriculture use during both the rainy and dry seasons [104].

In Arusha and Kilimanjaro regions of Tanzania, an evaluation of flat planting, open ridges, potholes (small holes), and tied ridges, as water-harvesting techniques showed significant maize yield increases under tied ridging, as this method retained more moisture than the other methods. The recommendations were that tied ridges were not suitable where the average annual rainfall is more than 800 mm, as they may cause waterlogging. In areas with sandy soils, tied ridging is not recommended due to high water percolation and waterlogging respectively, while in drier areas with about 500mm rainfall, tied ridging is recommended to farmers who have easy access to capital resources, while potholing is recommended to farmers with scarce resources. Other recommendations included the crest- and side-seed placement in ridges to eliminate water logging.

3.4.16. Zambia

Zambians use construction of small earth dams to curb the increased frequency of droughts [105]. Micro-basin water harvesting is used in rainfed agriculture. The basins act as water harvesting basins that store water for a much longer time [106] and can significantly increase productivity, for example doubling maize yields to 3 tons/ha [107]. River flood-plain recession irrigation is practiced along Lake Kariba in which crops are planted following a receding flood in the flat flood areas along the riverbanks. The crops utilize the residual soil moisture in these alluvial soils. Inland valley swamp

irrigation (*Dambos*) is implemented in low-lying areas where the water-table is high, enabling crops to be grown. Other water-management technologies include clay pot (sub-surface irrigation), also called 'pitcher' irrigation, and low-cost bucket- or drum-kit drip-irrigation. Micro-basins are constructed by making low earth ridges on all sides; they are normally circular, and square or diamond-shaped micro-catchments, 1-2m wide and about 0.5m deep [72].

3.4.17. Zimbabwe

In Zimbabwe, tied ridging and mulch ripping conserved higher topsoil moisture levels, especially at the beginning of the cropping season [28]. Mulching protected the soil from erosion and promoted infiltration. Inter-field-water harvesting techniques are promoted throughout southern Zimbabwe and include dead-level contours with or without infiltration pits, graded contour ridges and *Fanya Juus*. Infiltration pits within contour ridges are also being used in these areas [28]. Other technologies include dead-level and ordinary contours, dead-level contours with underground storage tanks, and infiltration pits. In-situ water-management techniques include planting basins and deep winter ploughing [28]. The micro-catchment structures include dead-level contours with or without infiltration pits [108]. Others include the tied contour ridges for water harvesting [76]. The tied-furrow system (1.5m–2.0m) offers advantages for crop production on soils with a relatively high clay content and under dry conditions, in terms of water concentration, soil conservation and productivity [37]. Table 2 below summarizes the technologies available by country.

Table 2. Summary of water-conservation, and management technologies by country.

Country	Water Harvesting		Soil-Moisture Management	Efficient Irrigation Techniques	Sources
	(In situ)	(Ex situ)			
Botswana	Compacted ridges, Double ploughing, Furrow- and precision-strip tillage systems, Tied-ridging	Ponds, Small dams	Minimum tillage, Surface-residue management		[37,38]
Burkina Faso	Stone rows/strips, Zai pits, Earth bunds, Contour ploughing, Tiarako bunds, Vallerani system, Ados	Boulis reservoirs, Micro-reservoirs, the Banka, Permeable rock dams	Grass strips		[41–49,109]
Ethiopia	Stone-faced soil bunds, Soil bunds, Soil-faced deep trench bunds, Grass strips, Terraces (fanya juu terraces), Ridge & basin, Micro-catchments	Ponds	Trash lines, residue management	Runoff/floodwater farming	[50–56]
Guinea		Improved wells, Hill reservoirs, Micro-dams			[57]
Kenya	Zai pits, Strip catchment, Conservation tillage, Terracing, Contour bunds, Semi-circular bunds, Negarims, Stone lines, retention ditches, open and tied ridges	Earth dams, Water pans, sub-surface dams, Sand dams	Trash lines, Grass strips	Furrow & precision strip tillage, Micro-basins	[58–72]
Malawi	Concrete-lined underground tanks, Earth dams, swales, infiltration pits, check dams, percolation pond, conservation agriculture, box ridges, Marker ridges, Ponds	Concrete lined underground tanks, earth dams,	Crop residues management, mulching, compost manure, grass strips/hedge-grows	Low-cost treadle pump, flood-plain agriculture, spate irrigation, use of residual moisture	[73,75,110]
Mali	Half-moons, Living hedges, Stone bunds/lines	Non-permeable dikes	vegetative strips		[76–80]

Namibia	Contour ditches & bunds, deep ripping, planting basins, compost		Ripping, Planting basins, Compost, Drip irrigation	Low-cost treadle/manual pumps, drip irrigation, Nombete low-cost indigenous irrigation technique	[81–83]
Niger	Zai pits (tassa), Half-moons (demi-lunes), Planting pit,		Fallow, Mulching, Stone strips, Tree plantation		[84–86,88,89]
Nigeria	Terracing, Bunding, Ridging, Trenching, Gabion structures, Cut-off drains, Terraces, Diversion ditches, Check dams	Earth dams		Agroforestry	[90–92]
Senegal	Stone lines with live hedges, Anti-salt & runoff retention dike, Piterki retention basins	Water reservoirs		Drip irrigation	[93,94]
Somalia	Soil bunds		Grass strips		[95,96]
South Africa	Mulching, Rainwater harvesting, Contour ridges and terraces, ploegvore (mechanized and pitting),	Gelesha (soil turning), Ama-pitsi (homestead ponds), Saaidamme (floodwater harvesting), Klipplete and vanggate (hardened surface & catchment tanks), granite dome water harvesting, Rock packs	Mulching, Grass strips on contour,		[97,98]
Sudan	Half-moon basins, Low-lying crescents, tied Ridging		Contour farming, Mulching, Ridge-furrow		[76,99]
Tanzania	Chololo pits, Tied ridges, Matengo pits	Chaco dams		Drip irrigation	[100,102–104]
Zambia	In-land Valley swamp Irrigation	Small earth dams, Ponds, Micro-basin water harvesting	Surface residue management, Minimum tillage	Clay pot (sub-surface) irrigation, Low-cost Bucket/Drum kit Drip Irrigation, river Flood Plain Recession Irrigation, In-land Valley swamp Irrigation (Dambos)	[105–107]
Zimbabwe	Tied ridging, Infiltration pits within contour ridges, Dead level contours, Fanya Juus, planting basins and deep winter ploughing	Dead level contours with underground storage tanks, Infiltration pits	Mulching, inter field-water harvesting techniques		[28,37,76,108,111]

The slope-specific requirements (Table 3), emphasize the need for topographical considerations in recommending technologies. For example: Bench terraces are suitable for steep terrain to mitigate erosion, while creating level planting surfaces; and check dams perform well on low-gradient land to store water and slow its flow.

Table 3. Slope requirements of soil and water technologies requirements.

Technology	Slope requirement
Bench terraces	Medium to steep slopes (12–47%). Bench terraces are not recommended for slopes less than 12%
Check dams	less than 2%
Contour bunds and hedgerows	Gentle to moderate slopes (0.5–3%)
'Fanya juu' terraces	Moderate slopes (less than 20%)
Planting Pits / Zai pits	Gentle slopes (less than 5 %)
Stone lines	Gentle to moderate slopes (less than 10%)
Trash lines	Slopes 2–30%
Grass strips	Fairly gentle slopes (0–6%)
Grassed waterway	Slopes of less than 20%
Retention ditches	Flat or gentle sloping land
Cut-off Drains	Hilly to steep slopes
Demilunes	Gentle slopes (less than 5 %)

Source: [112].

Additionally, contour bunds, stone lines, and trash lines provide adaptable solutions for areas with moderate slopes, balancing water retention with erosion control. Understanding these requirements ensures that farmers implement technologies that are both effective and sustainable for their specific landscapes.

In this review, the most widespread technologies based on the frequency of adoption across countries include bunds, grass strips, residues, stone lines, terracing and *Zai* pits.

Table 4. Most adopted land and water management technologies by functional category.

Technology (Functional Category)	Countries	No. of Countries
Bunds (stone, earth, contour, tied, etc.)	Burkina Faso, Ethiopia, Kenya, Mali, Namibia, Senegal, Sudan, Zimbabwe	8
Mulching / Residue Management	Ethiopia, Kenya, Malawi, South Africa, Sudan, Zambia, Zimbabwe	7
Grass Strips / Vegetative Barriers	Burkina Faso, Ethiopia, Kenya, Malawi, Somalia, South Africa	6
Ponds / Micro-dams / Water pans	Botswana, Ethiopia, Guinea, Kenya, Malawi, Zambia	6
Stone Lines / Stone Rows	Burkina Faso, Ethiopia, Kenya, Mali, Senegal	5
Terracing / Contour Ridges	Ethiopia, Kenya, Nigeria, Zimbabwe	4
Zai Pits / Planting Pits / Chololo Pits	Burkina Faso, Kenya, Niger, Tanzania	4
Check Dams / Water-Retention Dams	Malawi, Nigeria, Kenya, Zimbabwe	4
Drip Irrigation / Efficient Techniques	Namibia, Senegal, Tanzania, Zambia	4
Compost / Manure Application	Malawi, Namibia, Zimbabwe	3
Tillage Techniques (Minimum/Precision)	Botswana, Kenya, Zambia	3
Flood Recession Farming / Spate Irrigation	Malawi, Ethiopia, Zambia	3
Agroforestry / Tree Planting	Nigeria, Niger, Malawi	3
Infiltration Pits / Percolation Pits	Malawi, Zimbabwe	2

There is a significant adoption of traditional, low-cost, and community-driven technologies across West Africa, particularly in arid and semi-arid zones. Countries like Burkina Faso, Mali, Niger, Nigeria, and Senegal lead in these methods. *Zai* pits have been widely adopted in Burkina Faso and

Niger with Stone lines and bunds being prominent in Burkina Faso, Mali, and Senegal. Agroforestry and tree planting practices have been widely adopted in Nigeria and Niger, while Earth bunds, Tiarako bunds, contour ploughing, and living hedges are also common, reflecting an emphasis on moisture retention and erosion control. These technologies often combine Indigenous knowledge with labor-intensive, soil- and water-conservation methods suitable for subsistence and smallholder farming systems. East Africa shows significant adoption of integrated land- and water-management technologies, especially in highland areas with steep slopes and high rainfall variability. Conservation tillage, grass strips and terracing (*Fanya Juu*), are common in Ethiopia and Kenya, helping manage erosion on slopes and in moisture retention particularly vegetative barriers. Tanzania and Sudan use *Chololo* pits and tied ridges to adapt to erratic rains while *Zai* pits, semi-circular bunds, and contour bunds are also applied in Kenya and Tanzania. These technologies are typically more diverse, blending traditional with modern scientific approaches to water harvesting and soil fertility.

Southern Africa leads in water-efficient technologies with the adoption of improved water harvesting, irrigation, and residue-management technologies, particularly in Botswana, Malawi, Namibia, South Africa, Zambia, and Zimbabwe. Unlike West and East Africa, where soil conservation prevails, southern Africa integrates conservation agriculture with small-scale irrigation, supporting both rainfed and semi-commercial farming. Composting, crop-residue management, and mulching are widely used in Malawi, South Africa, and Zimbabwe while bucket-, clay-pot- and drip-irrigation are widely used in Namibia and Zambia for their water-use efficiency in smallholder and dryland systems. Micro-dams, ponds, and water pans are widely built in Botswana, Malawi, Zambia, and Zimbabwe, emphasizing ex-situ water harvesting while check dams, infiltration pits, and percolation ponds are used in Malawi and Zimbabwe. In addition, dead level contours, planting basins, and tied ridges, are used for in-situ moisture management in drier areas in both Namibia and Zimbabwe. Southern Africa combines conservation agriculture principles with investment in low-cost irrigation and infrastructure, suitable for both rainfed and semi-commercial systems.

section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

4. Discussion

The adoption of land- and water-management technologies across sub-Saharan Africa is uneven, with notable regional differences driven by agroecological suitability, institutional support, and socio-economic conditions [113].

The results show that West African countries like Burkina Faso, Mali, and Niger have made considerable strides in the uptake of practices such as half-moons, stone bunds, and *Zai* pits. This success can be attributed to decades of implementation by NGOs, and participatory projects that have aligned technologies with traditional farming systems [114]. *Zai* is a traditional rehabilitation technique that was developed in the early 1960s by farmers in northern Burkina Faso to restore their damaged land, deal with drought, and retain soil-moisture [115] while half-moons originated from the Sahel in the 1980s, in West Africa. Therefore, the two technologies are common in the Sahel, and hence their great uptake in Burkina Faso, Mali and Niger. In contrast, despite its similar climatic conditions Senegal has demonstrated relatively lower uptake of these technologies [116]. This lag may be due to institutional weaknesses, limited funding, and a lack of integrated policy strategies tailored to dryland agriculture particularly among farmers who have not been exposed to government, development and NGO programs [117]. In East Africa, countries like Ethiopia and Kenya lead in adopting agroforestry, terracing, and water harvesting, due to strong government programs and land-restoration incentives. This is coupled with collaborations between government agencies and NGOs [118]. Southern Africa has shown preference for conservation agriculture and cover crops, with support from national research institutions and regional policy harmonization [119]. This cross-country synthesis shows that successful technology adoption is not just a function

of environmental necessity, but of institutional readiness, community involvement, and sustained policy investment.

Policy frameworks and institutional strength are crucial in shaping the diffusion and sustainability of land and water management technologies [120]. In countries like Kenya, where land-tenure systems are more secure and supported by decentralization policies, farmers are more willing to invest labor and resources in long-term land improvements [121]. Additionally, extension services and farmer training programs, especially those provided by community cooperatives and field schools, raise awareness and boost adoption rates. [122]. The review underscores the importance of enabling environments for successful implementation. For example, Ethiopia's widespread adoption of soil and water conservation practices is facilitated by integrated watershed-management policies and active government involvement [123]. Conversely, Senegal's lower adoption can be linked to fragmented institutional roles and inconsistent policy incentives for sustainable agriculture [124]. Awareness-raising mechanisms, such as demonstration plots, local champions, and community-based resource groups, have played a significant role in improving technology uptake in Kenya, Malawi, and Tanzania [125].

Land- and water-management technologies carry important economic and social implications [126]. Technologies such as *Zai* pits and terracing, while effective, often demand substantial labor inputs and upfront costs, limiting accessibility for resource-constrained farmers [127]. Economic evaluations are rarely reported, but the results suggest that smallholders prioritize practices that show clear, short-term benefits, with minimal additional financial burden [128]. Gender dimensions are also critical [128], but under-researched and under-reported. Access to land, extension services, and credit significantly influence adoption [129], and women often face systemic barriers in all three [130]. Technologies that are labor-intensive or require land tenure security tend to exclude women unless tailored support is provided [131]. Youth engagement remains a largely unexplored frontier. With increasing rural youth unemployment, promoting technologies that are mechanized, entrepreneurial, or digitally supported could create new entry points for youth involvement. However, current literature lacks robust analysis on how land and water technologies affect or are adopted by young farmers. These gaps indicate a need for gender-responsive and youth-inclusive research and programming to ensure equitable access and impact.

This review identifies several limitations in the current body of research. First, there is a lack of long-term trials that assess how soil- and water-management technologies perform over multiple years under changing climate conditions [132]. Second, the economic dimensions of technology adoption are rarely analyzed in depth [133]. Yield gains are commonly reported, but data on labor costs, return on investment, and financial barriers are scarce. Without this, it is difficult to assess feasibility or incentivize scaling. Third, there is an absence of gender-disaggregated and youth-specific data [134]. Although women and youth play critical roles in agriculture, few studies explore how these groups interact with land- and water technologies or benefit from them. This lack of inclusivity weakens the evidence base for equitable development strategies. Finally, many technologies are assumed to be transferable across contexts without thorough testing. Technologies that are effective in one region may underperform elsewhere due to differences in community norms, institutions, soils, or topography [135]. This assumption of universality may reduce the effectiveness of technologies and reduce uptake.

To ensure that land- and water-management technologies are effective, inclusive, and scalable, future research should focus on several areas to benefit smallholder farmers across Africa's drylands. First, there is a critical need for long-term impact assessments. Lack of long-term trials limits understanding of the durability of sustainable land-management technologies under prolonged drought, soil stress, or changing climate. Future studies should therefore track soil health, water retention, yield stability, and farmer satisfaction over multiple seasons and under variable weather and land-use conditions. This will help smallholder farmers manage risk and plan better for the future. In addition, studying the economic viability of these technologies is equally important. This will help smallholder farmers to make decisions regarding the most promising technology

investment options. Inadequate finance to cover labor and input cost make smallholder farmers reluctant to adopt even these promising technologies. Therefore, future studies should include simple cost-benefit analyses, developed in partnership with farmers, to identify technologies with the best returns on investment. This will enable farmers to minimize risks and enhance access to microfinance or subsidies according to their profitability.

Disaggregated research on gender and youth is also crucial. Despite their significant contributions in agriculture, women and youth are frequently excluded from innovation and adoption pathways. Women face structural barriers such as insecure land tenure and limited access to information and tools [134], while youths have limited access to land, or find agriculture unattractive [136]. Future research must explore how land- and water technologies can be adapted to meet the specific needs of these groups. Doing so would ensure that more people benefit from sustainable practices, reduce inequality within farming communities, and build intergenerational interest in land management.

Additionally, future studies can assess and validate the adaptability of the diverse soil and water management practices in different locations. Technologies that are successful in one agroecological zone or region might not be effective in another. Soil type, rainfall variability, cultural preferences, and institutional environments differ greatly across the Sahel and sub-Saharan Africa. Evaluating and customizing technology to suit certain local conditions, prior to widespread promotion will save resource wastage and dissatisfaction. For farmers, this would require recommendations that are tailored to their field conditions and landscapes.

There is also a need to effectively integrate Indigenous and local knowledge into research and activities. This is because small-scale farmers across Africa have acquired generations of knowledge in managing scarce water, maintaining soil fertility, and coping with climate extremes. Investing in participatory research would enhance and improve current practices in addition to documenting local knowledge. This can promote cultural relevance, improve farmer ownership, and facilitate the adoption of new initiatives.

Finally, to engage the young generation and assist smallholder decision-making, there is a need to explore digital tools and rural innovations. These include using mobile phones and low-cost weather and soil sensors, which have become increasingly accessible. These can provide real-time guidance on where to access inputs, how to control runoff, and when to plant. Similarly, digital input supply agribusiness models involving water-harvesting and irrigation kits, or leasing farm equipment, can create opportunities for youth and local entrepreneurs. For smallholder farmers, digital and entrepreneurial innovations offer not only better access to information but also new income streams through job creation. These prospective research avenues promise to convert land- and water management from fragmented technical solutions into farmer-centric, contextually relevant techniques that enhance livelihoods, equality, and resilience within dryland agricultural systems.

Selection of Technologies for Adoption in Sédhiou and Tambacounda

Senegal has largely flat terrain, with the highest point being Baunez ridge situated 2.7km southeast of Nepen Diakha at 648m. Tambacounda lies at an elevation of 24m while Sédhiou lies at 33m. Therefore, adoption of soil- and water-management technologies needs to take slope into consideration, for more feasibility. Considering that most agricultural fields lie between a slope of 0 and 10%, the recommended technologies would include: agroforestry, deep ripping, drip irrigation, half-moons, infiltration pits, manure application, minimum tillage, mulching, residual moisture, road runoff water harvesting into pans and ponds, tied ridges, trash lines, water pans, and *Zai/Tassa* pits.

5. Conclusions

This review presents a synthesis of around **85 land- and water-management technologies** implemented across **17 climate-analogous countries in sub-Saharan Africa**, identified using K-means clustering based on bioclimatic variables. The technologies reviewed offer substantial

potential for improving resilience and productivity in Senegal's semi-arid zones, particularly **Sédhiou and Tambacounda**. These areas face declining yields, water stress, and land degradation which are challenges that demand site-appropriate, scalable solutions.

Despite the development of numerous effective soil- and water-conservation techniques across Africa, their adoption in the Sahel—and particularly in Senegal—remains limited due to weak institutional, financial, and political support, coupled with inadequate extension and monitoring systems [22]. Scaling these technologies is further constrained by insufficient financing and capacity within civil society, local authorities, and the private sector. Yet appropriate water management is essential for achieving optimal economic growth, food security, poverty reduction, climate resilience, biodiversity conservation, and sustainable agriculture. The review underscores that success depends not only on technology but also on systems that foster local ownership, stakeholder participation, and context-specific design. In arid regions, water management is as much a social and economic imperative as a technical one, requiring farmer empowerment, capacity building, and inclusive approaches for youth and women. Proven practices such as half-moons, mulching, rainwater harvesting into pans and ponds, trash lines, and *Zai* pits are especially well-suited to Sédhiou and Tambacounda's terrain. Evidence from cross-country experiences shows that adoption is strongest where awareness, funding, institutions, and policies converge, highlighting the need for integrated strategies to translate technologies into lasting resilience.

Unlocking the full potential of soil- and water-conservation technologies requires governments and development partners to invest in knowledge transfer, demonstration sites, and cross-country learning platforms, while embedding conservation into multisectoral policies, increasing local financing, and ensuring inclusive participation of women, youth, and local leaders. Success depends on early and meaningful stakeholder engagement, which fosters ownership, integrates local knowledge, and enhances the appropriateness of decisions, even in contexts where mistrust or conflicts of interest often undermine adoption. Sustainable implementation also requires balancing economic, environmental, and social factors, and demonstrating both on-site and off-site benefits through an Integrated Water Resources Management approach. Strong policy support is pivotal, with governments shaping land-use decisions through legislation and regulations, while public education and improved knowledge-sharing mechanisms bridge gaps between science, policy, and practice. Without these measures, proven solutions risk remaining fragmented and failing to drive the agricultural transformation urgently needed in the Sahel.

Recommendations/Future Steps

- **Integration into multi-sectoral policy frameworks:** Water management and conservation practices should be seamlessly integrated into multi-sectoral policy frameworks in the region. Given the inherently cross-sectoral nature of such projects, policy frameworks should reflect the interconnectedness of water management and conservation initiatives, from local to regional levels.
- **Adequate funding:** To upscale water-management and -conservation practices, there is a critical need for both internal and external resource mobilization. Adequate funding should be secured to implement techniques and technologies beyond the capacities of local communities, including water-harvesting technologies, soil-fertility improvement techniques, afforestation, and forest management, as well as capacity-building initiatives.
- **Private-sector involvement:** The advisory roles of technical services, especially the participation of the private sector, should be improved to bring on board more key stakeholders, promote scaling up and sustainability of the practices in the long term. This can be achieved through developing harmonized planning and the promotion of marketable goods and services derived from the implementation of Sustainable Land Management practices.
- **Empowering stakeholders:** Soil and water conservation stakeholders should engage in careful planning to better conserve and use their soil and water resources. The ultimate goal is to empower farmers with the necessary tools and technical knowledge to effectively conserve these

resources that will translate into improved agricultural productivity and livelihoods. Initiatives should be designed according to participatory and inclusive approaches that integrate ethnic, gender, and youth perspectives and knowledge.

- **Capacity building, research, education, and extension:** Emphasis should be placed on regular research, education, and extension (training) focused on soil- and water-conservation technologies for stakeholders, especially farmers. Continuous learning, awareness building, and knowledge dissemination are essential for the successful implementation of these conservation practices.
- **Site-Specific Approaches:** Soil- and water-conservation practices should be site-specific, considering the variations in soil types, crops, and climatic conditions among other factors, such as the technologies' installation and maintenance costs across various ecological zones in the country. Tailoring interventions to specific contexts will enhance their effectiveness.
- **Government Involvement:** Governments at all levels should be actively involved in providing technical support and incentives for improving land- and water-management practices. This involvement is crucial for minimizing land degradation and improving water quality, contributing to achieving relevant Sustainable Development Goals.
- Arising from the review, **the authors recommend** that the technologies listed in table 5 below be considered for adoption in Sédhiou and Tambacounda, Senegal and the Sahel region:

Table 5. Recommended land- and water-management technologies to boost Senegal's agricultural resilience.

Management approach		Technology
Efficient irrigation	1	Drip irrigation
	2	Residual moisture irrigation
Soil-moisture management	3	Agroforestry
	4	Deep ripping
	5	Manure application
	6	Minimum tillage
	7	Mulch application
	8	Trash lines
Water harvesting	9	Constructing half-moons
	10	Constructing infiltration pits
	11	Road runoff water-harvesting into pans & ponds
	12	Establishing tied ridges
	13	Establishing Zai/Tassa pits

This is mainly because Sédhiou and Tambacounda regions have a fairly undulating terrain which limits the application of most of the researched technologies, which are only applicable in areas with greater slopes.

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Abbreviations

The following abbreviations are used in this manuscript:

AVENIR Adaptation and Valorization of Entrepreneurship in Irrigated Agriculture
CIAT International Center for Tropical Agriculture
FAO Food and Agriculture Organization
GAC Global Affairs Canada
MEDA Mennonite Economic Development Associates
NGO Non-Governmental Organizations
PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SLM Sustainable Land-Management
SWC Soil and Water Conservation
UNDP United Nations Development Programme
UNEP United Nations Environment Programme

Appendix A

Table A1. Summary of 85 water conservation & management technologies by country.

strategy	measures	Technology	Kenya	Tanzania	Ethiopia	Somalia	Zambia	Zimbabwe	Botswana	Namibia	Malawi	South Africa	Sudan	Niger	Mali	Burkina Faso	Nigeria	Guinea	Senegal		
Water Harvesting (In-situ)	irriga	1	Inland valley swamp Irrigation																		
		2	Ados																		
	ridges/ terraces	3	box ridges																		
		4	Contour ridges and terraces														Vallera ni system				
		5	Marker ridges																		
		6	Ridges	open & tied	Tied				Tied; contour	Tied; compacted			contour	tied							
		7	Terracing			fanya juus			Fanya Juus												
		8	Dead level contours,																		
		catchment	9	Gabion structures (rock barrier cages)																	
			10	Strip catchment	strips																
11	check dams																				

1	2	Concrete lined underground tanks																	
	3	Earth dams														check dams			
	4	micro-basins	Negarims									Half-moon							
	5	Percolation ponds																	
	6	Piterki retention basin																	
	7	planting basins																	
	8	Ponds																	
	9	Rainwater harvesting,																	
	20	Retention ditches																	Anti-salt & runoff retention dike,
	21	Soil bunds	contour & semi circular		Stone face d/ Soil face														



soil						deep trench													
	2	Stone lines																	
	2	compost																	
	2	conservation agriculture																	
	2	grass strips																	
	2	hedges																	
	2	Mulching																	
	2	Tillage	conservation					deep winter ploughing/ripping	double ploughing/Furrow & precision strip tillage	deep ripping						contour ploughing			
	2	Cut-off drains,																	

		30	diversion ditches																	
		31	infiltration pits																	
		32	Pits	Zai	Cholo & Mate ngo				Infiltration pits				ploegvo re (mecha nized pitting),		Zai pits (tas sa)		Zai pits,			
		33	Swales (runoff channels)																	
Water Harvesting (Ex-situ)	dams	34	Small earth dams,		Chaco dams															
		35	sub-surface dams																	
		36	Sand dams																	
		37	Non-permeable dikes																	
		38	Permeable rock dams																	
	basins	39	Water pans																	
		40	Ponds										Ama-pitsi							

	reservoirs/tanks	4 1	Banka																	
		4 2	Micro-basin water harvesting																	
	reservoirs/tanks	4 3	Dead level contours with underground storage tanks,																	
		4 4	Concrete-lined underground tanks																	
		4 5	Klipplate and vaggate (hardened surface & catchment tanks),																	
		4 6	Boulis reservoirs																	
		4 7	Hill reservoirs,																	
	pits	4 8	Infiltration pits																	
	soil	4 9	Gelesha (soil turning),																	
	water harvesting	5 0	Saaidamme (floodwater harvesting),																	
		5 1	Granite dome water harvesting,																	
		5 2	Improved wells,																	
		5 3	Rock packs																	

	excess water	8 2	flood-plain agriculture,																	
		8 3	Runoff/ floodwater farming																	
		8 4	Use of residual moisture																	
	plants	8 5	Agroforestry																	
			#technologies/country	17	4	9	2	11	11	6	12	22	13	10	7	5	11	11	3	5

Table A2. In-situ water harvesting technologies (52).

Technology	Country	Definition
Ados	Burkina Faso	Earth bunds arranged in contour lines to stop runoff water and allow infiltration, increasing water retention in the soil.
<i>Ama-pitsi</i> /homestead ponds	South Africa	Hand-dug pits or small dams into which surface runoff is diverted and stored for crop and domestic use.
<i>Banka</i>	Burkina Faso	A traditional water conservation technique involves the construction of small earthen bunds.
Bench terraces	Kenya	Horizontal platforms with a raised embankment along the contour of sloping land to reduce soil erosion and enhance water retention.
Box ridges	Malawi	Elevated ridges, created to enhance soil moisture in the topsoil, particularly at the beginning of the cropping season.
<i>Chololo</i> pits	Tanzania	Pits designed to conserve moisture in the soil and improve fertility, ultimately increasing crop production.
Clay pot (sub-surface irrigation)	Zambia	A system using clay pots for sub-surface irrigation, providing controlled water supply to plants.
Compacted ridges	Botswana	Ridges consisting of plastic-covered structures that effectively harvest water during low-intensity rainfalls.
Contour ridges and terraces (<i>fanya juu, fanya chini</i>)	Kenya, Zimbabwe, South Africa, Ethiopia	Earth structures created along the contour of sloping land to minimize erosion and retain water.
Crib wall	Nigeria	A structure made of interlocking wooden or concrete elements to prevent soil erosion and retain water.
Cut-off drain/diversion ditch	Nigeria, Kenya	A constructed drain or ditch designed to divert water away from an area or prevent soil erosion.
Dead level contours with or without infiltration pits	Zimbabwe	Contour lines with or without pits constructed to improve water retention and prevent runoff.
Deep ripping	Namibia	Water conservation practice involving the use of deep working tines to break up compacted soil and enhance infiltration.
Demi-lunes/half moons	Niger, Mali, Burkina Faso	Earthen ridges promoting water infiltration, often combined with organic fertilizer application.
Diversion ditches	Nigeria	Constructed ditches designed to divert water away from an area or manage water flow.
Earth bunds	Kenya, Burkina Faso	Structural measures consisting of soil or stone embankments built along the contour to reduce runoff speed and prevent erosion.
Earthen bunds - contour bunds, semi-circular bunds, and Negarims micro-catchments	Kenya, Ethiopia, Somalia, Namibia	Various forms of earth bunds created for ponding runoff water and water harvesting.
Filter bund	Burkina Faso	A water and soil conservation technology built in a flowing watercourse to reduce runoff velocity and control soil erosion.
<i>Gelesha</i>	South Africa	Tilling soil immediately after harvest to ensure rain, dew, or frost infiltrates the tilled soil.
Graded contour ridges and <i>Fanya Juus</i>	Zimbabwe, Kenya, Tanzania, Uganda, Ethiopia	Ridges and structures created along the contour to enhance water retention and prevent erosion.
Grassed waterways	Kenya	Waterways with planted grass or vegetation to slow runoff, stabilize soil, and promote water infiltration.
Infiltration pits	Zimbabwe, Malawi, Kenya	Small pits dug into the ground to enhance soil-moisture retention and promote water infiltration.
In-land valley swamp irrigation (<i>Dambos</i>)	Zambia	Low-lying areas with a high-water table used for growing crops.
<i>Klipplate</i> and <i>vanggate</i>	South Africa	Water conservation practices involving the creation of compacted ridges and reservoir tillage.
Low-lying crescents	Sudan	Crescent-shaped structures used to break the force of runoff water and enhance infiltration.

<i>Matengo</i> pits	Tanzania	Excavated pits designed to harvest and store rainwater for agricultural use.
Micro-basin water harvesting	Zambia	Harvesting rainwater in small micro-basins to enhance water availability for agriculture.
Mulch ripping	Zimbabwe	Incorporating mulch into the soil using ripping equipment to improve water retention.
<i>Nombete</i> (meaning 'beds')	Namibia	Low-cost indigenous irrigation technique involving small beds for vegetable production, often practiced along rivers.
Open ridges	Tanzania	Ridges created with an open design, likely used for water harvesting purposes.
Percolation ponds	Malawi	Ponds designed to enhance water infiltration, often constructed for rainwater harvesting.
<i>Piterki</i> retention basin traditional ponds/water retention ponds	Senegal	Traditional ponds or basins constructed to retain water for agricultural use.
Planting basin	Zimbabwe, Namibia	Depressions or basins created for planting crops, enhancing water retention and infiltration.
<i>Ploegvoore</i> (mechanized pitting)	South Africa	Structures or practices promoting water retention and infiltration in agricultural fields.
Ridging	Tanzania, Zimbabwe, Botswana, Kenya, Ethiopia, Sudan	Creating ridges in the soil to improve water retention and prevent soil erosion.
River floodplain recession irrigation	Zambia	Utilizing river floodplains for crop irrigation during the recession phase of flooding.
Rocks packs	South Africa	Water harvesting technique involves filling crevices with soil and planting crops to capture runoff. Rocks are packed into large crevices in granite and basalt domes, filled with soil and planted with maize and other crops.
<i>Saaidamme</i>	South Africa	A traditional practice involving the bunding of waterlogged areas for rice cultivation.
Sand dunes stabilization	Niger	Stabilizing sand dunes to prevent soil erosion and enhance water retention.
Semi-circular bunds	Kenya, Tanzania, Burkina Faso	Earth bunds constructed in a semi-circular shape to retain water and prevent erosion.
Spate irrigation	Malawi	Utilizing floodwaters for irrigation, often practiced in arid and semi-arid regions.
Stabilization of gullies and riverbanks	Niger	Techniques and structures used to stabilize eroded gullies and riverbanks.
Stone bunds or lines	Mali, Kenya, Ethiopia	Bunds or lines made of stones to control soil erosion and manage water flow.
Strip catchment	Kenya,	Collecting runoff water using strips of impermeable material to enhance water availability.
Swales	Malawi	Shallow channels or depressions in the landscape designed to manage water flow and enhance infiltration.
<i>Tassa</i> and half-crescent shaped earthen mounds (the half-moons).	Niger, Mali, Burkina Faso	Mounds and structures designed to enhance water retention and infiltration.
Terracing	Kenya, Somalia, South Africa, Nigeria	Creating terraces on sloping land to minimize erosion and improve water retention.
<i>Tiarako</i> bund	Burkina Faso	Bunds constructed in a specific shape to enhance water retention and soil moisture.
Tied contour ridges for water harvesting/Tied ridges	Kenya, Tanzania, Zimbabwe, Botswana, South Africa, Sudan, Namibia	Ridges constructed along contours and tied together to enhance water retention and infiltration.
<i>Vallerani</i> system	Burkina Faso	A system designed for rainwater harvesting, involving the construction of embankments and check dams.
<i>Zai</i> pits	Kenya, Burkina Faso, Niger, Mali	Small pits dug into the ground to enhance water infiltration and soil fertility, commonly used in agroforestry.

Table A3. Table 8: Ex-situ water harvesting technologies (25).

Technology	Country	Definition
Above-ground tanks for domestic application	Malawi	Tanks designed for storing water above the surface, typically used for domestic purposes.
Anti-salt and runoff retention dike	Senegal	A technology designed to retain runoff water and reduce land salinity.
Artificial waterways	Kenya	Manufactured channels or water passages created for the purpose of managing water flow.
Blue-water structures	Kenya	Infrastructure designed to manage surface water, ensuring its availability for various uses.
Boulis reservoirs	Burkina Faso	Oval or circular structures dug into the ground to collect runoff water for different agricultural purposes.
Chaco dams	Tanzania	Dams used for harvesting runoff water for domestic, livestock, and agricultural use during both rainy and dry seasons.
Check dams	Kenya, Malawi, Mali, Nigeria	Small structures built across drainage channels to reduce water flow velocity and control soil erosion.
Compacted ridges	Botswana	Ridges consisting of plastic-covered structures that effectively harvest water during low-intensity rainfalls.
Concrete-lined underground tanks	Malawi	Underground tanks with concrete lining, often used to collect runoff from various surfaces.
Dead level contours with underground storage tanks	Zimbabwe	Contour lines with underground tanks for storing water and preventing soil erosion.
(Granite) Dome water harvesting	South Africa	Harvesting rainwater on natural hardened and impermeable surfaces like granite domes.
Earth dams	Kenya, Zambia, Malawi, Nigeria	Large reservoirs or embankments constructed to store rainfall runoff.
Flood-plain agriculture	Ethiopia, Zambia, Malawi, South Africa	Cultivation of floodplains using receding or rising floodwaters for crop production.
Geres reservoir	Burkina Faso	A reservoir used to collect runoff water for various agricultural purposes.
Hill reservoirs	Guinea	Reservoirs constructed on hills to collect and store rainwater for various agricultural purposes.
Low-cost bucket/drum-kit drip-irrigation	Zambia	Drip-irrigation system using low-cost buckets or drums for water supply.
Low-pressure micro-irrigation (including drip irrigation and water reservoirs)	Senegal	Micro-irrigation methods with low water pressure, including drip irrigation and water reservoirs.
Micro-catchments and ponds	Ethiopia, Kenya, Zambia, Burkina Faso	Small catchment areas designed to collect runoff water and store it in ponds.
Pans and small dams	Kenya,	Shallow excavated depressions designed to collect and store rainwater efficiently.
Road runoff	Kenya, Malawi	Capturing and utilizing runoff water from roads for agricultural purposes.
Sand and sub-surface dams	Kenya,	Dams constructed with sand and other materials below the surface to store water.
Small earth dams and ponds	Kenya	Small-scale dams and ponds constructed to collect and store rainwater for agriculture.
Use of treadle pump for irrigation	Malawi	Utilizing treadle pumps for irrigation to enhance water availability for crops.
Water pans	Kenya	Depressions or ponds constructed to collect and store rainwater for agricultural use.
Water storage	Somalia, Botswana	Various methods and structures for storing water, including tanks, reservoirs, and ponds.

Table A4. Planting crop or trees and residue management methods (4).

Method	Country	Definition
Agroforestry	Nigeria, Burkina Faso, Tanzania, Kenya	A land-use management system that integrates trees and shrubs with crops and/or livestock, promoting environmental sustainability.
Crop residues and mulching	Niger, Sudan, south Africa, Malawi, Zimbabwe, Kenya	The practice of leaving crop residues on the field or applying mulch to improve soil moisture and prevent erosion.
Grass strips along the contour	Kenya, Ethiopia, Somalia, Malawi, South Africa, Mali, Burkina Faso	Linear plantings of grass or other vegetation within agricultural fields to act as natural erosion barriers
Trash lines	Kenya, Ethiopia	Lines of crop residue or other material used to slow water runoff and enhance infiltration.

Table A5. Efficient irrigation techniques (4).

Technology	Country	Definition
Drip irrigation	Zambia, Namibia, Kenya	Precise irrigation method delivering water directly to the plant roots using a network of tubes and emitters.
Spate irrigation	Malawi	Utilizing floodwaters for irrigation, often practiced in arid and semi-arid regions.
Use of residual moisture	Zambia, Malawi	as the moisture dries up, farmers will use water from shallow wells, using watering cans or treadle pumps to irrigate crops
Use of treadle pump for irrigation	Malawi	Utilizing treadle pumps for irrigation to enhance water availability for crops.

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