SMART CONTROLLED IRRIGATION USING THE INTERNET OF THINGS AND CHALLENGES FOR INCREASING WATER USAGE EFFICIENCY: A REVIEW

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Abstract

Sustainable agriculture faces a persistent challenge in optimizing water usage, as conventional irrigation methods often result in significant inefficiencies and waste. This problem underscores the need for irrigation systems that can deliver water precisely and efficiently while reducing environmental impacts. Smart irrigation technologies based on the Internet of Things (IoT) have emerged as promising solutions to address these limitations. The aim of this study is to provide a comprehensive understanding of the current state, challenges, and potential of IoT-based smart irrigation systems to support broader adoption in sustainable agriculture. This review employs a narrative literature review method, synthesizing peer-reviewed studies published between 2015 and 2025 that examine smart irrigation architectures, sensor technologies, monitoring mechanisms, and real-time control strategies. The findings indicate that IoT-enabled irrigation systems can reduce water usage by up to 40% while improving crop yield performance. However, the literature also highlights persistent obstacles, including high implementation costs, limited digital infrastructure, and low adoption readiness among farmers. Thius, this review concludes that smart irrigation holds substantial potential to advance sustainable water management, yet further research is required to address technological, economic, and operational constraints that hinder large-scale deployment. Also, this study offers researchers a clearer map of existing gaps and future research directions providing a timely foundation for advancing innovation in smart irrigation and precision agriculture.

***Keyword**: Water Use Efficiency, Internet of Things (IoT), Smart Irrigation, Sustainable Agriculture, Irrigation Monitoring and Control*

1. INTRODUCTION

Irrigation is one of the key factors that must be prioritized to promote agricultural productivity [1, 2]. Conventional agricultural irrigation systems that waste farmers' time and energy have an unfavourable environmental impact by using water less effectively [3]. This environmental impact is water wastage, leading to lower groundwater levels. On the other hand, the water safety to be ingested by humans and restored to the environment must be assured. Several studies suggest changes in social-economic policies and technological innovation to reduce water usage in irrigation [1, 4]. Additionally, agriculture will always contribute to world water demand and expand in dry and semi-arid areas. In implementing sustainable agriculture, an agricultural system is needed, especially an effective and efficient irrigation system, so that the water used can be utilized as well as possible by minimizing the wastage of water use [5]. However, many existing irrigation systems remain inefficient due to lack of real-time monitoring and decision-making capabilities, particularly in smallholder farming contexts.

Previous research has explored various smart irrigation models using IoT and automation to optimize water usage [7–9], yet there remains a lack of in-depth discussion regarding their adaptability, limitations, and long-term sustainability in diverse agricultural settings. Furthermore, most studies have focused on technical performance without fully addressing broader socio-environmental impacts or integration with sustainable development frameworks. For these reasons, a technological approach is required to implement more efficient irrigation, increase agricultural productivity, and also more environmentally friendly [6].

The growing global fascination with digital technology-driven agriculture can be ascribed to its relatively uncomplicated field management capabilities and robust real-time system of monitoring. Smart irrigation systems utilizing data-driven techniques such as the Internet of Things (IoT) that improve agricultural productivity while minimizing the environmental footprint are one of the current technological approaches on the rise [7-9]. This technology enables irrigation to be regulated according to the sensor installed so that water usage can be more precise. Better insights may be produced from field data by using digital technologies like IoT, allowing farming techniques to be planned methodically with less manual work [10].

Despite the growing body of literature, there is still limited synthesis of how IoT-based smart irrigation systems can be effectively implemented to align with sustainability goals such as SDG 6, particularly in regions with resource constraints or limited infrastructure. The urgency lies in identifying not only the technological solutions but also the systemic barriers and enablers that determine successful implementation. This forms a critical gap that this study seeks to address. However, studies on this topic's challenges and prospects have been conducted and still need to be completed. This study aims to provide a more comprehensive view of the application of smart irrigation so that it can be implemented more broadly. With the increased use of IoT-based irrigation systems, it is hoped that water conservation will be consistent with SDG 6, which ensures that everyone has access to clean water and sanitation, and whose various targets and indicators pertain to all water functions and services, including irrigation.

2. METHODS

This study adopts a narrative literature review approach to synthesize current research on smart irrigation systems, with a specific focus on the integration of IoT technologies in agricultural water management. A narrative review was selected due to its suitability for providing a comprehensive and interpretive overview of a broad and evolving field, particularly when the aim is to identify research trends, technological developments, and thematic gaps rather than to perform quantitative synthesis. The review process involved a structured search and selection of peer-reviewed journal articles. To ensure both relevance and academic rigor, only articles published between 2015 and 2025 were considered. Priority was given to publications in indexed journals, open-access sources, and journals with established reputations in the fields of agricultural engineering, environmental sciences, and information technology. The literature search was conducted using established academic databases and repositories, including Elsevier, SpringerLink, Google Scholar, and ResearchGate. Relevant articles were identified using combinations of the following keywords: “smart irrigation,” “IoT in agriculture,” “real-time irrigation,” “wireless sensor networks,” and “agricultural automation.” Inclusion criteria required that articles explicitly address at least one of the following areas: (1) smart irrigation systems incorporating sensing or automation, (2) IoT-based monitoring and control in agriculture, or (3) system evaluations related to water-use efficiency and sustainability. Articles focused exclusively on conventional irrigation methods without technological integration were excluded.

The initial search yielded approximately 100 publications. A two-stage screening process was employed. In the first stage, titles and abstracts were assessed to determine thematic relevance. In the second stage, full-text articles were reviewed to evaluate methodological quality and the extent to which the content aligned with the objectives of this study. This process resulted in the selection of 35 articles that met all inclusion criteria and provided a diverse yet coherent representation of the current state of research in smart irrigation. Each selected article was subjected to a qualitative thematic analysis. Key information, such as the type of irrigation system examined, the sensors and controllers used, the technological framework, the metrics for performance evaluation, and reported outcomes was extracted and organized into thematic categories. These themes formed the basis for a critical synthesis aimed at highlighting the evolution of smart irrigation technologies, the reported benefits and limitations of various system configurations, and the outstanding challenges that remain in practice. Although this review does not involve quantitative meta-analysis, the methodological rigor applied in the search, selection, and synthesis processes ensures transparency, reproducibility, and academic reliability. The resulting analysis contributes to a deeper understanding of how IoT technologies are shaping irrigation practices, while also identifying key areas for future empirical investigation.

3. RESULTS AND DISCUSSION

3.1 Internet Of Things For Agriculture

The utilization of the Internet of Things (IoT) exhibits considerable promise in agricultural automation. The Internet of Things (IoT) refers to a network of tangible entities, called "things," which can establish network communication. This connectivity empowers these entities to gather and exchange data and engage with their surrounding environment [11]. In the current day, the integration of technology has become imperative within the agricultural sector due to the need for more conventional farming methods to meet the growing global food requirements. In the agriculture sector, IoT has made huge strides in agricultural management. The integration of various agricultural equipment and gadgets facilitates the establishment of a network, enabling them to collaborate and make informed decisions on irrigation and fertilizer supply [12]. Smart solutions enhance the precision and efficiency of equipment for monitoring plant growth and animal management. Data from various sensing devices is collected via wireless sensor networks (WSNs). To facilitate the evaluation and analysis of remote data for effective decision-making and subsequent decision implementation, it is imperative to establish a connection between cloud services and the Internet of Things (IoT) [13].

According to the Food and Agriculture Organization (FAO), an estimated 20 to 40% of agricultural produce is lost annually due to pest infestations, diseases, and inadequate crop surveillance [14]. Consequently, using sensors and intelligent systems enables the surveillance of meteorological parameters, assessment of fertility conditions, and accurate estimation of the optimal quantity of fertilizers necessary for promoting crop development. The fertility of the soil is negatively impacted by excessive fertilizer use. The potential exists for a significant reduction in human intervention across many agricultural activities through integrating the Internet of Things (IoT) with advanced intelligent systems for making decisions. The success of automated activities is contingent upon the efficacy of intelligent decision-making. Integrating the Internet of Things (IoT) and artificial intelligence (AI) yields a system capable of surpassing the precision of human decision-making. Artificial intelligence (AI)-enabled systems are computer systems demonstrating the capacity to do activities commonly associated with human intellect. These tasks encompass a range of abilities, such as language translation, visual perception, voice recognition, and decision-making [15].

Since it is connected to the internet, IoT devices aim to provide real-time data, which is predominantly unstructured. Automation and problem-solving have been simplified by utilizing advanced techniques and methodologies, including Machine Vision, Machine Learning, Artificial Neural Networks (ANN), and Natural Language Processing. Of these, ANN and Machine learning are the methods most widely applied in studies on automatization in agriculture [16].

According to Kaul, Enslin [17], Artificial Intelligence (AI) refers to the academic discipline and practical domain dedicated to advancing of intelligent machines, specifically intelligent computer programs. Artificial Intelligence (AI) is a rapidly advancing technology within the agricultural sector. Using AI-based machines and systems has significantly advanced contemporary agricultural production systems. According to Talaviya, Shah [18], implementing of this technology has resulted in advancements in crop production and real-time monitoring, harvesting, processing, irrigation, and marketing. Artificial Intelligence (AI) can address intricate irrigation system issues involving multiple variables, non-linear relationships, and time-dependent dynamics. Artificial intelligence algorithms can imitate the cognitive processes involved in human decision-making within a particular domain. In the context of irrigation, AI is especially valuable in managing systems that involve multiple interdependent variables, such as soil moisture, evapotranspiration, rainfall, and plant water needs. Its ability to simulate complex, nonlinear processes makes AI a crucial component in optimizing irrigation strategies that reduce water waste and enhance crop performance. However, despite the promise of IoT, AI integration, challenges remain in terms of implementation costs, infrastructure readiness (especially in rural areas), and user adoption by farmers with varying levels of digital literacy. These limitations should be addressed through context-sensitive policy, education, and scalable design frameworks, particularly in developing countries where agricultural transformation is most needed.

3.2 Irrigation Scheduling In Real Time

The scheduling of irrigation is critical in setting the timing and quantity of irrigation, which has a direct impact on water consumption efficiency [19]. An estimation of the required amount of water can be derived by employing a standardized approach to determine the necessity of irrigation and formulating a comprehensive strategy to determine the appropriate quantity of water to be administered. Understanding the dynamics of plant water usage, which are influenced by the weather, the properties of the soil, and plant physiology, is necessary to apply irrigation water efficiently [20].

Real-time irrigation scheduling plays a crucial role in water saving by effectively adjusting the quantity of irrigation provided to meet the specific needs of plants. Numerous irrigation scheduling methods have been developed with the aim of aiding irrigators in the precise application of water to crops [21]. Recent study indicates that growers who employ manual, volume-based, and time-based irrigation scheduling as their primary scheduling strategy experience significant water losses [10]. Monitoring the many elements that influence plant growth and implementing a control strategy is necessary to ensure the provision of suitable quantities of irrigation water. This is crucial for the effective implementation of real-time irrigation scheduling. This inefficiency has been well-documented in recent research and is further supported by the comparative data shown in Table 1. Table 1 illustrates that real-time irrigation systems integrated with IoT and AI technologies can reduce water use by up to 43% compared to manual methods, while also improving crop yields by up to 10%. In contrast, traditional and volume-based methods are associated with higher water wastage and lower yield benefits. To ensure the success of real-time irrigation scheduling, it is crucial to monitor environmental variables continuously and implement intelligent control strategies that can respond to real-time feedback. IoT-based systems, especially when combined with artificial intelligence—enable predictive modelling, dynamic adjustment, and system learning over time. As such, these systems represent not only a technological advancement but also a practical strategy aligned with sustainable development goals, particularly SDG 6 on water resource efficiency.

Table 1. Comparison of Water Usage and Yield Improvement Across Irrigation Scheduling Methods

Irrigation Method	Estimated Water Use (L/ha)	Estimated Water Wastage (%)	Yield Improvement (%)
Manual (Fixed Schedule)	12,000	40%	0%
Volume-Based Scheduling	10,500	30%	+2%
Sensor-Based IoT	7,200	15%	+8%
Real-Time IoT + AI	6,800	5%	+10%

3.3 Smart Irrigation System Monitoring

3.3.1 Sensor Of Soil

Several soil moisture sensors are used to analyze parameters such as conductivity and pH [22]. Crop yields can be predicted by measuring soil conductivity because soil texture and organic matter can be indirectly estimated [23]. These two factors are clues to water availability and the presence of potential pest plants. Therefore, the amount of herbicide applied to the soil can be estimated by measuring the electrical conductivity of the soil [24]. In addition, the pH of the soil is also very important for plant growth [25]. A pH range of 6 to 7 indicates the ideal level of plant nutrition [26]. A low pH of around 4 to 5 can be toxic to the growth of some plants because the soil is highly acidic and can contain iron, manganese, and aluminum [27].

3.3.2 Sensor of Thermal

Plant growth in indoor and outdoor smart agriculture is affected by temperature, making monitoring important [28]. Some plants are susceptible to temperature changes. High temperatures can even affect shoot and root growth in a short period. The fluctuation in soil temperature directly influences the absorption of soil nutrients and the maintenance of soil moisture levels. The soil temperature significantly influences several physical processes occurring within the soil [31].

3.3.3 Sensor of Moisture

The soil's moisture level is one of the most significant variables for the growth of plants.. Moisture monitoring is necessary to predict water loss due to evaporation, that essential for plants' photosynthesis [33]. Humid conditions encourage the growth of mold and bacteria that can cause plants to die and crop failure [34, 35]. Furthermore, it is worth noting that high humidity can also catalyze the proliferation of pests, such as fungus gnats, which thrive in damp soil and feed on the roots of plants. The Raspberry Pi and Arduino prototyping boards are commonly employed in developing various soil moisture monitoring systems for irrigation control within the context of the Internet of Things. This is connected to several sensors to measure soil moisture fluxes in real-time and monitor crop water use for scheduling and decision-making irrigation [6, 36-41].

4. CHALLENGES

4.1 Concerns on Devices

The standardization of devices plays a pivotal role in promoting the extensive integration of technology across many applications, encompassing a vast array of contexts. Nevertheless, there needs to be standardized formats for data processing. Diverse outcomes may arise as a consequence of misunderstandings resulting from coding mismatches. Standardized machinery can effectively mitigate the difficulties linked to interoperability across diverse applications, systems, tools, and products. Furthermore, introducing of the 5G network has considerably amplified the velocity of communication between devices and servers, surpassing the capabilities of its predecessor, 4G, by a magnitude of 100. The 5G network can accommodate significantly larger volumes of data, rendering it an optimal technological solution for transmitting information originating from distant sensors. Hence, adopting 5G as the emerging communication infrastructure is imperative to meet the heightened security demands of consumers and provide faster data transmission speeds. The need for interoperability stands out as a significant challenge within the domain of smart agriculture. The utilization of heterogeneous devices is employed during the process of system design.

4.2 Concerns on Cost

The expenses associated with implementing Internet of Things (IoT) technology in the agricultural sector can be categorized into two main components: hardware costs and software costs [42]. The hardware cost encompasses acquiring various components such as IoT modules, base station infrastructure, and devices. Furthermore, incorporating sophisticated and accurate sensors and equipment presents a significant financial obstacle regarding real-time monitoring of several variables and implementing precision agriculture. The costs associated with software in smart farming systems encompass significant development, maintenance, and deployment expenses. Operational costs encompass the regular payments associated with centralized services or Internet of Things (IoT) platforms. The high expenses associated with hardware and software pose significant obstacles for farmers in implementing tools and technology. Consequently, reducing system costs remains a prominent difficulty encountered by several studies. To facilitate the extensive implementation of IoT-enabled smart agriculture applications, it is imperative to effectively decrease the expenses associated with the system and provide diverse economic frameworks. Energy management is a significant concern in Wireless Sensor Network (WSN) systems since it is considered one of the most prominent and evolving concerns. Traditional energy usage is considered unreliable and unsustainable, mostly attributed to technological advancements. Therefore, it is crucial to investigate and assess various potential energy-collecting techniques, such as wind, water, solar, vibrational energy harvesting schemes, and biomass, to advance the progress of IoT-based smart agricultural applications.

4.3 Concern on System

Considering the diverse landforms and adjusting agricultural methods accordingly to accommodate varying environmental circumstances is essential in agriculture. However, it is crucial to recognize that sensor nodes deployed in the field are susceptible to environmental fluctuations, which can significantly impact the precision of the gathered real-time data. In precision agriculture, technologies can integrate smoothly with external devices and their immediate surroundings. In certain instances, device compatibility may be hindered by persistent fluctuations in environmental conditions or hardware malfunctions. The potential disruption of wireless communication channels can lead to interruptions in the communication between wireless nodes and the cloud. Hence, it is imperative to prioritize the mitigation of climatic fluctuations while devising sophisticated methodologies for atmospheric correction and cloud detection. Furthermore, hierarchical structures exhibit superior performance compared to field network topologies in the case of systems with extensive deployments. The writer responsible for the Hench project was required to develop and execute a farming system in a deliberate and balanced manner, with the additional objective of minimizing the overall cost while maintaining optimal performance. The platforms and solutions created must prioritize usability, as farmers constitute the predominant user base for these agricultural applications. Acknowledging the ease of operation and user interface in this instance is important. Before system implementation, real-time analysis is crucial to mitigate any losses that may occur after deployment.

5. CONCLUSION

The global concern surrounding global warming and climate change has gained significant global attention, mostly due to its far-reaching repercussions on the critical matters of water shortage and food security. Acknowledging this consciousness has prompted researchers to intensify their efforts in advancing advanced methodologies for live monitoring and regulation in precision agriculture. These strategies have been developed to mitigate the effects of this unavoidable phenomenon. This research examines the monitoring and control techniques employed in precision irrigation systems, drawing on past and pertinent studies that have concentrated on improving water conservation in agricultural practices. This review paper offers a complete examination of the current research trends regarding advancing control systems for precision irrigation. It aims to evaluate the potential research prospects in this field, specifically focusing on enhancing water conservation, optimizing crop output, and improving energy efficiency in irrigation practices. The objective is to stimulate novel concepts and engage readers in exploring ways to strengthen existing monitoring and advanced control methods to achieve more precise irrigation for food security and mitigate the risk of impending water crises by conserving water resources.

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