

CLIMATE-SMART IRRIGATION TECHNOLOGIES FOR A RESILIENT AND SUSTAINABLE AGRICULTURE

TECHNOLOGIES D'IRRIGATION INTELLIGENTES FACE AU CLIMAT POUR UNE AGRICULTURE RÉSILIENTE ET DURABLE

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ABSTRACT

Water scarcity ranks among humanity's greatest challenges, alongside land degradation and food insecurity. Resource insecurity is exacerbated by climate change, rising demands from competing sectors, and a growing population. To address the interconnected challenges of water scarcity, land degradation, and food insecurity, agriculture must adapt to change and adopt sustainable and innovative practices that enhance crop-water productivity, improve efficiency, and minimise environmental impact. This study applied a mixed-methods approach to identify and discuss novel irrigation technologies that optimise food production without increasing the amount of water applied and with positive environmental spinoffs. Identified strategies include investing in water-efficient technologies, mainstreaming climate-resilient underutilised indigenous crops, adopting soil health practices such as crop rotation, and supporting smallholder farmers with training on modern smart technologies. As part of the digital transformation in irrigation, the study highlights innovative technologies and practices that enhance resilience and adaptation, support on-farm irrigation scheduling, improve yields, and are tailored to specific crops, including indigenous underutilised crops. These user-friendly applications are crucial for crop cultivation, as the water requirements for most crops are now thoroughly documented. Digital tools are combining real-time soil data, meteorological forecasts, and crop-specific coefficients to optimise water use, often reducing consumption while enhancing crop health.

Keywords: Irrigation digital transformation; crop-water productivity; irrigated agriculture; water-use efficiency; climate-smart agriculture; sustainable food systems.

RÉSUMÉ

La pénurie d'eau figure parmi les plus grands défis de l'humanité, aux côtés de la dégradation des terres et de l'insécurité alimentaire. L'insécurité des ressources est aggravée par le changement climatique, l'augmentation de la demande des secteurs concurrents et la croissance démographique. Pour relever les défis interdépendants de la pénurie d'eau, de la dégradation des terres et de l'insécurité alimentaire, l'agriculture doit s'adapter au changement et adopter des pratiques durables et innovantes qui accroissent la productivité de l'eau agricole, améliorent l'efficacité et réduisent au minimum l'impact environnemental. Cette étude a appliqué une approche mixte afin de recenser et d'examiner de nouvelles technologies d'irrigation qui optimisent la production alimentaire sans

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augmenter la quantité d'eau apportée et qui génèrent des retombées environnementales positives. Les stratégies recensées comprennent l'investissement dans des technologies économes en eau, l'intégration systématique de cultures autochtones sous-utilisées et résilientes au climat, l'adoption de pratiques favorables à la santé des sols, telles que la rotation des cultures, et le soutien aux petits exploitants par une formation aux technologies intelligentes modernes. Dans le cadre de la transformation numérique de l'irrigation, l'étude met en avant des technologies et des pratiques innovantes qui renforcent la résilience et l'adaptation, facilitent la programmation de l'irrigation à l'échelle de l'exploitation, améliorent les rendements et sont adaptées à des cultures précises, notamment aux cultures autochtones sous-utilisées. Ces applications conviviales sont essentielles à la conduite des cultures, car les besoins en eau de la plupart d'entre elles sont désormais documentés de manière approfondie. Les outils numériques combinent des données pédologiques en temps réel, des prévisions météorologiques et des coefficients propres à chaque culture afin d'optimiser l'utilisation de l'eau, réduisant souvent la consommation tout en améliorant l'état sanitaire des cultures.

Mots clés : Transformation numérique de l'irrigation; Productivité de l'eau agricole; Agriculture irriguée; Efficacité de l'utilisation de l'eau; Agriculture intelligente face au climat; Systèmes d'alimentation durable.

1. INTRODUCTION

Over 60% of South Africa's available freshwater resources are used in agriculture, covering approximately 1.3 million hectares of irrigated land (StatsSA, 2019). The demand for irrigation water is expected to increase as the country plans to expand its irrigated area by over 45,000 hectares by 2030 to meet the rising food requirements of its increasing population (NDP, 2013). This is happening at a time when nearly 98% of the country's available freshwater resources are already allocated, leaving little room for economic growth. Projections suggest that agricultural productivity in South Africa will need to double from current levels by 2050 to feed a population estimated to increase to about 80 million people in the same period (Ngepah et al., 2022). However, climate change and limited energy resources compound these challenges, as rising temperatures increase the evapotranspiration rates. The country experiences highly variable annual rainfall ranging from 460 mm to 840 mm (McBride et al., 2022). Additionally, climate change is increasing rainfall variability, resulting in more frequent and intense droughts and floods (Ndlovu et al., 2021). Therefore, transforming water management in agriculture has become an urgent priority as water resources are fully or over-allocated and increasingly degrading and depleting.

South Africa's efforts to ensure water and food security are clearly outlined in the National Development Plan (NDP), where agriculture is recognised as a key pillar for driving economic growth (NDP, 2013). The NDP recognises that a transformed agricultural sector is essential for enhancing water and food security and creating employment opportunities. Agriculture plays a significant role in the country by contributing approximately 3% to the national gross domestic product (GDP) and 7% of formal employment (Jonck & Mabaso, 2025). The NDP aims to stimulate economic growth through agriculture by expanding the irrigated areas and creating jobs. It emphasises the importance of supporting smallholder farmers and reducing their vulnerability to climate change.

Addressing the interconnected challenges of water scarcity, land degradation, and food insecurity requires that agriculture adopt sustainable and innovative practices that enhance crop-water productivity, improve efficiency, and minimise environmental impact. Key strategies include investing in water-efficient irrigation, mainstreaming climate-resilient underutilised indigenous crops, adopting soil health practices such as crop rotation, and supporting smallholder farmers with training on modern smart technologies (Nhamo et al., 2023). This requires resilience-based interventions that are multidisciplinary and inherently interdisciplinary, involving specialist fields such as engineering, hydrology, climatology, and geology, which should also address institutional, policy, and management issues (Annapareddy et al., 2026). Ignoring these specialist areas in interventions yields only partial solutions and sectoral efficiencies at the expense of other equally important sectors (Nhamo et al., 2025).

Climate-smart agriculture offers numerous benefits, including addressing climate change while systematically considering the synergies and trade-offs between productivity, adaptation, and mitigation (Begna & Wakweya, 2025). It offers a holistic, context-specific approach to ensure food security while managing trade-offs between productivity, adaptation, and mitigation to protect livelihoods (Nhamo, Mpandeli, Liphadzi, Dirwai, et al., 2024). Innovative technologies are essential for enhancing water and food security, both at the off-farm level—such as water transport infrastructure and irrigation system distribution—and at the on-farm level, including efficient water application methods and advanced irrigation technologies (Mabhaudhi et al., 2018).

Specifically, improved irrigation techniques promote irrigation sustainability and optimise water resources management on farms (Nhamo et al., 2023). Despite acknowledging the significance of these innovative technologies for sustainable irrigation, their adoption has been notably slow, revealing the gap between scientific advancements, policy formulation, and practical implementation. Recognising these dynamics underscores the importance of adopting transformative, comprehensive strategies for irrigation development. (Mpandeli et al., 2019). This study, therefore, discusses novel irrigation technologies developed by the Water Research Commission (WRC) that optimise food production without increasing the amount of water applied and with positive environmental benefits, as part of the digital transformation in irrigation.

2. METHODS

The study provides an overview of key innovative technologies that optimise food production without increasing the amount of water applied and with positive environmental spinoffs. These technologies are centred on precision agriculture, smart irrigation, and controlled-environment agriculture, allowing for sustainable intensification, increasing yields per unit of land and water rather than expanding agricultural footprint. The study examines technologies that improve agricultural adaptation and resilience to adverse climatic extremes.

The mixed-methods approach used in the study included interviews with key stakeholders such as farmers, long-term on-field observations, and a review of some technologies developed by the Water Research Commission (WRC) of South Africa and its partners. Smart-irrigation technologies are significantly reducing the water footprint and virtual water content, particularly in the high-export fruit crop cultivation sub-sector (Thilakarathne et al., 2025). South Africa is a leading exporter of high-value fruit crops, including pears, grapes, apples, macadamia nuts, avocados, and cherries (Chisoro & Roberts, 2024). Innovative technologies, also known as Agriculture 4.0, are facilitating the shift of irrigated agriculture from static, wasteful irrigation to dynamic, demand-based systems, enabling growers to "produce more with less."

The innovations include smart water management, a component of the digital transformation that applies information and communication technology (ICT) and (near) real-time data and responses to measure, control, and distribute agricultural water to save water and energy (Nhamo, Mpandeli, Liphadzi, Hlophe-Ginindza, et al., 2024). Fig. 1 presents interrelated strategic technological pathways for sustainable water management that are improving crop-water productivity. The digital interventions are easing water scarcity in the country by regulating water for food production and domestic use, among other uses. These interventions are implemented on a small scale, managed locally, and are hydrologically independent and self-regulating. This approach is transforming rural livelihoods and enhancing adaptation and resilience to climate change (Nhamo et al., 2023).

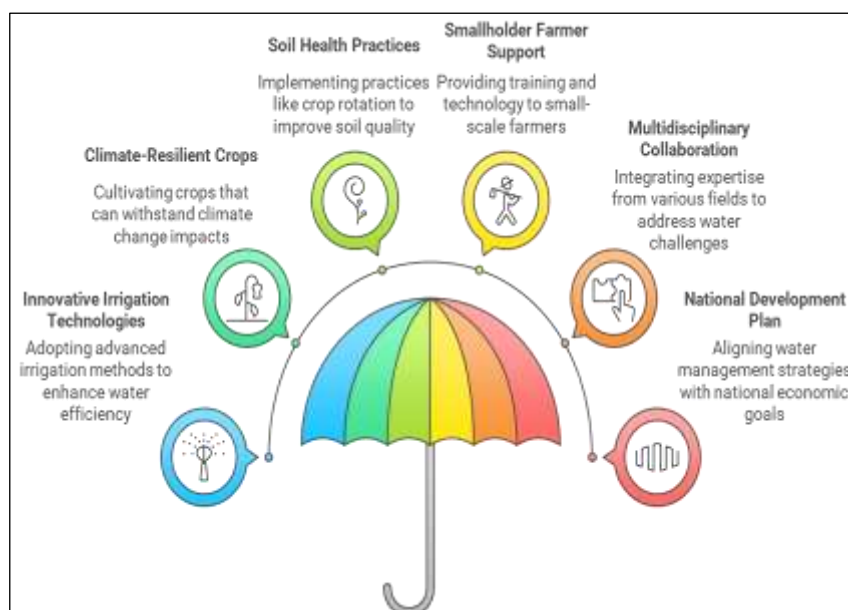


Fig. 1. Strategic pathways towards a sustainable water management

3. RESULTS AND DISCUSSION

A tool estimating crop evapotranspiration, yield, and water-use efficiency for small grains and underutilised indigenous crops such as soybean and sorghum in each quinary catchment is improving grain productivity in smallholder farming areas and irrigation schemes (Kunz et al., 2020). This tool is benefiting mostly rural farming communities by guiding best agronomic practices to maximise attainable yields. Additionally, another operational model, the OPERA, is increasing water-use efficiency and resilience of the irrigation sector, both at the smallholder and commercial sectors (De Clercq & de Witt, 2019). The OPERA enables the direct mapping of soil water requirements—similar to in-situ observations—using air- or space-borne radar. It also assesses crop water stress through thermal infrared sensors and models the interactions between crops, soil, and the atmosphere. When effectively combined with terrestrial measurements, these mapping tools provide valuable decision support for enhanced agricultural water management. Fig. 2 is a map showing the Flag Boshieho Irrigation Scheme, a thriving irrigation scheme in South Africa where some of these technologies are being successfully applied.

To address the challenges of salinity, a decision support system (DSS) and guidelines for transferring technology to manage irrigation-induced salinity effectively through precision agriculture were developed (Barnard et al., 2020). A related tool on an integrated bioeconomic model was developed to manage site-specific water and salt stress in irrigated agriculture (Matthews et al., 2022). This is achieved by linking the transient state of the soil-water-crop model (SWAMP) to an economic model and an optimisation process, enabling the assessment of site-specific water and salinity management strategies.

As part of the digital transformation in irrigation, smartphone applications have been developed to support on-farm irrigation scheduling (Dzikiti et al., 2020). These web-based and mobile applications are tailored to specific crops, including indigenous underutilised crops. Comprehensive guidelines for using these apps provide step-by-step instructions for farmers. These user-friendly irrigation applications are important in crop cultivation as water requirements for most crops are now well documented. For example, one such smartphone application forecasts water needs in apple orchards several days in advance, using readily available data as inputs. This orchard water-use app enhances irrigation scheduling and water allocation by offering detailed forecasts of actual orchard

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A project prototyped in the Inkomati-Usuthu Water Management Area (IUWMA) developed a tool for conjunctive groundwater and surface water use in solar-driven smallholder irrigated agriculture (Dzikiti et al., 2024). The tool supports conjunctive water use in areas suited for implementing solar pumps in smallholder irrigated agriculture in South Africa. The developed tool won the WatSave Award, Kuala Lumpur, Malaysia. Drone-related applications in agriculture are enhancing water management, specifically exploring how drones can enhance smart water management and precision agriculture on smallholder farms. Drone applications have produced valuable tools and models for real-time crop health monitoring, yield forecasting, and irrigation scheduling. Fig. 3 presents some of the innovative agricultural smart technologies that are transforming agricultural water management and optimising crop-water productivity, as part of the resilience of the agriculture sector.

- Increased productivity: Irrigated agriculture is producing (a) more food using fewer resources and (b) higher-quality food to enhance nutritional security and increase incomes.
- Enhanced resilience: Improved efficiencies in irrigated agriculture are reducing vulnerability to drought, pests, and diseases. It is strengthening the ability to produce sufficient food during prolonged drought and shorter growing seasons.

Reduced emissions: Innovative irrigation practices are leading to lower greenhouse gas emissions for each calorie or kilogram of food produced, as deforestation is reduced, and carbon sequestration is enhanced.

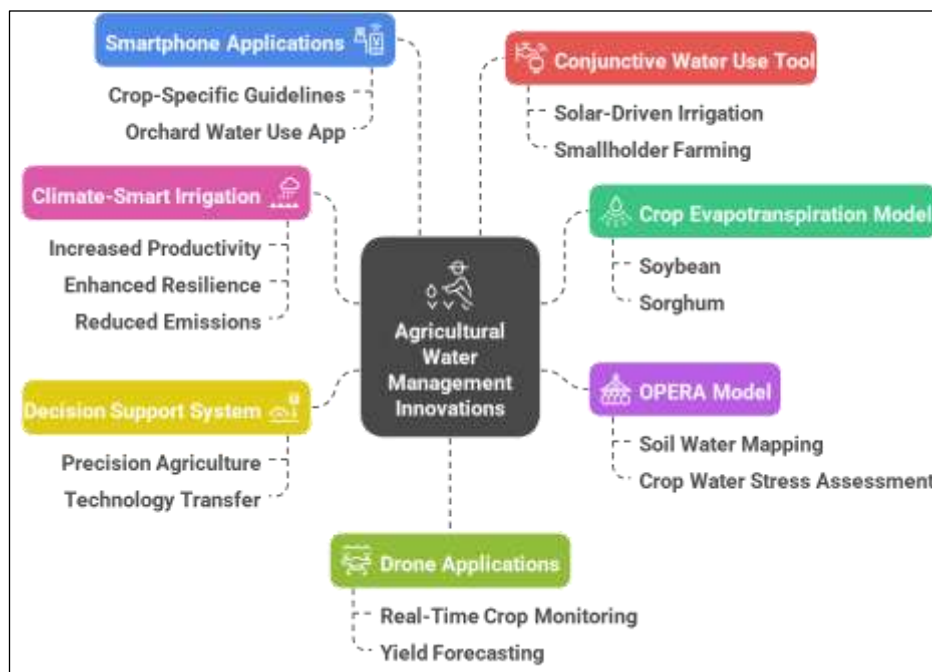


Fig. 3. Smart-irrigation technologies transforming the irrigation sector

3.1. Potential environmental impacts of irrigation development

However, besides the many benefits of irrigation and its sustainable expansion, many trade-offs accompany its development, including increased soil degradation and erosion; pollution of both surface and groundwater; degradation of water quality; increased eutrophication due to high nutrient levels in the irrigation and drainage water, resulting in algal blooms in irrigation canals and downstream waterways (Malakar et al., 2019). Irrigation projects that impound or divert river water may cause environmental disturbances and pose health risks due to hydrology and limnology changes in river basins (Kibret et al., 2021). Alterations in river flow regimes can potentially result in saltwater intrusion in river systems and into the groundwater of nearby agricultural lands (Richter & Thomas, 2007). If not well-planned, river diversion to irrigated lands reduces the water supply for downstream users. Some of the environmental impacts and possible solutions are shown in Table 1.

Table 1. Environmental impacts of irrigation development and practical solutions

Environmental impacts	Mitigatory solutions
Waterlogging and salinization	Situating irrigated lands where negative impacts are minimal
Changes and alterations to ecosystem services	Restoring degraded irrigated lands rather than establishing new ones
Water-borne and water-related diseases	Improving the efficiency of existing irrigation schemes
Destruction of natural habitats	Recycle wastewater for use in irrigation.

3.2. Role of irrigation technologies in improving crop-water productivity

Agriculture 4.0 smart technologies are optimising food production without increasing the water applied, while simultaneously providing positive environmental benefits (Nhamo et al., 2023). They are centred on precision agriculture, smart irrigation, and controlled-environment agriculture (CEA), as they allow for sustainable intensification, increasing yields per unit of land and water rather than expanding agricultural footprints. Smart irrigation systems that use Internet of Things (IoT) sensors and Artificial Intelligence (AI) are optimising water application by delivering it precisely to the roots, cutting water use by 40–60% (Obaideen et al., 2022). Table 2 showcases the key technologies and how they are transforming irrigated agriculture, whilst protecting the environment.

However, the role of smart technologies in reducing the water footprint and virtual water content in agriculture cannot be overemphasised, particularly within high-export fruit crop cultivation in South Africa, a sector with the resources to adapt. The shift toward smart farming solutions in South Africa is strengthening the sustainable, high-value agricultural export sector while simultaneously redefining water management (Nhamo et al., 2023).

Table 2. Technological innovations and their environmental and water use efficiency benefits

Irrigation technology	Water-use efficiency and environmental protection
Variable-rate irrigation (VRI)	Sensors and data analytics tailor water application to specific zones of a field, reducing waste from over-irrigation
Drip irrigation in crops	Shifting from traditional flooding to drip irrigation conserves up to 70% of water.
Soil moisture sensors and automation	Real-time data from capacitive probes/tensiometers allows AI algorithms to adjust water delivery based on root-zone needs.
Hydroponics and aeroponics:	The growing of crops in nutrient-rich water solutions without soil conserves water reduces water applied by between 90–95% as compared with conventional farming.
Vertical farming	This technology produces 10–20 times more crops per square meter with 95% less water and land, suitable for urban food security.
Drones and UAVs	Multispectral cameras detect water stress, pests, and deficiencies, enabling targeted interventions rather than blanket spraying.
Conservation tillage and mulching	These techniques minimise soil disturbance and use organic mulch to improve soil structure, enhance water retention, and decrease evaporation.

These technologies improve the productivity of lucrative citrus meant for the export market, such as table grapes and macadamia nuts, contributing significantly to foreign exchange earnings. These interventions enhance sustainability by optimising water marketing, reducing agricultural water consumption per unit of yield, and improving efficiency in mitigating water scarcity in arid regions. The future of South African high-value agriculture lies in optimising resource efficiency (water) to ensure the viability of exports, with smart solutions acting as a critical enabler of this transition. Adopting and implementing these smart technologies translates into water savings in irrigated agriculture (Dzikiti et al., 2020), as shown in Table 3.

Table 3. Technological benefits in irrigated agriculture

Technology	Resource Saved	Efficiency Gain	Environmental and spinoff
Vertical Farming	95-98% Water/Land	10–20× higher yield	Prevents deforestation
Drip Irrigation	40-60% Water	High water use efficiency	Reduces groundwater depletion
AI-Driven Weed Control	90% Herbicides	95% accuracy in weed detection	Protects soil microbiomes
IoT/Smart Sensors	20-30% Water	Real-time monitoring	Reduces nutrient runoff

4. RECOMMENDATIONS

- While these technologies are promising, high initial costs and the need for technical skills are significant barriers to adoption, particularly for smallholder farmers who lack the resources and literacy skills to adopt them. A pathway to address this challenge is to use extension services to support the smallholder farmers. Key recommendations to advance the adoption and implementation of smart-irrigation technologies should focus on mitigating high initial costs, increasing technical knowledge, improving infrastructure, and demonstrating proven value to farmers. These include:
- Tailored solutions: Smallholders benefit most from modular, low-cost technologies like solar drip kits and mobile apps, while large-scale commercial farms should focus on AI-driven automation.
- Holistic implementation: Precision irrigation should not be a siloed investment but part of a total precision agriculture approach, combining it with soil mapping and sensor technology.
- Policy and stakeholder support: Subsidies for drip irrigation and training in digital skills are necessary to bridge the gap between scientific advancement and practical farming, particularly in developing regions.
- Collaborations with technology providers: Developing partnerships between agricultural institutions and technology suppliers creates cost-effective, scalable, and user-friendly solutions tailored to local conditions.
- Updating agricultural colleges' curricula: Agricultural curricula in agricultural colleges need to be continuously updated to be able to respond to current challenges and technological advances. Continuous updates move education from traditional, inherited knowledge systems toward data-driven, sustainable, and productive agriculture.
- Incentivise the youth and women farmers: Incentivising the young and women farmers to engage in farming, as they are often more adaptable to using advanced digital tools. This is a form to create employment.

5. CONCLUSIONS

Climate-smart agriculture offers numerous benefits, including addressing climate change while systematically considering the synergies and trade-offs between productivity, adaptation, and mitigation. Innovative technologies are essential for enhancing water and food security, both at the off-farm level—such as water transport infrastructure and irrigation system distribution—and at the on-farm level, including efficient water application methods and adopting advanced irrigation technologies. Specifically, improved irrigation techniques serve as crucial tools for promoting the sustainability of irrigation and water resources on farms. Expanding the irrigated area is vital for enhancing food and water security. However, the first step towards effective agricultural water management is having a coherent policy framework across interconnected sectors. This is key to minimising policy spillovers and unintended trade-offs. Innovations that enhance water use efficiency are essential for the resilience and adaptation of the agricultural sector, ensuring food security for the increasing population. Despite acknowledging the significance of these innovative technologies for sustainable irrigation, their adoption has been notably slow, revealing the gap between scientific advancements, policy formulation, and practical implementation. While acknowledging the importance of innovative technologies for the sustainability of irrigation, it is equally critical to recognise trade-offs and synergies associated with irrigation expansion. Understanding these dynamics highlights the need for transformative and holistic approaches to irrigation development.

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