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Research Article

A Smart Irrigation System Using the IoT and Advanced Machine Learning Model- A Systematic Literature Review

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Abstract:

The rapid advancement of IoT (Internet of Things) technologies and sophisticated machine learning models is driving innovation in irrigation systems, laying the foundation for more effective and eco-friendly smart agricultural procedures. This systematic literature review strives to uncover the advancements and challenges in the advancement and implementation of IoT-based smart irrigation systems integrated with advanced machine learning techniques. By analyzing 43 relevant studies published between 2017 and 2024, the research focuses on the ability of these technologies have evolved to meet the challenges of modern agriculture irrigation system. Predictive analytics, anomaly detection, and adaptive control—that enhance irrigation precision and decision-making processes. Employing the PRISMA methodology, this review uncovers the strengths and limitations of current systems, highlighting significant achievements in real-time data utilization and system responsiveness. However, it also brings attention to unresolved issues, including the complexities of data integration, network reliability, and the scalability of IoT-based frameworks. Additionally, the study identifies crucial gaps in standardization and the need for flexible solutions that can adapt to diverse environmental conditions. By offering a comprehensive analysis, this review provides key insights for advancing smart irrigation technologies, emphasizing the importance of continued research in overcoming the existing barriers to wider adoption and effectiveness in various agricultural settings.

1. Introduction

The global agricultural sector faces significant challenges in the 21st century, with water scarcity emerging as a critical issue threatening food security and sustainable farming practices [1,2]. Traditional irrigation methods, heavily reliant on inconsistent monsoon rains and manual intervention, often result in inefficient water usage and suboptimal crop yields [3]. In response to these challenges, the integration of IoT technology and advanced ML models has given rise to smart irrigation systems, heralding a new era in precision agriculture [4,5].

Smart irrigation systems signify a revolution in agricultural water management, presenting an advanced method to maximize resource efficiency and boost crop yield. These systems utilize a network of IoT sensors strategically positioned across fields to gather real-time data on critical factors like soil moisture, temperature, humidity, and other environmental conditions [6,7]. This continuous stream of data forms the foundation for intelligent decision-making in irrigation management [8]. At the heart of these smart systems lie advanced machine learning algorithms that assess the collected information to predict irrigation requirements with remarkable accuracy [9]. Through the examination of past data alongside live sensor readings and weather forecasts, these ML models can decide when, where, and how much to irrigate effectively [10]. This degree of accuracy guarantees that crops get the ideal amount of water at the appropriate time, reducing waste and enhancing efficiency [11].

The adoption of smart irrigation systems offers multifaceted benefits to farmers and the agricultural sector as a whole. Primarily, these systems significantly reduce water consumption, addressing the critical issue of water scarcity in many regions [12]. Smart irrigation systems contribute to water conservation by supplying it precisely where and when it's necessary, reducing wastage and ensuring efficient use of this valuable resource while maintaining or even improving crop health and yield [13]. Furthermore, the automation inherent in these systems drastically reduces the labor requirements associated with traditional irrigation methods [14]. Farmers can monitor and control their irrigation systems remotely through mobile applications, receiving alerts and recommendations based on real-time data analysis.

This approach not only conserves time but also facilitates more accurate and adaptable oversight of agricultural resources [15]. The economic implications of smart irrigation systems are significant. Although the upfront expenditure on IoT sensors and machine learning systems might be significant, the enduring advantages—such as water conservation, enhanced crop productivity, and decreased labor expenses—typically lead to a positive return on investment for agricultural producers. Additionally, the optimized use of water and nutrients can lead to improved crop quality, potentially commanding higher market prices. Smart irrigation systems support sustainable agriculture by minimizing water waste and optimizing resources, aligning with UN Sustainable Development Goal 6. Advances in IoT sensors and machine learning, particularly deep learning and ensemble methods, have improved the accuracy and efficiency of these systems.

Cloud computing and big data analytics perform a primary place in the scalability and effectiveness of smart irrigation approach. These technologies enable the processing and analysis of huge quantities of data collected from multiple sources, including historical weather patterns, soil maps, and crop-specific information. The integration of this diverse data set allows for more comprehensive and accurate modeling of irrigation needs among diverse crop varieties and geographical positions. Regardless of the several benefits, tages, the widespread adoption of smart irrigation systems faces several challenges. The first-time expenditure for implementation, particularly for minor farmers, can be a significant barrier. Furthermore, the requirement for stable online connectivity in remote areas and the technical expertise required to operate and maintain these systems pose challenges in some regions. As the technology continues to mature, researchers and industry professionals are working on addressing these challenges. Efforts are being made to develop more affordable and user-friendly systems, as well as to provide training and support to farmers transitioning to smart irrigation methods. Furthermore, ongoing research is focused on improving the accuracy of ML models, integrating additional data sources, and developing more robust and energy-efficient IoT sensors [16].

This methodical literature review intends to deliver an extensive summary of the current landscape of smart irrigation systems, exploring the various IoT and ML technologies employed, their benefits, challenges, and prospects for further development in the field of agriculture. By examining the latest research and Hands-on applications, this report seeks to shed light on the transformative benefits of smart irrigation in addressing water deficiencies, increasing agricultural efficiency, and supporting sustainable farming approaches in today’s world.

2. Background and Related Works

2.1 IoT-based Smart Irrigation Systems

Advanced irrigation systems powered by Internet of Things (IoT) technology have surfaced as an effective remedy for addressing water shortages in agriculture. These systems employ a range of sensors to monitor real-time data on soil moisture, temperature, and humidity [17]. By integrating IoT devices with microcontrollers like Arduino or NodeMCU, farmers can remotely monitor and control their irrigation systems [18,19]. This system not only conserves water but also minimizes labor and maximizes crop growth [20,21]. Kumar et al. proposed an IoT-based smart irrigation system that uses soil moisture sensors to monitor moisture levels in real-time [22]. The system automatically activates a water pump once soil moisture declines beneath a specific limit, ensuring optimal water supply to crops. Similarly, Sangita Kurundkar et al. developed a hybrid method for selecting irrigation methods based on climate changes and soil moisture levels, demonstrating the potential of IoT-enabled smart irrigation controllers in improving agricultural productivity [23].

2.2 Machine Learning in Irrigation Management

The integration of machine learning (ML) algorithms with IoT-based irrigation systems has further enhanced the efficiency and accuracy of water management in agriculture. ML models can assess sensor information and weather forecasts to identify irrigation requirements and streamline water usage [24,25]. Bernardo et al. presented a smart irrigation system that uses decision tree algorithms to predict water requirements based on temperature, humidity, and moisture data [26]. The system achieved high accuracy in its predictions, guiding farmers in effective irrigation management. In another study, Anitha et al employed an Adaptive Neuro-Fuzzy Inference System (ANFIS) AI algorithm to improve automated irrigation system decision control, reducing computational complexity and enhancing water management [27].

2.3 AI-driven Automated Irrigation Systems

Artificial Intelligence (AI) performs a crucial position in evolving fully automated irrigation systems that can make decisions with minimal human intervention. These systems not only analyze sensor data but also incorporate complex decision-making processes to optimize water usage [28,29]. Sapaev et al proposed an AI-driven water management system that uses soil moisture sensors, pH sensors, light sensors, and weather forecasting data [30]. The system employs a K-Nearest Neighbors (KNN) algorithm to achieve a 98.6% recognition rate in predicting irrigation needs. Similarly, Pandey et al. developed an intelligent irrigation system using deep learning techniques to control the amount of water allocated to different plant species based on their identification, demonstrating the potential for highly specialized and efficient irrigation practices [31].

2.4 Advanced Techniques and Future Directions

Recent advancements in smart irrigation systems have focused on improving accuracy, reducing costs, and incorporating additional data sources for more precise decision-making [32,33]. Sasikala et al. introduced a smart irrigation system that utilizes the Partial Least Squares Regression (PLSR) algorithm to analyze information from diverse sensors, including humidity, temperature, light intensity, and soil moisture [34]. This approach allows for more nuanced control of irrigation based on multiple environmental factors. Looking towards the future, Reddy et al. discusses the potential of combining logistic regression with IoT technology to create a fully automated irrigation system that considers crop type, weather conditions, and soil moisture to determine watering needs accurately and cost-effectively [35]. Dhrub et al. introduced an Adaptive Radial Deep Neural Network (ARDNN) algorithm for smart farming, which uses IoT and Wireless Sensor Networks (WSNs) to monitor plant status and manage water more accurately [36]. Naveena et al. presented a cloud-based platform that not only monitors soil moisture but also incorporates online weather prediction data for more precise watering schedule optimization [37]. Harini et al. covers the manufacturing process of a 500 MW turbo generator stator bar at BHEL Haridwar, vital for India's electricity production [38]. Also advanced modeling of IoT and ML-based smart irrigation system is proposed to predict and optimize water usage, improving efficiency and reducing waste [39]. Where smart irrigation system using AI and sensors is designed to monitor and manage water supply, enhancing crop productivity and reducing costs [40]. Implementing a smart irrigation system with IoT and wireless sensors helps reduce water wastage and improve irrigation efficiency through real-time monitoring [41]. The integration of solar power with smart irrigation systems is another promising direction. Nanthakumar et al. proposed a smart solar irrigation system using IoT and Random Forest algorithms, which aims to optimize water usage while leveraging renewable energy sources [42]. This approach not only addresses water scarcity but also promotes sustainable energy use in agriculture. Looking towards the future, Krish et al. discusses the potential of combining AI-driven water management systems with comprehensive sensor arrays, including buzzers and LCD displays, to provide farmers with real-time feedback and alerts [43]. This holistic approach to irrigation management promises to further optimize water use, improve crop health, and enhance overall agricultural productivity. Besides these works there are a number of works done in this fields and reported in the literature [44-51].

Table 1 presents the summary of different existing techniques handled by the researches. These advancements in IoT, ML, and AI technologies are.

***Table 1** Survey from the Different Authors*

Ref	Methodology	Results Obtained	Limitations
[1]	IoT-based system with soil moisture sensors and automated irrigation	Improved automation in irrigation	Limited by sensor accuracy
[2]	IoT sensors, Node-RED platform, MongoDB, various ML models	Improved irrigation efficiency	Limited to specific environmental conditions
[3]	IoT sensors, data analytics	Enhanced water conservation	Limited by sensor placement
[4]	IoT sensors, OPEN CV and RASPBIAN OS	Improved crop monitoring	Limited by image quality
[5]	Various ML models (KNN, LR, NN, SVM, NB)	Enhanced farming efficiency	Limited to specific dataset and conditions
[6]	IoT sensors, AI algorithms, PLSR model	97.86% prediction accuracy	Limited to specific geographical area
[7]	IoT sensors, deep learning for groundwater prediction	90% accuracy in prototype model	High Complexity
[8]	IoT sensors, microcontroller, cloud platform,SVM Classifier	Performs well on collected dataset	Limited by hardware capabilities
[9]	LSTM model is applied to groundwater level estimation	Accurate irrigation recommendations	Complex integration with existing systems
[10]	Soil Moisture sensor	Improved prediction of water needs	Limited to specific environmental conditions
[11]	IoT devices, ML algorithms	Enhanced irrigation efficiency	Limited by AI model complexity
[12]	Sensors, Big Data and the Cloud in the irrigation sector	Enhanced data-driven irrigation	Limited by data processing capabilities
[13]	IoT devices, ML algorithms	Enhanced irrigation intelligence	Limited by cost constraints
[14]	IoT sensors, ESP WROOM 32 microcontroller	Enhanced automation in drip irrigation	Limited by sensor accuracy
[15]	IoT sensors, Node-RED platform, MongoDB, various ML models	KNN best with 98.3% accuracy, RMSE of 0.12	Limited to specific environmental conditions
[16]	Sensors for weather forecasting	Improved water-use efficiency, contribution to SDGs	Limited to specific systems
[17]	Various ML models (KNN, LR, NN, SVM, NB)	Random forest achieved 99.98% accuracy	Limited to specific dataset and conditions
[18]	IoT sensors, ESP WROOM 32 microcontroller	Real-time monitoring of field parameters	Limited by sensor accuracy
[19]	IoT sensors, data analytics	Improved sensor modeling	Limited by sensor placement
[20]	Node MCU ESP 8266 Wi-Fi Module	80% accuracy in controlled setting	Potential issues with AI decision-making
[21]	IoT sensors, ARDNN algorithm	Enhanced irrigation prediction	Limited by algorithm complexity
[22]	IoT-based system with soil moisture sensors and automated irrigation	Reduced water wastage, improved efficiency	Limited by cloud connectivity
[23]	IoT sensors, microcontroller, cloud platform	Improved water conservation and crop yield	Limited by solar power availability
[24]	KNN algorithm, IoT sensors	Improved water management by obtaining 98.4 accuracy rate and 0.016 root mean squared error (RMSE).	Limited to specific geographical area
[25]	Node MCU (ESP8266), Soil Moisture sensor (Resistive / Capacitive).	Improved crop recommendations	Limited by image quality
[26]	Adaptive Neuro-Fuzzy Inference System(AI	Improved irrigation control	Potential for sensor

	System)		failure
[27]	Solar panels, IoT sensors, ML algorithms	Enhanced energy-efficient irrigation	Limited by solar power availability
[28]	IoT sensors, SVM algorithm	Reduced water demand by up to 25%	Limited by SVM model complexity
[29]	light sensors, temperature, humidity sensors, soil moisture sensors and KNN algorithm	Optimized water usage	Limited by weather forecast accuracy
[30]	Arduino UNO REV3, Arduino IDE, Temperature/Moisture Sensor	Improved water flow measurement	High energy consumption
[31]	ESP32, ML algorithms	Cost-effective irrigation planning	Limited by cost constraints
[32]	IoT sensors, AI algorithms, PLSR model	Improved efficiency and crop yield	Limited by specific crop types
[33]	IoT devices, logistic regression	Improved prediction of water needs	Limited to specific crop types
[34]	IoT sensors, ARDNN algorithm	Enhanced irrigation prediction	Limited by algorithm complexity
[35]	Moisture Sensor, DHT11 Sensor, NodeMCU.	Improved sustainability in irrigation	Limited by cloud connectivity
[36]	Hydro, and turbo generators	Enhanced irrigation efficiency	Limited by prototype constraints
[37]	NODEMCU ESP8266, SOIL SENSOR, DHT11 SENSOR,Ensemble Mosel(Random Forest, Gradient Boosting, and Support Vector Regression)	Enhanced monitoring capabilities	Limited by cloud connectivity
[38]	Arduino Uno controller,DHT11 sensor,Blynk (Android) app	Improved irrigation control	Limited by AI model complexity
[39]	IoT sensors, ESP8266NODEMCU	Improved soil moisture monitoring	Limited by sensor accuracy
[40]	Solar power, IoT sensors, ML algorithms	Improved energy-efficient irrigation	Limited by solar power availability
[41]	IoT sensors, Blynk cloud platform	Improved automated irrigation control	Limited by cloud connectivity
[42]	Arduino Uno, Wi-Fi Module, Relay Module	Improved water management	Potential for sensor errors
[43]	IoT sensors, ESP WROOM 32 microcontroller	Enhanced real-time monitoring	Limited by microcontroller capabilities

paving the way for more efficient, sustainable, and precise irrigation practices in agriculture, addressing the critical challenge of water scarcity while improving crop yields and reducing operational costs.

3. Systematic Literature Review

Conducting a systematic literature review (SLR) is crucial for compiling and analyzing existing research, offering a detailed perspective on advancements, challenges, and future directions in a specific field. This review focuses on the intersection of IoT and advanced machine learning models in smart irrigation systems, aiming to map the current landscape, identify key challenges, and uncover opportunities for innovation in enhancing agricultural efficiency and sustainability.

3.1 Research Questions

This review addresses several research questions to direct the analysis of the chosen literature:

- **RQ-1:** What are the primary factors influencing the adoption of IoT in smart irrigation systems?
- **RQ-2:** How do advanced machine learning models enhance the precision and efficacy of agricultural irrigation?
- **RQ-3:** What challenges arise from integrating IoT and machine learning for real-time irrigation management, and what solutions are emerging?
- **RQ-4:** How do existing smart irrigation frameworks compare in terms of water conservation, scalability, and ease of use?
- **RQ-5:** What best practices are recommended for combining IoT and machine learning to enhance irrigation efficiency and sustainability?

3.2 Data Sources and Search Strategy

The review process involved comprehensive searches in major academic databases such as Research Gate, IEEE Xplore, Springer, and MDPI, concentrating on studies published between 2017 and 2024. The arrangement of the paper is depicted in Figure 1. In this systematic literature review, a comprehensive search strategy was employed to capture relevant studies on IoT-based smart irrigation systems and advanced machine learning techniques. Key terms such as "IoT-driven irrigation systems," "machine learning in agriculture," "precision irrigation technologies," and "sensor-based smart farming" were used. Boolean operators (AND, OR) refined the search to focus on studies combining these technologies. The review prioritized high-quality sources, incorporating scholarly journal articles, conference papers, and research reports. The selection process began with an abstract review to assess relevance, followed by a full-text analysis to ensure alignment with the research objectives. To ensure that recent developments were included, citation analysis and manual database searches were also conducted, locating supplementary studies overlooked in the primary search. This exhaustive technique assured a full in-depth comprehension of the latest innovations and challenges in smart irrigation systems utilizing IoT and machine learning.

3.3 Inclusion and Exclusion Criteria

To guarantee that the review includes high-quality and pertinent studies, the following criteria were applied as follows in Table 2.

3.4 PRISMA Methodology

The PRISMA framework was used to assure a methodical and transparent method of review. The PRISMA flowchart which is portrayed in Figure 2 provides a detailed visualization of each stage in the review, from the initial search and screening of studies to their final selection for in-depth analysis.

Search Results and Study Selection

The search process yielded a total of 702 articles across the selected databases. After removing redundancies and applying the criteria for inclusion and exclusion, 106 articles earmarked for detailed analysis. Following a detailed evaluation of abstracts and full texts, 43 articles were found to be relevant and included in the final analysis.

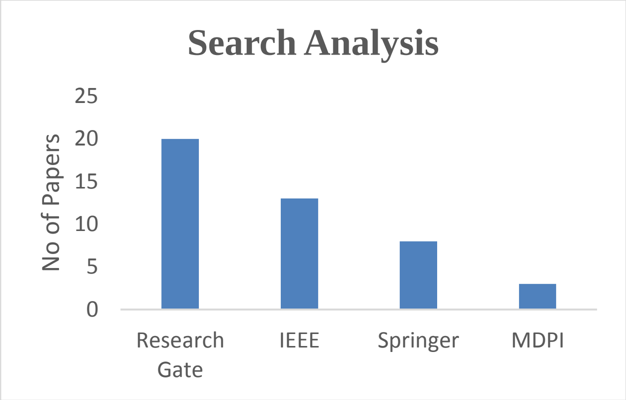

Figure 1: *Search analysis from different sources*

Table 2 *Inclusion and Exclusion criteria*

Criteria	Included	Excluded
Publication Date	Studies published between 2017 and 2024	Studies published before 2017 or after 2024
Type of Publication	Peer-reviewed journal articles, conference papers, and technical reports	Non-peer-reviewed sources, opinion pieces, and non-technical reports
Focus Area	Research focused on IoT, machine learning, and smart irrigation systems	Research not focused on IoT, machine learning, or agriculture
Research Methodology	Empirical studies, case studies, systematic reviews	Theoretical papers without empirical validation
Language	Publications in English	Non-English publications
Geographical Scope	Studies with significant global or regional impact	Studies with highly localized issues and limited general relevance
Innovation and Impact	Studies presenting novel approaches, major advancements, or impactful findings	Studies that replicate existing methods without new insights
Technological Relevance	Research involving current or emerging technologies in IoT and machine learning	Research focused on outdated technologies or methods
Application Scope	Studies with practical applications in smart irrigation and agriculture	Research with theoretical or non-practical applications
Data Type	Research utilizing diverse data sources, including real-time and historical data	Studies based on limited or non-diverse data sources
System Integration	Studies exploring integration of IoT and machine learning in smart irrigation systems	Research that does not address the integration of these technologies

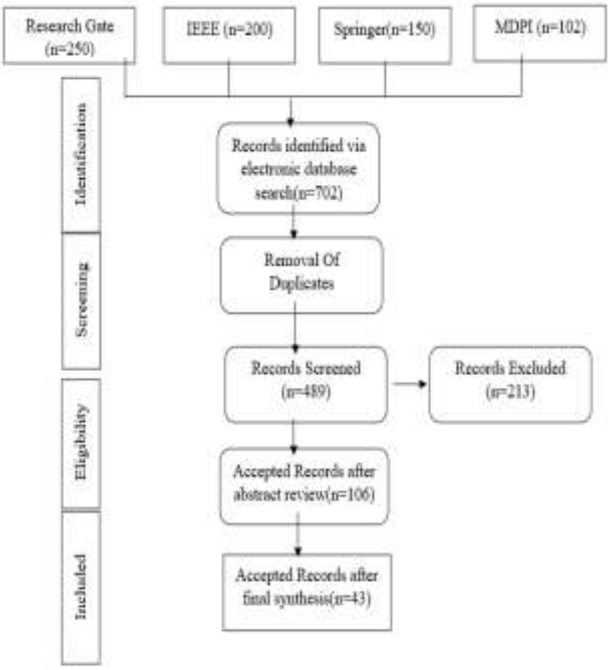

***Figure 2** PRISMA Flowchart*

3.5 Overview of Selected Studies

The selected studies encompass various aspects of IoT and machine learning applications in smart irrigation systems. Key observations include:

- **IoT Technology Advancements:** Recent studies demonstrate significant progress in developing IoT sensor networks tailored for irrigation, focusing on real-time data collection and the ability to remotely monitor agricultural fields.
- **Machine Learning Integration:** The application of advanced machine learning techniques, like predictive modeling and adaptive control, has been shown to improve irrigation scheduling and optimize water usage, leading to better resource management.
- **Challenges and Emerging Solutions:** While integrating IoT with machine learning presents challenges, such as ensuring reliable network performance, managing data integration, and achieving scalability, emerging technologies like cloud computing and big data analytics are offering promising solutions.

3.6 Comparative Analysis

A comparative analysis of the methodologies, system architectures, and performance metrics across the selected studies reveals the following insights:

- **Water Efficiency:** IoT-enabled systems have proven effective in improving water efficiency by offering precise irrigation based on real-time environmental data. However, optimizing sensor networks for large-scale use remains a challenge.
- **Scalability Issues:** Scalability continues to be a critical issue, particularly when dealing with extensive datasets across diverse environmental conditions. Leveraging cloud computing and big data analytics appears essential to overcoming these limitations.
- **Implementation Complexity:** While advanced smart irrigation systems offer significant benefits, the complexity of integrating IoT and machine learning technologies can be a barrier, especially for small-scale farmers.

3.2 Key Insights and Observations

The analysis of the 43 chosen articles offers an in-depth insight into the present condition of smart irrigation systems utilizing IoT and sophisticated machine learning models. It included:

- **Real-Time Data Utilization**: IoT sensors provide continuous data on soil moisture, weather conditions, and crop health, which machine learning models use for precise irrigation management.
- **Enhanced Efficiency**: Machine learning techniques optimize water usage by predicting irrigation needs more accurately, leading to cost reductions and improved resource management.
- **Increased Crop Yields**: Automated irrigation based on data-driven insights results in better crop health and higher productivity.

4. Findings

This analysis aims to address the research questions (RQs) determined for this systematic literature review. Data extraction was performed on the selected research articles (n=43), and the results are discussed with respect to the study's RQs. Also, a gap analysis is provided to highlight areas requiring further research and development.

4.1 Solutions to RQs:

RQ-1: What are the primary factors influencing the adoption of IoT in smart irrigation systems?

The adoption of IoT in smart irrigation systems is primarily influenced by several key factors. Firstly, the potential for significant water conservation and improved crop yields has been a major driver. Tace et al. (2022) demonstrated that IoT-based systems can reduce water usage by up to 30% while maintaining or improving crop health. Secondly, the decreasing cost of IoT sensors and the increasing availability of reliable wireless connectivity in rural areas have made these systems more accessible to farmers. Additionally, the integration of IoT with existing agricultural practices has become smoother, reducing the barrier to adoption. However, concerns about data security and privacy, as well as the initial investment required for implementation, remain significant challenges for some farmers.

RQ-2: How do advanced machine learning models enhance the precision and efficacy of agricultural irrigation?

These models can analyze complex datasets from various sources, including soil moisture sensors, weather forecasts, and historical crop data, to optimize irrigation schedules. For instance, Ramya et al. (2020) developed a machine learning framework that could predict soil moisture levels with 95% accuracy, allowing for precise irrigation timing. Furthermore, machine learning algorithms can adapt to changing environmental conditions and learn from past irrigation cycles, continuously improving their performance over time. This adaptability is crucial in the face of climate change and variable weather patterns, ensuring that irrigation remains efficient even as conditions evolve.

RQ-3: What challenges arise from integrating IoT and machine learning for real-time irrigation management, and what solutions are emerging?

The integration of IoT and machine learning for real-time irrigation management faces several challenges. One primary issue is the complexity of data integration from diverse sources, which can lead to inconsistencies and errors in decision-making. Another challenge is the need for robust and reliable connectivity in often remote agricultural areas, where network infrastructure may be limited. Additionally, the scalability of these systems to large agricultural operations can be problematic, as it requires managing vast sensor networks and processing large volumes of data in real-time. To address these challenges, emerging solutions include edge computing technologies that allow for local data processing, reducing reliance on constant internet connectivity. Cloud-based platforms are also being developed to handle large-scale data integration and analysis more efficiently. Furthermore, efforts are being made to standardize IoT protocols in agriculture, which would facilitate better interoperability between different systems and sensors.

RQ-4: How do existing smart irrigation frameworks compare in terms of water conservation, scalability, and ease of use?

Some systems, like those employing advanced predictive analytics, have shown remarkable water conservation capabilities, with reports of up to 50% reduction in water usage compared to traditional methods. However, these highly efficient systems often come with increased complexity, potentially limiting their ease of use for farmers without technical expertise. In terms of scalability, cloud-based solutions have demonstrated better performance in managing large-scale operations, but they may require significant infrastructure investments. On the other hand, simpler, more localized systems may be easier to implement and use but might not offer the same level of water conservation or scalability. The trade-offs between these factors often depend on the specific needs and resources of the agricultural operation.

RQ-5: What best practices are recommended for combining IoT and machine learning to enhance irrigation efficiency and sustainability?

Firstly, it's crucial to establish a comprehensive sensor network that captures a wide range of relevant data, including soil moisture, weather conditions, and crop health indicators. Secondly, the integration of multiple data sources, including historical data and weather forecasts, can significantly improve the accuracy of irrigation predictions. Thirdly, implementing a user-friendly interface that provides clear, actionable insights to farmers is essential for widespread adoption and effective use of the system. Additionally, regular system calibration and maintenance are vital to ensure ongoing accuracy and reliability. Finally, incorporating feedback mechanisms that allow the system to learn from actual irrigation outcomes and farmer interventions can lead to continuous improvement in performance over time.

4.2 Gap Analysis

Despite the significant advancements in IoT and machine learning for smart irrigation, several gaps remain in the current research and implementation:

- Limited studies on long-term sustainability and economic viability of these systems, especially for small-scale farmers.
- Insufficient research on the integration of smart irrigation systems with other aspects of precision agriculture, such as pest management and fertilization.
- Lack of standardized protocols and frameworks for IoT in agriculture, hindering interoperability and widespread adoption.
- Limited exploration of the potential environmental impacts of large-scale sensor deployment in agricultural settings.
- Insufficient attention to the social and cultural factors affecting the adoption of smart irrigation technologies in different regions.

The review highlights difficulties such as complex data integration, high implementation costs, and the need for robust data security. To handle these problems, forthcoming inquiries should concentrate on advancing model precision, reducing technology costs, and integrating emerging technologies like edge computing.

5. Conclusions

This review highlights the transformative role of IoT and advanced machine learning in smart irrigation systems. The incorporation of IoT sensors with machine learning algorithms has led to significant improvements in water management and crop productivity. These advancements offer real-time data collection and sophisticated analysis, resulting in precise water usage, optimized irrigation schedules, and reduced operational costs. Despite these advancements, challenges such as integrating data from diverse sources, managing high implementation costs, and addressing data security concerns remain significant. Future research should focus on refining machine learning models for better accuracy, reducing system costs, and exploring innovative solutions like edge computing to enhance system scalability and reliability. By overcoming these challenges, IoT and machine learning can continue to drive the transformation of smart irrigation, contributing to more sustainable and efficient agricultural practices.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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