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EMERGING AND APPROPRIATE TECHNOLOGY AND INNOVATION



SMART IRRIGATION TECHNOLOGIES FOR SUSTAINABLE WATER MANAGEMENT: INNOVATIVE RESEARCH AND PRACTICES IN AFRICA.

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Abstract

Smart irrigation technologies are transforming agricultural water management by enhancing efficiency, reducing waste, and improving crop productivity. With climate change, water scarcity, and food security challenges intensifying, the need for data-driven, automated irrigation solutions has become urgent, particularly in Africa, where unpredictable rainfall and outdated irrigation systems threaten agricultural sustainability. This paper explores the concept of smart irrigation, detailing its principles, tools, and technologies, including IoT sensors, AI-driven forecasting, drones, and cloud-based irrigation control systems. It examines global and African trends in research and adoption, highlighting case studies from Egypt, Morocco, Nigeria, Ghana, and Kenya to showcase real-world applications. While smart irrigation offers significant benefits such as water conservation, improved yields, and climate resilience, challenges persist, including high implementation costs, limited digital infrastructure, and low farmer awareness. This study identifies key research gaps, emphasising the need for scalable, locally adaptable smart irrigation solutions tailored to African smallholder farmers. Finally, the paper discusses strategies for promoting widespread adoption, including government incentives, private sector investments, and farmer education programs, to ensure the long-term sustainability and integration of smart irrigation into African agriculture.

Keywords: Smart Irrigation; Precision; Water Management; Data driven.

Introduction

Agriculture is the largest consumer of freshwater resources, accounting for approximately 70% of global water withdrawals (Ritchie and Roser, 2024). However, a significant portion of this water is lost due to inefficient irrigation practices, including overwatering, poor distribution, and evaporation. In many regions, particularly in Africa, where rainfall is highly variable and droughts are becoming more frequent, these inefficiencies pose a serious threat to food security (Tefera *et al.*, 2025). Farmers who rely on traditional irrigation methods often struggle with water shortages, soil degradation, and declining crop yields. As climate change continues to disrupt weather patterns, ensuring the efficient use of water in agriculture has become a global priority. One of the most promising solutions to this challenge is smart irrigation, which leverages technology to optimize water usage and improve agricultural productivity.

Smart irrigation is a modern, technology-driven approach that allows farmers to apply water more efficiently by considering real-time environmental conditions. Unlike conventional irrigation systems that rely on preset schedules or manual estimation, smart irrigation systems integrate Internet of Things (IoT) sensors, artificial intelligence (AI), automation, and weather data analytics to determine the precise amount of water needed by crops at any given time. These systems monitor soil moisture levels, weather forecasts, and plant water requirements, adjusting irrigation schedules accordingly to prevent both overwatering and under watering. By

ensuring that water is delivered to crops only when necessary, smart irrigation significantly reduces water wastage, enhances soil health, and increases crop yields (Obaideen *et al.*, 2022; Ahmed *et al.*, 2023; Gamal *et al.*, 2023). The adoption of smart irrigation is particularly important in the context of global water scarcity. Studies indicate that over one billion people worldwide lack access to sufficient freshwater, and agricultural overuse is a key contributor to this crisis (Kumari *et al.*, 2021). Africa, in particular faces severe water management challenges, with many countries experiencing seasonal droughts, declining groundwater reserves, and inefficient irrigation infrastructure (Lankford and Dickinson, 2007; Hamza, 2020; Akinsete *et al.*, 2024). Farmers who rely on outdated irrigation techniques, such as flood irrigation or manual watering, often struggle with high water loss rates, increased energy costs, and soil degradation (Rai *et al.*, 2017). These challenges highlight the urgent need for sustainable irrigation solutions that can help conserve water while maintaining or increasing agricultural productivity. Beyond water conservation, smart irrigation technologies also play a crucial role in climate change adaptation. Rising temperatures, erratic rainfall, and shifting growing seasons are making traditional irrigation methods less effective, forcing farmers to seek innovative alternatives. Smart irrigation helps mitigate these risks by providing real-time insights into changing environmental conditions and adjusting irrigation practices accordingly. This not only improves water-use efficiency but also enhances farm resilience to climate variability (Frisvold and Bai, 2016; Bwambale *et al.*, 2022; Obaideen *et al.*, 2022). Moreover, with the integration of solar-powered irrigation systems, smart irrigation can further contribute to sustainable energy use, reducing dependence on fossil fuels and lowering greenhouse gas emissions from agricultural activities (Schnetzer and Pluschke, 2017). The growing interest in smart irrigation is part of a broader movement towards digital agriculture, where modern technology is used to enhance productivity and sustainability in farming. Innovations such as AI-driven irrigation models, automated drip systems, drones for crop monitoring, and cloud-based water management platforms are transforming the agricultural sector. In some regions, these technologies have already demonstrated their ability to reduce water usage by up to 50% while increasing yields and profitability (Obaideen *et al.*, 2022). As African countries work towards achieving climate-smart agriculture, the widespread adoption of smart irrigation technologies will be critical. By addressing the challenges of water scarcity, climate change, and inefficient farming practices, smart irrigation has the potential to revolutionize African agriculture, making it more productive, sustainable, and resilient. However, achieving this transformation will require significant investment in research, infrastructure, and farmer education. This paper will explore the implementation of smart irrigation, its benefits and drawbacks, global and African trends in research and development, and the challenges that must be overcome to ensure its widespread adoption.

Understanding smart irrigation.

Efficient water management is a critical aspect of modern agriculture, especially in the face of climate change, increasing food demand, and diminishing freshwater resources. Traditional irrigation methods, which rely on manual scheduling, historical climate patterns, or arbitrary water application, have long been the backbone of global agriculture. However, these methods often lead to inefficiencies, water wastage, soil degradation, and fluctuating crop yields (Rai *et al.*, 2017). Smart irrigation refers to the use of advanced technologies and data-driven

approaches to optimize water use in agriculture, ensuring crops receive the right amount of water at the right time. The emergence of smart irrigation has revolutionized water management in agriculture by incorporating technology-driven, data-supported, and precision-based approaches that ensure optimal water use while improving productivity and sustainability. Unlike traditional systems, which often rely on human judgment and fixed schedules, smart irrigation systems use advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, and remote sensing to provide accurate and real-time insights into soil moisture levels, weather conditions, and crop water requirements. These technologies enable farmers to make data-driven irrigation decisions, optimizing water efficiency while ensuring that crops receive adequate hydration for optimal growth (Obaideen *et al.*, 2022; Ahmed *et al.*, 2023; Gamal *et al.*, 2023). The implementation of smart irrigation is particularly important in regions experiencing water scarcity or unpredictable rainfall patterns, as it enables farmers to adapt to climate variations, reduce dependency on groundwater, and maintain consistent agricultural productivity (Nikolaou *et al.*, 2020). In addition, smart irrigation contributes to sustainable farming practices by minimizing runoff, soil erosion, and nutrient leaching, which are common problems associated with overwatering (Gowtham and John, 2024).

Key Principles: Precision, Automation, and Data-Driven Decision-Making

The effectiveness of smart irrigation is built upon three fundamental principles: precision, automation, and data-driven decision-making. These principles ensure that irrigation practices are efficient, responsive, and environmentally sustainable.

Precision in irrigation refers to the accurate application of water to crops based on their specific needs (Mushtaq *et al.*, 2024). Unlike traditional methods that apply water uniformly across a field, smart irrigation systems assess factors such as soil type, crop type, growth stage, and real-time weather conditions to determine exactly how much water each plant requires. This approach prevents overwatering and underwatering, promoting better root development, healthier plants, and higher yields. Precision irrigation is particularly beneficial in areas facing water scarcity, as it enables farmers to maximize the use of limited water resources while maintaining optimal crop health (Gamal *et al.*, 2023; Balas *et al.*, 2024).

Automation is a key advantage of smart irrigation, allowing irrigation systems to operate without constant human intervention (Selvaraj *et al.*, 2020). By integrating IoT sensors, AI algorithms, and cloud-based control systems, smart irrigation can automatically adjust water application based on real-time data (Reddy *et al.*, 2024). For example, if soil moisture sensors detect that the soil is sufficiently wet after rainfall, the system delays scheduled irrigation, preventing unnecessary water use. Additionally, automation enables farmers to remotely monitor and control irrigation activities using mobile applications and smart controllers, reducing the need for manual labor and increasing efficiency (Obaideen *et al.*, 2022).

One of the most transformative aspects of smart irrigation is its ability to make data-driven decisions based on real-time and historical agricultural data. Through big data analytics and AI-powered insights, smart irrigation systems can predict optimal watering schedules, detect irrigation inefficiencies, and provide recommendations for improving water use (Gowtham and

John, 2024). These systems continuously collect and analyze data from multiple sources, including soil sensors, satellite imagery, climate models, and weather stations, to generate accurate and reliable irrigation plans. By using data-driven decision-making, smart irrigation helps farmers: reduce water usage without compromising crop growth, identify potential irrigation problems (e.g., leaks, blockages, or malfunctions in irrigation lines), adapt to changing environmental conditions, such as prolonged droughts or unexpected rainfall and enhance long-term sustainability by optimizing water resources for future agricultural needs.

Tools and Technologies for Smart Irrigation

The success of smart irrigation relies on the integration of advanced technologies that enhance precision, automation, and efficiency in water management (Bhushan *et al.*, 2023). These technologies enable farmers to monitor, analyze, and optimize irrigation schedules based on real-time environmental conditions. By leveraging Internet of Things (IoT) devices, artificial intelligence (AI), remote sensing, and cloud computing, smart irrigation systems minimize water waste, improve crop yields, and enhance sustainability.

IoT-Based Sensors for Smart Irrigation

One of the most transformative advancements in smart irrigation is the use of Internet of Things (IoT) sensors, which provide real-time data on various environmental conditions. These sensors collect information on soil moisture, weather conditions, and water flow, enabling farmers to make data-driven decisions regarding irrigation timing and water allocation (Morchid *et al.*, 2024).

Soil Moisture Sensors

Soil moisture sensors detect the amount of water present in the soil, helping farmers determine whether crops require additional irrigation. These sensors are typically buried at different soil depths and send data to automated irrigation systems or mobile applications, allowing for remote monitoring and control (Garg *et al.*, 2016; Obaideen *et al.*, 2022).

Weather Sensors

Weather conditions significantly impact irrigation needs. Temperature, humidity, solar radiation, and wind speed sensors help in predicting evaporation rates and water requirements for crops. These sensors are integrated into weather stations, which collect local climate data and adjust irrigation schedules based on real-time weather forecasts (Ivanova, 2025). This ensures that irrigation occurs only when necessary, reducing the risk of waterlogging during rainy periods and drought stress during dry seasons.

Water Flow Sensors

Water flow sensors monitor the rate and volume of water moving through irrigation systems, detecting leaks, inefficiencies, or blockages. These sensors help in preventing water loss and ensure that irrigation is evenly distributed across fields. They also track water consumption patterns, making it easier to optimize resource allocation and reduce costs (Wahid *et al.*, 2022).

By combining soil moisture, weather, and water flow sensors, highly responsive and efficient irrigation systems are created, ensuring that crops receive the right amount of water at the right time.

Drones for Irrigation Monitoring and Mapping

Drones are becoming an essential tool in precision agriculture, particularly for irrigation management. Equipped with high-resolution cameras, thermal imaging sensors, and multispectral sensors, drones provide aerial views of crop health, soil moisture levels, and irrigation distribution patterns (Guebsi *et al.*, 2024). Thermal and multispectral sensors on drones can detect variations in soil moisture levels, identifying areas of overwatering or drought stress. Allowing farmers to adjust irrigation strategies accordingly, ensuring that water is distributed evenly (Qu *et al.*, 2024). Drones can generate detailed irrigation maps, showing which areas of a farm require more or less water. By analyzing this data, farmers can develop site-specific irrigation plans, reducing water waste while maximizing crop health (Azharuddin *et al.*, 2024). Drones can help in identifying leaks, clogged irrigation lines, or malfunctioning sprinkler systems that might otherwise go unnoticed. This prevents unnecessary water loss and ensures that irrigation systems function optimally. With their ability to provide quick, accurate, and large-scale assessments of water distribution, drones enhance the efficiency and precision of irrigation management, especially in large farms or areas with difficult terrain.

AI and Machine Learning for Irrigation Forecasting

Artificial Intelligence (AI) and machine learning are revolutionizing smart irrigation by enabling predictive analytics and automated decision-making. These technologies analyze historical and real-time data to develop accurate irrigation models that optimize water use. AI algorithms analyze soil moisture levels, weather conditions, crop types, and growth stages to predict the exact amount of water needed at different times. This ensures that irrigation schedules align with crop water demand, preventing overuse or underuse of water resources (Nyakuri *et al.*, 2023). Machine learning models analyze historical weather patterns, soil moisture levels, and crop water requirements to predict future irrigation needs with high accuracy. By continuously learning from past data, these models can recognize trends in rainfall patterns, temperature fluctuations, and evaporation rates to determine when and how much water crops will require (Umutoni and Samadi, 2024). This prevents overwatering, soil erosion, and nutrient leaching, while also conserving water and reducing energy costs associated with pumping and irrigation system operation. AI-driven irrigation systems continuously learn and improve over time by analyzing past irrigation performance and crop responses. These systems can adjust water distribution patterns based on real-time data, ensuring maximum efficiency. By integrating AI-driven insights with real-time sensor data, smart irrigation systems can achieve unprecedented levels of efficiency, helping farmers save water, reduce costs, and improve crop resilience to climate variability.

Cloud Computing and Mobile Applications for Remote Irrigation Control

Cloud computing and mobile applications provide farmers with remote access to their irrigation systems, allowing them to monitor and control water distribution from anywhere (Mani *et al.*, 2023). Smart irrigation systems store sensor data and weather information in cloud servers,

where AI algorithms process the data to generate real-time irrigation recommendations. This ensures that farmers receive instant updates on soil moisture levels, water usage patterns, and irrigation schedules (Et-taibi *et al.*, 2024). Many smart irrigation systems are equipped with mobile apps that allow farmers to: view real-time sensor data (soil moisture, weather, water flow), manually adjust irrigation settings if needed, receive alerts for irrigation system malfunctions or water shortages and integrate weather forecasts into irrigation planning. Farmers can use Mobile applications are used to set automated irrigation schedules, ensuring that crops receive the right amount of water even when the farmer is away (Stefanov *et al.*, 2024). This is particularly useful in large-scale farming operations, where manual irrigation monitoring can be time-consuming. Cloud computing and mobile technology enhance accessibility and ease of use, making smart irrigation systems more user-friendly and adaptable for farmers, including smallholder farmers with limited technical knowledge.

Smart Drip and Sprinkler Systems

Modern irrigation systems, such as smart drip irrigation and precision sprinkler systems, are essential components of smart irrigation. These technologies apply water directly to plant roots or distribute it efficiently over large areas, minimizing waste and maximizing effectiveness (Ray and Majumder, 2024). Smart drip irrigation delivers water directly to plant roots through emitters, minimizing evaporation and runoff, it is controlled by moisture sensors and AI, ensuring optimal water distribution. It is ideal for water-scarce regions and high-value crops. Smart sprinkler systems use weather-based controllers to adjust irrigation based on rainfall, humidity, and temperature. Smart sprinklers are equipped with water pressure sensors to optimize spray distribution. It prevents overwatering by automatically shutting off during rainy conditions. Both smart drip and sprinkler systems contribute to higher water-use efficiency, improved plant health, and significant reductions in water consumption, making them key technologies for sustainable irrigation.

Categories of Smart Irrigation Systems

Smart irrigation systems vary in complexity and function, but they all share a common goal: to optimize water use in agriculture while improving crop yields and conserving resources. Different categories of smart irrigation systems exist, each employing unique technologies to achieve efficiency. Among the most prominent are sensor-based irrigation, weather-based irrigation, AI-driven predictive irrigation, and cloud-controlled irrigation. These systems work either independently or in combination, depending on the farm's size, available infrastructure, and specific water management needs.

Sensor-Based Irrigation

Sensor-based irrigation relies on real-time data collection from soil moisture, temperature, and water flow sensors to regulate irrigation based on actual field conditions (Obaideen *et al.*, 2022). Unlike traditional irrigation, which often leads to overwatering or underwatering due to guesswork, sensor-based irrigation ensures that water is applied only when necessary. The process begins with soil moisture sensors, which are strategically placed at different depths to monitor water availability in the root zone. These sensors continuously measure moisture levels and transmit the data to an automated irrigation controller. If the soil moisture content is

sufficient, irrigation is delayed or stopped; if it falls below the required threshold, water is applied automatically (Obaideen *et al.*, 2022). Other types of sensors complement this system. Water flow sensors track the volume of water moving through irrigation pipes, helping detect leaks and inefficiencies (Wahid *et al.*, 2022). Temperature and humidity sensors monitor environmental conditions, allowing the system to adjust irrigation in response to factors such as increased evaporation rates (Ivanova, 2025). Over time, the collected data enables farmers to fine-tune irrigation schedules according to crop growth stages, soil types, and weather patterns. The biggest advantage of sensor-based irrigation is its precision, which reduces water waste, minimizes nutrient leaching, and enhances soil health. However, this system requires careful calibration and high-quality sensors to ensure accurate readings, making initial setup costs relatively high.

Weather-Based Irrigation

Weather-based irrigation, also known as climate-responsive irrigation, integrates meteorological data to make dynamic adjustments to watering schedules. Instead of directly measuring soil moisture, this system uses temperature, humidity, wind speed, solar radiation, and precipitation forecasts to estimate how much water crops will need. By calculating evapotranspiration rates, which represent the total water loss through evaporation from soil and transpiration from plants, weather-based irrigation ensures that crops receive adequate hydration without unnecessary watering (Jamal *et al.*, 2023; Mabhaudhi *et al.*, 2025). The process begins with automated weather stations or satellite-based remote sensing systems that collect climate data. This information is transmitted to a central irrigation controller, which processes it alongside historical climate records to predict short-term and long-term water requirements. This approach is particularly effective for large-scale farms and regions with fluctuating rainfall patterns, as it helps maintain consistent soil moisture without human intervention. One of the key benefits of weather-based irrigation is its ability to cover wide geographic areas without requiring soil moisture sensors in every field. This makes it cost-effective and scalable, especially for commercial farms that rely on centralized irrigation management (Ray and Majumder, 2024). However, because this system depends on external weather data rather than direct soil measurements, forecast inaccuracies or sudden climate shifts can lead to miscalculations in irrigation timing.

AI-Driven Predictive Irrigation

AI-driven predictive irrigation represents the next frontier in precision water management, utilizing machine learning, big data analytics, and historical climate trends to anticipate crop water needs before they arise (Elshaikh-Hayaty *et al.*, 2024). Unlike sensor-based or weather-based irrigation, which react to immediate conditions, AI-driven irrigation proactively schedules water application based on predictive models. These models analyze massive datasets, including past weather patterns, soil properties, crop water usage, and satellite imagery, to forecast irrigation requirements with high accuracy. The system continuously refines itself through self-learning algorithms, which means it improves over time by recognizing patterns and adapting to site-specific conditions. For instance, if an AI model detects a recurring pattern of drought stress at a particular time of the year, it will adjust irrigation schedules accordingly in advance. Similarly, if historical data suggests that certain

soil types retain water longer than others, the system customizes irrigation frequency to reflect those differences. This reduces reliance on manual oversight, allowing for fully automated, adaptive irrigation management. A major advantage of AI-driven irrigation is its ability to optimize water use under unpredictable climate conditions, making it particularly valuable in regions prone to seasonal droughts, erratic rainfall, and shifting temperature patterns.

Cloud-Controlled Irrigation

Cloud-controlled irrigation represents the ultimate remote irrigation management system, enabling farmers to monitor and adjust watering schedules from anywhere in the world through mobile applications, IoT connectivity, and cloud computing platforms. This system integrates sensor data, weather analytics, and AI-driven predictions, storing all the information in a cloud-based database. Farmers can access this data via their smartphones, tablets, or computers, receiving real-time updates on soil moisture levels, water usage, and potential irrigation system malfunctions (Sumathi, 2020; Reddy *et al.*, 2024). One of the most significant advantages of cloud-controlled irrigation is its flexibility and accessibility. Unlike traditional systems that require on-site management, this technology allows farmers to remotely adjust irrigation schedules, ensuring crops are watered efficiently even when they are not physically present. If a system detects an issue, such as a leak, low soil moisture, or an impending storm, the farmer receives an immediate notification and can take action before damage occurs. Additionally, cloud-based platforms often integrate weather forecast services and AI-driven analytics, automatically adjusting irrigation schedules based on climate predictions and crop growth cycles. Cloud-controlled irrigation is particularly useful for large-scale farms, greenhouse operations, and commercial agribusinesses that require centralized irrigation management across multiple locations. However, it depends on strong internet connectivity and secure cloud storage, which can be a challenge in remote agricultural regions. There is also a concern over cybersecurity risks, as hackers could potentially disrupt cloud-based irrigation networks, leading to data breaches or system failures.

Pros and Cons of Smart Irrigation Technology

Smart irrigation technology has emerged as a critical solution to the challenges of water management in agriculture, offering a way to maximize efficiency while reducing waste. One of the most notable benefits of these systems is their capacity for water conservation, which is particularly important in regions facing drought or water scarcity. Unlike traditional irrigation methods that operate on fixed schedules, smart irrigation dynamically adjusts water distribution based on soil moisture levels, weather conditions, and crop needs, reducing excessive water use. Additionally, by preventing overwatering, these systems help to protect soil structure, prevent nutrient leaching, and reduce runoff, ultimately leading to healthier crops and better long-term soil fertility. Another significant advantage of smart irrigation is its positive impact on crop productivity and farm efficiency (Dickson and Amannah, 2023). By maintaining consistent soil moisture levels tailored to specific crop requirements, plants experience less water stress, leading to higher yields and better-quality produce. This is especially important in modern agriculture, where climate variability can disrupt traditional farming cycles. Smart irrigation also reduces labor dependency, as automated systems eliminate the need for manual monitoring and irrigation adjustments. Farmers can remotely control irrigation schedules via

mobile applications, freeing up time to focus on other critical farm operations. The integration of fertigation (fertilizer application through irrigation) further enhances productivity by delivering nutrients efficiently alongside water, ensuring that crops receive both essential hydration and nourishment in precise amounts. This results in improved resource efficiency and increased profitability for farmers (Ranjan and Sow, 2021).

Despite these advantages, the widespread adoption of smart irrigation technology faces several challenges. High initial investment costs remain a major barrier, particularly for smallholder farmers who lack the financial resources to purchase advanced irrigation systems. The cost of sensors, automated valves, IoT connectivity, and cloud-based platforms can be substantial, and many farmers struggle to justify this expense without guaranteed returns. Additionally, maintenance costs and technical support requirements add to the financial burden, as sensors and control systems require periodic calibration and servicing to function optimally (Wanyama *et al.*, 2024). Another obstacle is the limited accessibility of technology in rural agricultural areas, where poor infrastructure, lack of internet connectivity, and unreliable power supply make it difficult to implement cloud-based irrigation management. Farmers in these regions often rely on traditional irrigation methods due to their simplicity and low cost, creating a significant gap in the adoption of smart irrigation solutions (Ray & Majumder, 2024). Beyond financial and infrastructural challenges, technical knowledge and digital literacy also play a critical role in determining the success of smart irrigation adoption. Many farmers, particularly those in developing regions, are unfamiliar with AI-driven analytics, IoT-based automation, and remote irrigation control, making it difficult for them to utilize these systems effectively (Arpula *et al.*, 2024). Without proper training and support, there is a risk that farmers may underutilize or mismanage smart irrigation technologies, leading to inefficiencies. Furthermore, the increasing reliance on cloud computing and digital platforms raises concerns about data privacy and cybersecurity. As farm operations become more interconnected, the potential risks of unauthorized access, hacking, and data breaches increase, posing a threat to both farmers' financial security and operational stability (Maraveas *et al.*, 2024). Ensuring that these digital irrigation systems are secure, user-friendly, and adaptable to different farming scales will be crucial in making smart irrigation a viable solution for global agriculture.

While smart irrigation technology presents unquestionable benefits in water conservation, productivity enhancement, and operational efficiency, it is not without its challenges in affordability, accessibility, and technical complexity. Overcoming these barriers will require collaborative efforts from governments, private sector investors, and agricultural researchers to develop cost-effective, user-friendly solutions that can be widely implemented. With the right policy support, financial incentives, and farmer training programs, smart irrigation has the potential to revolutionize agricultural water management, ensuring a more sustainable and resilient future for food production worldwide.

Global and African Trends in Smart Irrigation Research & Development

Smart irrigation has gained significant attention worldwide as climate change, population growth, and water scarcity threaten global food security. Researchers, governments, and agribusinesses are investing heavily in developing advanced irrigation solutions that improve water efficiency, reduce environmental impact, and boost crop yields. The level of research and

adoption varies across regions, with developed countries leading in innovation, while Africa is gradually integrating these technologies into its agricultural sector.

Countries with advanced agricultural technologies, such as the United States, Israel, Australia, and China, have pioneered precision irrigation solutions that optimize water use while maintaining high crop yields. These nations have integrated machine learning algorithms, big data analytics, and automated irrigation controllers into their farming systems, significantly reducing water waste. In the United States, extensive research in AI-powered irrigation scheduling has led to predictive irrigation models that reduce water consumption by over 30% in large-scale farming operations. The University of California, Davis, has developed Decision Support Tools (DSTs) that use satellite imagery, evapotranspiration (ET) data, and real-time soil moisture analysis to provide farmers with precise irrigation schedules (Snyder *et al.*, 2012; Orang *et al.*, 2013; Jha *et al.*, 2022). Additionally, the NASA OpenET initiative leverages remote sensing and thermal imaging to measure water loss from crops, assisting farmers in optimizing water use across vast agricultural landscapes (FAO, 2023; DeMarco, 2024). In California's Central Valley, where water resources are critically scarce, agribusinesses have adopted sensor-based irrigation systems such as Hortau's wireless irrigation controllers, which allow real-time adjustments to water application rates.

Israel, with its chronic water scarcity, has become the world leader in drip irrigation technology and AI-assisted irrigation management (Marin *et al.*, 2017). The Israeli company Netafim, the pioneer of drip irrigation, has developed smart fertigation systems that regulate both nutrient delivery and water application based on real-time plant uptake data (Girma & Jemal, 2015). Research institutions such as the Volcani Center and Technion – Israel Institute of Technology have further refined machine-learning-based irrigation algorithms that predict crop water demand based on historical weather data and real-time microclimate readings. Australia has focused on large-scale irrigation automation, particularly in the Murray-Darling Basin, where water availability is tightly regulated (Walker *et al.*, 2021). The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has led efforts to develop climate-adaptive irrigation scheduling systems that integrate weather forecasts, soil-water balance models, and AI-driven decision support tools. China has leveraged AI, IoT, and satellite-based remote sensing to scale smart irrigation deployment across its agricultural zones (Onojehuo *et al.*, 2018). Large-scale farms in Xinjiang and Inner Mongolia now use 5G-enabled irrigation controllers (China Mobile, 2023), developed in partnership with Huawei, allowing for fully automated, cloud-controlled water management. This technology has been particularly effective in the North China Plain, where over-extraction of groundwater has necessitated precision water-saving techniques (Du *et al.*, 2024). Globally, research is increasingly focused on integrating renewable energy sources into smart irrigation systems. The EU's Smart Water Grid Initiative has developed solar-powered irrigation controllers that function independently of traditional electricity grids, making them viable for deployment in off-grid agricultural zones. Additionally, AI-driven irrigation models are being refined to account for long-term climate variability, ensuring that irrigation infrastructure remains adaptive in the face of unpredictable weather patterns.

Smart Irrigation in Africa

The adoption of smart irrigation technologies across Africa varies widely, influenced by factors such as climate conditions, water availability, policy frameworks, and technological infrastructure. While North and Southern Africa have made significant strides in integrating AI-driven irrigation, IoT-based soil monitoring, and cloud-controlled water distribution, regions such as West, East, and Central Africa are still in the early stages of research and deployment. However, efforts by governments, research institutions, and agritech startups are gradually expanding the use of precision irrigation solutions.

North Africa faces acute water scarcity challenges, with high dependence on irrigated agriculture due to low rainfall and desert conditions (Altaeb, 2024). Egypt has made significant strides in smart irrigation as part of its national strategy to combat water scarcity and enhance agricultural productivity. The country's reliance on the Nile River for irrigation, coupled with increasing pressure on its water resources, has necessitated the modernization of its irrigation systems (Tawfik *et al.*, 2024). The Egyptian government has introduced IoT-driven irrigation management, AI-assisted water distribution, and automated irrigation networks to optimize water use, particularly in large-scale farming and urban green areas. One of the most notable smart irrigation projects in Egypt is the Madinaty Smart Irrigation System (SIS), a large-scale implementation of IoT-based irrigation technology in an urban setting. Located in northeast Cairo, Madinaty covers 32,000 hectares, with over 5.7 million square meters of green spaces requiring irrigation (Nassar *et al.*, 2023). To address these issues, the SCADA (Supervisory Control and Data Acquisition) system was deployed, integrating moisture sensors, microcontrollers, weather monitoring stations, and automated valves to control irrigation in real time. The Madinaty SIS uses field controllers and SCADA-based decision-making algorithms to determine plant water requirements based on soil temperature, moisture levels, wind speed, and solar radiation. These inputs are processed through a cloud-based data center, which adjusts irrigation schedules dynamically. The results have been highly effective, with water consumption reduced by 48% compared to manual irrigation systems. Additionally, solar-powered components have been integrated to reduce reliance on conventional energy sources, making the system both cost-effective and environmentally sustainable (Nassar *et al.*, 2023). Morocco has emerged as a leader in smart irrigation, driven by government policies, public-private partnerships (PPPs), and advanced water-saving technologies. Nearly 20% of its arable land is irrigated, with efforts focused on drip irrigation, AI-driven water distribution, and seawater desalination for agriculture. Morocco's Green Morocco Plan has focused on modernizing irrigation systems through AI-powered water distribution networks and GIS-based moisture mapping (Brahim *et al.*, 2024). In the Souss-Massa region, Morocco has pioneered the first large-scale seawater desalination plant for irrigation, providing drought-resistant water sources for 13,600 hectares of high-value crops such as citrus and vegetables. This PPP project, developed in collaboration with the private sector, integrates IoT-controlled irrigation scheduling to minimize water waste and optimize crop hydration. Additionally, the National Office for Health Security of Food Products (ONSSA) regulates irrigation water quality, ensuring compliance with food safety standards (Malabo Montpellier Panel, 2018).

West Africa, despite its vast arable land, faces low adoption rates of smart irrigation due to reliance on rain-fed farming, limited digital infrastructure, and high costs of automated systems. However, countries such as Nigeria, Ghana, and Senegal have begun integrating

sensor-based irrigation, AI-driven crop water modeling, and solar-powered precision irrigation systems into their agricultural sectors. Nigeria has been exploring sensor-based drip irrigation as a solution to improve water efficiency and crop productivity, particularly in semi-arid northern regions. A recent study at Bayero University, Kano, tested an automated tensiometer-controlled drip irrigation system for tomato production. The system, which triggers irrigation based on real-time soil moisture readings, demonstrated a 5% water savings and a 6% increase in water productivity compared to conventional drip irrigation (Ahmad and Shanono, 2022). The Transforming Irrigation Management in Nigeria (TRIMING) project, supported by the World Bank, is working to modernize irrigation schemes in Kaduna, Kano, and Sokoto states by integrating IoT-driven irrigation scheduling and cloud-based water distribution networks. Additionally, agritech startups such as Green eden farms Zenvus have developed AI-powered soil sensors that provide real-time irrigation recommendations via mobile apps, helping smallholder farmers optimize water use. Ghana has embraced solar-powered precision irrigation through initiatives such as the Ghana Climate Innovation Centre (GCIC), which supports startups developing IoT-based irrigation management solutions. Recent efforts have focused on solar photovoltaic (PV) irrigation to provide a cost-effective alternative to fossil fuel-powered pumps. The Ghana Irrigation Development Authority (GIDA) and private agritech firms have worked on suitability mapping for solar-powered irrigation, identifying areas where solar pumps can enhance smallholder irrigation efficiency. A study by the International Water Management Institute (IWMI) found that solar PV irrigation systems can significantly reduce operating costs, increase water use efficiency, and improve farmers' economic resilience, particularly in northern Ghana (Gebrezgabher *et al.*, 2021). Additionally, research at Kwame Nkrumah University of Science and Technology (KNUST) has developed automated drip irrigation systems powered by solar energy, ensuring year-round water availability for small-scale farmers.

East Africa is witnessing steady growth in smart irrigation adoption, driven by government-backed research, agritech startups, and donor-funded projects. Countries such as Kenya, Ethiopia, and Tanzania have introduced mobile-integrated irrigation solutions, AI-driven irrigation recommendations, and automated solar-powered irrigation networks to improve water use efficiency. Kenya has been making progress in smart irrigation through research, policy reforms, and private sector initiatives. The National Irrigation Board (NIB) has played a key role in expanding irrigation infrastructure, with government policies such as Vision 2030 and the Big Four Agenda emphasizing irrigation development for food security. One of the major projects under this agenda is the Galana Kulalu Food Security Project, which aims to increase maize production through large-scale irrigation and mechanized farming (Malabo Montpellier Panel, 2018). Technological advancements have also contributed to Kenya's smart irrigation efforts. Meru University of Science and Technology developed a sensor-based automatic irrigation system that uses soil moisture sensors and solar-powered pumps to automate irrigation. The system ensures efficient water use by triggering irrigation only when needed (Malabo Montpellier Panel, 2018). Additionally, research institutions such as Jomo Kenyatta University of Agriculture and Technology have introduced an IoT-driven communal irrigation system. This model uses soil moisture sensors to notify an irrigation administrator via mobile alerts when crops require watering. The administrator, equipped with a solar-

powered water pump mounted on a tricycle, delivers water to the fields, ensuring timely irrigation while minimizing waste (Maitethia *et al.*, 2022). Private sector initiatives have further expanded smart irrigation adoption. Companies like SunCulture provide solar-powered drip irrigation kits, enabling smallholder farmers to irrigate without relying on grid electricity or fossil fuels. Ethiopia has vast irrigation potential, with an estimated 5.3 million hectares of land suitable for irrigation. However, less than a quarter of this area is currently utilized, largely due to reliance on inefficient furrow and flood irrigation methods that lead to water wastage and soil degradation (Alemaw & Agegnehu, 2019). Recent efforts focus on data-driven solutions to optimize water use. The Coalition of the Willing (CoW) has been working to enhance digital agriculture through soil and agronomy data mapping, geospatial analysis, and national data-sharing initiatives (Tamene *et al.*, 2021). Additionally, remote sensing (RS) and geographic information systems (GIS) are being integrated to monitor soil moisture, assess crop health, and improve irrigation efficiency.

South Africa has significant irrigation potential, with approximately 1.3 million hectares under irrigation, accounting for 10% of cultivated land. Institutional support plays a key role in smart irrigation adoption. The Water Research Commission (WRC) leads research on efficient irrigation and water management, while the Agricultural Research Council (ARC) develops precision irrigation techniques and farmer training programs. Additionally, organizations like the South African Irrigation Institute (SABI) promote best practices in irrigation design and management (Malabo Montpellier Panel, 2018). The private sector has also driven innovation, with companies such as NETAFIM and Irritech introducing drip and micro-irrigation systems that optimize water use. The city of Cape Town's water restrictions during the 2018 drought demonstrated the importance of adaptive water management strategies.

Research Gaps in Smart Irrigation

Despite advancements in smart irrigation, several critical gaps hinder its widespread adoption in Africa. Data availability and digital infrastructure remain major challenges, as many rural areas lack reliable internet connectivity and real-time climate data, limiting the effectiveness of AI-driven irrigation models. Additionally, scalability in smallholder farming is difficult due to fragmented land ownership, low mechanization, and high costs of IoT-based systems, making it harder for small-scale farmers to benefit from precision irrigation technologies.

Another key barrier is the lack of financing for farmers, as high upfront costs and limited access to agricultural credit prevent widespread adoption of sensor-based and automated irrigation systems. Without government subsidies or private-sector investments, many farmers cannot afford modern irrigation technologies. Lastly, there is a significant gap in African-centered research on AI-driven irrigation, as most existing models are designed for large-scale, commercial farms in developed countries. Research tailored to Africa's diverse climatic zones, soil types, and farming practices is essential to developing cost-effective, adaptive smart irrigation solutions for the continent.

Adoption, Flexibility, and Sustainability of Smart Irrigation in Africa

The adoption of smart irrigation in Africa is influenced by cost, farmer awareness, government support, and private-sector investments. High initial costs limit accessibility for smallholder

farmers, while limited technical knowledge slows adoption (Durga *et al.*, 2024). Government policies, including subsidies and financial incentives, alongside private-sector partnerships, are crucial for scaling these technologies. Smart irrigation must be flexible and adaptable to Africa's diverse farming systems, particularly for smallholder farmers. Integrating indigenous water management practices with modern irrigation solutions and expanding solar-powered irrigation can enhance adoption, especially in off-grid rural areas (Bwambale *et al.*, 2022). For long-term sustainability, smart irrigation plays a key role in climate-smart agriculture, helping farmers adapt to unpredictable rainfall patterns and droughts. The economic and environmental benefits include higher crop yields, reduced water waste, and energy efficiency. Expanding regional and continental policy frameworks will be critical in making smart irrigation a widespread and sustainable solution for Africa's agricultural future.

Conclusion

Smart irrigation represents a critical advancement in sustainable water management, addressing key challenges in climate change adaptation, water conservation, and food security. By integrating real-time monitoring, AI-driven decision-making, and automation, these technologies enable efficient water use, improved crop yields, and reduced labor dependency. While developed countries lead in innovation, Africa is steadily adopting sensor-based, AI-powered, and solar-driven irrigation solutions, as seen in Egypt, Morocco, Nigeria, Ghana, and Kenya. However, high costs, technical barriers, and inadequate infrastructure remain obstacles to large-scale implementation. Overcoming these challenges requires strong policy support, increased investment, and knowledge transfer to ensure that smart irrigation technologies become accessible, scalable, and sustainable for African farmers. By fostering collaboration between governments, private enterprises, and research institutions, Africa can accelerate the adoption of climate-smart irrigation, securing a more resilient and productive agricultural future.

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