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Innovative Technologies for Improved Water Productivity and Climate Change Mitigation, Adaptation, and Resilience: A Review

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ABSTRACT: Water scarcity, exacerbated by climate change, poses severe challenges to agriculture, food security, and sustainable development, particularly in vulnerable regions. This study examines innovative technologies for improving water productivity and mitigating the impacts of climate change. Key technologies discussed include precision irrigation techniques such as micro-sprinklers and drip systems, smart water management solutions, and water recycling methods. These approaches enhance water efficiency, minimize waste, and strengthen resilience in agricultural systems. Case studies illustrate the successful adoption of these technologies, underscoring their role in addressing climate change impacts. Climate adaptation strategies, such as drought-resistant crop varieties, bio-based filtration systems, and low-energy desalination, are also explored. Despite their potential, barriers such as high implementation costs, limited technical expertise, and institutional inefficiencies constrain widespread adoption. The study concludes by emphasizing the need for increased investment in water-saving technologies, capacity building, public-private partnerships, and policy reforms to advance water security and climate resilience.

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Water is an indispensable resource for life, playing a vital role in sustaining ecosystems, supporting agriculture, and driving socioeconomic development. However, water availability and accessibility have become critical global challenges, exacerbated by the escalating impacts of climate change (Van Ginkel *et al.*, 2018; Joshua 2021). Agriculture, which accounts for approximately 70% of global freshwater withdrawals, is particularly vulnerable to these pressures. This reliance is even more pronounced in developing regions, where inefficient irrigation practices, erratic rainfall patterns, and rising temperatures further exacerbate the challenges of water productivity and food security while contributing to environmental degradation (Food and Agriculture Organization [FAO], 2022; World Bank, 2020). Climate change amplifies these challenges by altering precipitation patterns, increasing the frequency of extreme weather events, and disrupting critical water systems. These changes directly impact agricultural yields, ecosystem stability, and human survival (Annappa *et al.*, 2023; Intergovernmental Panel on Climate Change [IPCC], 2021). Addressing these issues necessitates comprehensive strategies for both mitigation—reducing greenhouse gas emissions from water-related activities—and adaptation—enhancing resilience to climatic uncertainties. Mitigation technologies, such as low-energy

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desalination, biofiltration systems, and renewable energy-powered water management, combined with adaptation solutions like drought-resistant crop varieties and precision irrigation, offer transformative potential to enhance water productivity and build resilience to climate variability (FAO, 2012; African Development Bank, 2022). Innovative water management technologies have emerged as a solution in addressing these interrelated challenges. Solutions such as precision agriculture, drip irrigation, remote sensing, and advanced water recycling methods offer promising avenues for optimizing water use, reducing waste, and building resilience against climate change (World Resources Institute [WRI], 2021; FAO, 2022). Moreover, these technologies align closely with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). However, despite global advancements, the adoption of these innovations in Africa—and particularly in Nigeria—remains uneven due to socio-economic, institutional, and technical barriers (African Development Bank, 2022). This paper review different innovative technologies that can improve water productivity while contributing to climate change mitigation, adaptation, and resilience. The objectives are threefold: first, to assess the current state of water challenges and climate impacts in the region; second, to evaluate the effectiveness and adaptability of existing technologies; and third, to provide actionable recommendations for integrating these innovations into sustainable development frameworks.

Global Water Challenges: Water resources are central to sustaining life and development, yet their availability and distribution remain starkly unequal across the globe. Regions such as Africa, South Asia, and the Middle East face acute water scarcity, while even water-rich regions are grappling with challenges of overextraction, pollution, and climate variability (Li and Wu, 2024). Globally, over 2 billion people lack access to safe drinking water, with the most affected populations residing in developing regions (WHO and UNICEF, 2021). Increasing demand due to population growth, urbanization, and agriculture, combined with inefficient water management practices, has strained water systems worldwide.

At a glance, Africa seems to possess plentiful water resources, including major rivers, expansive lakes, extensive wetlands, and scattered but significant groundwater reserves. These resources are primarily concentrated in the Central African sub-region and the island nations (African Union *et al*., 2000; Baker *et al*., 2018). Water scarcity is a defining challenge in Africa, where over 400 million people lack access to basic drinking water services (WHO and UNICEF, 2021). This problem is compounded by rising demand due to population growth, urbanization, and increasing agricultural needs. Furthermore, the continent's reliance on rainfall which fluctuates greatly across seasons and regions, intensifies water insecurity. With just 5% of farmland in Sub-Saharan Africa under irrigation, agriculture remains particularly susceptible to unpredictable rainfall and extended droughts (Mirash, 2023). Groundwater serves as a crucial safeguard against seasonal water shortages, but is frequently underutilized due to inadequate infrastructure. In urban areas, overexploitation contributes to the depletion of aquifer levels (MacDonald *et al*., 2012). The Intergovernmental Panel on Climate Change (IPCC) has noted that Africa is one of the regions most vulnerable to climate change, which significantly affects its water resources. Changes in precipitation patterns, rising temperatures, and increased evapotranspiration rates reduce water availability, particularly in arid and semi-arid regions such as the Sahel (IPCC, 2021). This has dire implications for water-dependent sectors, including agriculture, energy, and public health. Nigeria's water crisis mirrors the broader challenges faced across Africa, but is intensified by its large population and rapid urbanization. With a growing population exceeding 220 million, the country faces immense pressure on its water resources. Despite possessing substantial water resources, including rivers such as the Niger and Benue, and significant groundwater reserves, over 60 million Nigerians lack access to clean water (UNICEF, 2022). This disparity is most pronounced in rural areas, where less than 50% of households have access to basic drinking water services (Omole and Longe, 2008).

The MENA region is the most water-stressed globally, with approximately 83% of its population facing extremely high-water stress. Countries like Bahrain and Kuwait rely heavily on desalination due to limited freshwater resources (World Bank, 2007). Although South Asia is home to more than one quarter of the world's children, the region has only 4 per cent of the world's renewable water. Droughts are becoming more frequent and more severe, lasting longer in many South Asian countries because of climate change and increased water demand (UNICEF, 2021). Countries like India grapple with severe groundwater depletion due to over-extraction for agriculture and domestic use. The region's reliance on monsoon rains makes it susceptible to both floods and droughts, further complicating water management (WRI, 2021). Additionally, rapid urbanization and industrialization increase competition for limited water resources, leading to conflicts over water access (Food and Agriculture Organization [FAO], 2022).

Europe generally enjoys better access to freshwater resources; however, certain regions face challenges related to pollution and over-extraction. Southern Europe experiences significant water stress due to increased demand from agriculture during hot summers. Climate change impacts such as altered rainfall patterns are expected to exacerbate these issues (World Meteorological Organization [WMO], 2024).

Innovative Technologies for Water Productivity: Enhancing water productivity in agriculture is essential for combating water scarcity, securing food supplies, and strengthening climate resilience. Several innovative technologies have emerged, that can change water management practices, improving resource efficiency, minimizing waste, and fostering sustainable development. Among many, some are:

Micro sprinkler and drip irrigation tools: Micro-irrigation systems, particularly micro-sprinkler and drip irrigation are transformative tools for enhancing water productivity in agriculture. These systems are designed to deliver water directly to the plant's root zone, significantly reducing water wastage and improving resource efficiency. Micro-irrigation systems (MIS), particularly micro-sprinkler irrigation, have become increasingly significant in recent years due to the growing need for the efficient use of water resources (Suresh, 2019). Drip irrigation is important in sustainable agriculture for its precise delivery of water and nutrients to plant roots (Shemer *et al.,* 2023). When compared to other irrigation techniques, micro-irrigation may use less irrigation water. Less water is evaporated as a result of the smaller wetted area. There is virtually no surface drainage in these systems (Kumar *et al*., 2023). In India, the government has promoted drip irrigation through initiatives like the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), resulting in a 40–50% increase in water savings and higher yields in crops like sugarcane and cotton (Gandhi *et al.,* 2021).

Precision Agriculture: Precision farming or site-specific crop management is a concept based on sensing or observing and responding with management actions to spatial and temporal variability in crops (Monteiro *et al.,* 2021). Precision agriculture employs advanced technologies to monitor and manage water use efficiently at the field level, enhancing crop yields while reducing water wastage. Important advancements include moisture sensors for soil, automated irrigation systems, and data analytics tools. Field and crop sensors are used to deliver precise data on soil conditions, along with comprehensive details on climate, fertilizer needs, water supply, and pest issues (Monteiro *et al.,* 2021). Using electrodes, soil water content sensors, such as frequency domain reflectometry (FDR) and time domain reflectometry (TDR) sensors, measure the amount of water (by mass or volume) in a specific unit of soil. Changes in capacitance, which are impacted by the dielectric constant of the soil, are the basis for these measurements (Monteiro *et al.,* 2021). Good irrigation control reduces nutrient leaching, saves water and energy, and improves grain quality and crop yields. Utilizing soil sensor technology for measuring soil moisture and scheduling irrigation is one of the simplest and most impactful methods to improve irrigation efficiency. These sensors assess or estimate soil water levels, providing the foundation for implementing water-saving irrigation practices and refining agricultural techniques (Trivedi *et al.,* 2023). Sub-Saharan Africa, where outdated flood irrigation remains prevalent, could greatly benefit from these systems, especially when combined with weather forecasting models to allow for adaptive irrigation in times of drought. Data analytics tools further complement these technologies by analysing inputs from soil, weather, and crop health to provide actionable insights for maximizing water efficiency (Akhter and Sofi 2023). Platforms like CropX and Netafim, used in African countries, have successfully reduced water and fertilizer use while boosting productivity.

Smart Water Management Systems: Smart water management systems leverage cutting-edge technologies such as Geographic Information Systems (GIS) and remote sensing to monitor and optimize water resource distribution. Innovative technologies that integrate satellite data, meteorological forecasts, and advanced hydrological models are crucial for improving water productivity and addressing climate change challenges in agriculture (Akhter and Sofi 2023). IoT-based smart irrigation systems offer a solution by optimizing water use through real-time data from soil moisture sensors and weather forecasts. The system employs a machine learning algorithm to evaluate the inputs and deliver real-time irrigation suggestions. Tested on a pilot scale, it enhances water efficiency and provides autonomous control of irrigation, highlighting its promise for sustainable water use in agriculture (Corbari *et al.,* 2019). For Africa, and particularly Nigeria, adopting such precision irrigation systems can mitigate water scarcity, reduce agricultural vulnerability to climate extremes, and build resilience through more accurate water management, ensuring sustainable agricultural productivity in the face of climate change. However, despite the potential benefits, there are limited documented examples of large-scale implementation of smart water management systems in Nigeria. While some small-scale pilot projects may exist, the adoption of GIS, IoT-enabled irrigation, and real-time water management tools in Nigerian agriculture remains at an embryonic stage compared to countries like Ethiopia and Kenya. For instance, in Ethiopia, GIS mapping has significantly improved water access in rural areas by optimizing distribution networks (Abagissa *et al.,* 2024). Smart distribution systems, incorporating IoT-enabled sensors, are also gaining traction in urban areas. For example, Nairobi, Kenya, has piloted systems that monitor water pipelines in real time, reducing non-revenue water losses by up to 25% (Memeu *et al.,* 2022). Unfortunately, Nigeria has not yet fully tapped into these innovations, presenting both a gap and an opportunity for future development.

Water Recycling and Reuse: Water recycling and reuse involves collecting, treating, and repurposing wastewater, especially from municipalities, industries, and agriculture. Recycled water can be used for irrigation, industrial activities, and even domestic purposes if adequately treated. In some cases, treated wastewater is indirectly utilized for drinking by being injected into groundwater aquifers to enhance capacity and reduce saltwater intrusion. Water recycling and reuse play a crucial role in adapting to climate change, as increasingly erratic weather patterns, such as severe droughts and rising sea levels, are expected to negatively impact the quantity and quality of freshwater resources (UNEP, n.d.). Recycling and reusing water are crucial strategies for enhancing water productivity in regions facing water scarcity. Industrial facilities and municipal governments increasingly adopt wastewater treatment systems to recycle water for non-potable purposes, such as irrigation and industrial processes (Singh *et al*., 2023). A notable example is the Goreangab Water Reclamation Plant in Windhoek, Namibia, which recycles municipal wastewater into potable water, meeting over 25% of the city's needs (Du Pisani, 2006). In the Nile Valley, for instance, about 20 percent of the water is recycled in this way between the Aswan dam and the sea. The large-scale paddy systems of South-Eastern Asia follow very similar patterns of re-use. A good estimation of the rate of re-use is essential in gauging the effectiveness of water saving measures: efforts to increase water use efficiency by reducing distribution and on-farm losses may turn out to have marginal net impact when assessed at basin scale (FAO).While promising, scaling these systems in Africa faces challenges such as high infrastructure costs and public resistance.

Desalination Technologies: Desalination technologies provide an additional method to increase freshwater supplies, especially in coastal areas. Reverse osmosis (RO) systems are the most widely used desalination method, capable of converting seawater into potable water (Feria-Díaz *et al.*, 2021). Countries like Algeria and Morocco have invested in large-scale desalination plants, providing critical water supplies to urban populations However, desalination remains energy-intensive and costly, with electricity accounting for up to 40% of operating costs (Feitelson and Jones, 2014; Tigrine *et al.*, 2023). To address this, solar-powered desalination systems are emerging as a sustainable alternative. A pilot project in Kenya's Kilifi County has demonstrated the feasibility of using renewable energy to reduce the environmental footprint and operating costs of desalination (Leijon *et al*., 2020).

Rainwater harvesting techniques: Rainwater harvesting is the collection and storage of rainwater for various uses, including irrigation, domestic use, and groundwater recharge. It has emerged as a sustainable and cost-effective method for addressing water scarcity and enhancing water productivity, particularly in arid and semi-arid regions (Nandi and Gonela, 2022). There are various methods of rainwater harvesting, including surface runoff harvesting, underground tanks and percolation pits, rooftop rainwater harvesting (RRWH), check dams, and contour bunding. In response to challenges posed by climate change, such as erratic rainfall patterns, rainwater harvesting provides a dependable solution for alleviating the effects of water shortages. For instance, in Burkina Faso, the construction of small earth dams and ponds has improved water availability for livestock and irrigation in semi-arid regions (Barry *et al*., 2022). In India's Rajasthan state, check dams have revitalized groundwater tables and transformed once-barren lands into productive agricultural fields (Agoramoorthy *et al*., 2008). In Uganda, underground storage tanks have been introduced in water-stressed communities, providing a sustainable water source for agriculture and household use during dry periods (Baguma and Loiskandl, 2010).

Recession and flood management Agriculture: Flood recession agriculture (FRA)—an agricultural practice that relies on residual soil moisture and nutrients left by receding floodwaters—is widely practiced in river floodplains, lake margins, and other wetlands where water levels rise and fall predictably. For example, farmers along the floodplains of the White Volta River in northern Ghana engage in FRA under low-input, low-output conditions, making use of the nutrient-rich soils to cultivate crops (Balana *et al.*, 2019). In Nigeria, floodplain (fadama) agriculture is widely practiced, particularly in the semi-arid regions of the north, where farmers rely on the residual moisture from seasonal floods for cropping (Hegerty, 2018). This agricultural practice plays a crucial role in enhancing food security and supporting livelihoods, especially during the dry season when rain-fed farming is not possible. As the water recedes, these fertile, wetted soils offer high agricultural productivity, with crops being harvested before the seasonal rains return to inundate the area again (Everard, 2016). Flooding, while a natural phenomenon, has been increasingly exacerbated by climate change, causing widespread damage to farmlands, particularly in regions like sub-Saharan Africa and South Asia (Annappa *et al*., 2023). However, recession farming provides an opportunity for farmers to capitalize on the period following floods, cultivating crops in areas enriched by floodwaters before they are submerged once more.

Drought management techniques: Droughts is defined by extended periods of water scarcity, present a major challenge to agriculture by jeopardizing crop yields and global food security. Implementing effective drought management strategies is crucial for minimizing their impacts and strengthening the resilience of agricultural systems (Nairizi, n.d.). One of the most widely adopted methods for managing drought is mulching, a practice that involves covering the soil with organic or inorganic materials to reduce evaporation, improve soil moisture retention, and moderate soil temperatures. Organic mulches, such as straw, grass clippings, and leaves, not only conserve water but also enrich the soil with nutrients as they decompose. In drought-stricken regions of sub-Saharan Africa, farmers often use locally available organic materials for mulching, which helps sustain crop growth during periods of low rainfall (Demo and Bogale, 2024). In India, plastic mulching has been successfully employed in arid areas to significantly reduce water loss and maintain soil moisture, particularly in vegetable farming (Poonia and Parihar, 2020).

Polyculture is the practice of growing multiple crops together, is another effective strategy for managing drought. By diversifying crops within the same field, farmers can optimize water use and create microclimates that reduce the overall water demand of the system (Moreira *et al.,* 2024). Deep-rooted plants in polyculture systems help access water from deeper soil layers, while shallow-rooted crops utilize surface moisture. This complementary use of resources enhances overall water efficiency and increases the system's resilience to drought. For example, in the semi-arid regions of Ethiopia, intercropping maize with legumes has proven to improve yields while conserving soil moisture (Mekuria *et al*., 2023).

Recycling organic waste is another critical component of drought management, contributing to soil health and water retention. Composting agricultural and household organic waste generates nutrient-rich organic matter that improves soil structure and increases its water-holding capacity. This practice is particularly beneficial in arid and semi-arid regions, where soils are often degraded and have low organic matter content (Chatterjee *et al*., 2017). In Kenya’s drylands, projects promoting the use of compost have shown remarkable success in restoring soil fertility and improving water retention, enabling farmers to grow crops even in low-rainfall conditions (Kebenei and Mucheru-Muna, 2021). In addition, using biochar—a form of charcoal produced from organic waste—has gained attention as a soil amendment for its ability to retain water and nutrients, making it a valuable tool in drought-prone areas (Oni *et al.*, 2019).

Greenhouse and hydroponic agriculture: Greenhouse and hydroponic agriculture are transformative agricultural systems designed to address the growing challenges of food security, resource scarcity, and climate change. These innovative approaches optimize environmental control and resource use, ensuring sustainable agricultural production even in adverse conditions. Both systems have demonstrated remarkable potential in enhancing crop productivity, reducing water use, and minimizing environmental impacts (Santosh and Shukla, 2024; Naresh *et al*., 2024). In regions prone to extreme weather events, such as sub-Saharan Africa and the Middle East, greenhouses have enabled farmers to grow high-value crops like tomatoes, peppers, and cucumbers throughout the year (Shamshiri *et al*., 2018). Advanced technologies, such as automated climate control systems and integrated pest management, further enhance the efficiency of greenhouse operations (Santosh and Shukla, 2024).

Hydroponic agriculture, on the other hand, involves growing plants without soil, using nutrient-rich water solutions to deliver essential nutrients directly to plant roots. This system is particularly advantageous in arid regions where soil quality is poor or water resources are limited (Naresh *et al*., 2024). Hydroponics uses up to 90% less water than traditional soil-based farming, making it a viable solution for regions facing severe water scarcity. Crops grown hydroponically exhibit faster growth rates and higher yields due to the precise control of nutrient levels and environmental conditions (Rajaseger *et al*., 2023). Combining hydroponics with greenhouse technology, often referred to as controlled-environment agriculture (CEA), has further revolutionized food production (Santosh and Shukla, 2024).This synergy maximizes resource efficiency while minimizing the environmental footprint. For instance, vertical farming systems, which integrate hydroponics within multi-tiered greenhouse structures, are gaining popularity in urban areas. In the United Arab Emirates, vertical farms equipped with hydroponic systems have been instrumental in reducing the country's dependence on food imports while using significantly less water and land (Schnitzler, 2012; Abdelfatah and El-Arnaouty, 2023).

Deficit irrigation Techniques (Alternate Wetting and Drying irrigation in rice fields): Deficit irrigation techniques have emerged as a vital strategy to optimize water use in agriculture, especially in water-scarce regions. These methods intentionally apply less water than the crop's full requirement, focusing on sustaining yield while conserving water resources (Costa *et al*., 2007; Laita *et al*., 2024). Among these techniques, Alternate Wetting and Drying (AWD) irrigation is a proven and widely adopted approach in rice cultivation. This method, developed to address the high water consumption of rice fields, has demonstrated significant benefits in water savings, greenhouse gas reduction, and productivity (Haomiao *et al*., 2022).AWD involves alternately flooding and draining rice fields during specific stages of crop growth rather than maintaining continuous flooding. The fields are flooded only when soil moisture drops below a threshold, often indicated by the presence of cracks or by using simple water-level indicators like perforated pipes. This approach reduces water use by 15–30% compared to traditional methods, making it a highly effective solution for regions experiencing water scarcity (Martínez-Eixarch *et al.,* 2021).The adoption of AWD in Africa, particularly in regions like Senegal and Nigeria, has also shown promise. In Senegal's Senegal River Valley, farmers implementing AWD increased water productivity by 25%, enabling expanded cultivation areas with the same water resources (Krupnik *et al*., 2012; Djaman *et al*., 2015; Ume and Ume, 2024).

Soil and Agronomic management approaches to climate mitigation and adaptation: Soil and agronomic management practices play a critical role in addressing climate change by enhancing soil health, improving agricultural productivity, and reducing greenhouse gas emissions. These approaches aim to build resilient farming systems capable of mitigating climate impacts while adapting to changing environmental conditions. By focusing on techniques that improve soil structure, fertility, and carbon sequestration, farmers can ensure long-term sustainability and contribute to global climate goals (FAO, 2018; Tahat *et al*., 2020; Padhan and Jat, 2023) One key strategy is the adoption of conservation agriculture (CA), which emphasizes minimal soil disturbance, crop residue retention, and crop rotation. CA practices help maintain soil structure, reduce erosion, and enhance water infiltration. By minimizing tillage, CA also reduces carbon dioxide emissions from soil, contributing to climate mitigation. (FAO, 2018). Another effective approach is the application of organic amendments, such as compost, manure, and biochar, to improve soil fertility and sequester carbon. These amendments enrich the soil with organic matter, enhancing its ability to retain water and nutrients. Biochar, in particular, has gained attention for its dual benefits of long-term carbon storage and improved soil properties (Oni *et al*., 2019).

Agroforestry systems, which integrate trees and shrubs into agricultural landscapes, offer another sustainable solution. Trees act as carbon sinks, absorbing carbon dioxide from the atmosphere, while their roots improve soil structure and prevent erosion (Olaniyan *et al.,* 2024). Soil cover management is another crucial practice for climate adaptation. Techniques like mulching help maintain soil moisture, reduce temperature fluctuations, and suppress weed growth. In India, rice farmers using straw mulch experienced a 20% reduction in water usage and improved soil organic matter content, which enhanced resilience to heat stress (Demo and Bogale, 2024). Cover cropping, where crops like legumes or grasses are planted during fallow periods, also protects soil from erosion and adds nitrogen, promoting sustainable nutrient cycling (Koudahe *et al*., 2022). Soil water management techniques, such as contour farming and terracing, are particularly valuable in areas prone to erosion and water runoff. These methods conserve soil moisture, prevent land degradation, and ensure that water is efficiently used (Trivedi and Nandeha, 2024).

Case Studies from around the world: In addressing the pressing challenges of climate change, countries around the world have implemented a wide array of mitigation and adaptation strategies, which have demonstrated varying degrees of success. Climate change mitigation involves efforts to reduce or prevent the emission of greenhouse gases, while adaptation focuses on adjusting practices, systems, and infrastructure to minimize the negative impacts of climate change. Ethiopia has made notable progress in implementing community-based adaptation strategies to address climate change. The country has faced frequent droughts, which have led to decreased agricultural productivity and food insecurity, prompting rural-urban migration (Okesanya *et al.,* 2024). Technologies like Wetting Front Detectors (WFD) and Chameleon sensors were introduced to guide irrigation practices on wheat farms during the irrigation season. The project also evaluated the impact of these tools on water use, crop yields, and fertilizer efficiency, with promising results for improving water productivity in wheat cultivation. (FAO and IWMI 2021). The government has emphasized irrigation in its Growth and Transformation Plan (GTP II) and National Agricultural Investment Plan (NAIP), aiming to extend irrigation to 4.1 million hectares for small-scale and 954,000 hectares for medium- and large-scale schemes by 2020, leveraging renewable energy sources. Initiatives such as the Climate Resilient Green Economy (CRGE) strategy and the Participatory Small-Scale Irrigation Development Programme (PASIDP) demonstrate Ethiopia's commitment to sustainable water management and climate adaptation (Malabo Montpellier Panel 2024). Rainwater harvesting, a traditional practice in Namibia, has been enhanced with modern technologies like plastic tanks and barrels to supplement household water supplies and combat water scarcity exacerbated by climate change. By integrating these innovative water solutions with indigenous methods, African nations are proactively addressing the impacts of climate change on water resources, promoting greater efficiency and sustainability in agriculture and water management (Okesanya *et al.,* 2024). Kenya is a leader in the adoption of renewable energy in Africa, with innovative solutions such as the use of off-grid solar systems in rural areas. The introduction of solar-powered water pumps has revolutionized agriculture in arid regions, allowing farmers to irrigate their crops even in the absence of reliable rainfall. This technology has led to an increase in agricultural productivity and improved food security (Leijon *et al*., 2020). Kenya has embraced innovative water technologies to boost agricultural productivity, particularly in irrigation. Solar-powered systems like SunCulture's AgroSolar kits combine efficient drip irrigation with renewable energy, enabling smallholder farmers to increase yields by over 300% and save substantial costs compared to traditional methods. Similarly, Meru University's sensor-based automatic irrigation app leverages soil moisture sensors and solar-powered controls to optimize water usage, though its upfront cost limits widespread adoption (Malabo Montpellier Panel 2024). A project in Tanzania explored the feasibility of introducing simple soil sensor technology to improve irrigation efficiency for smallholder farmers. The technology, costing an estimated $50–100, includes a sensor, LED lamp for irrigation alerts, and cloud-based real-time data analysis. Targeting crops like tobacco, highland rice, and maize, the sensors demonstrated potential to enhance water use efficiency, reduce costs, and increase yields. However, challenges such as farmers' reliance on traditional practices, upfront costs, and limited rural connectivity were identified. Addressing these barriers through training, financial support, and improved infrastructure could enable widespread adoption and bolster climate-resilient agriculture in Tanzania (Malabo Montpellier Panel 2024).

Morocco has leveraged advanced water technologies to combat climate change and enhance agricultural resilience. Key among these is the adoption of drip irrigation under the National Program for Irrigation Water Saving (PNEEI) and the Plan Maroc Vert, which modernized traditional systems to significantly reduce water losses. Subsidies of up to 80–100% have enabled smallholder farmers to adopt these efficient systems, expanding the area equipped with drip irrigation from 108,400 hectares in 2000 to over 450,000 hectares by 2014, with a target of 550,000 hectares by 2020 (Malabo Montpellier Panel 2024). Innovative solutions like desalination for irrigation have also been implemented, notably in the Chtouka region, where a PPP project provides irrigation water for 13,600 hectares, reducing dependence on freshwater resources (Malabo Montpellier Panel 2024). The Regional Offices of Agricultural Development (ORMVA) utilize computer-assisted tools to manage irrigation systems, ensuring efficient water use and improved maintenance.

Australia has implemented several innovative practices to address water scarcity in agriculture, including the use of biochar. Biochar, a form of charcoal made from organic material, is being integrated into soil management practices to improve water retention and soil fertility. This practice has been particularly useful in Australia's arid regions, where the challenge of maintaining soil moisture is critical for crop survival (McHenry, 2009). The

Australian government, along with research institutions, has supported biochar projects that enhance water retention in sandy soils, which are prevalent in many parts of the country. Research has shown that biochar can increase the water-holding capacity of soil by up to 20%, making it a crucial tool for improving water productivity in drought-prone areas (McHenry, 2009; Singh *et al.*, 2014).

In Northern China, where water scarcity is a significant issue, advanced irrigation technologies such as sprinkler and drip irrigation have been promoted as part of national water conservation projects. The government's "Water Saving Irrigation Project" aims to reduce water consumption by using efficient irrigation systems, coupled with soil moisture sensors, to optimize water use for crops like wheat and corn (Cremades *et al.*, 2015; Zhang *et al.*, 2019). The implementation of these water-efficient irrigation techniques has increased water productivity by over 30% in dryland regions. Farmers have also adopted practices like water-saving mulching to reduce evaporation. The success of these technologies in reducing water wastage and enhancing crop yields has been evident in provinces like Shandong and Hebei, where water resources are particularly limited (Li *et al.*, 2020).

In the United States, the use of precision irrigation systems, particularly in arid regions like California, has made significant strides in improving water productivity. The adoption of drip irrigation and the use of soil moisture sensors have enabled farmers to use water more efficiently by ensuring that irrigation is applied only when needed (Mushtaq *et al.*, 2024). Special projects, such as the California Water Efficiency Program, support farmers in upgrading their irrigation systems to conserve water while maintaining high yields (Morales, 2023). The integration of real-time data through Internet of Things (IoT) sensors has allowed farmers to track soil moisture levels and adjust irrigation schedules accordingly.

In Nigeria, integrated soil fertility management (ISFM) has been an essential approach for enhancing agricultural productivity, especially under the stress of climate change. This approach combines organic inputs (like manure) and inorganic fertilizers, improving the soil's nutrient content while enhancing its water retention capacity. This is particularly vital for smallholder farmers who face water scarcity issues (Ande *et al.*, 2017; Nafiu, 2019). A special initiative by the International Institute of Tropical Agriculture (IITA) focuses on promoting ISFM practices to boost water productivity in maize cultivation. By improving soil structure and water retention, ISFM helps mitigate the impact of water shortages on crop yields (Vanlauwe *et al.*, 2006). According to Vanlauwe *et al.* (2006), this practice has led to a 25% increase in maize yield, with soil amendments allowing better moisture retention and reducing the need for frequent irrigation.

Climate Change Mitigation and Adaptation Strategies: Technological advancements play a critical role in reducing water-related greenhouse gas (GHG) emissions(UNFCCC n.d). Low-energy desalination technologies, such as reverse osmosis (RO) systems powered by renewable energy sources like solar and wind, have emerged as vital solutions for minimizing carbon footprints in regions that rely on desalinated water (Feitelson and Jones 2014). Conventional desalination techniques consume a lot of energy and increase GHG emissions. However, advancements in energy-efficient methods, like solar desalination and membrane distillation, have greatly lowered energy use, reducing their environmental impact. Similarly, bio-based filtration systems, which utilize natural materials like algae, reeds, and aquatic plants, have shown great promise in wastewater treatment and water purification (Li *et al.*, 2022). These systems offer an eco-friendly alternative to chemical filtration processes and can help reduce emissions associated with the industrial treatment of water. These technologies also support a circular economy by allowing the reuse of water and minimizing waste. Reforestation and wetland restoration are powerful natural solutions for enhancing carbon sequestration, a critical component in mitigating climate change (Prajapati *et al.*, 2023) Forests and wetlands absorb carbon dioxide, reducing the overall concentration of greenhouse gases in the atmosphere. Reforestation projects, such as the Great Green Wall in Africa, aim to restore degraded lands and sequester significant amounts of carbon while also improving local water cycles and biodiversity (African Forest Forum. 2022).

Technological innovations in agriculture, particularly the development of drought-tolerant crops, are crucial for adapting to climate variability. Crops engineered to withstand water scarcity are less dependent on rainfall and can thrive in arid conditions. These crops often have deeper root systems, reduced transpiration rates, and improved water-use efficiency (Paul, Nuccio, & Basu, 2018). Water harvesting systems, such as rainwater harvesting (RWH) and runoff collection techniques, are increasingly being adopted to mitigate water shortages In urban and rural settings alike, these systems capture rainwater for storage and subsequent use in irrigation, drinking, and sanitation. Technologies such as rooftop rainwater harvesting systems and percolation ponds allow communities to collect water during rainy periods for use in dry spells, thereby increasing their resilience to varying precipitation patterns. (Rao *et al*., 2024).

One of the most promising technological adaptations for water management is smart irrigation systems, which use advanced sensors and real-time data to optimize water use in agriculture. These systems combine weather forecasts, soil moisture sensors, and plant data to precisely determine when and how much water is needed, ensuring that crops receive adequate water while minimizing waste (Trivedi *et al.*, 2023). This precision irrigation technology significantly reduces water usage, increases water-use efficiency, and boosts crop yields in water-scarce regions. Drip irrigation and sprinkler systems powered by smart technology are widely used to deliver water directly to the roots of plants, thus reducing evaporation and runoff(Akhter & Sofi 2023).The integration of soil moisture sensors and climate sensors into irrigation systems allows farmers to monitor soil health and adjust watering schedules accordingly. For example, sensors that measure moisture levels at various soil depths enable farmers to irrigate based on the real-time water needs of crops rather than relying on predetermined schedules. These smart systems are often linked to mobile apps, providing farmers with easy access to data and remote control over their irrigation systems, even in remote locations. Early warning systems for water-related disasters, including floods, droughts, and storms, are essential for reducing the effects of climate change. These systems use meteorological data, satellite imagery, and climate modelling to predict extreme weather events and issue alerts in advance (Girotto *et al*. 2024).

Challenges in Implementing Innovative Technologies: In many developing countries, several challenges hinder the widespread adoption of innovative water management technologies. Limited access to advanced technology and infrastructure remains a significant barrier. High import costs and the need for maintenance of sophisticated systems like smart irrigation or water filtration devices, coupled with unreliable electricity supply, make these technologies difficult to implement. Additionally, a lack of technical skills to operate and maintain such systems further slows their uptake. For many smallholder farmers, particularly in rural regions, there is a lack of awareness and trust in new technologies, which often causes hesitation to adopt them. The persistence of traditional farming practices, deeply ingrained in local communities, contributes to resistance against change. Cultural factors, including reluctance to deviate from established agricultural methods, also impede the acceptance of modern solutions, even when these have the potential to improve water efficiency.Institutional weaknesses exacerbate these challenges, as poor coordination between government bodies, NGOs, and the private sector hinders the effective implementation of water management technologies. Although there are government initiatives aimed at promoting sustainable practices, bureaucratic inefficiencies, insufficient funding, and lack of clear policies often delay or limit the success of large-scale projects. Moreover, without adequate training and capacity-building efforts for local stakeholders, the long-term success and sustainability of these technologies are at risk.

Conclusion: Effective water resource management is essential for ensuring food security, sustaining ecosystems, and mitigating climate change impacts. Innovative technologies such as smart irrigation, water recycling, and renewable-energy-powered desalination hold immense potential to enhance water productivity and resilience to climate variability. However, widespread adoption is hindered by barriers like high costs, limited technical expertise, and weak institutional frameworks. Addressing these challenges requires increased investment, capacity building, and strengthened public-private partnerships. Policymakers should provide financial incentives for water-efficient technologies, promote research on climate-resilient innovations, and establish robust institutional frameworks to enforce water management policies. Training programs should empower farmers and practitioners with the skills to implement modern irrigation and conservation techniques. With the right policies, investments, and collaborations, sustainable water management practices can secure a resilient, water-efficient future, contributing significantly to climate change mitigation and adaptation efforts.

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