

CHAPTER 8

# Integrating Emerging Irrigation Technologies to Advance Agricultural Production and Resilience in Africa

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## Introduction

### Africa's agricultural productivity gap

**A**griculture remains the cornerstone of African economies; it reduces inflation and provides employment, livelihoods, food, and nutrition to over 70 percent of the continent's population (World Bank 2016). The agriculture sector contributes over 20 percent to Africa's GDP; this is significantly higher than the global average of about 5 percent and highlights its strategic role in national development (Tavneet and Udry 2022). This reliance on agriculture underscores its importance in ensuring economic stability, social cohesion, and food sovereignty across the continent.

Africa possesses tremendous agricultural potential. The continent is home to extensive arable land, abundant water resources, a rapidly growing and youthful labor force, favorable agroecological conditions, and a vast reservoir of biological resources. Despite these advantages, agricultural productivity has remained unacceptably low. Yields of key staple crops, especially those cultivated under rainfed conditions, consistently fall below both global averages and the benchmarks set by the African Union (AU). Average cereal yields, for instance, remain below the AU target of 2 tons per hectare (t/ha) (AUC 2025), while legume yields continue to trail behind those of Asia, Europe, and North America.

This underperformance is particularly alarming in the context of the continent's rapidly growing population, projected to reach 2.5 billion by 2050 (AGRA 2023), which will place increasing pressure on food systems, land, water, and natural resources. Substantial gains in productivity will be crucial to meeting the rising demand for food and nutrition. Achieving this will require not only technological and institutional innovations but also more resilient and sustainable production systems that are better adapted to the region's climatic realities.

Evidence indicates that irrigated and input-intensive agricultural systems consistently outperform traditional, rainfed practices and frequently yield harvests that exceed regional targets. The adoption and diffusion of modern water management technologies across Africa (Addorisio, Spadoni, and Maesano 2025), however, remain limited and uneven, particularly in sub-Saharan Africa (SSA). SSA has the lowest irrigation rates in the world; of the total cultivated land area on the African continent, only 13 million hectares (less than 6 percent) is irrigated (World Bank 2016; Xie et al. 2014). While countries such as Egypt,

South Africa, and Mauritius exhibit relatively higher irrigation coverage, the overall continental average remains far below global standards. This structural constraint exacerbates yield gaps, weakens agricultural resilience to climate shocks such as erratic rainfall and drought, and hinders the realization of the continent's agricultural potential. It is therefore imperative to accelerate the development and adoption of water-efficient irrigation systems as a core strategy for transforming African agriculture (Addorisio, Spadoni, and Maesano 2025).

### The role of irrigation in agricultural transformation

The Sahel region exemplifies the acute vulnerabilities associated with rainfed agriculture in semi-arid climates. Characterized by low and erratic rainfall, the region frequently suffers from crop failures, food shortages, and socioeconomic instability. Similar challenges persist across SSA, which, in turn, constrain the continent's agricultural performance. Of the 6 percent of cultivated land in Africa that is currently irrigated, over two-thirds is located in just the five countries of Egypt, Madagascar, Morocco, South Africa, and Sudan, and in SSA, the share drops to merely 3.5 percent (Scheumann, Houdret, Brüntrup 2017).

Projections by the FAO nevertheless indicate that the irrigated area in SSA could expand by an additional 40 million hectares by 2030 if financing constraints were adequately addressed (Scheumann, Houdret, and Brüntrup 2017). A wide array of technologies and strategies is available for improving water management, including water harvesting, aquifer recharge, soil moisture conservation, and various forms of irrigation. These practices have demonstrated potential for improved efficiency; progress is, however, hindered by limited access to these innovations and weak mechanisms for scaling them up. Many smallholder farmers thus remain reliant on rainfall, which leaves them vulnerable to recurring droughts, food insecurity, and economic instability.

Africa's irrigation landscape is highly diverse. It encompasses traditional systems, formal irrigation schemes developed at various scales (small, medium, and large), and farmer-led and mechanized irrigation initiatives. Each of these systems has distinct advantages and implementation challenges. Economically, the benefits of irrigation are considerable, with irrigated plots yielding on average 30 to 60 percent more than rainfed plots. Irrigation also supports the use of improved seed varieties, extends cropping periods, and allows for more

intensive cultivation cycles (Rosegrant, Ringler, and Zhu 2009). Reflecting this, the 2014 Malabo Declaration emphasized irrigation investment as being central to achieving the goal of ending hunger by 2025, with African leaders pledging to double irrigated land area within the decade (AUC 2014).

Beyond boosting on-farm productivity, irrigation can catalyze broader rural development by generating non-farm employment, increasing household incomes, spurring local economic activity, and improving food security. Irrigation also plays a pivotal role in reducing Africa's growing dependency on food imports, thereby enhancing food sovereignty. Despite its immense promise, however, the performance of large-scale irrigation investments has been mixed. Historically, and particularly during the mid-20th century, large-scale projects focused mainly on constructing dams and canal networks, as well

as on centralized schemes aimed at supporting food security and commercial agriculture (Higginbottom et al. 2021).

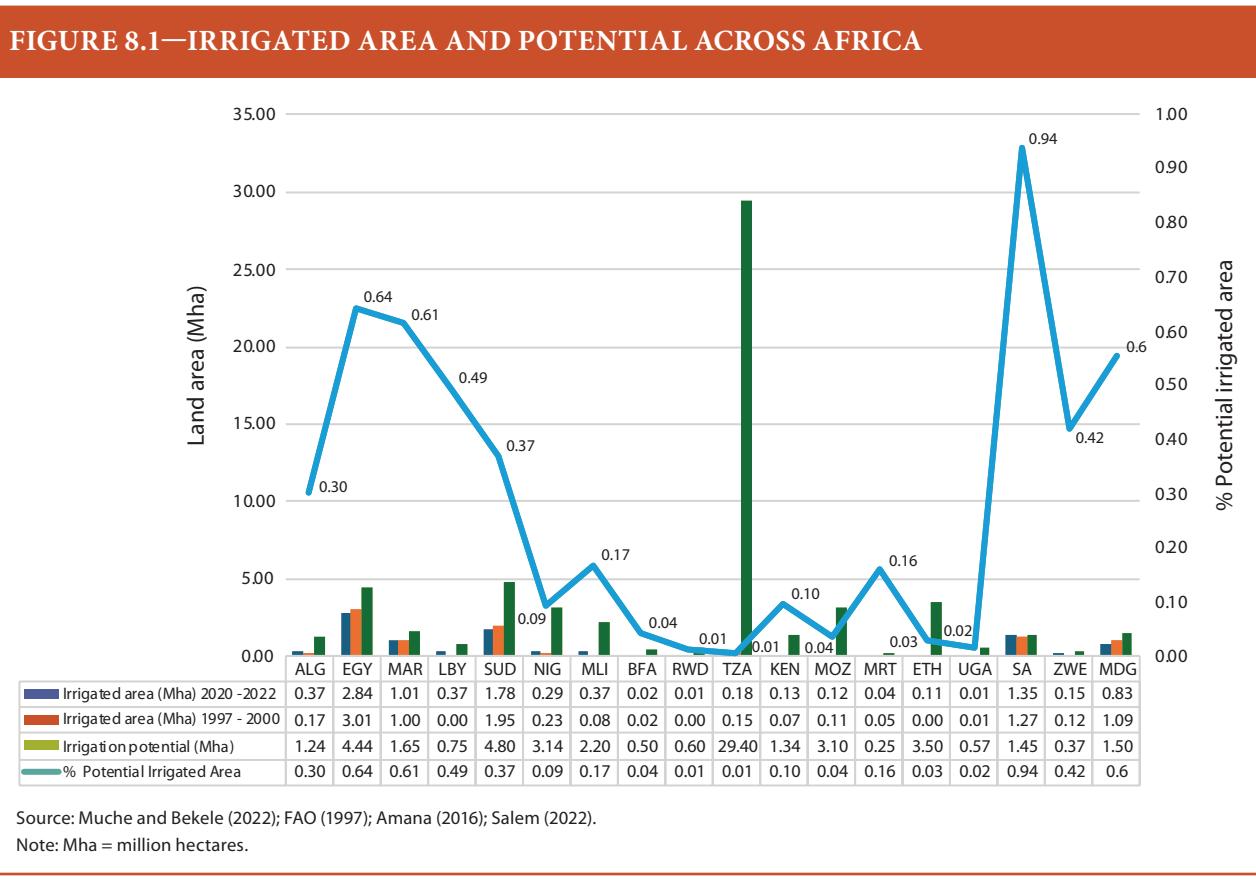
In recent years, there has been a notable shift toward smallholder and farmer-led irrigation systems, but large-scale schemes continue to dominate the funding landscape. They often face challenges related to high development costs, low efficiency, poor maintenance, and a lack of alignment with the needs of small-scale farmers. There is thus an emerging consensus around the need for more adaptive, cost-effective, and inclusive approaches to irrigation development that can deliver better outcomes across different farming contexts.

Figure 8.1 illustrates the evolution of irrigated areas across various African countries between 1997 and 2022. While some countries have registered notable improvements, others have witnessed stagnation or even regression. In general,

except for Egypt, Morocco, South Africa, and Madagascar, most African countries use less than half of their irrigation potential. Northern Africa remains the most developed in terms of irrigated land, while other subregions continue to lag. Not surprisingly, there is more irrigated land area in Northern Africa than in subregions where investment in irrigation remains low (Figure 8.2).

Extreme weather events have further aggravated the situation. In 2024, the Africa Center for Strategic Studies (ACSS 2024) reported that 27 tropical African countries had experienced unusually heavy rainfall compared to historical norms (Figure 8.3). These anomalies affected over 11 million people, resulting in approximately 2,500 fatalities, displacing more than 4 million individuals, and inundating millions of hectares of cropland. Hundreds of thousands of head of livestock were lost. Reed et al. (2022) found that around 12 percent of those affected by food insecurity between 2009 and 2020 had been directly impacted by flooding. Notably, such climatic extremes can have paradoxical effects, undermining food security in some regions while improving it in others; outcomes can thus be complex and uneven.

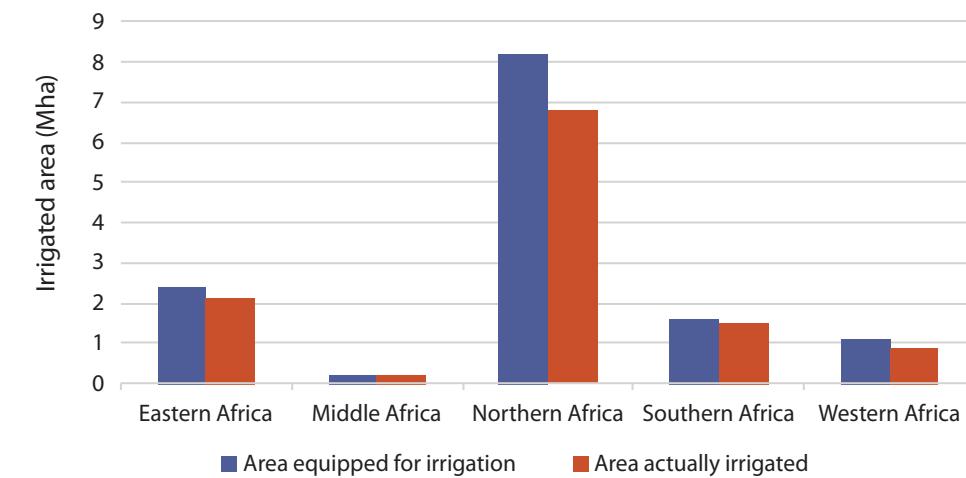
**FIGURE 8.1—IRRIGATED AREA AND POTENTIAL ACROSS AFRICA**



Source: Muche and Bekele (2022); FAO (1997); Amana (2016); Salem (2022).

Note: Mha = million hectares.

FIGURE 8.2—ACTUAL AND POTENTIAL IRRIGATED AREA BY REGION



Source: Siebert and Frenken (2014).

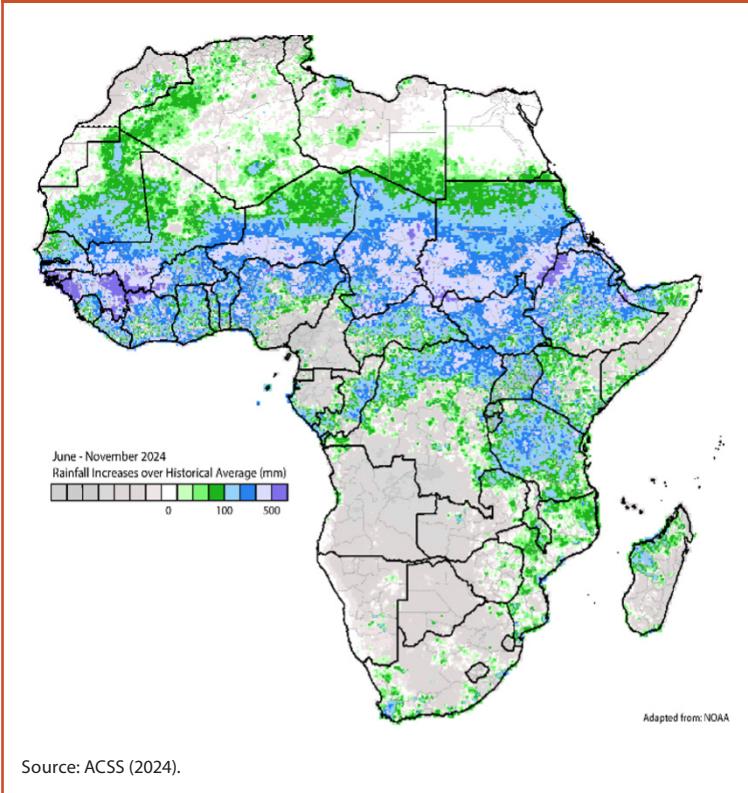
Note: Mha = million hectares.

African agriculture is also increasingly burdened by structural and environmental challenges other than floods; these include land degradation, pests and disease outbreaks, competition over water resources, and limited access to agricultural inputs and financing. These constraints have been exacerbated by climate change, underscoring the need for an urgent reassessment of agricultural development strategies. Systemic investments in climate-smart irrigation and complementary technologies will be vital in reversing productivity declines and building long-term resilience.

### Productivity of large-scale and small-scale irrigation systems

Large-scale irrigation systems, particularly those dependent on dam infrastructure, have long been a prominent feature of African agricultural and irrigation development. According to the International Commission on Large Dams, a dam qualifies as “large” if it exceeds 15 meters in height or stores more than 3 million cubic meters ( $m^3$ ) of water (Saruchera and Lautze 2019). Globally, there are an estimated 45,000 large dams, half of which are primarily used for supplying irrigation water. These dams support 30 to

FIGURE 8.3—AREAS ACROSS AFRICA EXPERIENCING A SIGNIFICANT INCREASE IN RAINFALL AND CONSEQUENT FLOOD RISKS



40 percent of the world's irrigated land and contribute 12 to 16 percent of global food production (FAO 2007).

Africa has approximately 1,300 large and medium-sized dams. Of these, fewer than 5 percent have reservoir capacities exceeding 1 billion  $m^3$ , and over a third have capacities below 10 million  $m^3$  (FAO 2007). More than half of these dams were constructed primarily for irrigation, while about 20 percent serve multiple purposes, including municipal water supply and energy generation. Despite the investment in these dams, their performance has often fallen short of expectations. A study by Higginbottom et al. (2021) that assessed 79 large irrigation schemes across the continent found that only 25 percent were operating at more than 80 percent of their intended capacity, and 20 percent were completely

inactive. These findings echo the conclusions of Inocencio et al. (2007), who also documented systemic underperformance and inefficiencies.

Small-scale irrigation systems, on the other hand, have demonstrated greater adaptability and stronger outcomes in many contexts. These systems are often more responsive to local needs, less capital-intensive, and better aligned with smallholders' capacities. When supported by targeted investment and capacity building, small-scale irrigation can significantly enhance productivity and resilience (Mupaso, Makombe, and Mugandani 2023; Gebrezgabher et al. 2021). Empirical evidence from Ethiopia and Tanzania shows that smallholder irrigation raised household incomes significantly (Mume 2021; Osewe, Liu, and Njagi 2020). In Asia as well, regions with more irrigated land consistently report lower poverty rates and reduced income inequality than those regions that rely solely on rainfed farming (Scheumann, Houdret, and Brüntrup 2017). Figure 8.4 shows the available total renewable water resources (TNWR) per capita (in  $\text{m}^3/\text{year}$ ), that is, the volume of renewable natural freshwater (both groundwater and surface) that is available each year to every person in a country. This gives an idea

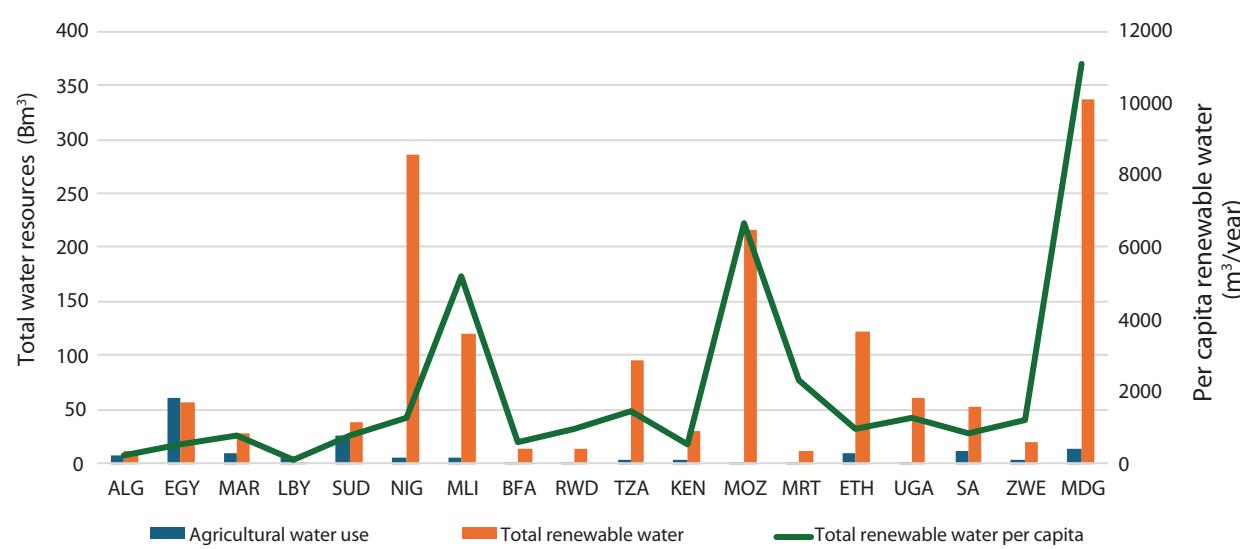
of the volume of water available for productive use each year. Except for Algeria, Egypt, Sudan, and Libya, in most other African countries, a significant portion of the renewable water resources is available for agriculture and irrigation expansion (Figure 8.4).

Despite a range of interventions over recent decades, the failure to fully capitalize on Africa's irrigation potential has perpetuated widespread poverty and deepened food insecurity. The African Development Bank (AfDB 2015) projects that the number of undernourished people will rise from approximately 240 million in 2015 to 320 million by 2025. Similarly, the United Nations Economic Commission for Africa forecast projected that the continent's annual food import bill could surge from US\$15 billion in 2018 to US\$110 billion by 2025 (UNECA 2019). Recent estimates from UNCTAD and FAO indicate that Africa's food import bill is already approaching US\$100–110 billion annually (UNCTAD 2021; FAO 2022), corroborating the earlier UNECA projection for 2025.

A new wave of technological innovation, however, offers an opportunity to alter this trajectory. Emerging irrigation technologies are expanding access to efficient irrigation; these include solar-powered pumps, real-time moisture sensors, drip and sprinkler systems, and equipment powered by renewable energy. These solutions are increasingly affordable and scalable. They are benefiting both the smallholder farmers who constitute the majority of Africa's agricultural base, and emerging medium- and large-scale commercial farms.

Technologies such as machine learning, precision agriculture, Geographic Information Systems (GIS), and big data analytics have clear applications in irrigation management. They facilitate site-specific input application, optimize yields, reduce waste, and enhance the sustainability of agricultural systems (Akhter and Sofi 2022). The efficient water management enabled by these technologies enhances nutrient use, improves energy efficiency, and boosts economic returns, while strengthening the resilience of farming systems to climate shocks.

**FIGURE 8.4—GENERAL AGRICULTURAL WATER USE AND RENEWABLE WATER RESOURCES IN AFRICA**



Note:  $\text{Bm}^3$  = billion cubic meters.

Source: FAO (2026).

Other regions, such as Asia and Europe, have adopted these innovations more extensively, while Africa has not yet fully unlocked their potential. Strategic investment in the deployment of irrigation technologies, coupled with supportive policy reforms, institutional strengthening, and human capacity development, will be essential to achieving an inclusive and climate-resilient agricultural transformation. This chapter reviews the status of emerging irrigation technologies, examines their potential to revolutionize productivity and water-use efficiency, and explores the barriers and opportunities related to their adoption across African farming systems.

## Agricultural production trends under normal and drought conditions

Under normal conditions, agricultural production in Africa tends to be characterized by yields that are seasonally stable but significantly below potential. This relatively poor performance is due to the limited use of inputs, inadequate mechanization, and insufficient access to extension services. Under drought conditions, yields can decline sharply; experimental and modeling evidence suggests that water stress can reduce yields of major crops by 25–50 percent, with maize particularly sensitive at high temperatures (Ritchie 2024). Water-dependent crops such as vegetables and rice are particularly vulnerable, while sorghum and millet exhibit slightly better tolerance. Climate variability is also contributing to soil-moisture stress, declining groundwater levels, and competition for increasingly scarce water resources, especially in transboundary basins (UNECA 2025).

## Adaptation measures to minimize crop failure and yield penalties across scales

Adaptation strategies to minimize crop failure and reduce seasonal water scarcity vary by scale. At the smallholder level, adaptation involves shifting planting calendars, utilizing early-maturing and drought-tolerant seed varieties, mulching, and adopting agricultural conservation practices. Irrigation practices led by smallholder farmers (supplemental and full irrigation) have become a major adaptation strategy across SSA. Large-scale actors, however, employ more capital-intensive strategies such as formal intensive irrigation; this includes real-time data monitoring, pivot irrigation with moisture sensors, and climate insurance schemes (World Bank 2018).

Practices that are employed at all scales include integrated soil fertility and water management, bundling irrigation investments with extension support, and promoting farmer cooperatives for joint access to equipment and inputs. Public policy also plays a critical role, including adaptive subsidies, irrigation infrastructure investments, and climate-resilient agricultural extension programs, all of which have been found to be effective across diverse contexts (Srivastava et al. 2024).

## The role of irrigation technologies in enhancing production and household resilience

Different irrigation technologies have played distinct roles in enhancing production and resilience. Drip and sprinkler systems have improved water-use efficiency by over 40 percent in smallholder settings (Liu et al. 2024), particularly in arid and semi-arid zones. These systems mitigate yield losses during dry spells, allowing for continued crop growth and the maintenance of income stability. In parallel, solar-powered pumps have expanded access to groundwater where surface water is unavailable, increasing cropping intensity and allowing off-season vegetable production.

At larger scales, center-pivot irrigation and automated irrigation systems that are linked with satellite or sensor data have enhanced productivity per hectare, while reducing labor and input costs. These technologies also enable diversified cropping systems, which reduce environmental stress on soils and water sources (Chen et al. 2023). Importantly, irrigation technologies also support gender-responsive and inclusive outcomes when combined with equitable extension and financial services, thus contributing to broader livelihood resilience (Srivastava et al. 2024).

## Conceptual framework: Linking emerging technologies to agricultural transformation

### *Africa's agricultural productivity challenge*

Agriculture remains central to Africa's economy, employing over 60 percent of the population and, in many countries, contributing substantially to GDP; productivity levels, however, remain persistently low. Cereal yields in SSA average only 1.6 t/ha in 2022, which is less than half the global average (World Bank 2024). These yield gaps are driven by limited input use, poor access to water,

fragmented markets, and chronic underinvestment in infrastructure. Bridging this productivity gap is essential not only to meeting the rising demand for food but also to reducing poverty and facilitating structural economic transformation.

### ***Role of irrigation in closing yield gaps***

Irrigation is widely recognized as a key driver of productivity growth, with irrigated plots being able to produce two to four times more than rainfed plots of similar size (Su and Singh 2024); however, less than 6 percent of arable land in SSA is irrigated, compared to 37 percent in Asia (FAO 2026). Expanding and improving irrigation infrastructure can increase cropping intensity, mitigate climate risks, and enhance rural incomes; this is especially the case when systems are accessible to smallholders and adapted to climatic realities. This expansion, however, must be done sustainably in order to reduce the risk of groundwater depletion, especially with increased use of solar irrigation pumping systems (Pavelic et al. 2021). Innovative and sustainable water management is thus pivotal to narrowing Africa's agricultural yield gaps with minimal environmental trade-offs (Olusola et al. 2025).

### ***Climate vulnerability and the urgency of technological change***

The effects of climate change and environmental sustainability sharpen the imperative for agricultural transformation. Increasingly erratic rainfall, extreme temperatures, and recurrent droughts pose serious threats to agricultural stability and food security. Technologies that improve water-use efficiency, bolster drought resilience, and reduce dependence on unreliable rainfall are no longer optional, they are essential (Sharma et al. 2023). Advances in irrigation, energy systems, and digital tools can mitigate the impacts of these climate shocks.

### ***Large-scale vs small-scale irrigation: Historical performance and lessons***

Historically, irrigation investment in Africa has focused on large-scale schemes, many of which failed to deliver anticipated outcomes due to unrealistic planning, weak management, and limited farmer participation (Higginbottom et al. 2021). By contrast, small-scale and farmer-led irrigation has shown greater adaptability and economic returns, particularly when supported by technical and financial assistance (Bjornlund, van Rooyen, and Stirzaker 2016). These experiences are tailored to diverse agroecological zones.

### ***Emerging irrigation technologies: A new paradigm***

Recent technological advancements, such as sensor-based irrigation, solar-powered pumps, and digital water monitoring systems, are reshaping and enabling improvements in yield and achieving environmental sustainability. These emerging technologies include digital agriculture, which utilizes next-generation technologies such as machine learning, artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and remote sensing (Fuentes-Peñailillo et al. 2024). Often associated with concepts such as "Agriculture 4.0" and "Smart Agriculture Transformation" (SAT), these technologies enable real-time optimization of water resources, reduce energy expenditure, and connect farmers to weather data, market prices, and advisory services via mobile platforms (APO 2019). Adoption remains uneven, however, being hindered by systemic barriers across technical, institutional, and financial domains (Fuentes-Peñailillo et al. 2024).

### ***Objectives and structure of the section***

This section proposes a conceptual framework that connects emerging technologies with agricultural transformation, with particular emphasis on irrigation and water management. The following section introduces the theoretical rationale and outlines the framework, drawing on innovation diffusion theory, behavioral technology adoption models, and empirical evidence from Africa. The framework articulates the role of enabling environments, the fit between technologies and user contexts, adoption pathways, and the resulting transformation outcomes.

### ***Conceptual framework***

Africa's agricultural transformation represents both a critical development priority and a strategic opportunity for structural change. With agriculture employing over 60 percent of the continent's population (Baale 2024), the sector remains the backbone of rural livelihoods, food systems, and national economies; yet productivity growth has remained sluggish due to a confluence of biophysical, economic, and institutional constraints. Particularly in SSA, where nearly half of the population remains engaged in agriculture (World Bank 2025a), persistent yield gaps reflect long-standing weaknesses in input delivery systems, water governance, market access, and institutional coordination. These constraints are compounded by the accelerating impacts of climate change, which amplify

rainfall variability, drought frequency, and flood events, thereby undermining production stability and threatening household resilience.

Addressing these interlinked challenges requires innovations that can simultaneously improve resource-use efficiency, sustain productivity, and build resilience against climatic and economic shocks. Among the most promising pathways is technological transformation in agricultural water management (AWM), particularly in irrigation, drainage, and water-lifting systems. Emerging water management technologies now offer possibilities for expanding irrigation coverage, optimizing input use, and integrating data-driven decision-making into farm operations.

This section presents a conceptual framework for understanding how technological, contextual, and behavioral factors interact to drive agricultural transformation through improved water management. This framework, which we are calling the Evidence-Linked Impact Framework, integrates and synthesizes two major theoretical strands: the Context–Intervention–Mechanism–Outcome (CIMO) logic used in impact evaluation (Pawson and Tilley 1997; Denyer, Tranfield, and van Aken 2008) and the Unified Theory of Acceptance and Use of Technology, or UTAUT (Venkatesh et al. 2003). This Evidence-Linked Impact Framework illustrates how different combinations of technologies, user contexts, and enabling environments generate multidimensional impacts on productivity, resilience, inclusion, and economic returns.

The purpose of the framework is not to predict specific quantitative results, but to articulate the logical relationships and processes that underpin the observed diversity in technology performance and adoption patterns. It thereby provides a structured basis for interpreting subsequent empirical findings. It integrates these with systems-based perspectives on agricultural water management and innovation (Higginbottom et al. 2021), producing an evidence-anchored framework that explains how enabling conditions, interventions, and behavioral moderators interact to generate multidomain transformation outcomes. This feedback loop reflects adaptive learning and policy reinforcement processes that sustain change over time (Habtewold and Heshmati 2023).

### ***Rationale for a water-technology–centered transformation framework***

Technological innovation has long been recognized as a cornerstone of agricultural transformation, but its success depends critically on the alignment

between the characteristics of the technology, the conditions of its use, and the institutional environment that governs adoption and scaling. Within African agriculture, the most binding constraints on productivity and climate adaptation are water-related, ranging from erratic rainfall to inefficient irrigation and limited storage capacity. Innovations in water management technologies are thus uniquely positioned to act as catalysts for sustainable transformation.

A water-technology–centered framework helps conceptualize this transformation in terms of how technologies work, for whom they work, and under what enabling conditions. It visualizes agricultural transformation not as a linear process but as an evolving interaction among five elements:

1. **Enabling conditions** such as policies, financing systems, and infrastructure, which determine feasibility,
2. **Technology characteristics** such as cost, usability, and scalability, which determine suitability,
3. **Farmer contexts and typologies**, which influence adoptability,
4. **Mechanisms of change**, which explain how technologies translate into outcomes, and
5. **Impact domains**, which capture the multidimensional nature of transformation.

By linking these elements, the framework offers a coherent way to understand how improvements in agricultural water management contribute to structural change. It situates water technologies within broader systems of governance, social relations, and behavioral incentives, highlighting the complementarity between technological advancement, institutional reform, and user adaptation.

### ***Theoretical foundations***

The framework combines two theoretical lenses to capture both the systemic and behavioral dimensions of technological change:

#### ***The Context–Intervention–Mechanism–Outcome (CIMO) logic***

The CIMO framework is widely used in policy analysis and impact evaluation, providing a structured approach for connecting causal processes to development outcomes. Applied to agricultural water management (AWM), it is

formulated as follows:

- Context (C): This refers to the socioecological, economic, and institutional setting in which agricultural water technologies are introduced. It includes agroecological conditions, regional infrastructure, governance systems, and farmer typologies (for example, smallholder, emerging commercial, or large-scale farms).
- Intervention (I): This refers to the type of technology or package introduced. It encompasses legacy systems (traditional canal or furrow irrigation), emerging or digital systems (drip, sprinkler, solar-powered, sensor-based, or data-enabled tools), and integrated bundled systems that combine multiple innovations (such as solar pumping coupled with precision irrigation and decision-support tools).
- Mechanism (M): This is the set of physical, informational, and behavioral processes through which interventions influence performance; examples include precision water delivery, energy independence, automation and control, and information-guided scheduling.
- Outcome (O): This refers to the resulting effects across multiple domains, namely productivity, water-use efficiency, climate resilience, inclusion, and economic returns. This formulation allows for flexibility in analyzing how varying contexts and interventions activate different mechanisms that yield differentiated outcomes. It recognizes that the same technology may produce distinct results depending on where and how it is implemented.

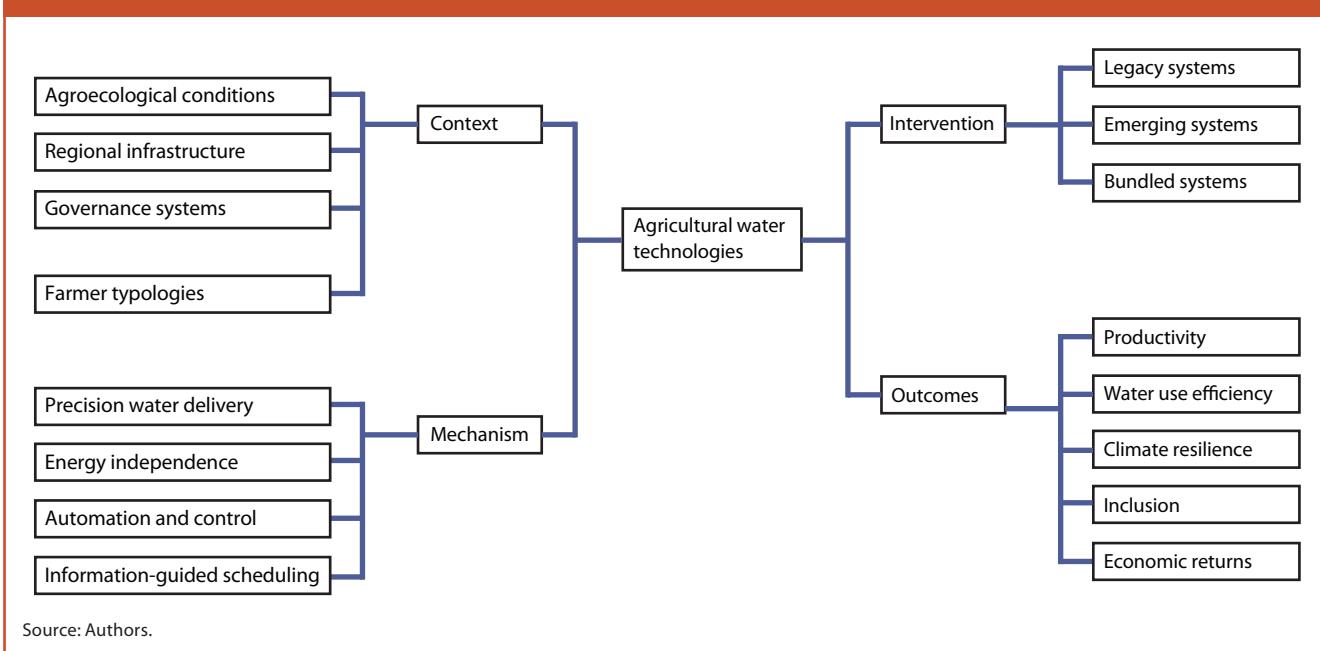
Figure 8.5 presents this conceptual framework. It illustrates how enabling contexts, technology interventions, and behavioral moderators interact through identifiable mechanisms to generate

multidomain outcomes and drive systems-level agricultural transformation in Africa. The figure is schematic; it is intended to depict conceptual relationships rather than empirical data.

The framework illustrates how contextual, technological, and behavioral factors interact to generate agricultural transformation outcomes. Sensitivity to contextual factors such as region, farm typology, policies, and infrastructure enables the introduction of suitable interventions. These interventions activate mechanisms of change, including precision delivery, energy independence, information-guided scheduling, and automation; their effects are moderated by the Unified Theory of Acceptance and Use of Technology (UTAUT) constructs, including performance expectancy, effort expectancy, social influence, and facilitating conditions. The resultant improvements in productivity, water-use efficiency, resilience, inclusion, and economic returns aggregate into systems-level transformation.

To account for behavioral variability, the framework incorporates insights from the UTAUT model (Venkatesh et al. 2003). This theory emphasizes how

**FIGURE 8.5—EVIDENCE-LINKED IMPACT FRAMEWORK FOR AGRICULTURAL WATER MANAGEMENT IN AFRICA**



user perceptions and social factors influence technology uptake. It identifies four key determinants of adoption behavior:

- **Performance expectancy:** the perceived usefulness of a technology in improving productivity or efficiency
- **Effort expectancy:** the perceived ease of use and compatibility with existing skills or resources
- **Social influence:** the role of peers, networks, and institutions in shaping attitudes toward adoption
- **Facilitating conditions:** the degree of support provided by infrastructure, finance, and extension systems

In this framework, the UTAUT constructs guide the behavioral moderators that explain why different technologies behave differently across users and regions depending on perceived usefulness, ease of use, social influence, and the availability of supportive services and infrastructure.

### ***Technology characteristics and farmer contexts***

Agricultural water management technologies differ widely in complexity, scale, and operational requirements. Understanding these differences is central to explaining why adoption rates, learning curves, and impact profiles vary across users.

Technology characteristics include:

- **Ease of use and operational simplicity**, which influence the learning requirements and labor costs associated with adoption
- **Affordability and financial accessibility**, which determine whether farmers can invest in or maintain technologies
- **Energy efficiency**, which affects both operational costs and environmental sustainability
- **Scalability and interoperability**, which govern the ability to integrate technologies across farm sizes or production systems

Farmer contexts are equally diverse. Smallholders tend to operate in resource-constrained environments, depend heavily on seasonal rainfall, and face

liquidity and information barriers. Commercial farms, in contrast, typically have better access to finance, infrastructure, and skilled labor, but are more sensitive to profitability and market risk. Gender, age, and social networks further mediate access to technologies and information.

By combining technology attributes with user contexts, the framework captures the heterogeneity of adoption behavior. It also underscores that water management innovation must be evaluated not only on technical merit but also on its social inclusiveness and institutional fit.

### ***Water-technology categories***

To conceptualize the diversity of interventions, the framework distinguishes three broad categories of technologies:

1. **Legacy systems:** These include conventional surface irrigation systems such as flood, furrow, and canal irrigation. They are typically large-scale, capital-intensive, and characterized by significant water loss and low flexibility. Legacy systems persist in many regions due to sunk investments, established infrastructure, and institutional inertia, even though they often exhibit low water-use efficiency.
2. **Emerging or digital systems:** These are more recent innovations that introduce precision, control, and energy efficiency into irrigation. Examples include drip and sprinkler irrigation, solar-powered pumps, soil moisture sensors, automated valves, and digital decision-support platforms. These technologies aim to optimize water use, reduce energy dependency, and improve yield stability.
3. **Bundled or integrated systems:** These combine multiple innovations into coherent packages, for example, a solar-powered drip system that is linked to a mobile-based advisory service or a weather-informed decision support tool. Bundled systems represent a more advanced technological regime that integrates hardware, software, and institutional components to generate synergistic effects across multiple domains.

Conceptually, these categories represent a continuum of technological maturity, from path-dependent legacy infrastructure to adaptive, data-driven systems that are better aligned with climate resilience and sustainability goals.

## Mechanisms of change

The framework identifies four primary mechanisms through which AWM technologies influence agricultural transformation:

1. **Precision delivery:** aligning irrigation supply with crop demand to minimize losses and maximize productivity
2. **Energy independence:** reducing reliance on fossil fuels and ensuring consistent access to water through renewable-energy-based systems
3. **Information-guided scheduling:** enabling farmers to make timely and data-informed decisions about irrigation, nutrient management, and cropping patterns
4. **Automation and control:** integrating sensors and remote-operation systems that improve efficiency, reduce labor intensity, and enable adaptive management

When technologies are bundled, these mechanisms may operate simultaneously and with cumulative effects. Their strength and effectiveness depend on both contextual enablers and behavioral moderators.

## Expected adoption dynamics and transformation pathways

Adoption and sustained use of AWM technologies occur through a dynamic interaction of technical performance, behavioral motivation, and institutional support. Within this framework, adoption is conceptualized as a process of learning, adaptation, and reinforcement, rather than a one-time event.

Smallholders are generally influenced by *facilitating conditions* and *social learning*, responding to peer demonstrations, extension services, and affordability mechanisms. Commercial and larger farms, on the other hand, are more sensitive to *performance expectancy* and *effort efficiency*, focusing on profitability, precision, and risk management.

When mechanisms of change operate effectively across user categories, a sequence of multidimensional outcomes can be expected:

- **Productivity gains** through efficient resource use and stable water supply
- **Improved water-use efficiency** through precision and automation
- **Enhanced climate resilience** through better drought and flood management

- **Greater inclusion** as marginalized groups access affordable, simplified systems
- **Stronger economic returns** through energy savings, reduced input costs, and year-round production

At scale, these outcomes interact to produce systems-level agricultural transformation that is characterized by higher national food security, more sustainable water resource management, and broader social inclusion.

## Hypothesized causal pathways and feedback loops

The framework envisions agricultural transformation as an iterative process. It proceeds from enabling environments and the introduction of technology to mechanism activation and outcome generation, followed by feedback loops that reinforce further innovation and institutional adaptation.

- **Stage 1: An enabling environment** provides the foundation for introducing technologies through supportive policy, finance, and infrastructure
- **Stage 2: Interventions** activate key mechanisms of change within specific contexts
- **Stage 3: Mechanisms** generate multidimensional outcomes in productivity, efficiency, and resilience
- **Stage 4: Feedback loops** emerge as successful outcomes incentivize reinvestment, policy learning, and diffusion of best practices

These loops ensure that transformation is self-reinforcing rather than episodic, embedding technology adoption within broader systems of governance, finance, and social learning.

## Synthesis and transition to empirical analysis

In summary, this conceptual framework links water management technologies to agricultural transformation through a structured chain of contexts, interventions, mechanisms, and outcomes. It explains why different technologies and farmer groups may experience divergent impacts and how enabling environments mediate those effects.

**TABLE 8.1—INPUT SEARCH STRATEGY INTO SCOPUS AND WEB OF SCIENCE**

Framework	Definition	Search string
S	Farming typologies	smallholder farm* OR commercial farm* OR emerging farm* OR large-scale OR livestock OR mixed farming
PI	Emerging irrigation technologies	emerging technolog* OR water management technolog* OR smart irrigation OR precision irrigation OR climate-smart OR drip irrigation OR sprinkler irrigation OR deficit irrigation OR hydroponics OR sensor-based irrigation OR Drones OR solar irrig* OR water quality monitoring OR water lift* OR desalination OR DEWATS OR waste water OR Aquaponics OR Aquaculture
D	Agricultural resilience and production	productivity OR food security OR drought OR adaptation OR climate adaptation OR sustainable agriculture
E	Global experiences and implementation, feasibility, and inclusivity	case study OR global experiences OR policy OR water governance OR best practices OR economic feasibility OR social inclusivity* OR digital inclusion OR environmental sustainability
R	Research type	barriers OR adoption OR challenges OR constraints OR opportunities

The framework also emphasizes that technological innovation alone is insufficient for transformation. Success depends on the interplay between technology design, user behavior, and institutional capacity.

The results section operationalizes this framework by empirically examining patterns of technology use, adoption dynamics, and multidomain impacts across Africa. Drawing on a harmonized evidence base of documented cases, the analysis tests how enabling environments, technology types, and behavioral factors jointly explain the observed variations in adoption and transformation outcomes.

### Formulating a search strategy

The study was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol (PRISMA-P), which standardizes the literature search, screening, and synthesis (Page et al. 2021). The study applied the SPIDER (Sample, Phenomenon of Interest, Design, Evaluation, Research type) framework (Methley et al. 2014) for formulating the search strategy shown in Table 8.1. It is worth mentioning that the search was conducted in the Scopus and Web of Science (WoS) databases. Database selection was based on their comprehensiveness in information archiving.

### Selection process

The selection process focused on Africa over the period from 2000 to 2025 and involved duplicate removal and literature screening. The screening was

**TABLE 8.2—INCLUSION–EXCLUSION CRITERIA APPLIED FOR RELEVANCE SCREENING**

Inclusion	Exclusion
Articles published in English	Articles from predatory journals
Original research in a peer-reviewed journal	Articles not published in English
Articles that describe different irrigation approaches, such as bucket irrigation, drip, and sprinkler irrigation	Full articles that could not be retrieved
Articles relating to line source wetting patterns	Articles with insufficient methodologies
Articles with English abstracts	
Conference proceedings MSc and PhD dissertations	Proceedings and dissertations not published in English

Note: The Beall (2011) list of predatory journals was applied to identify predatory journals.

conducted in three steps by two independent reviewers, with a third party acting as an arbiter in cases of conflict. The screening process was guided by the inclusion and exclusion criteria outlined in Table 8.2.

### Data analyses

A two-step analytical approach was employed to assess trends and patterns in irrigation and agricultural water management (AWM) technologies across Africa.

## Bibliometric analysis

The Biblioshiny toolkit (Aria and Cuccurullo 2017) was used to conduct a bibliometric analysis. It enabled the mapping of publication trends, thematic clusters, and technology-related keywords associated with irrigation development and resilience. The analysis identified the evolution of research focus areas, particularly climate-resilient irrigation, digital innovation (such as AI, IoT, and remote sensing), and investment or policy initiatives shaping technology adoption.

## Content analysis

A full-text screening of peer-reviewed and grey literature was then performed to extract empirical evidence on irrigation technologies and their performance. The content analysis focused on identifying technologies relevant to African contexts, assessing their technical, social, economic, and environmental scalability, and determining opportunities for digitizing and integrating AWM systems.

## Results and discussion

### Literature search

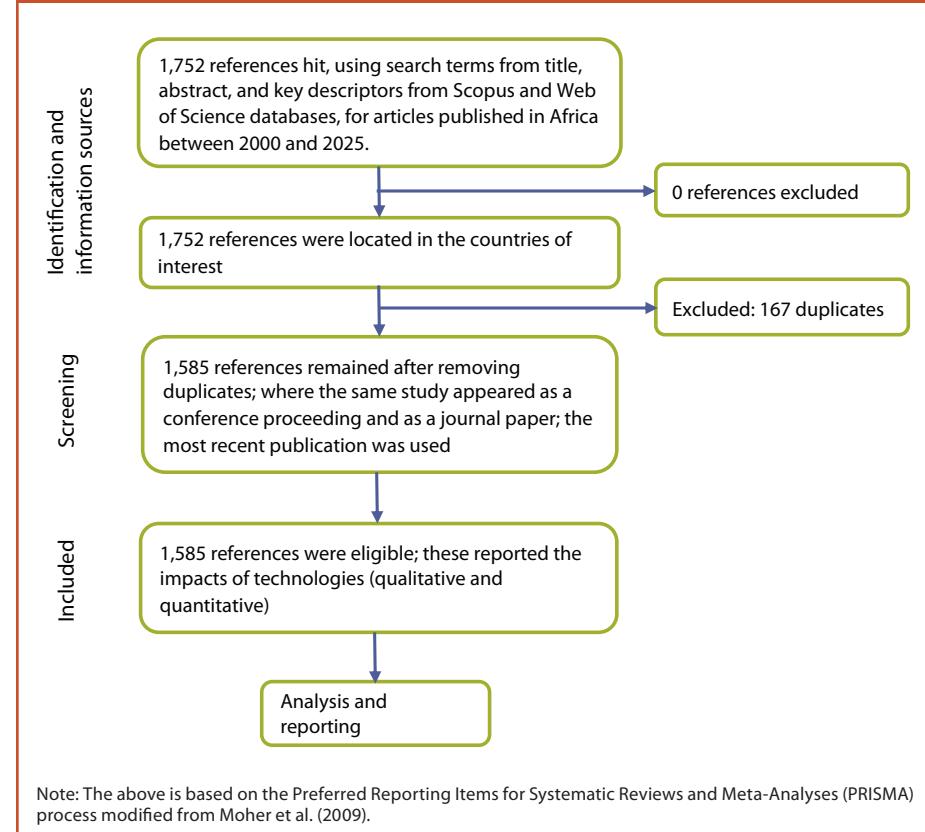
The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart (Figure 8.6) outlines the number of articles included in the literature synthesis. A total of 1,752 articles from Scopus and Web of Science were identified, published in Africa between 2000 and 2025. A total of 167 references were duplicates and were excluded, leaving 1,585 articles that were downloaded and analyzed for reporting.

### Emerging agricultural water management technologies in Africa

#### Overview of technology mentions

Based on 1,585 documented observations, this analysis provides a detailed mapping of agricultural water management (AWM) technology use across all subregions in Africa. The dataset reveals a dynamic and evolving landscape where long-standing irrigation systems coexist with an increasing array of modern, digitally enabled innovations. The technologies identified range from flood, furrow, and canal irrigation to data-driven solutions such as decision support systems (DSS), soil-moisture sensors, remote sensing tools, and solar-powered irrigation systems.

**FIGURE 8.6—SCHEMATIC REVIEW PROCESS DEPICTING THE ARTICLES THAT WERE IDENTIFIED, SCREENED, AND INCLUDED FOR LITERATURE SYNTHESIS**



The frequency distribution of technology mentions (Figure 8.7) shows that drip irrigation is by far the most frequently cited technology, accounting for about 45 percent of all entries. This is followed by furrow irrigation (approximately 13 percent), sprinkler irrigation (around 9 percent), solar pumps (7 percent), and flood irrigation (6 percent).

Canal irrigation represents a smaller share, at around 2 percent. These traditional irrigation approaches remain widespread but often exhibit lower multidomain impact scores across the five domains analyzed: productivity, water use efficiency, climate resilience, gender inclusion, and economic returns.

In contrast to previous assumptions that drip and sprinkler systems were niche or donor-driven, the data confirm their widespread institutionalization, particularly in regions such as North Africa, Southern Africa, and parts of East Africa. Technologies such as canal irrigation (2 percent) and rainwater harvesting systems also remain visible in the dataset, particularly in arid and semi-arid zones (Magombeyi and Taigbenu 2008).

At the same time, a clear rise in digitally enabled and adaptive technologies is evident. For example:

- **Smartphone-based irrigation apps** account for about 5 percent of mentions
- **Tensiometers** (often used in automated drip systems) contribute about 4 percent
- **Remote sensing and GIS technologies** appear in roughly 3 percent of documented cases, often supporting irrigation planning and zonal water allocation

- **Weather forecast tools**, used to align irrigation with expected rainfall, also account for about 4 percent
- **Decision support systems (DSSs)**, while still emerging, represent about 2 percent of mentions
- **Chameleon soil sensors** are captured in the dataset, appearing in approximately 1 percent of observations

These technologies collectively reflect a shift toward data-informed, automated, and climate-responsive water management. Unlike traditional systems that require constant human intervention, these innovations introduce a layer of intelligence and responsiveness, often improving irrigation timing, water-use efficiency, and crop-level decision-making. They are increasingly featured in donor-funded pilots, national digital agriculture strategies, and climate-resilient water infrastructure programs, particularly in Eastern and Southern Africa.

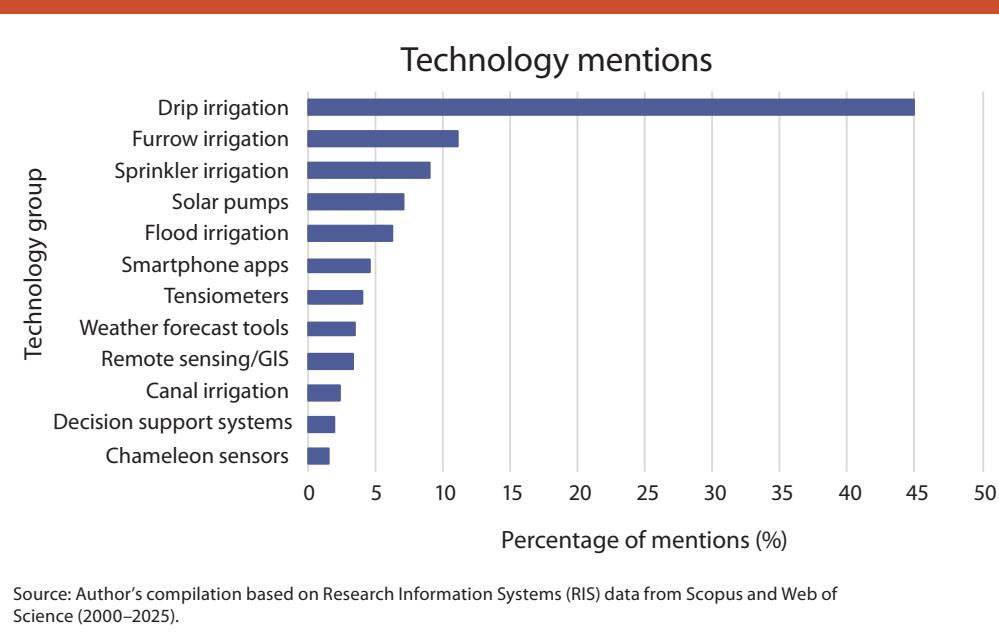
The dataset also reveals that while traditional technologies dominate in volume, their associated impact scores measured across the five performance domains are often more modest and less multidimensional; these domains include productivity, water-use efficiency, climate resilience, gender and inclusion, and economic returns. Flood and canal irrigation, for example, while widespread, typically demonstrate lower outcomes in efficiency and inclusion.

Technologies such as DSS, weather forecasting tools, and soil-moisture sensors, though less frequent in occurrence, demonstrate consistently higher multidomain performance. As shown in Table 8.6, these technologies report above-average impacts in economic returns (up to 49 percent), water-use efficiency (up to 50 percent), and climate resilience (up to 48 percent), confirming their growing potential for high-impact scaling (Chilundo et al. 2020; Moyo et al. 2020).

This pattern illustrates a transitional phase in African AWM, in which modern technologies are layered onto existing systems rather than fully replacing them. Farmers and institutions appear to be engaging in incremental modernization, integrating innovation through retrofits, bundling, and service-based delivery models.

Ultimately, this duality underscores a pragmatic evolution: Africa's AWM systems are not merely shifting from old to new; they are becoming more hybrid, targeted, and context-specific, reflecting

**FIGURE 8.7—FREQUENCY DISTRIBUTION OF TECHNOLOGY MENTIONS**



a balance between infrastructure maturity, technological capacity, and climate urgency.

At the same time, there is a notable prevalence of digitally enabled technologies; for example, climate-smart irrigation (3.1 percent), GIS and remote sensing tools (2.7 percent), decision support systems (1.9 percent), and solar-powered pumps (1.8 percent) collectively underscore a shift toward more data-driven, automated, and adaptive water management strategies. These technologies are increasingly prioritized in donor programming and national strategies, particularly in response to climate variability and water scarcity.

The dataset indicates that while traditional methods still dominate in terms of volume of mentions, modern innovations are gaining traction, especially those that promise multifunctional impacts across environmental and socioeconomic indicators. This duality highlights the transitional nature of AWM adoption in Africa, where innovation is being integrated into long-standing systems rather than replacing them outright.

### ***Regional distribution of technologies***

AWM technologies are unevenly distributed across African regions. As shown in Table 8.3, Eastern Africa dominates with 47 percent of all technology mentions, followed by Northern Africa (23 percent) and Western Africa (17 percent). Southern and Central Africa trail behind, with only 9 percent and 4 percent, respectively. This variation reflects differences across regions in terms of institutional capacity, investment climate, and technology access. Eastern Africa's high share likely reflects its relatively strong donor engagement, widespread

**TABLE 8.3—NORMALIZED REGIONAL DISTRIBUTION OF AGRICULTURAL WATER MANAGEMENT (AWM) TECHNOLOGIES**

Region	Share of technology mentions (%)
Eastern Africa	47
Northern Africa	23
Western Africa	17
Southern Africa	9
Central Africa	4

agricultural research and development systems, and government incentives for irrigation expansion (UNECA 2025).

Northern Africa benefits from decades of experience with irrigation infrastructure and from recent efforts to digitize water monitoring. Western Africa is emerging as a digital frontier with increasing mentions of mobile irrigation tools and DSS pilots. Conversely, the limited representation of Central Africa (4 percent) indicates a need for intensified support and improvements in reporting.

### ***Key emerging technologies and their impacts***

Table 8.4 presents a synthesis of some of the most influential emerging AWM technologies, emphasizing their regional prevalence and their potential impacts on crop productivity. Drip irrigation, for instance, which is widespread in Northern and Southern Africa and in parts of Eastern Africa, can increase water-use efficiency by 30 to 60 percent and can deliver yield gains of up to 50 percent in high-value crops like vegetables (Mugejo et al. 2025); its targeted water delivery also enhances nutrient uptake and reduces weed pressure.

Solar-powered irrigation systems (SPIS) are increasingly used to enable off-grid irrigation in water-scarce regions, offering farmers a reliable and renewable alternative to diesel- or grid-powered pumps. Evidence from Sub-Saharan Africa demonstrates that SPIS improves water access and reduces operating costs, thereby supporting more consistent crop production across Western, Eastern, and Southern Africa (Hartung and Pluschke 2018; IRENA 2016). Studies also highlight their economic viability and technical adaptability for smallholder farming systems, with reduced fuel expenditure and low maintenance needs contributing to their long-term cost-effectiveness (Ani 2025; Chaudhari et al. 2025). These features make SPIS a scalable option for expanding irrigated agriculture in underserved rural landscapes.

Technologies that support precision agriculture, such as remote sensing, GIS, and automated soil-moisture sensors, have proven effective in improving irrigation scheduling and reducing water loss. These are especially common in Northern, Eastern, and Southern Africa. GIS-based tools, for example, can improve efficiency by 10-30 percent (FAO 2017).

Smartphone-based irrigation scheduling tools are part of emerging digital decision-support systems that combine weather data, soil moisture sensing, and machine learning algorithms to guide on-farm water management. Experimental

TABLE 8.4—KEY EMERGING AGRICULTURAL WATER MANAGEMENT TECHNOLOGIES IN AFRICA

Emerging technology	Popularity by region	Crop productivity impact (corrected where evidence exists)	Key references
Drip irrigation	Northern, Southern, and parts of Eastern Africa	30 to 60 percent increase in water-use efficiency; yield gains of up to 50 percent in high-value crops	FAO (2017)
Solar-powered irrigation systems (SPIS)	Western, Eastern, and Southern Africa	Improves reliability of irrigation, reduces energy costs, and enhances water availability. Studies show improved crop performance and water-use efficiency, with strong potential for expanding irrigated horticulture	Hartung and Pluschke (2018); IRENA (2016); Chaudhari et al. (2025)
Remote sensing and GIS for water monitoring	Northern, Eastern, and Southern Africa	10 to 30 percent better targeting of irrigation schedules and reduced water loss	FAO (2017)
Smartphone-based irrigation scheduling apps	Eastern and Southern Africa (emerging)	Machine-learning-enabled irrigation tools demonstrate 20 to 43 percent water savings while maintaining yields	Umutoni and Samadi (2024)
Automated soil-moisture sensors	Southern and North Africa	20 to 40 percent water savings and improved yield consistency	UNECA (2025)
Hydroponics and aquaponics	Urban areas in Western and Northern Africa	High productivity per unit area and year-round vegetable production in controlled environments	Aydin (2023)
Desalination for agriculture	Northern Africa (pilot phase)	FAO field evidence shows improved vegetable crop performance when desalinated or blended brackish water is used, due to reduced soil salinity	Elmahdi, Badawy, and Alejandro Paltan Lopez. (2022)
Drones for irrigation assessment	Southern and Eastern Africa (pilot projects)	10 to 15 percent improvement in irrigation planning accuracy	ADF (2020)
AI-powered weather forecasting tools	Across regions, limited adoption	Improves planning accuracy; may reduce climate-related losses by 10 to 25 percent	Oğuztürk (2025)
Chameleon soil sensors	Southern Africa and parts of Eastern Africa	Farmer-reported yield improvements of up to 100 percent and reductions in water use of up to 30 percent due to improved soil-moisture monitoring	CSIRO (2023); Stirzaker, Mbakwe, and Mziray (2017)
Water harvesting technologies (zai pits and contour bunds)	Western and Eastern Africa, Sahel	Zai pits increase cereal yields by approximately 120 to 130 percent in Kenya and up to 310 percent in Niger	Kimaru-Muchai et al. (2021)
Decision support systems (DSS) for irrigation	Eastern and Southern Africa	Improve water-use efficiency and support more consistent crop performance; studies report gains in water productivity that can fall within the 10 to 20 percent range in horticultural systems	Morched et al. (2025)
Weather-indexed insurance linked to irrigation	Eastern and Western Africa	Stabilizes income and encourages irrigation investment	UNECA (2025)
Tensiometers and IoT-enabled sensors	Eastern and Southern Africa	10 to 25 percent increase in irrigation efficiency and yields	Morched et al. (2025)

evidence shows that such systems can substantially reduce irrigation water use while sustaining crop performance. For example, machine-learning-enabled scheduling achieved 20–31 percent water savings in field trials (Adeyemi et al. 2018) and up to 43 percent savings in LSTM-based systems without reducing yields (Kashyap et al. 2021), as summarized in Umutoni and Samadi (2024).

These results highlight the potential for smartphone-enabled advisory tools to improve irrigation efficiency in Eastern and Southern Africa.

Urban-focused innovations such as hydroponics are reshaping food production systems in rapidly growing cities. By using controlled-environment cultivation and vertical space, hydroponic systems achieve high productivity per

unit area and allow year-round production, making them well-suited to food-insecure urban centers (Aydin 2023).

Desalination for agriculture is increasingly being piloted in the MENA region, particularly in North African countries such as Tunisia, Morocco, and Algeria, where saline and brackish groundwater severely constrain horticultural production. FAO-supported field experiments in Tunisia show that using desalinated or blended brackish water for greenhouse vegetables reduces soil salinity and improves crop performance compared with irrigation using saline groundwater alone. These findings demonstrate the potential of agricultural desalination to sustain and enhance vegetable production under the severe water scarcity conditions facing farming systems across the MENA region (Elmahdi et al. 2022).

Emerging technologies such as drones for irrigation assessment and AI-powered weather forecasting tools, now used across pilot sites in Eastern and Southern Africa, are improving irrigation planning and reducing inefficiencies. Meta-analysis of AI-driven irrigation systems shows water-use reductions of 30 to 50 percent and yield gains of 20 to 30 percent through real-time monitoring and adaptive decision support (Oğuztürk 2025). Chameleon soil sensors and tensiometers, common in Southern and Eastern Africa, enhance real-time water management, leading to improvements of 10 to 30 percent in yield and efficiency (Chilundo et al. 2020; Moyo et al. 2020).

Finally, water harvesting technologies such as zai pits and contour bunds remain critical in Western and Eastern Africa and across the Sahel, where they substantially improve soil moisture retention and crop productivity. Evidence from eastern Kenya shows that zai pits can more than double sorghum yields, increasing production from about 1.9 megagrams per hectare under conventional practice to over 4.3 megagrams per hectare when organic amendments are used, which represents yield gains of approximately 120 to 130 percent. A study by CCARDESA (2024), in Southern Africa and Ismail et al. (2023) in Tanzania also reported higher yields under zai pits than flat cultivation. Studies from the Sahel report similarly striking improvements under different crops, with some experiments in Niger showing increases of up to 310 percent under zai-based moisture-conservation practices (Kimaru-Muchai et al. 2021; Fatondj 2025).

These findings underscore the need to support scalable, context-specific innovations while expanding pilots into mainstream programming, particularly in regions like Central Africa, where adoption remains low.

### ***Leading regional technologies and programs***

The distribution of AWM technologies across Africa reflects both enabling environments and regional investment histories. Consistent with the conceptual framework, regional adoption patterns mirror differences in infrastructure, institutional capacity, and financing mechanisms (UNECA 2025). Table 8.5 summarizes dominant technologies, leading countries, and representative programs, illustrating how local conditions shape technology portfolios.

In North Africa, advanced irrigation methods such as drip, sprinkler, and canal-based systems dominate, particularly in Egypt, Morocco, and Tunisia. Long-standing public investment and strong water governance institutions have enabled large-scale modernization initiatives such as Plan Maroc Vert (PMV) and the Nile Valley modernization project (Mugejo et al. 2025; World Bank 2025b). These programs exemplify how supportive policy and financing environments accelerate adoption of precision and water-saving irrigation systems (Addorisio, Spadoni, and Maesano 2025).

In West Africa, technological diffusion in agricultural water management is increasingly driven by decentralized and energy-efficient technologies, especially solar-powered and low-lift irrigation pumps. Evidence from Burkina Faso shows strong adoption of subsidized solar-powered pumps among smallholder horticultural farmers, driven by lower operating costs and ease of use (Sanogo et al. 2025). In Ghana, solar irrigation is expanding through multiple initiatives, including GIDA's efforts to convert existing electric pumps to solar, and NGO- and donor-supported projects such as NewEnergy, PICA, and EnDev (Gebrezgabher et al. 2021). Nigeria is also documenting rapid growth in solar pumping systems as a cost-competitive alternative to diesel for small-scale irrigation and rural water supply (Popoola and Temitope 2025). Although alternate wetting and drying (AWD) remains primarily a rice-specific technology, recent studies from West Africa indicate increasing experimentation with AWD in irrigated rice systems in Ghana and Nigeria (Uduma et al. 2016; Gao et al. 2024). Soil and water-retention bunds continue to form part of broader water-harvesting practices in semi-arid West Africa, though they are less formally institutionalized than solar pumping. Together, these innovations reflect a growing shift toward

low-cost, decentralized AWM solutions across the region. These examples demonstrate regional progress toward climate-smart, smallholder-oriented irrigation solutions that reduce dependence on grid power.

East Africa shows high uptake of rainwater harvesting systems, small-scale gravity-fed irrigation, and decision support systems (DSS). Ethiopia, Kenya, and Tanzania lead this innovation frontier through programs such as the sustainable irrigation financing and investment platform, the One Acre Fund, and Ethiopia's national irrigation strategy (Barasa, Wanyama, and Nandutu 2020). These initiatives integrate digital tools and farmer-led models within national climate-resilience strategies.

In Central Africa, adoption remains limited to traditional basin irrigation and isolated small-scale pilots in Cameroon and the Democratic Republic of Congo, reflecting persistent financing and institutional gaps (World Bank 2025b). Strengthening enabling policies and cross-border knowledge exchange remains a priority for this subregion, in line with broader evidence that cross-border knowledge flows are central to innovation and performance (Rammal, Rose, and Ferreira 2023; Wamala 2022). Southern Africa presents a hybrid model that combines conventional systems such as drip, sprinkler, and center-pivot irrigation with emerging smart irrigation tools. South Africa, Zambia, Zimbabwe, and Malawi feature prominently in these initiatives. Pilot efforts, including decision support systems in the Limpopo Basin and Malawi's Sustainable Drip Irrigation initiative, illustrate the region's gradual integration of automation, solar power, and data-driven scheduling. These experiences highlight how digital and renewable-energy innovations can enhance the performance of existing irrigation infrastructure.

These findings confirm the diverse and regionally differentiated landscape of AWM adoption across Africa. They underscore the need to tailor future investments, policies, and technical assistance to each region's institutional capacity, resource endowments, and technological readiness.

### ***Temporal trends in technology uptake***

The evolution of AWM technologies in Africa over time highlights a steady transition from large-scale,

state-managed irrigation schemes to more decentralized, technology-integrated approaches. This evolution has progressed in the following stages:

- **1960s–1980s:** This era saw heavy investments in dam-based, centralized irrigation schemes such as the Gezira Scheme in Sudan and the Tono Dam irrigation project in Ghana. These schemes were characterized by strong government involvement and public financing.
- **1990s–2000s:** Public investment in irrigation declined significantly, leading to a shift toward farmer-led, small-scale irrigation. During this period, treadle pumps and bucket irrigation became common across Eastern and Southern Africa.
- **2010s:** A surge in innovation introduced solar-powered irrigation systems, mobile-based advisory services, and the first wave of weather-indexed insurance programs. These technologies emphasized affordability and accessibility.
- **2020s:** The current decade is marked by the integration of artificial intelligence, machine learning, satellite data, big data analytics, and GIS-based tools into irrigation management. Technologies such as smart irrigation controllers, automated soil sensors, and digital decision-support systems are increasingly widespread.

**TABLE 8.5—TECHNOLOGY ADOPTION PER REGION AND LEADING PROGRAMS**

Region	Common agricultural water management technologies	Leading countries	Notable programs/projects
North Africa	Drip, sprinkler, canal-based surface irrigation	Egypt, Morocco, Tunisia	SDG 1 - End poverty
West Africa	Solar pumps, low-lift pumps, alternate wetting and drying (AWD), and bunds	Nigeria, Ghana, Burkina Faso	Ghana Irrigation Development Authority (GIDA), ECOWAS water resources management (WRM)
East Africa	Small-scale gravity, rainwater harvesting, decision support systems (DSS)	Ethiopia, Kenya, Tanzania	Smallholder Irrigation and Value Addition Project (SIVAP), One Acre Fund, Ethiopian irrigation strategy
Central Africa	Low adoption, traditional basin systems	Cameroon, DRC	Pilot irrigation schemes (small-scale)
Southern Africa	Center-pivot, drip, and sprinkler irrigation, smart-irrigation tools	South Africa, Zambia, Malawi	A water decision support system developed for the Limpopo basin, solar-driven irrigation (SDI) pilots in Malawi

These trends reflect broader shifts in global agricultural development, which is moving towards climate-smart, data-informed, and inclusive systems (UNECA 2025).

### ***Technologies by frequency and linked impact***

Table 8.6 presents a detailed analysis of the most frequently reported AWM technologies in Africa. It shows their relative frequency of mention and the associated positive outcomes across five domains: productivity gains, water-use efficiency, climate resilience, gender and social inclusion, and economic returns.

Drip irrigation emerges as the most frequently cited technology, accounting for 45.0 percent of all mentions. It demonstrates strong performance in productivity gains (59.5 percent) and water-use efficiency (20.6 percent) and contributes meaningfully to economic returns (13.0 percent). Although its inclusion-related impact is relatively modest (2.4 percent), its widespread application in both donor-driven and commercial settings affirms its role as a foundational technology in AWM programs.

Furrow irrigation, the second-most frequently mentioned technology at 11.2 percent, shows a robust multidomain impact, reporting 51.8 percent for productivity, 13.6 percent for water-use efficiency, and 20.9 percent for economic returns. It also demonstrates notable inclusion relevance (5.5 percent) and moderate climate-resilience impact (8.2 percent), reinforcing its versatility and adaptability across farming systems.

Sprinkler irrigation (9.2 percent) also performs well across key domains, especially productivity (62.2 percent) and water-use efficiency (18.9 percent), with moderate outcomes in climate resilience (4.4 percent) and gender inclusion (4.4 percent). These findings support its continued use in structured and semi-automated field irrigation setups.

Solar-powered pumps, cited in 7.2 percent of cases, show exceptional results in economic returns (49.3 percent) and climate resilience (8.5 percent), underscoring their value in off-grid and water-stressed environments. Though currently underrepresented in gender-related outcomes (0 percent), their productivity impact is still notable at 42.3 percent, positioning them well for scaling with targeted inclusion strategies.

Flood irrigation, a legacy system mentioned in 6.4 percent of records, remains relevant in specific agroecological zones. It records 41.3 percent in productivity impact, 28.6 percent in climate resilience, and 7.9 percent in gender inclusion outcomes, thus highlighting its persistence despite known water inefficiencies.

**TABLE 8.6—FREQUENCY AND MULTIDOMAIN IMPACTS OF AGRICULTURAL WATER MANAGEMENT TECHNOLOGIES IN AFRICA**

Technology	Frequency (%)	Climate resilience (%)	Economic returns (%)	Inclusion and gender (%)	Productivity gains (%)	Water-use efficiency (%)	n
Drip irrigation	45.00	4.50 [3.2–6.4]	13.03 [10.7–15.8]	2.37 [1.4–3.8]	59.48 [55.8–63.2]	20.62 [17.8–23.9]	725
Furrow irrigation	11.16	8.18 [5.2–13.4]	20.91 [15.5–27.3]	5.45 [3.1–10.0]	51.82 [44.4–58.9]	13.64 [9.2–19.3]	180
Sprinkler irrigation	8.99	4.44 [1.9–8.7]	10.00 [5.8–15.6]	4.44 [1.9–8.7]	62.22 [54.0–69.6]	18.89 [13.1–25.7]	145
Solar pumps	7.13	8.45 [4.8–15.3]	49.30 [40.6–58.6]	0.00 [0.0–3.2]	42.25 [34.0–51.7]	0.00 [0.0–3.2]	115
Flood irrigation	6.32	28.57 [20.6–37.8]	11.11 [6.1–18.3]	7.94 [4.0–14.7]	41.27 [32.1–50.9]	11.11 [6.1–18.3]	102
Smartphone apps	4.59	6.52 [2.9–14.9]	43.48 [32.6–54.6]	26.09 [17.1–36.7]	23.91 [16.0–35.2]	0.00 [0.0–4.9]	74
Tensiometers	4.03	0.00 [0.0–5.6]	0.00 [0.0–5.6]	0.00 [0.0–5.6]	50.00 [37.5–61.1]	50.00 [37.5–61.1]	65
Remote sensing/GIS	3.53	34.29 [24.0–48.1]	2.86 [1.0–11.9]	2.86 [1.0–11.9]	60.00 [46.7–71.4]	0.00 [0.0–6.3]	57
Weather forecast tools	3.41	48.57 [36.6–61.7]	34.29 [24.0–48.1]	0.00 [0.0–6.3]	17.14 [9.8–29.4]	0.00 [0.0–6.3]	55
Canal irrigation	2.42	0.00 [0.0–6.8]	30.30 [19.5–43.5]	0.00 [0.0–6.8]	54.55 [41.5–67.3]	15.15 [7.9–27.1]	39
Decision support systems	1.98	0.00 [0.0–10.7]	0.00 [0.0–10.7]	0.00 [0.0–10.7]	60.00 [42.3–74.5]	40.00 [25.5–57.7]	32
Chameleon sensors	1.49	25.00 [11.0–42.1]	25.00 [11.0–42.1]	0.00 [0.0–12.9]	50.00 [32.1–67.9]	0.00 [0.0–12.9]	24

Note: Each percentage shows the share of studies reporting a positive outcome in that domain, with brackets indicating the 95 percent confidence interval (evidence precision).

Emerging digital tools such as smartphone apps (4.7 percent) demonstrate strong outcomes in economic returns (43.5 percent) and gender inclusion (26.1 percent), although their impact on productivity is lower (23.9 percent). This suggests that their value lies in service delivery and information access rather than in direct yield effects.

Several sensor-based and digital systems also feature in the dataset. Tensiometers (4.1 percent) deliver balanced performance, with 50 percent positive outcomes in both productivity and water-use efficiency. Remote sensing and GIS tools (3.6 percent) are associated with 60 percent productivity and 34.3 percent climate resilience, confirming their importance in spatial planning and climate adaptation. Weather forecast tools, equally frequent at 3.6 percent, show the highest climate-resilience score (48.6 percent) and strong economic relevance (34.3 percent), reinforcing their utility in early warning and adaptive planning systems.

Canal irrigation, though representing only 3.4 percent of mentions, reports consistent performance in productivity (54.5 percent), water-use efficiency (15.2 percent), and economic returns (30.3 percent), reaffirming its continued utility in structured surface irrigation schemes.

Agricultural water productivity decision support systems (DSS), though less frequently cited (2.0 percent), stand out with 60 percent productivity and 40 percent water-use efficiency impacts, confirming their role in precision irrigation strategies. The reason is their less frequent application in the Global South due to public unavailability or lack of localization, which renders them inapplicable to Global South smallholder systems (Mabhaudhi et al. 2023). Finally, Chameleon sensors (1.6 percent) also show promising results, with a 50 percent productivity impact and a 25 percent impact on both climate resilience and economic returns, thus highlighting their potential as cost-effective monitoring tools.

Interestingly, while both traditional and digital systems demonstrate inclusion outcomes, these vary widely. Smartphone apps and flood irrigation show the highest gender responsiveness (26.1 percent and 7.9 percent, respectively), while systems such as drip and sprinkler irrigation demonstrate lower inclusion scores (2.4 percent and 4.4 percent, respectively). Contrary to expectation, zai pits and contour bunds were not detected in the data, likely due to alternative terminology or underrepresentation in peer-reviewed sources.

These findings reinforce two key insights. First, legacy technologies such as furrow, flood, and canal irrigation remain highly relevant due to their broad

applicability and established infrastructure. Second, emerging digital and sensor-based systems, although less common, exhibit high performance across multiple impact domains, indicating strong potential for future scaling, particularly when deployed as part of bundled AWM solutions.

### ***Domain-specific impacts and pathways to change***

Table 8.7 synthesizes both the quantitative performance and the qualitative pathways through which leading AWM technologies generate outcomes across five domains: productivity, water-use efficiency, climate resilience, inclusion, and economic returns. The discussion below highlights the main patterns evident in the table.

**Productivity and efficiency gains** are driven by precision delivery systems, such as drip and sprinkler irrigation, and by automation tools, such as soil-moisture sensors. **Climate-resilience benefits** arise from off-grid, adaptive, and information-guided systems such as solar-powered pumps, rainwater harvesting, and forecast-based irrigation. **Inclusion** improves when technologies are affordable, community-managed, or supported by credit schemes, while **economic returns** increase with efficiency, energy independence, and risk reduction. Bundled AWM technologies that combine these features consistently outperform single interventions, offering 10 to 25 percent higher multidomain benefits.

These consolidated results show that productivity and efficiency gains arise primarily from precision and automation technologies, while resilience improvements depend on renewable energy, off-grid operation, and information-guided scheduling. Inclusion outcomes are strongest where delivery models are community-based or supported by targeted financing for women and youth, and economic returns increase where water- and energy-use efficiencies translate into lower input costs. Bundled AWM systems, such as solar-powered drip irrigation integrated with decision-support tools, produce the most balanced multidomain outcomes, confirming that technology design, user capability, and enabling institutions must act in concert to drive sustainable agricultural transformation across Africa.

### ***Technology bundling and co-impacts***

Bundled AWM technologies include combinations of hardware and software systems, such as solar-powered drip irrigation integrated with DSS tools. Across all major impact domains, such bundled technologies consistently outperform single interventions. As shown in Figure 8.8, this finding is based

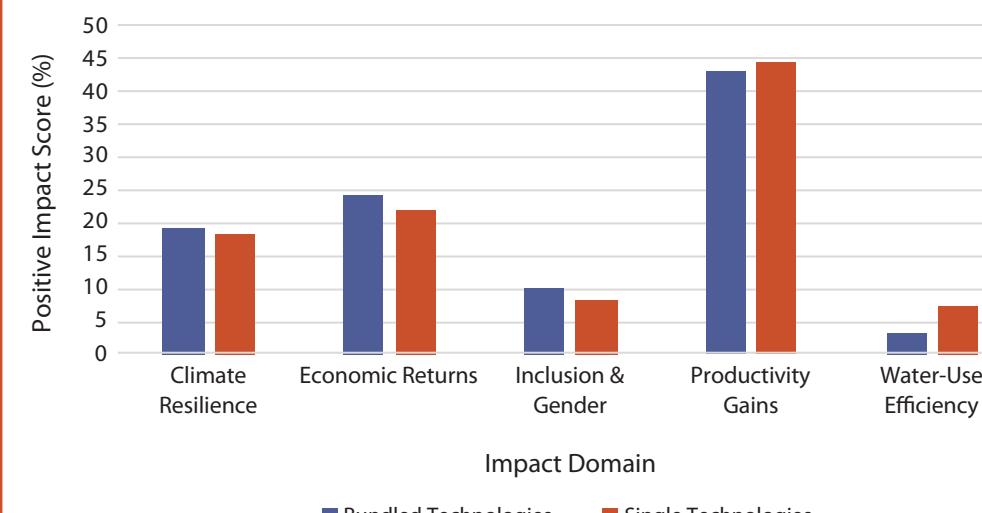
TABLE 8.7—CONSOLIDATED IMPACTS AND PATHWAYS OF AGRICULTURAL WATER MANAGEMENT (AWM) TECHNOLOGIES ACROSS DOMAINS

Technology category	Productivity gains	Water-use efficiency	Climate resilience	Gender and inclusion	Economic returns	Main pathways/
Precision irrigation (drip and sprinkler)	↑ 40–60% yields through root-zone watering and uniform distribution	High – minimizes losses, improves nutrient uptake	Moderate – stabilizes yields under moisture stress	Moderate – mobile units manageable with training; cost limits access	High: above 3:1 ROI from input savings and intensification	Precise water delivery, reduced evapotranspiration, labor/time savings
Energy-efficient systems (solar pumps and AWD rice)	↑ 25–50% yields via reliable water supply and multiple cropping	Medium to high – saves 20 to 30% water	High – off-grid access, lower GHG emissions	High when financed via cooperatives and youth/ women groups	High–low recurrent costs, improved market participation	Renewable-energy pumping, seasonal reliability, emissions reduction
Digital and sensor-based technologies (soil sensors, digital irrigation, DSS)	Moderate to high – better timing and precision	Very high – real-time automation avoids over/under-watering	High – rapid response to anomalies	Low to moderate – requires literacy and access; inclusive if bundled	Moderate to high – savings and risk reduction	Automation, decision support analytics, data-driven scheduling
Water harvesting and low-cost community systems	↑ 25–30% yields in drylands	Medium – storage losses possible	High – critical buffer in droughts	High – accessible to women and poor households	Moderate – low capital costs, modest returns	Collective rain-runoff capture, equitable management
Information and planning tools (GIS, forecasts, climate-smart apps)	Indirect – improves input targeting	Medium – enhances monitoring and allocation	Very high – anticipatory planning for climate extremes	Moderate – depends on digital access and extension coverage	Moderate – reduces losses and input waste	Early warning systems, zoning, risk forecasting
Bundled integrated systems such as solar-drip and DSS	Highest – synergistic gains across crops	High – combined hardware and data optimize use	Highest – renewable, adaptive, forecast-driven	High – inclusive service packages expand reach	Highest – 10 to 25% greater multidomain impact than single techs	Converging mechanisms: precision + energy + data + inclusion support

Note: AWD = alternate wetting and drying; DSS = decision support system; GIS = Geographic Information System; GHG = greenhouse gas; ROI = return on investment.

on a meta-analysis of 1,585 documented AWM cases extracted from Scopus and Web of Science between 2000 and 2025. Each case was coded by technology type, region, farm typology, and five standardized impact domains (productivity, water-use efficiency, climate resilience, gender and inclusion, and economic returns). The relative performance of bundled versus single technologies was computed from the mean proportion of positive outcomes reported per domain across all studies. Bundled systems demonstrated higher mean scores than single-technology averages: 24.4 percent in economic returns, 19.2 percent in climate resilience, and 10.0 percent in gender and inclusion; for comparison, single-technology averages showed scores of 21.8 percent, 18.3 percent, and 8.1 percent, respectively. These cross-study estimates indicate that integrated AWM packages offer roughly a 10 to 25 percent higher likelihood of achieving multidimensional development benefits.

FIGURE 8.8—IMPACT SCORES FOR BUNDLED VS SINGLE TECHNOLOGIES



While single technologies demonstrate slight advantages in productivity gains (44.6 percent) and water-use efficiency (7.3 percent), their benefits are typically confined to field-level performance. By contrast, bundled systems achieve broader, system-wide outcomes by simultaneously addressing technical, behavioral, and institutional dimensions. Integrated packages that combine hardware, such as pumps and irrigation kits, and software, such as smartphone apps and forecast or scheduling tools, with institutional support mechanisms, such as extension services and cooperatives, expand the range of positive impacts across multiple domains.

Despite these advantages, bundled deployments account for only 18 percent of observed cases, showing that most AWM programs still rely on fragmented or single-technology approaches. This pattern echoes earlier evaluations and is a warning that uncoordinated implementation limits the transformative potential of water management investments. Integrated AWM packages, in contrast, directly advance several of the Sustainable Development Goals (SDGs), notably SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). They do so by simultaneously enhancing productivity, efficiency, and adaptive capacity.

These findings reinforce the central proposition of the Evidence-Linked Impact Framework: that technological innovation alone cannot deliver transformation without complementary enabling conditions. Bundled AWM interventions, by aligning technology design with information systems, institutional coordination, and inclusive financing, offer a practical pathway toward scalable resilience, inclusivity, and sustainability in African agriculture.

### ***Domain-specific impacts and pathways to change***

Figure 8.9 highlights the dominance of productivity gains as the most frequently cited impact domain among AWM technologies in Africa, accounting for approximately 45 percent of all documented mentions. This is followed by economic returns (23 percent) and climate resilience (18.7 percent). Gender and inclusion and water-use efficiency are cited less frequently, at 8.8 percent and 5.7 percent, respectively. These patterns suggest a prevailing focus on technologies that deliver immediate

agronomic and profit gains (especially yield improvements) over those aimed at systemic adaptation or social transformation.

The relatively low share of climate-resilience references points to an important gap in how technologies are framed and evaluated. Given the increasing volatility of African agroecological systems, there is a clear need to elevate the role of AWM tools in climate adaptation strategies. Similarly, while gender-inclusive outcomes are not the most cited, evidence from bundled and integrated approaches shows that they can co-deliver across these dimensions when designed holistically.

The figure supports calls for more balanced impact reporting and more integrative evaluation frameworks. These should go beyond productivity to measure sustainability, equity, and resilience outcomes, which are critical to Africa's long-term agrifood transformation.

### ***National examples and innovation programs***

Table 8.8 outlines selected national-level examples of innovative AWM implementation that demonstrate how government and public-private partnerships are enabling technology adoption across different agroecological contexts. These

**FIGURE 8.9—POPULARITY OF IMPACT TYPE**

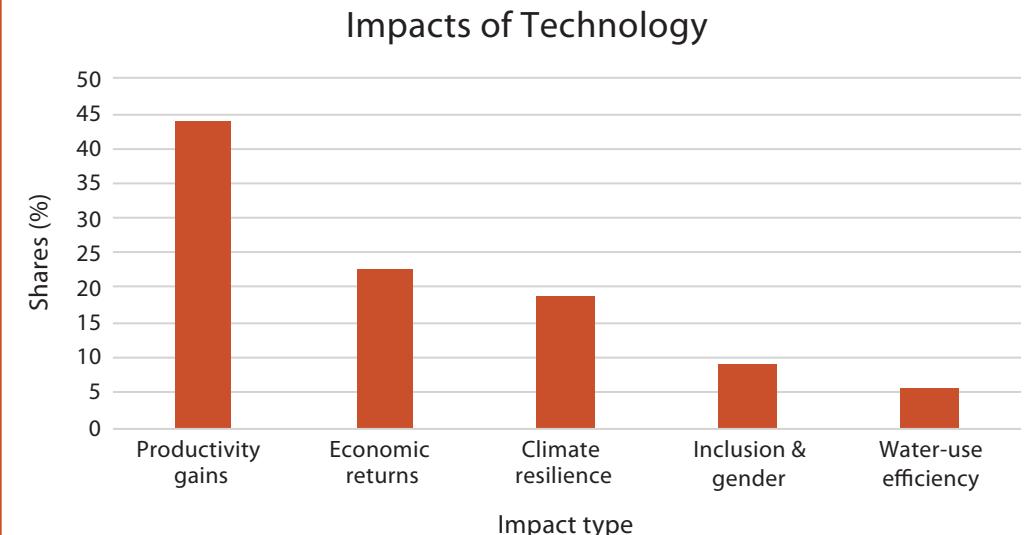


TABLE 8.8—COUNTRY-LEVEL AWM INNOVATION HIGHLIGHTS

Country	AWM initiative	Technology focus
Ethiopia	National irrigation strategy	Decision support systems, sensors
Kenya	Ministry of Agriculture public-private mobile irrigation program (NISIP) (Kenya, Ministry of Water, Sanitation and Irrigation 2025)	Smartphone-based scheduling, solar pumps
South Africa	Limpopo smart-irrigation project	Automated systems, solar-powered irrigation
Morocco	The Green Morocco Plan for agriculture	Drip irrigation, climate-smart irrigation
Ghana	Savannah Zone Agricultural Productivity Improvement Project	Rainwater harvesting, treadle pumps

cases reflect diverse entry points, ranging from irrigation strategies and digital advisory services to solar-powered automation and community-driven models.

In Ethiopia, the national irrigation strategy has emphasized the integration of DSSs and sensor-based monitoring, enabling data-driven irrigation planning. This aligns with Ethiopia's broader push toward climate-smart agriculture and public sector modernization.

Kenya's Ministry of Agriculture, in collaboration with private sector partners, has deployed mobile irrigation scheduling platforms that interface with weather data and on-farm irrigation needs. These tools are bundled with solar pumps and have helped scale smart irrigation among smallholder farmers.

In South Africa, the Limpopo smart irrigation project exemplifies large-scale public sector investment in climate-resilient infrastructure. The initiative uses automated systems linked with solar energy to irrigate high-value horticultural crops, targeting both efficiency and carbon-reduction goals.

The Green Morocco Plan for agriculture represents a long-standing and successful policy that has accelerated the adoption of drip irrigation and other water-efficient technologies, particularly in arid regions. It includes incentives, subsidies, and credit access programs for farmers.

Ghana, under the Savannah Zone Agricultural Productivity Improvement Project (SAPIP), has scaled up simple but impactful AWM technologies such as rainwater harvesting and treadle pumps, focusing on semi-arid zones where conventional irrigation is not feasible.

These cases underscore the critical role of enabling environments in scaling AWM innovations, including supportive policy frameworks, institutional delivery mechanisms, and adaptive programming.

### ***Typology and adoption contexts***

#### ***Results on farm typologies and popular technologies***

To further understand how AWM technologies align with farming realities in Africa, the analysis disaggregates adoption drivers using the Unified Theory of Acceptance and Use of Technology (UTAUT) framework (Venkatesh et al. 2003). It assesses how four key adoption constructs vary by farm typology (Figure 8.10):

##### ***1. Effort expectancy is the dominant concern***

- Among commercial farms, effort expectancy significantly accounts for the UTAUT-related mentions, indicating that ease of use is central to technology uptake; this aligns with evidence that commercial farms seek scalable solutions with minimal labor overhead (Mdoda, Christian, and Gidi 2023; Midamba, Kwesiga, and Ouko 2024).
- For smallholders, it also leads at 32 percent, suggesting that usability remains critical but is less dominant than among commercial operations.

##### ***2. Smallholders show greater behavioral and social sensitivity***

- Behavioral intention and social influence together make up 47 percent of UTAUT mentions for smallholders; this aligns with evidence that social networks strongly influence technology adoption, with farmers relying on trusted peers for information, confidence-building, and decision-support (Varshney et al. 2022).
- For commercial farms, these factors are absent or marginal, pointing to more individual or institutional decision-making frameworks.

##### ***3. Performance expectancy is higher in commercial contexts***

- For commercial farms, performance expectancy (33 percent) reflects clear expectations around return on investment; these farms are more likely to adopt new technologies if they are proven to enhance yields or reduce costs, which are usually high for solar irrigation, drip systems, and DSS.

- Among smallholders, its share is lower (21 percent), perhaps due to uncertainty about outcomes or a focus on other survival priorities (Figure 8.10).

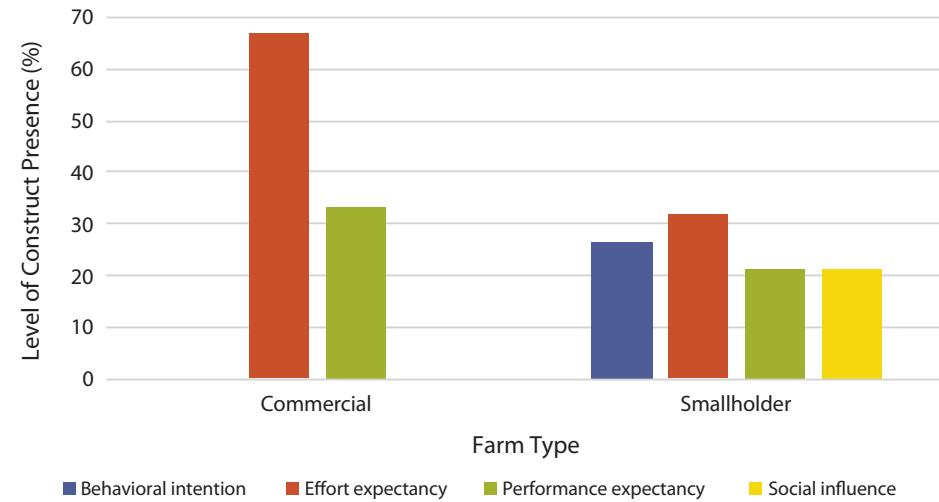
Figure 8.11 presents adoption patterns for the 10 most frequently mentioned AWM technologies, disaggregated by farm typology (smallholder and commercial), based on evidence extracted from RIS (Research Information Systems) bibliographic records.

#### *Adoption by farm typology*

1. *Smallholder farms (< 2 ha): Emphasis on low-cost and inclusive technologies:* Smallholder farmers are primarily associated with affordable, decentralized, and donor-supported AWM technologies. The most prominent technologies for this group include:
  - Drip irrigation, which appears in about 26 percent of smallholder-related mentions, reflecting NGO- and government-supported interventions aimed at improving water efficiency on small plots
  - Flood irrigation (about 27 percent) remains widespread due to its simplicity, legacy infrastructure, and limited upfront costs
  - Weather forecast tools (about 25 percent) are integrated into mobile services and community bulletins that help smallholders plan around rainfall variability
  - Smartphone-based advisory tools and mobile irrigation apps are emerging, particularly in bundled advisory platforms

These findings reinforce earlier assessments that inclusive, climate-resilient irrigation solutions are critical for smallholders (Mugejo et al. 2025). The prevalence of these technologies also aligns with the UTAUT construct of facilitating conditions (for example, access to mobile networks and extension services), which are shown to significantly drive technology adoption in this segment (Venkatesh et al. 2003).

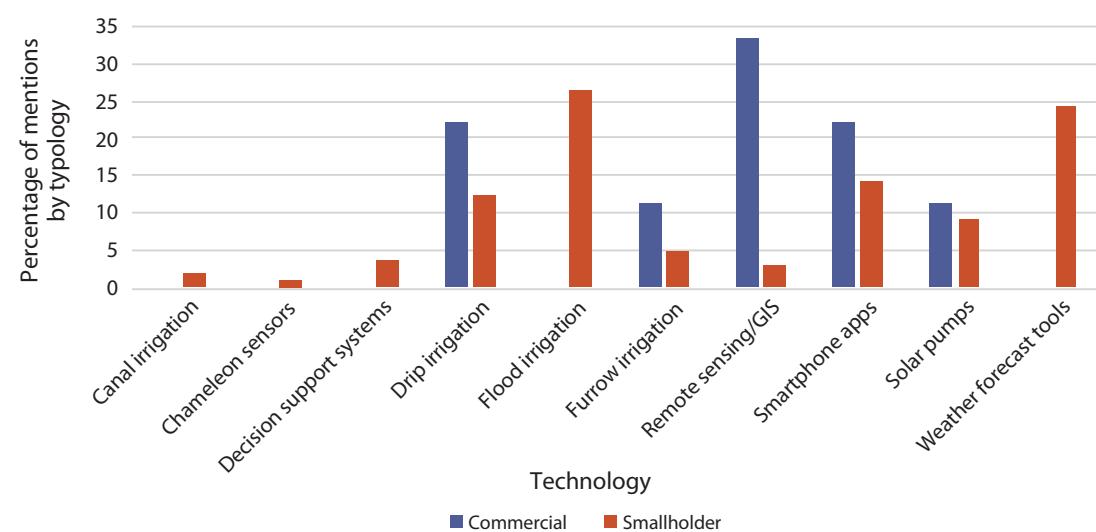
**FIGURE 8.10—ADOPTION BY FARM TYPOLOGY AND UTAUT CONSTRUCTS**



Source: Authors.

Note: UTAUT = Unified Theory of Acceptance and Use of Technology.

**FIGURE 8.11—PERCENTAGE OF MENTIONS OF TOP 10 AGRICULTURAL WATER MANAGEMENT TECHNOLOGIES BY FARM TYPOLOGY**



Source: Authors.

Note: AWM = agricultural water management; GIS = Geographic Information System.

2. *Commercial farms (>20 ha): Adoption of precision and digitally driven systems:* Commercial farms demonstrate a clear preference for precision technologies that require upfront capital but offer high returns. The top technologies identified in this category include:
  - Remote sensing and GIS tools (about 33 percent of commercial mentions), which support spatially optimized irrigation decisions
  - Smartphone-based irrigation systems (about 33 percent), which are used to coordinate operations at scale with real-time feedback
  - Drip irrigation, which is also prominent (about 22 percent), although it is deployed more by commercial farms in more technically sophisticated and sensor-integrated systems than it is by smallholders
  - Hydroponics, automated irrigation, and DSS tools; these appear mainly in commercial contexts, suggesting that these farms are moving toward fully digitized irrigation management.

These findings correspond with reports that large farms benefit more than smallholders from technical expertise, economies of scale, and access to formal credit (AGRA 2022). Within the UTAUT framework, this group is more driven by performance expectancy, that is, the belief that adoption will lead to better productivity and profitability.

3. *Medium-scale farms (2–20 ha): Absent in the dataset but prominent in literature:* Although medium-scale farms were not detected in this dataset, evidence from across SSA suggests that this segment often blends traditional systems such as canal irrigation with selective upgrades such as solar pumps and DSS (Jayne et al. 2019). Their adoption patterns are often shaped by expanding access to extension services, increasing land ownership, and growing market integration. This supports the idea that effort expectancy and facilitating conditions jointly influence their uptake trajectory.

### ***Implications for policy and programming***

The data reinforces the notion that AWM technology adoption is shaped by farm size and typology, and that the resulting strategic implications of adoption, in turn, vary distinctly by farm typology. For smallholders, scaling impact requires bundling low-cost tools such as zai pits, drip kits, and weather forecast services

with training and microcredit, thereby addressing affordability and capability constraints. In the case of medium-scale farms—which represent a critical transitional group—the focus should be on strengthening extension services and improving access to credit in order to facilitate the uptake of intermediate technologies such as solar pumps and soil-moisture sensors. Meanwhile, commercial farms, which are typically equipped with better financing and technical capacity, would benefit from targeted innovation incentives and private sector partnerships that enable the expansion of high-tech systems such as hydroponics, AI-based forecasting tools, and GIS-integrated irrigation platforms. Tailoring these strategies to the specific needs and operating contexts of each farm segment is essential to achieving scalable and sustainable adoption of AWM technologies.

### ***Discussion of visualizations and tables***

The combined results from Figures 8.7 to 8.11 and Tables 8.4 to 8.8 reveal a transformative shift in Africa's agricultural water management landscape toward smarter, more inclusive, and more context-sensitive approaches. Technologies such as drip and sprinkler irrigation, and solar-powered pumps lead not only in frequency of mention but also in demonstrated impact across multiple domains. Drip irrigation, for instance, which represents 45 percent of all technology mentions, scores high in both productivity gains (59.5 percent) and water-use efficiency (20.6 percent), reinforcing its central role in AWM transitions.

Meanwhile, digitally enabled solutions such as decision support systems and smartphone irrigation apps, though less frequently cited, consistently outperform in multidomain impact, particularly in economic returns and climate resilience. These patterns suggest that technology popularity is increasingly aligning with measurable effectiveness, particularly where supportive infrastructure and institutional capacity exist.

Regional disparities persist, however. Central Africa and parts of West Africa continue to show low adoption of digital and bundled systems, scoring poorly on connectivity, extension services, and digital literacy. These limitations constrain the potential of high-impact technologies and risk exacerbating regional inequalities in agricultural performance and resilience.

Bundled technologies, such as a combination of solar-powered drip irrigation and DSS, consistently demonstrate higher positive impact scores across all five of the domains analyzed. These bundles, however, account for only 18 percent of recorded use cases, pointing to a widespread tendency to deploy single technologies. Unlocking the full potential of AWM requires

systematic integration of tools, particularly those that span both hardware and digital services.

Specialized innovations such as hydroponics and desalination hold particular value for urban, peri-urban, and water-stressed environments. Although adoption remains limited (less than 2 percent each), their impact scores in terms of productivity (61 to 78 percent) and economic return (81 to 84 percent) confirm their potential as niche but high-return options, especially when deployed through public-private partnerships (World Bank 2025b).

On the other end of the spectrum, decentralized and accessible systems such as zai pits, rainwater harvesting, and contour bunds deliver social equity and gender inclusion benefits, particularly in smallholder contexts. These tools are often linked to community-managed delivery models and donor-backed microfinance programs, suggesting that equity and access can be maximized through appropriate targeting and financial support.

Despite these promising trends, several structural barriers remain. Adoption of emerging AWM technologies is hindered by:

- High initial costs and limited financing mechanisms for smallholders,
- Cultural resistance to nontraditional irrigation practices,
- Digital illiteracy and gendered access constraints, and
- Poor internet coverage in rural areas and uncertainty over data privacy.

Addressing these constraints will require coordinated investment from governments, development agencies, research institutions, and the private sector. Particularly important are strategies that:

- Blend public and private finance to increase access to equipment and services,
- Set up localized demonstration sites to build trust and familiarity,
- Simplify user interfaces and digital advisory tools, and
- Integrate extension systems with digital service providers.

Importantly, technology alone is insufficient. Without supportive policies, regulatory frameworks, and institutional integration, the sustainability of AWM transitions remains uncertain. Governments must foster policy coherence, fund capacity building, and ensure that innovation incentives do not exclude marginalized groups.

## Conclusions

This analysis of 1,585 documented agricultural water management (AWM) technology cases across Africa reveals a significant paradigm shift from legacy irrigation systems such as flood, furrow, and canal-based methods to more integrated, digitally enabled, and climate-resilient approaches. While traditional methods still dominate by count, they consistently underperform newer innovations when evaluated across multiple impact domains, including productivity, water-use efficiency, climate resilience, gender and youth inclusion, and economic return.

Emerging technologies such as drip irrigation (45 percent), solar-powered pumps (7.2 percent), decision support systems (2.0 percent), GIS and remote sensing (3.6 percent), and soil-moisture sensors (4.1 percent) have consistently demonstrated superior performance, especially when deployed in bundled configurations. Bundles that combine solar pumps, drip systems, and DSSs, for example, yield the highest cross-domain benefits, amplifying both agronomic and socioeconomic outcomes.

The analysis underscores important distinctions by farm typology. Smallholder farmers tend to adopt low-cost, donor-supported systems such as rainwater harvesting, zai pits, and treadle pumps, which deliver significant equity and inclusion impacts. Commercial farms, on the other hand, more frequently utilize advanced, sensor-based, and automated systems, benefitting from water and energy savings, and higher productivity and profitability. The adoption and impact of technologies are also highly regionalized, with Eastern (47 percent) and Northern Africa (23 percent) leading in innovation uptake, and Central Africa (4 percent) remaining underserved.

Gender and youth dimensions are becoming increasingly prominent in AWM interventions. Technologies such as solar-powered irrigation and rainwater harvesting are particularly well-suited to women and youth when accompanied by appropriate financial instruments, training, and support mechanisms. The Unified Theory of Acceptance and Use of Technology (UTAUT) framework confirms that adoption is driven by a combination of performance expectancy, facilitating conditions, and social influence.

While technologies such as drip and canal irrigation maintain a high frequency of use, they vary greatly in impact. Newer tools such as hydroponics, digital irrigation systems, and weather-indexed insurance, although used less frequently, increasingly demonstrate high multidimensional benefits as more

evidence becomes documented. Regional disparities also remain stark: Eastern Africa leads in uptake and innovation, whereas Central Africa is significantly lagging, often due to institutional and infrastructure barriers.

### **Policy and investment recommendations**

1. *Scale bundled AWM technology packages:* Bundled solutions that integrate energy-efficient delivery (e.g., solar) with precision irrigation (e.g., drip) and data-driven management (e.g., DSS) consistently outperform standalone approaches across domains. National governments, supported by international donors and CGIAR centers, should incorporate these bundled technologies into irrigation master plans and allocate targeted grants or channel funds for their deployment, especially in semi-arid regions. This can be supported by improving both upstream and downstream supply chains.
2. *Promote regionally differentiated investment approaches:* Central and Southern Africa require foundational support, including infrastructure development, early-stage pilot programs, and institutional capacity building. Regional economic communities such as the Southern African Development Community (SADC) and the Economic Community of Central African States (ECCAS) should lead coordination efforts, while development banks such as AfDB and the International Fund for Agricultural Development (IFAD) should provide concessional finance that is tailored to regional needs. Eastern and Northern Africa should focus on digital upgrades and market-oriented bundling.
3. *Expand digital infrastructure and innovation ecosystems:* National ICT and agriculture ministries should invest in mobile broadband expansion, digital public goods such as open-source DSS, and last-mile delivery platforms. Private sector tech startups should be engaged through innovation incubators and results-based finance to localize tools such as smartphone irrigation schedulers, solar irrigation pumps, IoT soil sensors, and AI-driven forecast systems.
4. *Enable inclusive finance for women, youth, and marginalized farmers:* Agricultural development agencies and microfinance institutions should jointly deliver gender-responsive, bundled financial products that combine equipment financing, weather-indexed insurance, and digital literacy training. Programs like Malawi's Sustainable Drip Irrigation
5. *Integrate AWM into climate, nutrition, and economic development frameworks:* AWM should be mainstreamed in National Adaptation Plans (NAPs), Nationally Determined Contributions (NDCs), and National Agricultural Investment Plans (NAIPs). Tools like AWD and zai pits should be positioned as triple-duty solutions for productivity, GHG mitigation, and drought resilience. Cross-ministerial coordination platforms should ensure harmonized delivery.
6. *Enhance regional coordination, learning, and knowledge exchange:* The African Union Commission (AUC), the Comprehensive Africa Agriculture Development Programme (CAADP), and the African Continental Free Trade Area (AfCFTA) should spearhead continent-wide benchmarks and peer review systems. Institutions such as the African Water Facility and IWMI should establish regional knowledge hubs, innovation dashboards, and training programs to share lessons on bundled AWM technologies and inclusive delivery models.

program and Kenya's One Acre Fund should be scaled regionally. In Northern Africa, Morocco's Green Generation Program-for-Results strategy and Egypt's Sustainable Agricultural Development Strategy have institutionalized credit-linked irrigation subsidies, public-private partnerships for solar pumping, and collective water-user financing models, thus demonstrating coordinated policy and investment mechanisms for irrigation expansion.

5. *Integrate AWM into climate, nutrition, and economic development frameworks:* AWM should be mainstreamed in National Adaptation Plans (NAPs), Nationally Determined Contributions (NDCs), and National Agricultural Investment Plans (NAIPs). Tools like AWD and zai pits should be positioned as triple-duty solutions for productivity, GHG mitigation, and drought resilience. Cross-ministerial coordination platforms should ensure harmonized delivery.
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### **Outlook**

Africa stands at a transformative juncture in its pursuit of climate-smart, inclusive, and productivity-enhancing agricultural systems. The continent must now transition from fragmented pilot efforts to scaled, coordinated deployment of proven AWM innovations. Regional disparities in technology access and enabling environments can be overcome by tailored, actor-specific investment and policy strategies.

By aligning national strategies, donor financing, private sector innovation, and community-led delivery mechanisms, AWM systems in Africa can evolve into digitally enabled, socially inclusive, and environmentally resilient platforms. This transformation is critical to achieving the continent's agricultural and climate ambitions by 2030 and beyond.