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Advancing smart irrigation systems with the Internet of Things and machine learning: a review for water-secure agricultural practices in water-scarce regions

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KEYWORDS

Internet of Things, machine learning, smart irrigation systems, sustainable agriculture, water resource management

HIGHLIGHTS

- Provides a unified IoT–ML framework for smart irrigation in water-scarce regions.
- Synthesizes global case studies showing water savings up to 90% with smart systems.
- Identifies major barriers: cost, connectivity, interoperability, and data security.
- Proposes a research roadmap linking smart irrigation with food security and SDGs.
- Examines renewable-energy, blockchain, and low-cost IoT solutions for smallholders.

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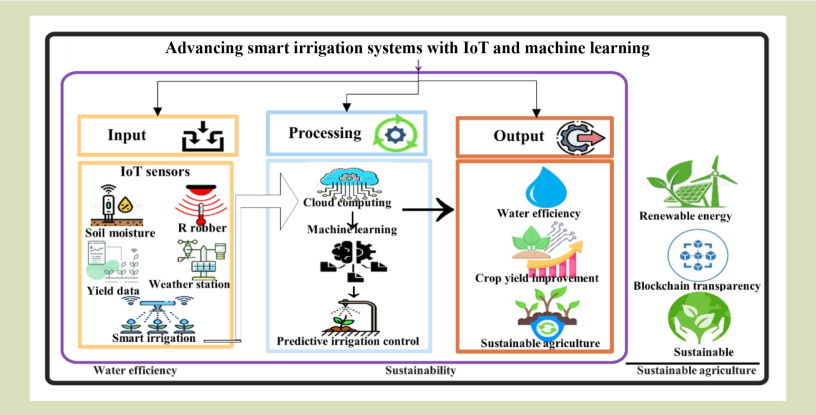
GRAPHICAL ABSTRACT



ABSTRACT

Efficient water resource management in agriculture is essential for ensuring food security and environmental sustainability, particularly in water-scarce regions. This review examines the integration of Internet of Things and machine learning technologies in the development of smart irrigation systems aimed at optimizing water use. By leveraging real-time data from soil moisture sensors, weather stations and crop-specific inputs, these systems enable precise irrigation scheduling and predictive decision-making. Internet-of-Things-based frameworks offer remote monitoring and control through mobile and cloud platforms, enhancing operational efficiency and crop yield. Machine learning algorithms, including supervised and deep learning models, further contribute by forecasting water requirements and detecting anomalies in irrigation patterns. Despite the promising benefits, such as reduced water waste, lower operational costs and improved crop productivity, significant challenges persist. These include high initial infrastructure costs, data integration issues, network limitations and concerns about data security. This review examines the integration of Internet of Things and machine learning technologies from case studies across Asia, Africa and the Middle East, highlighting both success stories and deployment barriers. Additionally, future prospects such as integration with renewable energy sources, blockchain for data transparency and low-cost solutions for smallholders are discussed. Efficient water resource management in agriculture is essential for ensuring food security and environmental sustainability, particularly in water-scarce regions. Ultimately, the convergence of the Internet of Things and machine learning in smart irrigation presents a transformative approach to achieving sustainable agriculture under the pressures of climate change and water scarcity.

1 Introduction

Water scarcity is one of the most pressing global challenges, critically limiting agricultural productivity and food security, particularly in drought-prone and semiarid regions. Rising population pressures, climate change and unsustainable water management practices have intensified stress on existing irrigation systems, necessitating the development of data-driven, resource-efficient and climate-resilient agricultural solutions[1,2]. Currently-applied mitigation strategies, such as the breeding of drought-tolerant crop cultivars, soil moisture conservation and optimized irrigation have improved water use efficiency but remain insufficient to overcome the magnitude of the global water crisis. The concept of agricultural economic water scarcity highlights regions where improved irrigation infrastructure could potentially feed an additional 840 million people worldwide[3]. Therefore, a major scientific and socioeconomic imperative is to design intelligent irrigation systems capable of achieving more crop production per unit of water applied through technological convergence.

Although long-established irrigation systems, such as flood and furrow irrigation, remain common, modern technologies particularly drip, sprinkler and smart irrigation offer up to 30% higher water use efficiency and substantial yield gains[4]. However, their large-scale deployment is often constrained by high installation costs, maintenance requirements and the absence of digital monitoring infrastructure, especially for smallholders in developing regions[5,6]. The persistent disparity between technological innovation and practical field-level adoption thus forms the core research problem addressed in this review[7].

The motivation of this review arose from the urgent global need to develop scalable, affordable and intelligent irrigation systems that can operate effectively under conditions of increasing water scarcity. The growing convergence of the Internet of Things and machine learning provides a transformative opportunity to revolutionize agricultural water management. These technologies enable real-time sensing, predictive analytics and autonomous control of irrigation systems, thereby reducing water waste, improving crop yields and minimizing manual intervention. This review addresses the question how can the Internet of Things and machine learning be strategically integrated to achieve sustainable, efficient and equitable irrigation practices across diverse agricultural ecosystems.

The scope of this review extends beyond a normal review of smart irrigation technologies. It critically examines Internet-of-Things- and machine-learning-driven smart irrigation systems across water-scarce regions worldwide, evaluating their technical architectures, algorithmic models, energy efficiency and socioeconomic feasibility. Also, it examines the integration of renewable energy sources, cloud computing and blockchain-based traceability to improve data transparency and sustainability[7]. The review systematically synthesizes evidence from literature published between 2019 and 2025 to identify research trends, implementation barriers and opportunities for global scalability.

Smart agriculture provides the foundation for resilient and water-secure food systems by integrating advanced digital technologies that enhance productivity, reduce waste and improve long-term food security. Core components of smart agriculture such as Internet-of-Things-enabled sensing, cloud-based analytics, renewable energy-supported automation and intelligent robotics are increasingly used to strengthen agricultural resilience under water stress. Recent studies demonstrate this progression: high-technology agriculture systems using the Internet of Things and cloud computing have improved real-time irrigation scheduling and resource optimization for food-secure farming[4]; Internet-of-Things-based smart irrigation management systems using telemetry and embedded computing have shown measurable gains in agricultural water security[8]; and integrated smart agriculture frameworks combining renewable energy resources, Internet-of-Things-based energy management and precision robotics provide a path toward highly automated, sustainable agricultural practices in water-scarce regions[9]. Together, these advances broaden the scope of smart agriculture and reinforce its role in safeguarding food production through intelligent, water-efficient cultivation strategies.

This review also positions smart irrigation within the broader framework of smart agriculture and water-secure food systems. Smart agriculture integrates advanced technologies such as the Internet of Things, cloud computing, robotics and renewable energy systems to enhance productivity while conserving natural resources. In this context, the paper links irrigation innovation to food security objectives by emphasizing precision water delivery, autonomous monitoring and energy-efficient management practices. These components collectively contribute to climate-resilient agriculture and sustainable resource governance, as evidenced by recent advancements in smart agricultural research[10,11]. For example, the high technology agriculture system to enhance food security demonstrates how the Internet of Things and cloud computing can be integrated to develop intelligent irrigation systems that optimize water use and crop productivity[12,13]. Similarly, the Internet-of-Things-based smart irrigation management system uses embedded systems, telemetry data and cloud computing to strengthen agricultural water security through real-time monitoring and adaptive control[14–16]. Complementing these approaches, the smart agriculture technology framework integrates renewable energy resources, Internet-of-Things-based energy management and precision robotics to enhance resource efficiency, reduce environmental impact and promote long-term sustainability across diverse agricultural systems[17,18]. The main contribution of Present study is to provide a comprehensive synthesis that bridges the technological and practical gaps in smart irrigation research (Table 1). Specifically, it: (a) compares global case studies to identify success factors and constraints**;** (b) analyzes Internet of Things and machine learning integration with renewable energy systems for scalability and resilience**;** and (c) proposes a research roadmap for affordable, sustainable and adaptive irrigation management**.** Unlike previous reviews that focus narrowly on either Internet of Things or machine learning applications, this review develops a unified, cross-disciplinary framework emphasizing interoperability, affordability and sustainability. As freshwater resources become increasingly constrained, the urgency for such integrated digital solutions intensifies in light of rising energy costs, soil salinity and groundwater depletion[19,20].

2 Materials and methods

This review uses a systematic literature analysis to evaluate recent advancements in smart irrigation technologies that integrate the Internet of Things and machine learning for water-secure agricultural practices. The methodology was designed to ensure comprehensive coverage of peer-reviewed journal articles, technical conference proceedings and case studies from diverse geographic and agroclimatic contexts, including both developed and resource-constrained regions. The source selection process emphasized studies published within the last five years that describe or assess Internet-of-Things-enabled sensor networks, cloud-based irrigation control platforms and machine-learning-driven irrigation prediction models. Particular attention was given to research that combined wireless soil moisture monitoring, real-time meteorological data acquisition and mobile-enabled irrigation management. Technologies were classified according to three functional domains: (1) Internet-of-Things-based data acquisition frameworks, including in-field sensor arrays for soil and crop monitoring; (2) Cloud and edge computing platforms for automated irrigation scheduling and control; and

Table 1 Comparative overview of previous review papers and their limitations in IoT- and ML-based smart irrigation

Focus of study	Limitations in previous work	Contribution of this review	Source
IoT automation in irrigation	Limited to sensor-level integration without decision analytics	Adds machine-learning-driven decision frameworks and explicit water-security focus	[21]
ML algorithms for irrigation	No IoT data-architecture or interoperability discussion	Integrates IoT connectivity, renewable-energy context and edge-AI scalability	[22]
4IR technologies in Sub-Saharan irrigation	Region-specific, lacks cross-comparative synthesis	Provides a global comparative perspective emphasizing inclusivity of smallholders	[23]
Smart farming and food security	Omits explicit water-security and sustainability linkage	Bridges IoT, ML and food-security frameworks with sustainable-development alignment	[24]
IoT and ML integration for precision irrigation	Fragmented analysis, absence of renewable-energy or blockchain dimension	Presents a unified framework combining IoT, ML and blockchain-enabled data security	[25]
Cloud-based smart-irrigation reviews	Focuses only on cloud storage without predictive intelligence	Introduces machine-learning-enabled predictive analytics for autonomous irrigation scheduling	[8]
AI-based sustainable agriculture	Emphasizes robotics, neglects water-resource management	Refocuses AI toward irrigation efficiency, adaptive control and climate resilience	[26]
IoT and ML in smart irrigation (meta-review)	Limited comparative synthesis, lacks affordability and policy analysis	Unified review integrating sustainability, affordability, policy and data-security dimensions	This review

Note: IoT, Internet of Things; ML, machine learning; AI, artificial intelligence; 4IR, Fourth Industrial Revolution.

(3) machine-learning-based decision models such as support vector machines, random forest and long short-term memory neural networks for predictive water management. Data were synthesized to evaluate how these integrated systems improve irrigation timing, water allocation and crop yield performance. A comparative analytical framework was applied to quantify reported water savings, operational efficiency gains and agronomic benefits. Studies using message queuing telemetry transport or similar lightweight communication protocols were prioritized because of their relevance to scalable field deployments. In addition, research exploring the interoperability of Internet of Things modules with renewable energy systems and precision agriculture robotics was incorporated to reflect emerging trends in sustainable smart farming. To ensure a critical perspective, this review not only collates existing technological frameworks but also identifies their practical limitations, including cost constraints, network reliability challenges and barriers to smallholder adoption. Comparative tables summarize the scope, methodology and reported outcomes of prior reviews and implementation studies, highlighting gaps addressed in this work. Conceptual diagrams are included in subsequent sections to visualize how Internet of Things sensor networks, machine learning algorithms and cloud platforms interact within smart irrigation systems. These enhancements align with recommendations to provide greater clarity, improved readability and a distinctive contribution to the research landscape.

3 Results and discussion

3.1 Technological framework of smart irrigation systems

Water scarcity in agriculture necessitates the development of technologies that enable efficient water management while maintaining crop productivity[27,28]. Smart irrigation systems provide an integrated framework that combines Internet of Things technologies, machine learning methods and soil water management strategies to optimize irrigation scheduling and water use efficiency. The motivation for this review is the pressing need for scalable and sustainable irrigation solutions in water-scarce regions, where standard practices often result in significant resource losses. The scope of present study is to critically analyze existing Internet-of-Things- and machine-learning-enabled irrigation technologies, identify their limitations and highlight pathways for innovation. The principal contribution of this review lies in synthesizing the state-of-the-art approaches into a structured framework, supported by comparative tables and concept diagrams, to guide future research and practical deployment. Smart irrigation systems integrate soil sensors, wireless communication networks and cloud computing to enable real-time monitoring, automated control and data-driven decision-making. By combining predictive analytics with adaptive control algorithms, these systems address both temporal and spatial variability in soil and climate conditions. Previous studies have demonstrated water savings ranging from 56.4%

to 90% using data preprocessing techniques such as outlier removal and soil moisture prediction[29]. However, adoption barriers remain, particularly related to infrastructure costs, interoperability and the need for tailored solutions for smallholders [22,23].

3.1.1 Internet of Things sensors and devices for precision irrigation

Wireless sensor networks and low-cost microcontrollers are central to smart irrigation networks, enabling the collection of real-time soil moisture, temperature and humidity data[30,31]. Communication protocols such as Message Queuing Telemetry Transport and WebSocket transmit this information to gateways and cloud platforms, supporting seamless mobile and web-based monitoring[32,33]. The integration of affordable sensors improves accessibility for small-scale agricultural operations and supports localized precision irrigation, which has been shown to reduce water waste and improve yield[3] (Table 2).

3.1.2 Data acquisition, cloud platforms and communication networks

Smart irrigation frameworks combine Internet of Things networks with cloud computing to store, process and analyze large environmental datasets[34,35]. Centralized platforms provide decision-support dashboards, enabling automated irrigation scheduling while allowing manual override through mobile applications[35,36]. Advanced machine learning algorithms enhance these systems by predicting irrigation requirements based on multi-year environmental and crop data, thereby improving operational efficiency and water use sustainability[11].

3.1.3 Integration of weather data, soil moisture and crop-specific factors

The latest irrigation control systems combine weather forecasts, soil moisture measurements and crop growth models to determine dynamic irrigation schedules[15,37]. Adaptive controllers minimize both over- and under-watering and enable remote management of irrigation settings[38,39]. Research indicates that these integrated systems can reduce water consumption by up to 30% without compromising crop health, contributing to sustainable agricultural practices[39]. Table 3 presents a comparative analysis of prior smart irrigation research and the current study. As shown in Fig. 1, the conceptual framework integrates Internet of Things technologies with machine learning techniques to optimize smart irrigation systems.

Table 2 Summary of current Internet of Things sensor technologies

Sensor type	Parameter measured	Communication protocol	Energy source	Application	Source
Soil moisture sensor	Soil water content	LoRa/Zigbee	Solar	Precision irrigation	[30]
Weather station	Temperature, rainfall	Wi-Fi/GSM	Battery	Climate monitoring	[31]
Flow meter	Water flow rate	MQTT	Alternating current/solar	Irrigation optimization	[32]

Note: LoRa, long range; GSM, global system for mobile communication; and MQTT, message queuing telemetry transport.

Table 3 Comparative analysis of prior smart irrigation research and this review

Focus and technology used	Key limitations identified	Contribution of this review	Source
IoT-based sensors and cloud monitoring	Limited discussion on ML-based decision optimization	Integrates IoT and ML with structured comparative analysis	[27]
Soil-water management framework	Lacks systematic performance comparison of algorithms	Highlights algorithmic performance (SVM, RF and LSTM)	[28]
Low-cost sensor networks	No predictive analytics included	Adds ML-based prediction models for irrigation scheduling	[31]
IoT-ML integrated smart irrigation	Addresses fragmented literature and inconsistent results	Provides consolidated framework, critical discussion and future directions	This review

Note: IoT, Internet of Things; ML, machine learning; SVM, support vector machine; RF, radio frequency; LSTM, long short-term memory.

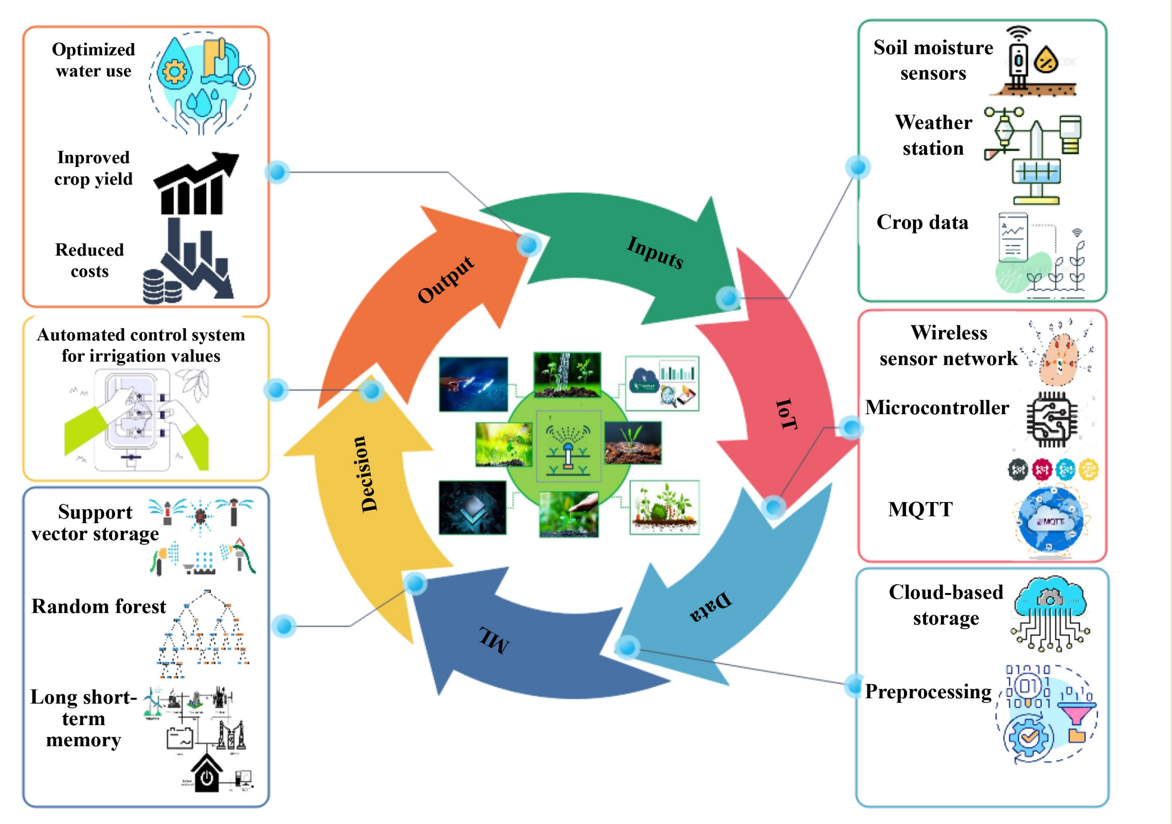


Fig. 1 Conceptual framework of Internet-of-Things (IoT)- and machine-learning (ML)-based smart irrigation systems. MQTT, message queuing telemetry transport.

3.2 Machine learning techniques in smart irrigation

Machine learning techniques have shown significant potential in enhancing smart irrigation systems. Various algorithms, including logistic regression, random forest, support vector machine and convolutional neural networks, have been applied to classify Internet-of-Things-generated irrigation data, with random forest achieving the highest accuracy of 99.98%[40]. These techniques can predict crop water requirements based on soil moisture, temperature and humidity data[41]. Machine learning applications in smart irrigation optimize water use, improve yield production, reduce manual intervention and help prevent crop diseases[42]. A systematic literature review of 55 studies published between 2017 and 2023 identified nine widely used machine learning models in smart irrigation systems, demonstrating their superior performance compared to conventional approaches[43]. However, the study also highlighted the need for further research to obtain more generalizable results and address existing challenges in machine-learning-based smart irrigation systems. Figure 2 shows the distribution of technological components used in

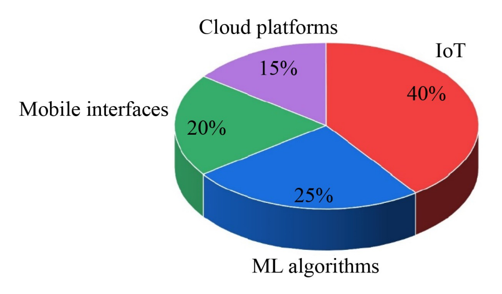


Fig. 2 Technological component distribution in smart irrigation systems. IoT, Internet of Things; ML, machine learning.

smart irrigation systems, with Internet of Things sensors and machine learning algorithms forming the core architecture.

3.2.1 Supervised and unsupervised learning models for irrigation prediction

The selected studies were analyzed for various machine learning approaches for irrigation prediction and management. Supervised learning models like support vector machines have shown high accuracy (97.5%) in predicting optimal irrigation times based on soil temperature and moisture data[44]. Unsupervised learning techniques, including competitive network, soil moisture controller and K-means clustering, have been applied to Internet of Things sensor data for real-time irrigation decision-making[45]. This work discusses of computational and statistical methods for irrigation prediction highlights the effectiveness of techniques such as logistic regression, decision trees and artificial neural networks[46]. Additionally, self-supervised contrastive learning has shown promising results in irrigation detection using satellite imagery, outperforming current supervised methods with up to nine times better precision and 90% better recall[44]. This study examines the advancements in machine learning contribute to more efficient water management and sustainable agricultural practices.

3.2.2 Predictive analytics for optimizing water use based on historical and real-time data

The selected studies show that real-time data are revolutionizing water management by optimizing operations and addressing challenges in developing regions. Utilities can leverage real-time network modeling and operational analytics dashboards to monitor system vital signs, spot patterns and improve customer service[47]. Ensemble learning models, such as extreme gradient boosting and random forest, have shown superior performance in predicting water pump status, quality and quantity in developing countries[48]. Statistical approaches for meter anomaly detection, demand forecasting and association analysis can benefit both utilities and customers by identifying malfunctioning meters and optimizing water supply[49]. The adoption of Industry 4.0 technologies, including Internet of Things sensors, advanced metering and digital twins, enables utilities to overcome infrastructure challenges and improve operational efficiency through sophisticated data analysis and insights[50]. These advancements in predictive analytics and smart technologies are transforming water management practices worldwide (Fig. 3).

3.2.3 Applications of deep learning and neural networks in forecasting irrigation needs

This review has examined deep learning techniques for forecasting irrigation needs in precision agriculture. Long short-term memory networks have shown promising results in predicting soil moisture content and irrigation requirements[51,52]. Convolutional neural networks and long short-term memory (hybrid CNN-LSTM) models have also been applied successfully to irrigation prediction tasks[53]. This work discusses deep learning approaches outperform current methods in accuracy and adaptability to unpredictable climates[51]. Integration of Internet of Things technologies with deep learning models enables real-time data collection and monitoring, enhancing decision-support systems for farmers[51,52]. Results are presented that artificial neural networks can achieve higher accuracy (97.2%) in classifying temperature and moisture data compared to long short-term memory (95.7%) and Convolutional Neural Network (93.4%) models[54]. This work discusses advancements contribute to more efficient water management and sustainable agricultural practices (Table 4).

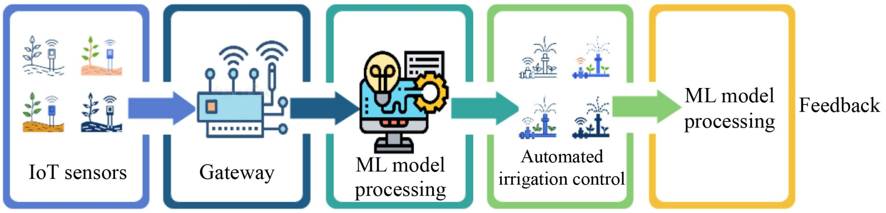


Fig. 3 Conceptual framework illustrating Internet of Things (IoT) and machine learning (ML) integration for smart irrigation systems.

Table 4 Machine learning algorithms used in irrigation

Algorithm	Input data	Output/Prediction	Accuracy	Source
SVM	Soil moisture, temp	Optimal irrigation time	97.4%	[17]
Random forest	Weather, soil	Water demand prediction	98.2%	[18]
LSTM	Temporal data	Soil moisture forecast	95.6%	[51]

Note: SVM, support vector machine; LSTM, long short-term memory.

3.3 Benefits of smart irrigation in water-secure agriculture

Smart irrigation systems are transforming water management in agriculture by leveraging real-time monitoring and automated control to optimize water use while enhancing crop productivity[55,56]. Studies have examined integrated sensors to track soil moisture, temperature and meteorological conditions, thereby enabling precise irrigation scheduling and automated water delivery[56,57]. The primary benefits include improved water use efficiency, reduced labor and operational costs, enhanced crop quality and decreased environmental impact through minimization of water wastage[58]. Nonetheless, these systems remain vulnerable to cybersecurity risks, power constraints and computational limitations, necessitating robust countermeasures[57]. Despite these challenges, smart irrigation is a promising strategy for addressing water scarcity and advancing sustainable agricultural practices[57,58].

3.3.1 Reduction in water consumption and operational costs

Significant reductions in water consumption and operational expenses are achievable through intelligent water management. Industrial processes such as paper milling, dairy production and electronics manufacturing have demonstrated potential water use reductions of up to 50%[59]. Water utilities can reduce annual electricity bills by as much as 22% by adopting demand-management strategies such as fixed-price contracts and time-of-use electricity shifting[60]. Similarly, optimized pumping schedules in water supply systems have been shown to lower daily energy costs by up to 43.7%[61]. Public sector facilities, initiatives, such as continuous monitoring, rapid leak detection and timely equipment maintenance, have resulted in 31% monthly water cost savings[62]. Results are presented illustrate the broad economic and environmental benefits of integrated water conservation strategies.

3.3.2 Improved crop yields through precise water management

Precision irrigation technologies have demonstrated substantial potential for enhancing both water use efficiency and agricultural productivity. Using sensors, automation and real-time data, these systems apply water in alignment with specific crop requirements and environmental variables[55,63]. Variable rate irrigation techniques have been reported to reduce water use by up to 25% relative to conventional methods while simultaneously improving crop yields due to more uniform soil water distribution[63,64]. Also, integrated modeling frameworks combining water distribution models with crop simulation tools provide a rigorous basis for evaluating agronomic, resource and environmental impacts of precision irrigation strategies[64]. These approaches are particularly advantageous in water-limited regions and contribute directly to achieving sustainable development objectives.

3.3.3 Environmental benefits: reduced runoff and minimal soil degradation

Smart irrigation practices and complementary soil conservation techniques mitigate water runoff, erosion and nutrient losses while enhancing soil quality. For example, conservation tillage and direct drilling have been shown to significantly reduce soil erosion compared to current methods[65]. Narrow grass hedges lowered runoff by up to 52% and reduced soil loss by up to 63% under different tillage conditions[66]. Soil and water conservation measures such as narrow terraces and fish-scale pits achieved runoff reductions of 77.7%–92.1% and sediment loss reductions of 31.5%–71.2% on sloped terrain[67]. Compost application has been found to improve soil infiltration, reduce runoff by about 50% and decrease nitrogen and phosphorus losses by about 50% compared to standard fertilizers[68]. Narrow terraces also cut nitrogen losses by 73.6% and phosphorus losses by 42.9%[67]. Figure 4 shows the comparative water savings achieved using

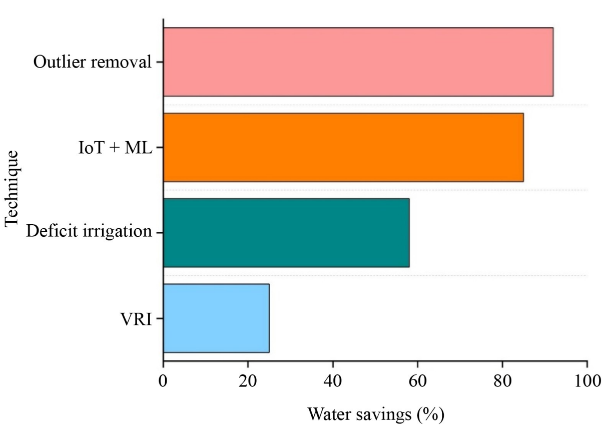


Fig. 4 Water savings comparison across smart irrigation methods. VRI, Variable Rate irrigation; IoT, Internet of Things; ML, Machine Learning.

various smart irrigation techniques, where Internet of Things and machine learning integration delivered savings exceeding 85%.

3.3.4 Comparative analysis of related reviews

Studies on smart irrigation technologies have evaluated Internet of Things applications[55], precision irrigation methods[63], automated irrigation systems[57] and integrated modeling approaches[9,64]. While these studies demonstrate significant advancements in optimizing water use and improving crop productivity, most lack a unified perspective that combines Internet of Things and machine learning approaches with detailed consideration of cybersecurity vulnerabilities, scalability challenges and sustainability metrics[24]. Also, previous works often focus on isolated aspects of smart irrigation rather than providing an integrated assessment linked to sustainable development goals. This review analyzes these gaps by synthesizing cross-technology insights, incorporating both field deployment data and modeling studies, and presenting a structured comparative framework to guide future research and real-world applications.

Studies on smart irrigation technologies have examined various aspects of Internet of Things applications, precision methods and automated systems. Internet of Things-based solutions integrated with machine learning techniques offer real-time data use and enhanced decision-making for irrigation management[14,69]. The present review aims to determine how to optimize water use efficiency and crop productivity can be achieved through automated data collection, analysis and application[69]. Smart irrigation technologies encompass wireless communication systems, advanced monitoring devices and sophisticated control strategies for improved scheduling[70]. The transition from conventional to precision irrigation methods addresses water scarcity challenges and promotes sustainable agriculture. Implementation of smart techniques such as Internet of Things, wireless sensor networks and artificial intelligence contributes to water conservation across various crops[71]. However, challenges remain in data integration, network reliability and scalability of Internet-of-Things-based frameworks[14]. Results are presented the transformative potential of integrating Internet of Things and machine learning in agriculture. These technologies enable real-time data collection, precision agriculture and improved resource management[72,73]. Internet of Things sensors gather the needed environmental data, while machine learning algorithms analyze this information to optimize crop yield, detect diseases and enhance water management[74]. Studies emphasize the importance of Internet-of-Things-enabled machine learning systems for automating irrigation processes, leading to water conservation and reduced operational costs[10]. However, challenges, such as data privacy, security and infrastructure requirements, must be addressed for successful implementation[72,74]. The synergy between Internet of Things and machine learning offers significant opportunities for sustainable and efficient agricultural practices, but requires collaboration among stakeholders to overcome obstacles and maximize benefits[72,73]. Smart irrigation systems, integrating Internet of Things and automated technologies, are crucial for achieving sustainable agriculture and contributing to multiple UN Sustainable Development Goals[15,75]. This work discusses optimize water use efficiency, enhance crop performance and support precision monitoring through soil data, plant water status and remote sensing[75]. The transition from conventional to smart irrigation methods addresses challenges related to water scarcity and climate change[75,76]. Implementing smart irrigation requires a holistic approach, considering technical, social and environmental aspects[76]. Internet-of-Things-based irrigation systems contribute significantly to Sustainable Development Goals, particularly goal 6 on water management, by improving water conservation and resource efficiency. While smart irrigation offers numerous benefits, challenges in implementation and adoption remain, necessitating continued research and development to enhance sustainability and reduce costs[77]. This synthesis addresses gaps in urban energy planning, cross-chain technology, Industrial Internet of Things and wireless network optimization. This highlights the need for integrated modeling approaches and comprehensive scenarios in urban energy systems[78]. The selected studies were emphasizing the importance of bridging separate distributed ledger technology designs to enable more powerful applications[79]. For the Internet of Things, it proposes a unified characterization of application domains, requirements and technological gaps, offering a systematic approach to address research challenges[80]. In wireless networks, the synthesis compares various optimization techniques, revealing that hierarchical frameworks excel in scalability and energy efficiency, while deep reinforcement learning effectively balances latency reduction and energy savings in urban Internet of Things networks[81]. These insights provide a structured comparative framework to guide future research and real-world applications across these interconnected technological domains. Table 5 provides an overview of prior studies on smart irrigation technologies, highlighting their key limitations. Fig. 5 presents the conceptual framework for the integration of the Internet of Things and machine learning in smart irrigation systems.

3.4 Case studies and applications in water-scarce regions

Water scarcity in arid and semiarid environments present significant challenges to sustainable development and resource governance. The present studies across diverse geographical regions illustrate the complexity of these challenges and the need for integrated, multidisciplinary solutions. In Namibia, advanced treatment methods are used to recover potable water from wastewater, demonstrating the potential of technological interventions for water security. In the Middle East, persistent water scarcity has influenced regional stability and sociopolitical dynamics[83]. In the Kairouan Region of Tunisia, a system dynamics model revealed the risk of aquifer depletion, highlighting the need for strategic policy interventions[84]. Similarly, integrated water resource management approaches have been applied in the Elqui Valley in Chile to improve irrigation efficiency and mitigate water deficits[85]. These cases underscore the importance of adopting interdisciplinary frameworks that incorporate technological, societal, economic and institutional dimensions in addressing water scarcity. Sustainable solutions require balancing competing water uses, strengthening governance mechanisms and deploying both structural (infrastructure-based) and non-structural (policy-based) measures to achieve long-term water security[86].

3.4.1 Real-world examples of smart irrigation systems in water-scarce regions

Smart irrigation systems have been implemented in numerous water-scarce regions to improve agricultural efficiency and optimize water allocation. In sub-Saharan Africa, Industry 4.0 technologies, including the Internet of Things, artificial intelligence and aerial drones, are being adapted for precision

Table 5 Overview of previous studies on smart irrigation technologies and associated limitations

Focus area	Key findings	Identified limitations	Contribution of this review	Source
IoT in agriculture	Demonstrated improved water efficiency using IoT-enabled sensors	Limited discussion on ML integration and cybersecurity challenges	Combines IoT and ML perspectives with detailed vulnerability assessment	[55]
Precision irrigation	Showed benefits of VRI for water savings	Lacked structured comparison of multiple technologies	Provides an integrated cross-technology synthesis	[82]
Smart farming technologies	Highlighted potential for food security enhancement	Did not address economic viability and scalability issues	Examines both technical and economic aspects	[58]
Automated irrigation systems	Focused on control algorithms and soil data analytics	Overlooked environmental sustainability metrics	Links technology assessment to sustainability and SDGs	[57]
Irrigation modeling	Modeled water and crop productivity responses	Outdated with respect to modern IoT-ML advances	Updates review with post-2020 literature and advanced analytics	[64]
Crop-water-energy nexus	Emphasized integrated modeling approaches	Limited to simulation studies; minimal field validation	Incorporates field deployment case studies and real-world performance data	[9]

Note: IoT, Internet of Things; ML, machine learning; VRI, variable rate irrigation; SDGs, UN Sustainable Development Goals.

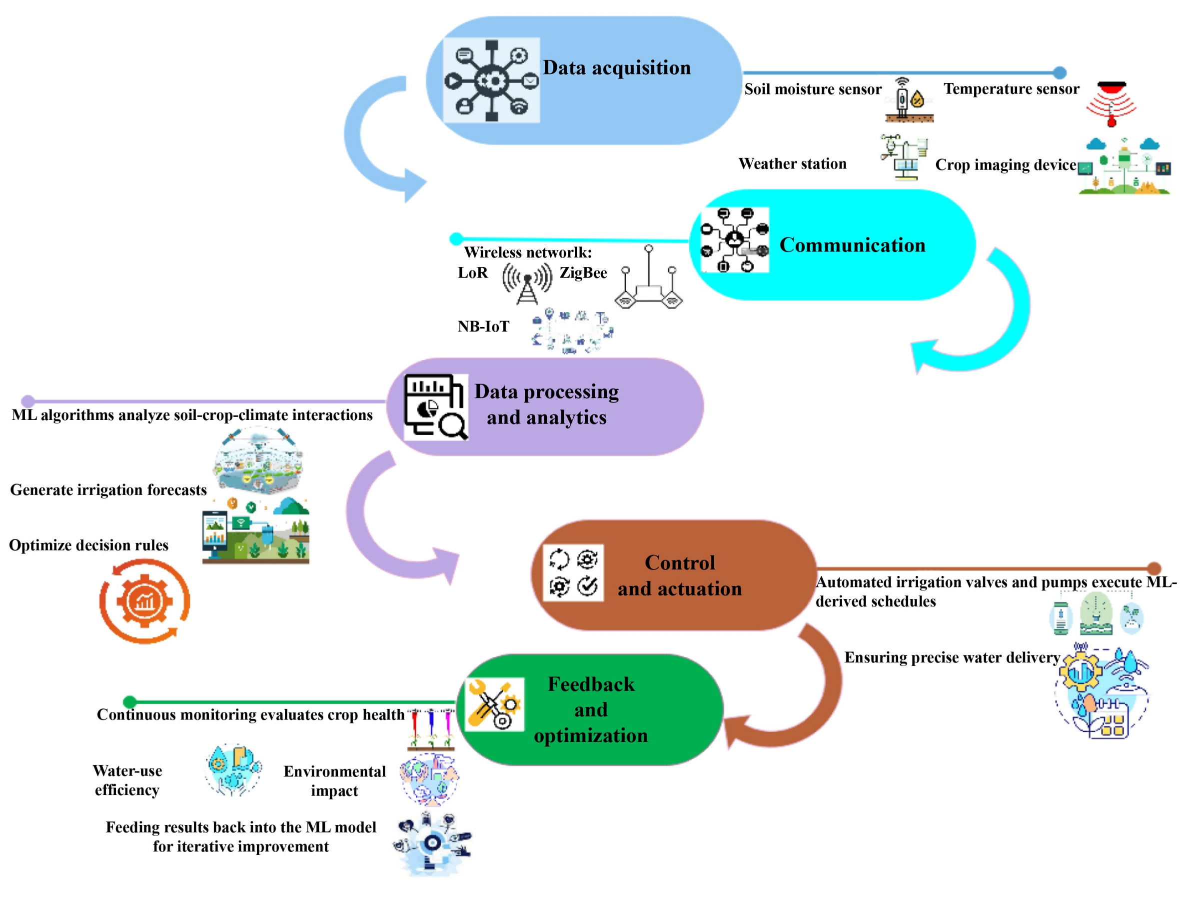


Fig. 5 Conceptual framework for smart irrigation using machine learning. LoRa, long range; IoT, Internet of Things; ML, machine learning.

irrigation, despite challenges such as limited infrastructure, high deployment costs and inadequate technical capacity[87]. Internet-of-Things-enabled systems have been developed to integrate soil, microclimate and water-quality data with indigenous agricultural knowledge and regional weather patterns, supporting more accurate irrigation decisions[88]. Field evidence demonstrates significant water savings; for example, one study in Zimbabwe reported up to a 25% reduction in water use compared to conventional irrigation practices[89]. This review analyzes commonly used environmental sensors to identify local moisture deficits and activate irrigation valves only in affected areas, thereby improving both water and energy efficiency[90]. While adoption barriers remain particularly concerning financial investment, policy support and capacity building the potential for transformative impacts in water-scarce regions is evident[87].

3.4.2 Challenges encountered during deployment and lessons learned

Implementing advanced water management technologies in water-scarce regions often faces institutional, technical and social constraints. Case studies from Israel, South America and Southern Africa reveal several lessons: early stakeholder engagement, community participation and strong public awareness programs are critical to fostering acceptance of new technologies[91]. Israel's success in mitigating water scarcity illustrates the importance of integrated water resource management, large-scale infrastructure investment and institutional reforms[92]. Desalination technologies, while increasingly widespread, face significant hurdles such as public perception, environmental impacts and high energy requirements[93]. The implementation of efficient irrigation methods, wastewater reuse programs and demand-management strategies has been shown to yield robust results when combined with monitoring systems such as HydroMet stations for hydrological forecasting and flood-warning applications, although logistical and security issues can impede deployment[94]. Overall, successful approaches must balance technological innovation with governance reforms and active societal participation[95].

3.4.3 Success stories of enhanced water efficiency and agricultural productivity

Evidence from various global contexts indicates substantial improvements in agricultural water productivity through modern irrigation strategies and management practices. In Australia, cotton farming achieved a 40% increase in water use productivity over a decade, driven by improved yield and irrigation efficiency, with whole farm irrigation performance improving from 57% to 70%[96]. In Mexico, modernization of irrigation infrastructure enabled water savings of 1800–2000 $m^3\ ha^{-1}$ and raised overall efficiency from 55% to 85%[97]. Malawi reported a 33% increase in crop water productivity between 2000 and 2013, leading to measurable gains in national food security[98]. Strategies underpinning these results include optimizing crop selection, reducing conveyance losses, improving soil and crop management practices and adopting precision irrigation technologies[99]. This review analyzes success stories demonstrate that systematic integration of advanced irrigation systems with sound agronomic practices can simultaneously enhance water efficiency, increase agricultural output and contribute to sustainable resource use. Figure 6 shows the prediction accuracy of different machine learning models applied to smart irrigation scenarios.

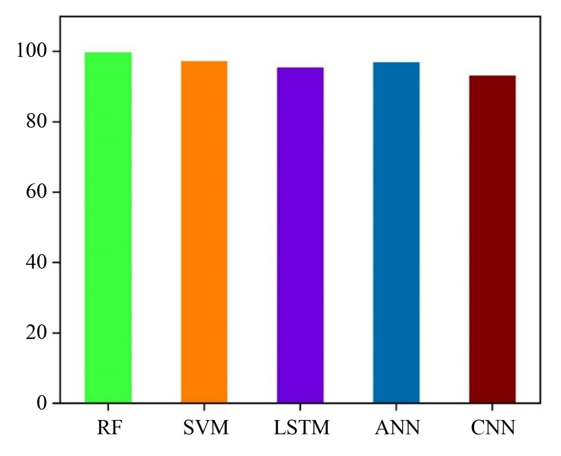


Fig. 6 Performance accuracy of machine learning models in smart irrigation. RF, radio frequency; SVM, support vector machine; LSTM, long short-term memory; ANN, artificial neural network; CNN, convolutional neural network.

To synthesize these findings, Table 6 provides a comparative analysis of selected cases, summarizing the regions studied, technologies implemented, key benefits and major challenges encountered.

Smart irrigation technologies have emerged as crucial tools for addressing water scarcity and promoting sustainable agriculture. These systems, often leveraging Internet of Things capabilities, can reduce water consumption by up to 30% while increasing crop yields by up to 125%[106]. The implementation of smart irrigation varies between regions, with Africa focusing on low-cost, locally-adapted solutions, while the USA emphasizes advanced technology and scalability[107]. Internet of Things technologies such as soil moisture sensors, weather-based controllers and automated systems improve irrigation accuracy and water use efficiency[108]. However, challenges persist, including high initial costs and the need for specialized infrastructure, which can limit adoption, particularly on small-scale farms[4,106]. To overcome these barriers and maximize the potential of smart irrigation, a comprehensive approach involving government incentives, accessible training and the promotion of affordable technologies is recommended[4]. The adoption of innovative water management technologies in agriculture offers significant benefits for improving water productivity, food security and climate resilience. This review analyzes, including precision irrigation and smart water management systems, enhance efficiency and minimize waste[109]. Precision agriculture techniques also optimize resource use and reduce environmental impacts[110]. However, the successful implementation of these technologies faces several challenges. High costs, limited technical expertise and institutional inefficiencies hinder widespread adoption[109,110]. Policy frameworks and institutional readiness are key to facilitating the deployment of these technologies[111,112]. To overcome these barriers, increased investment, capacity building and supportive policies are necessary[109,110]. Additionally, considering the interconnections between water, energy and food systems is essential for effective implementation of these technologies[111]. Figure 7 shows the adoption patterns of smart irrigation across the present review in water-scarce regions.

Table 6 Results are presented of smart irrigation and water management case studies in water-scarce regions

Region/Country	Technology/Approach	Reported benefits	Key challenges and lessons learned	Source
Namibia	Advanced wastewater treatment for potable reuse	Secures urban water supply; reduces dependence on groundwater	High infrastructure costs; requires strict water-quality monitoring	[83]
Middle East	Integrated water resource strategies	Supports agricultural production and regional stability	Political tensions; limited transboundary cooperation	[83]
Tunisia (Kairouan)	System dynamics modeling of aquifer use	Identifies groundwater depletion risk; informs policy reforms	Requires reliable data inputs and technical capacity	[84]
Chile (Elqui Valley)	Integrated water resource management	Improves irrigation efficiency; mitigates water deficits	Coordination among multiple stakeholders is complex	[85]
Sub-Saharan Africa	IoT and AI-enabled smart irrigation	Up to 25% water savings; improved decision-making from soil and climate data	Limited infrastructure, high costs, policy and investment gaps	[87,100,101]
Israel	Integrated water management and institutional reform	Enhanced national water security; widespread adoption of efficient irrigation	High capital requirements; desalination energy demands	[92,95,102]
Australia	Modernized cotton irrigation systems	40% increase in water-use productivity; irrigation efficiency improved from 57% to 70%	Technology adoption costs; need for continuous training	[103]
Mexico	Irrigation infrastructure modernization	Water savings of 1800–2000 $\mathrm{m^3 \cdot ha^{-1}}$; efficiency increased from 55% to 85%	Financial and institutional barriers to scaling	[104,105]
Malawi	Improved crop management and precision irrigation	33% increase in crop water productivity; improved food security	Requires farmer training and extension support	[98,99]

Note: IoT, Internet of Things; AI, artificial intelligence.

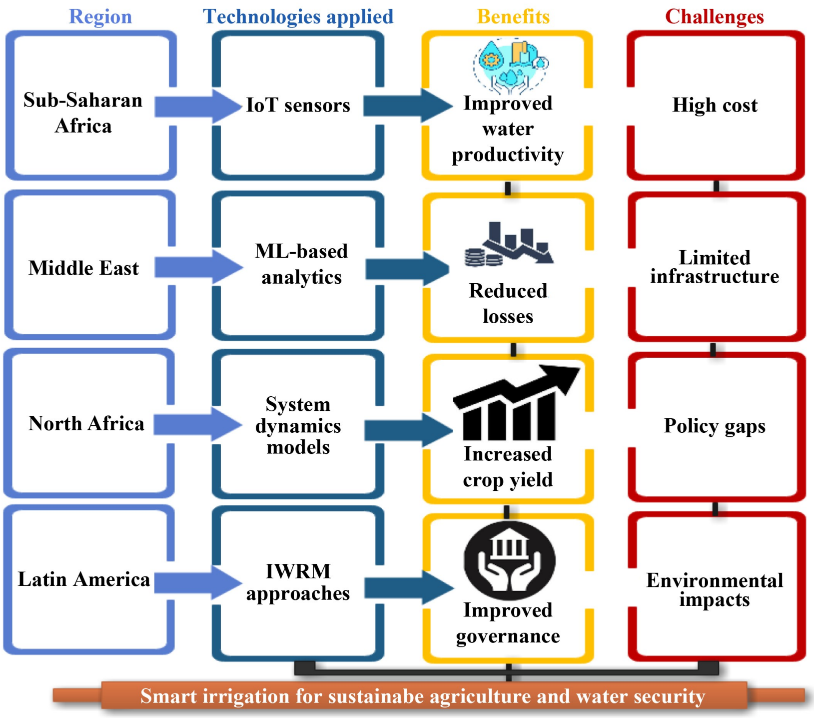


Fig. 7 Adoption of smart irrigation in water-scarce regions: case study insights. IoT, Internet of Things; ML, machine learning; IWRM, integrated water resources management.

3.5 Challenges and barriers in smart irrigation systems

The selected studies were analyzed for smart irrigation systems integrating Internet of Things and machine learning technologies that have shown significant potential to optimize agricultural water use and address food security challenges in water-scarce region[113,114]. The results presented used real-time data acquisition, predictive analytics and adaptive control mechanisms to enhance irrigation precision and improve decision-making[113]. Internet-of-Things-enabled solutions facilitate automated irrigation and continuous monitoring, improving both crop productivity and water conservation[113,114] (Fig. 8). In parallel, machine learning algorithms, including deep learning and visual transformers, have been used for weed detection, crop health assessment and yield prediction, contributing to higher agricultural efficiency[114]. Despite these advancements, several barriers hinder large-scale deployment, including high capital costs, complex integration requirements, network reliability issues, lack of standardization and concerns regarding data privacy[69,113].

3.5.1 High initial investment and infrastructure requirements

Smart irrigation systems using with the Internet of Things and machine learning can reduce water consumption by up to 30% and improve crop yields by up to 125%[106]. Key components such as soil moisture sensors, automated control valves and climate monitoring stations enable precise water management[11,115]. Advanced machine learning models provide predictive scheduling and dynamic irrigation adjustments[115]. However, high upfront costs and the need for specialized digital infrastructure remain significant barriers, particularly on small-scale and resource-constrained farms[106]. While some case studies demonstrate up to 90% water savings over existing irrigation methods[116], these benefits are often accessible only to well-capitalized farming operations.

3.5.2 Data privacy, security and the need for standardization

The integration of Internet of Things devices with machine learning-driven analytics generates large volumes of heterogeneous data from sensors, drones and satellites[69]. This review analyzes data streams enable automated irrigation management and end-to-end optimization, but also create data security[74]. Inadequate interoperability standards complicate the aggregation and sharing of agricultural data[113]. Without common protocols, it becomes difficult to scale solutions across diverse agroclimatic regions. Addressing cybersecurity threats and data ownership concerns is essential for gaining farmer trust and facilitating adoption.

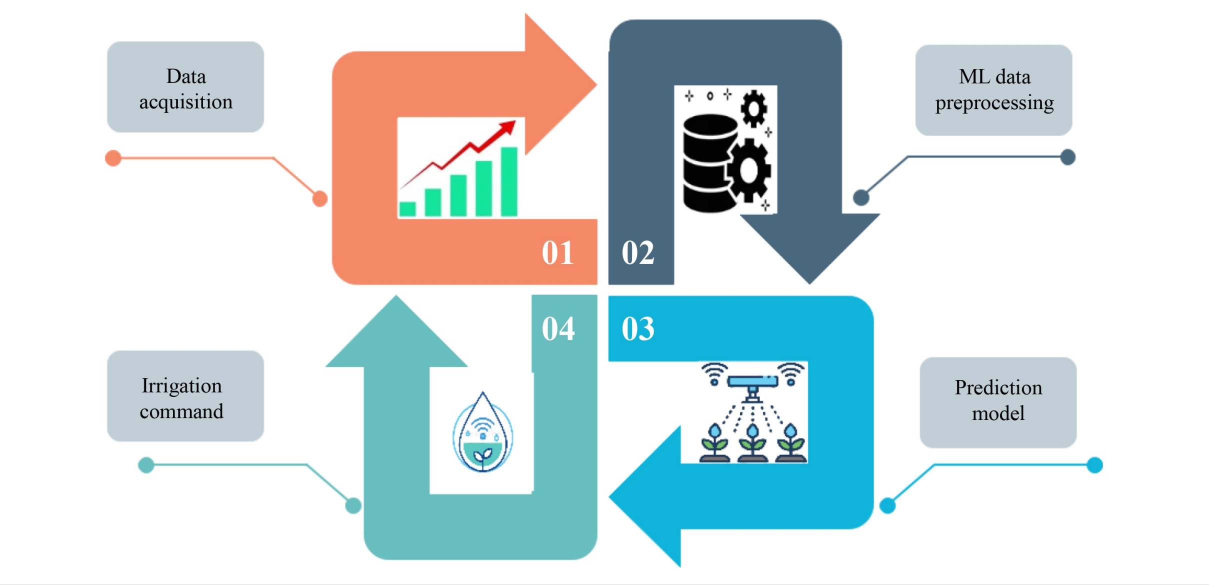


Fig. 8 Flow diagram of data acquisition, processing and decision-making in machine-learning-enabled smart irrigation. ML, machine learning.

3.5.3 Connectivity issues and communication network limitations

Internet-of-Things-enabled irrigation systems depend on robust wireless communication networks for reliable real-time operation[117]. In many remote or rural areas, poor internet coverage, inconsistent power supply and inadequate infrastructure limit the effectiveness of these technologies[71]. Wireless sensor networks, long-range Internet of Things protocols and long-range narrowband Internet of Things (LoRa and NB-IoT) have shown promise in improving coverage, but performance is still constrained by signal reliability and energy requirements[116]. Automated irrigation studies have demonstrated significant water savings under controlled conditions; however, scaling these systems to geographically dispersed fields remain an open challenge. Figure 9 gives the main barriers that hinder the implementation of smart irrigation systems.

3.6 Future directions and innovations

This work discusses in Internet of Things and machine learning are revolutionizing smart irrigation systems for sustainable agriculture. These technologies enable real-time data use, system responsiveness and precision irrigation management[113]. Machine learning models can provide optimal irrigation decision management, while digital farming solutions allow for remote monitoring and control[118]. Low-cost sensors and Internet of Things technologies are making smart irrigation systems more accessible to smaller farmers, monitoring parameters such as water quantity and quality, soil characteristics and weather conditions[119]. Machine learning applications in agriculture extend beyond irrigation, encompassing crop management, livestock management and soil management[120]. However, challenges remain, including data integration, network reliability and scalability of Internet-of-Things-based frameworks[113]. Future research should focus on overcoming these barriers to promote wider adoption and effectiveness of smart irrigation systems in various agricultural settings.

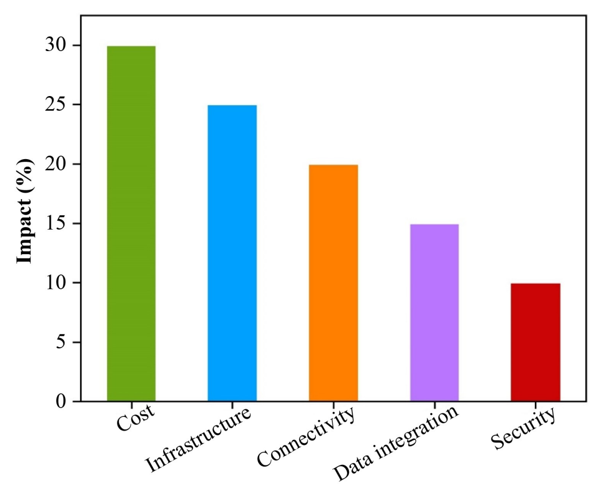


Fig. 9 Barriers to the Implementation of smart irrigation as determined by the current review.

3.6.1 The role of artificial intelligence and the Internet of Things in enhancing system scalability and flexibility

This review examines the integration of Internet of Things and machine learning technologies in agriculture is revolutionizing farming practices, particularly in smart irrigation systems for water-scarce regions. These technologies enhance precision, efficiency and sustainability in agriculture[113,121]. Internet-of-Things-based smart irrigation systems, coupled with advanced machine learning models, offer real-time data utilization and adaptive control, improving water management and crop productivity[113]. The Internet of Things combined with artificial intelligence enables automated processes, minimizing human effort and water waste in irrigation[121]. Results are presented the implementation of these technologies extends to various aspects of farming, including crop monitoring, soil analysis and decision support systems[71]. However, challenges such as high costs, digital skills gaps and data management issues need to be addressed for wider adoption[122]. Despite these obstacles, the future of the Internet of Things and artificial intelligence in agriculture looks promising, with potential for significant contributions to global food security and environmental sustainability.

3.6.2 Integration of renewable energy sources (solar and wind) with irrigation networks

The selected studies were analyzed to highlight the integration of the Internet of Things, machine learning and renewable energy in smart irrigation systems to address water scarcity and enhance agricultural sustainability. These systems use solar and wind power for irrigation while feeding excess energy back to the grid[123]. Internet-of-Things-based setups incorporate soil moisture sensors and machine learning algorithms to optimize watering schedules and prevent over-irrigation[115,124]. This

Present study examines the integration of renewable energy in water systems is driven by the need to reduce greenhouse gas emissions and combat global warming[125]. Smart irrigation systems offer remote monitoring and control via mobile devices, improving resource efficiency and crop yields[123,124]. However, challenges remain in data integration, network reliability and scalability of Internet of Things frameworks[115]. Future research should focus on overcoming these barriers and developing flexible solutions adaptable to diverse environmental conditions.

3.6.3 Development of low cost, low energy systems tailored for smallholders

This review examines the integration of Internet of Things and machine learning technologies in smart irrigation systems for sustainable agriculture. These technologies enable real-time data use, system responsiveness and precision in irrigation management[113]. Low-cost solutions incorporating soil moisture sensors and automated valve control can reduce water demand by up to 25% compared to existing methods[126]. Smart irrigation systems leverage various hardware modules, communication technologies and machine learning algorithms for predictive analytics and efficient water management[11]. A comprehensive approach combining predictive analytics, smart irrigation and soil health monitoring can provide actionable insights for optimizing crop growth, water use and soil health, particularly benefiting small-scale farms[127]. However, challenges remain in data integration, network reliability and scalability of Internet-of-Things-based frameworks[113], necessitating continued research to overcome barriers to wider adoption and effectiveness in diverse agricultural settings.

3.6.4 The potential of blockchain for improving traceability and transparency in water use

The selected studies were analyzed for the integration of blockchain, Internet of Things and machine learning to enhance traceability and efficiency in agricultural water management. Blockchain technology can secure data from Internet of Things sensors, ensuring transparency and trust among stakeholders in precision irrigation systems[128]. This Present work addresses security challenges in smart irrigation networks and promotes efficient resource utilization[129]. Combining blockchain with deep learning and Internet of Things can automate greenhouse operations, improving crop yields and establishing immutable records for supply chain traceability[130]. This present study examines the integration of Internet of Things and machine learning technologies enable smart secure sensing in agriculture, with blockchain providing a security architecture for Internet-of-Things-based systems[131]. Overall, the integration of blockchain, the Internet of Things and artificial intelligence in agriculture offers promising solutions for water-secure practices in water-scarce regions, enhancing resource management, crop quality and stakeholder trust throughout the agricultural supply chain.

3.6.5 Comparative analysis

Smart irrigation systems integrating Internet of Things and machine learning technologies are emerging as crucial solutions for water scarcity in agriculture. These systems use real-time environmental data from Internet of Things sensors to optimize irrigation schedules and water use. Machine learning algorithms analyze historical and current data to predict soil moisture levels, detect crop diseases and determine optimal crop selection for maximum yields. Various machine learning models, such as k-nearest neighbor algorithm and TimeGPT, Model have demonstrated high accuracy in predicting soil moisture and irrigation needs[132]. The present review aims the integration of machine learning with computer vision enables crop quality monitoring and yield assessment[133]. These smart systems allow for remote monitoring and control, reducing stress on farmers[134]. By leveraging Internet of Things and machine learning technologies, smart irrigation systems contribute to sustainable agriculture by improving water management, reducing operational costs and increasing crop productivity[129,135]. While several other reviews have examined these domains, a systematic comparison highlights gaps in existing literature and the novelty of this work. Table 7 presents a comparative analysis of related studies, identifying their regions of focus, adopted technologies, benefits and persisting challenges. Table 7 provides an evaluation of prior reviews on Internet-of-Things- and machine-learning-enabled smart irrigation systems and determine how this paper contributes beyond existing literature. It synthesizes global case studies and reviews to reveal limitations such as insufficient coverage of smallholder applications, lack of integration with renewable energy and limited discussion of scalability and data security. This work discusses this comparison establishes the basis for the framework presented in Fig. 8, which integrates technological solutions with sustainability goals. Below Table presents a comparative analysis of related studies, detailing their regions of focus, adopted technologies, reported benefits and key challenges.

Table 7 Comparative analysis of related studies: regions, technologies, benefits and ongoing challenges

Region/Scope	Technology focus	Benefits reported	Key challenges highlighted	Source
Middle East, North Africa	IoT sensors with cloud integration	Enhanced water productivity	High deployment cost; limited farmer skills	[118]
Sub-Saharan Africa	Low-cost wireless sensor networks	Improved monitoring of soil moisture	Lack of infrastructure; energy supply issues	[119]
Australia, Latin America	ML-based irrigation decision systems	Increased crop yield and water use efficiency	Network reliability; scalability of ML frameworks	[113]
Global (review articles)	IoT + AI in precision irrigation	Real-time data processing and automation	Data security gaps; inconsistent policy and governance	[120,136]

Note: IoT, Internet of Things; ML, machine learning; AI, artificial intelligence.

The selected studies were analyzed advances beyond prior research by synthesizing insights on renewable energy integration, blockchain enabled transparency and cost-effective adaptive solutions for smallholders, thereby presenting a comprehensive framework for sustainable irrigation management. Previous studies have investigated various innovative approaches to sustainable irrigation, integrating renewable energy, blockchain technology and intelligent agricultural systems. Hossain et al.[137] proposed an Internet of Things and machine learning blockchain framework for intelligent farm management, enabling remote monitoring and improved water control. Enescu et al.[138] introduced a blockchain-based irrigation solution for small-scale farms utilizing photovoltaic energy, incorporating SolarCoin as a utility token to incentivize adoption. Su and Singh[6] conducted a review of advanced irrigation technologies, emphasizing the potential of high-efficiency irrigation systems and precision agriculture to enhance water use efficiency, while underscoring the necessity of a multidisciplinary strategy to overcome adoption barriers. Bhat et al.[139] developed an integrated smart farming framework combining renewable energy resources, Internet-of-Things-enabled environmental monitoring and precision robotics. Their case study in the United Arab Emirates demonstrated successful cross-prototype integration and identified optimal configurations for multiple energy resources, providing a promising model for sustainable and efficient agriculture. This study examines the integration of advanced technological solutions with sustainability objectives is reshaping environmental and resource management across diverse industries. Technologies such as Internet of Things, artificial intelligence and blockchain are enabling real-time monitoring, advanced data analytics and informed decision-making in domains including air quality control, water resource management and biodiversity conservation[140]. Such approaches enhance resource efficiency, minimize environmental impacts and generate new economic opportunities[141]. In the chemical industry, digitalization and Internet of Things deployment have markedly improved operational efficiency and reduced production costs[142]. Also, inter-company network integration accelerates the development and diffusion of innovative technologies, optimizing resource utilization while delivering both environmental and social benefits[142]. Although challenges remain particularly regarding implementation costs and technological constraints this integrated paradigm offers significant potential to advance sustainable development and systemic resilience across sectors[140,141]. Figure 10 shows how the integration of technological solutions with sustainability objectives enhances environmental and resource management outcomes.

3.6.6 Research roadmap: integrating smart agriculture and food security

The future of sustainable irrigation lies in the integration of Internet of Things, machine learning and smart agriculture technologies to ensure water-efficient food production and long-term agricultural resilience. As the global population is projected to exceed 9.7 billion by 2050, the demand for food will increase by nearly 70%, intensifying pressure on finite water resources[2,143]. Smart agriculture, supported by real-time Internet of Things sensing, autonomous decision-making and predictive machine learning algorithms, offers a transformative solution for optimizing water use while maintaining or enhancing crop yields[144,145]. Figure 11 presents the proposed research roadmap for Internet-of-Things- and machine-learning-based smart irrigation systems, connecting technological innovation with global food security objectives. The framework identifies three progressive stage, challenges, research focus areas and expected outcomes, that together

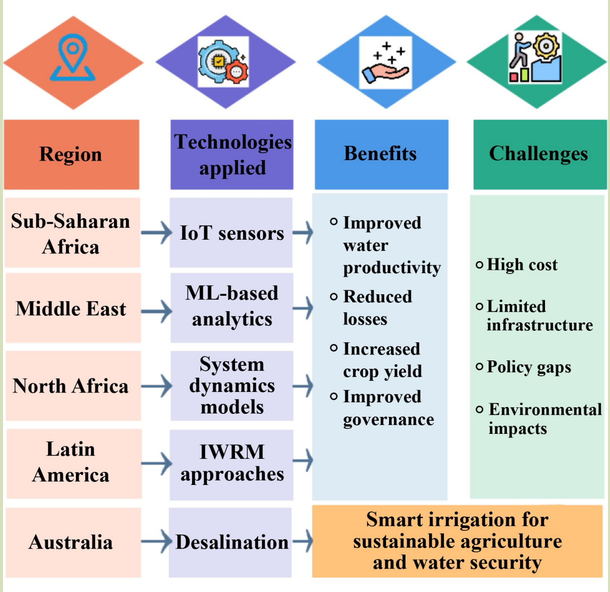


Fig. 10 Integration of technological solutions with sustainability objectives. IoT, Internet of Things; ML, machine learning; IWRM, integrated water resources management.

define the pathway toward sustainable and resilient agricultural systems.

There are three main challenges: (1) high implementation cost and lack of low-cost digital tools accessible to smallholders[146]; (2) energy dependency of irrigation networks, which limits deployment in remote and off-grid regions[31]; and (3) data fragmentation and cybersecurity vulnerabilities that compromise reliability and trust in digital farming systems[147,148].

This leads to research focus areas that should be prioritized: (1) optimized irrigation through machine-learning-enabled precision water management using soil plant atmosphere data integration[149]; (2) renewable energy integration, particularly solar- and wind-powered Internet of Things systems for off-grid farms[150]; (3) secure and interoperable data ecosystems using blockchain and edge computing for decentralized agricultural management[151]; and (4) food security linkage, emphasizing adaptive irrigation scheduling to mitigate yield loss and promote sustainable food systems under climate variability[152,153].

Such research could deliver a range of outcomes: (1) reduced operational and water management costs, promoting affordability for small-scale farms; (2) improved energy efficiency and carbon footprint reduction through renewable-powered Internet of Things systems; (3) enhanced data transparency, interoperability and security across smart agriculture infrastructure; (4) strengthened food security and resilience by improving yield stability, resource efficiency and adaptive management under drought and water stress conditions. The roadmap thus connects technological advancement with sustainable development goals[3,31,143,147,153] Zero Hunger, Clean Water and Sanitation, Affordable and Clean Energy, and Climate Action. Future research should expand field-based validation of these integrated Internet of

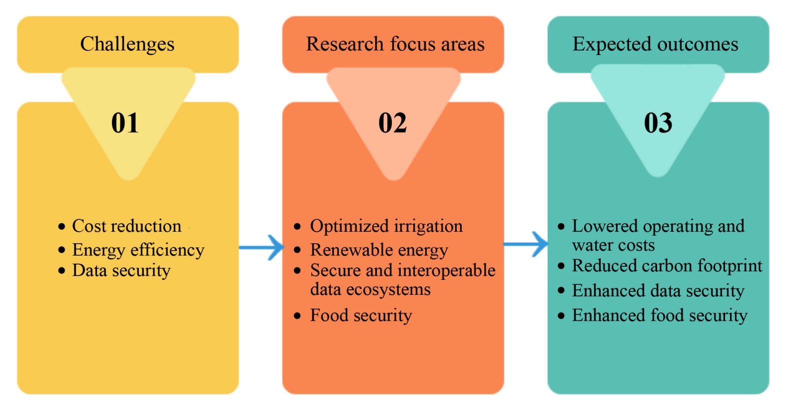


Fig. 11 Proposed research roadmap for Internet-of-Things (IoT)- and machine-learning (ML)-based smart irrigation systems linking smart agriculture innovations with food security outcomes.

Things and machine learning systems, develop open-source frameworks for cost reduction and strengthen policy mechanisms for equitable access to smart agriculture (Fig. 11).

4 Conclusions

This review examined the integration of Internet of Things and machine learning technologies is transforming irrigation management and paving the way for sustainable, water-efficient agriculture. Results are presented for these smart systems enable real-time monitoring, predictive control and automated irrigation, which together improve water use efficiency, crop productivity and cost-effectiveness. This is despite their potential, large-scale adoption being limited by high initial costs, inadequate infrastructure, and the lack of unified data and security standards. Future research and policy efforts should focus on developing affordable, energy-efficient technologies for smallholders, integrating renewable energy sources and establishing supportive regulatory frameworks. Overcoming these barriers will accelerate the shift from the existing to intelligent irrigation systems, ensuring resilient food production in the face of climate change and global water challenges.

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Compliance with ethics guidelines

Nazir Khan Mohammadi, Hameedullah Mohammadi, Mohammad Gul Arabzai, Muneeb Ur Rahman, and Zikui Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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