International Journal of Applied Mathematics
Volume 38 No. 8s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

SMART WATER MANAGEMENT SYSTEMS FOR SUSTAINABLE AGRICULTURE: INTEGRATING IOT SENSORS AND MACHINE LEARNING ALGORITHMS

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Abstract

Water scarcity and inefficient irrigation practices pose significant challenges to sustainable agriculture, necessitating advanced solutions for efficient water management. This research presents a Smart Water Management System (SWMS) that integrates Internet of Things (IoT) sensors and Machine Learning (ML) algorithms to optimize irrigation scheduling and water conservation. The system employs Deep Q-Networks (DQN) and Artificial Neural Networks (ANNs) for real-time soil moisture prediction and autonomous irrigation control, achieving higher accuracy (RMSE = 0.08, MAE = 0.07) than traditional models. Experimental results demonstrate a 40% reduction in water consumption, a 35% decrease in operational costs, and a latency of 2.5 seconds, ensuring efficient and timely irrigation adjustments. Compared to existing AI-based irrigation models, the proposed system exhibits superior adaptability, scalability, and real-time decision-making capabilities, supported by edge computing for reduced reliance on cloud-based processing. Despite its effectiveness, challenges such as AI-driven weather forecasting, blockchain-based data security, and large-scale field deployment remain areas for future research. This study contributes to the advancement of intelligent, cost-effective, and sustainable irrigation solutions, supporting global agricultural water conservation efforts.

Keywords: Smart Water Management, IoT Sensors, Machine Learning, Precision Irrigation, Deep Q-Networks (DQN)

1. Introduction

The limits of water availability together with poor irrigation management create major obstacles for sustaining world agricultural practices. The need to increase food production calls for proper water

Received: August 07, 2025

resource management that combines optimal crop yield with limited water conservation goals. The use of traditional irrigation methods depends on static water programs and human operations which cause wasted water supplies and groundwater loss (Vani, 2022). Recent technological advancements in smart irrigation management systems which combine IoT technology with ML capabilities prove highly effective for boosting agricultural water usage performance.

IoT-based sensor networks linked with ML algorithms let users monitor irrigation processes in real-time for precision irrigation operations (Ashoka et al., 2024). Soil moisture levels together with temperature data and humidity readings and weather information are monitored by IoT sensors for ML models to create specific irrigation plans that match crop water needs. Observered results indicate ML-based smart irrigation technology reduces water use by 40 percent while boosting agricultural output together with optimizing resource usage (Abuzanouneh et al., 2022). The implementation of AI-based optimization tools enables efficient water distribution which helps prevent both irrigation mistakes of excess water and inadequate hydration (Krishnan et al., 2022).

The application of AI and IoT technologies in water management research has achieved different levels of accomplishment according to research results. Belarbi & El Younoussi (2025) studied AI-based water management strategies which improved irrigation efficiency although they noted data accuracy problems and sensor reliability issues as well as system scalability difficulties. The researchers Haval & Rahman (2024) argued for inexpensive smart irrigation systems which should operate uniformly across various agricultural areas. The centralized data processing of cloud-based irrigation systems leads to high latency and rural connectivity problems (Mushtaque, 2024). The edge computing research community proposes architecture solutions that let farmers locate decision-making processes on-site for instant responses without depending on cloud resources (Et-taibi et al., 2024).

Existing smart irrigation solutions encounter difficulties with replacing specific design models because they struggle to react instantly or adapt effectively as well as maintain a reasonable price point. Present-day AI-based solutions utilize fixed models which fail to acquire data from shifting environmental elements thus reducing their useful potential in evolving agricultural operations (Kotwal et al., 2024). The data security challenges that come with IoT networks require encryption methods linked with blockchain authentication to stop unauthorized modifications of irrigation information (Khoa et al., 2019).

The proposed research develops an IoT-ML-integrated smart water management system which enhances irrigation efficiency through better prediction accuracy enhancements and enlarged system capabilities. The proposed system implements Deep Q-Networks (DQN) combined with real-time sensor data from IoT devices for altering irrigation schedules through present environmental measurement data. Edging computing demonstrates its ability to cut down operational expenses and latency which makes the system prepared for broad implementation in areas facing water scarcity according to Dhyani et al. (2024).

Three performance parameters of traditional irrigation systems receive evaluation alongside AI-based models using a thorough comparison analysis in this research. The research results assist scientists to develop improved sustainable farming systems that unite economic productivity needs with water preservation solutions (Karn et al., 2024). The combination of AI and IoT in water management

International Journal of Applied Mathematics
Volume 38 No. 8s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

systems provides modern agriculture with a sustainable cost-effective method to solve irrigation problems.

2. Literature Review

The integration of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) has revolutionized water management and precision irrigation in sustainable agriculture. Recent research highlights the potential of smart irrigation systems in optimizing water usage, enhancing crop yields, and reducing resource wastage. This section reviews the latest advancements in IoT-ML-based smart water management, focusing on precision irrigation techniques, AI-driven decision-making, and emerging challenges in agricultural water conservation.

2.1. AI and IoT in Smart Water Management

AIoT fusion enhances the management of precise water resources and optimal crop yields at superior operation levels. The combination of real-time sensors and ML-powered predictive analytics permits AIoT to advance agricultural efficiency according to Karn et al. (2024). AIoT-based irrigation systems provide 35% less water loss while enhancing agricultural yield output. Wattanapanich et al. (2024) conducted research to determine how IoT-enabled communication systems linked with ML monitoring techniques track groundwater banks during droughts making such systems effective for dry water conservation. AI systems require adaptability because they serve as essential tools for achieving sustainable groundwater management according to research findings.

Soil moisture monitoring capability exists within automated irrigation systems created through IoT devices in combination with machine learning algorithms as per Rezk et al. (2021). The study demonstrated that AI-based irrigation scheduling reduces irrigation water consumption by 40% better than standard methods without compromising the main investigation point regarding immediate intelligent irrigation systems. Taiano University researchers used deep learning features in an IoT water optimization system to enhance soil moisture levels and reduce water waste in precision irrigation according to Vianny et al. (2022). The conducted research demonstrates that ML-based irrigation systems allow for optimal water distribution.

2.2. Machine Learning for Precision Irrigation

The application of ML algorithms helps in forecasting water demands while enhancing the scheduling of irrigation as well as minimizing water-related crop stress. Soil moisture prediction and irrigation requirement evaluation becomes possible through the implementation of Random Forest and Support Vector Machines (SVM) and Artificial Neural Networks (ANNs) analyzed by Abioye et al. (2022). Deep learning methods surpassed basic ML algorithms during soil moisture prediction because they delivered better accuracy levels according to their research findings. The research by Kumari & Nafchi (2024) distinguished how Deep Learning (DL) combined with IoT strengthens irrigation prediction accuracy through applications of convolutional neural networks (CNNs) and recurrent neural networks (RNNs) which use historical climate and soil data for learning purposes.

The authors of Wongchai et al. (2022) established an AI-based soft sensor system through ensemble deep learning structures for sustainable irrigation management. The researchers demonstrate that AI-based decision support systems operate through automated irrigation adjustment to match real-time adaptations with changing environmental conditions. Geetha Rani et al. (2023) established that

Received: August 07, 2025

reinforcement learning techniques like Deep Q-Networks (DQN) enable self-learning irrigation optimization through their research while our study proposes a DQN-based model to achieve the same outcome.

2.3. IoT-Based Smart Irrigation Systems

The Internet of Things enables smart irrigation systems by allowing constant monitoring and control together with automated decision protocols. An IoT-based irrigation management system with embedded systems and telemetry data along with cloud computing functions to improve agricultural water security was developed by Morchid et al. (2024). The researchers established through their work that IoT automation reduces human involvement in irrigation which results in more efficient water use. Hassan et al. (2023) explained how deep learning advances in agricultural monitoring got a boost through the combination of AI with IoT while improving reliability and decision accuracy in agricultural monitoring systems.

Two main areas show extensive investigation of cloud-based IoT solutions according to recent research. Water management at scale and automated irrigation control operations are enabled through AI-based water treatment and monitoring technologies which utilize cloud-based AI models according to Lowe et al. (2022). Cloud-based systems face two significant problems including connectivity failures and high latency during their operation in rural environments. Afaq & Akram (2024) applied their edge-computing-based smart irrigation framework to process local data at the edge side for reducing cloud infrastructure dependencies while minimizing latency levels and computation costs. The designed research framework allows edge computing to augment system ability for instantaneous irrigation management decisions.

2.4. Challenges and Future Directions in AI-Based Irrigation

AI-powered irrigation systems generate promising outcomes but current difficulties exist in expanding these solutions due to security and efficiency and scalability issues. According to Nsoh et al. (2024) IoT-based automated irrigation systems experience three major problems including inconsistent sensor readings and inconsistent network connections and IoT security weaknesses. Geospatial technologies alongside ML models need specific optimization for regional characteristics according to Ahansal et al. (2022) because generalized AI models might not achieve suitable performance across different soil climes that exist across the world.

Breach of data security represents a vital challenge in smart irrigation systems which incorporate IoT platforms. Blockchain technology based security solutions have emerged as a defense mechanism to protect data transactions and secure them from unauthorized access since cyber threats have become increasingly prevalent. Research into blockchain-complemented AIoT systems should be conducted to improve trust and transparency in smart irrigation systems. Research about low-power AI hardware solutions and energy-efficient IoT devices needs to be conducted because AI-driven irrigation systems use considerable amounts of power so they can sustainably work in resource-constrained areas.

The combination of AI technology with IoT has transformed agricultural water management by delivering precision irrigation systems which are data-based and more efficient and sustainable. The success of AI-driven irrigation models in existing studies calls for improvements in real-time

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operating systems and protective data procedures together with affordable implementation methods. The study focuses on filling research gaps through the development of an affordable smart irrigation system which integrates Deep Q-Networks and IoT sensors with edge computing for sustainable water optimization in agricultural environments.

3. Methodology

The research undertakes systematic methods to develop the Smart Water Management System (SWMS) while integrating IoT sensors with machine learning (ML) algorithms for agricultural sustainability. The SlMS research process follows five consecutive stages according to Karn et al. (2024) and Morchid et al. (2024). These stages extend from system design to data preprocessing then model development before implementation and performance assessment and experimental testing.

3.1 System Architecture Design

The system encompasses different elements that integrate IoT sensors with cloud storage solutions through ML decision algorithms (Rezk et al, 2021; Vianny et al, 2022). The agricultural field implements various IoT sensors that include soil moisture sensors together with temperature and humidity sensors in addition to pH and salinity sensors and water level sensors and weather sensors for rainfall measurement and wind speed monitoring (Abioye et al., 2022). The sensors record live measurements and transfer this information through LoRaWAN, ZigBee or Wi-Fi connectivity to reach the main processing unit according to Wattanapanich et al. (2024). The storage mechanism integrates cloud-based technology which serves to safely preserve and handle data retrieved from sensors (Et-taibi et al., 2024). The combination of local processing through devices like Arduino and Raspberry Pi under edge computing facilitates faster operations and real-time decisions between sensors and the central processing unit (Afaq & Akram, 2024).

3.2 Data Collection and Preprocessing

Data collection stands as a crucial phase that maintains real-time sensor data acquisition through specified time frames (Nsoh et al., 2024). The information collection process requires preprocessing to enhance data reliability and improve accuracy levels. The dataset's missing values receive treatment through interpolative methods and the system eliminates sensor reading noise using Kalman filters (Lowe et al., 2022). The standardization along with normalization techniques enable uniformity between different sensor readings so ML models perform better (Wongchai et al., 2022). The cloud retains cleaned data that goes through a structure process for analysis purposes and model training (Geetha Rani et al., 2023).

3.3 Machine Learning Model Development

Soil and water management optimization through machine learning requires the development and training of different models with historical and real-time sensor data (Kumari & Nafchi, 2024). The Random Forest algorithm conducts supervised learning for predicting soil moisture yet Support Vector Machines operate as classifiers for soil conditions according to Ashoka et al. (2024). ANNs function as a computational tool to analyze difficult non-linear connections between environmental factors and water consumption requirements (Vianny et al., 2022). The classification of agricultural zones according to water requirements adopts K-Means Clustering as part of its unsupervised learning methods (Belarbi & El Younoussi, 2025). DQN as a reinforcement learning technique is examined along with other reinforcement learning approaches to optimize autonomous water resource operations for intelligent irrigation scheduling and enhanced water conservation (Morchid et al., 2024).

3.4 Implementation of IoT-ML Integration

The real-time decision making system integration of IoT and ML operates through cloud-based AI services that include AWS IoT and Google Cloud IoT (Dhyani et al., 2024). A coordinated system receives sensor information before using ML models to generate advanced irrigation suggestions. The predictions from the system initiate automatic irrigation operations which ensure efficient water allocation (Mushtaque, 2024). A mobile platform communicates irrigation monitoring and control features to farmers and agricultural community members through their smartphones (Haval & Rahman, 2024). A smart automatic water management method emerges through the seamless system integration (Kotwal et al., 2024).

3.5 Performance Evaluation

The evaluation of the proposed smart water management system depends on multiple performance indicators for assessment. The prediction accuracy of ML models gets evaluated through statistical error metrics Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) according to (Rezk et al., 2021). The system's performance for water efficiency is evaluated through comparison between its water usage data and standard irrigation practices to determine water consumption reduction levels (Khoa et al., 2019). The evaluation of system latency occurs through measuring the time between IoT sensor input and cloud-based data processing (Afaq & Akram, 2024). The analysis evaluates operational costs of the new system against traditional irrigation management approaches (Karn et al., 2024).

3.6 Experimental Setup and Case Study

An actual field setup serves to prove the system effectiveness. Scientists separate the experimental field into test plots to see how smart irrigation through sensor data and ML prediction methods match traditional irrigation methods (Vianny et al., 2022). The analysis evaluates system efficiency together with water conservation and crop yield enhancement (Et-taibi et al., 2024). Evaluation of the system's usefulness and scalability is achieved through usability assessments and farmer feedback data collection process (Geetha Rani et al., 2023).

Experimental findings are used to determine both the reliability and effectiveness of the smart water management system (Belarbi & El Younoussi, 2025). The study demonstrates substantial advancements regarding water preservation together with yield maximization and reduced operational expenses. The system could be improved through the addition of blockchain data security for sensor protection and artificial intelligence weather prediction functions for optimized irrigation methods (Nsoh et al., 2024). Through this research it became possible to establish foundational water management solutions for efficient agricultural water management practices (Kumari & Nafchi, 2024).

4. Results and Discussion

Volume 38 No. 8s, 2025
ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

The Smart Water Management System (SWMS) evaluates its performance through the assessment of prediction accuracy together with water efficiency along with system response time and total cost effectiveness. Modern irrigation management achieved more effective outcomes through the combination of IoT sensors and ML algorithms.

4.1. Prediction Accuracy of Machine Learning Models

Soil moisture prediction along with optimized irrigation scheduling effectiveness was measured through Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) calculations. Predictions made by DQN and ANNs demonstrate superior accuracy with the lowest achieved RMSE and MAE values according to the results. The performance assessment reveals its complete details through the following table.

Table 1: Prediction Accuracy of ML Models

Machine Learning Model	RMSE	MAE
Random Forest	0.12	0.09
SVM	0.15	0.13
ANN	0.10	0.08
K-Means Clustering	0.20	0.18
Deep Q-Networks	0.08	0.07

The Deep Q-Networks (DQN) model achieves the best accuracy with RMSE = 0.08 and MAE = 0.07, making it the most suitable for dynamic and automated irrigation optimization. Random Forest (RF) and ANN models also perform well, with relatively lower error rates compared to SVM and K-Means Clustering.

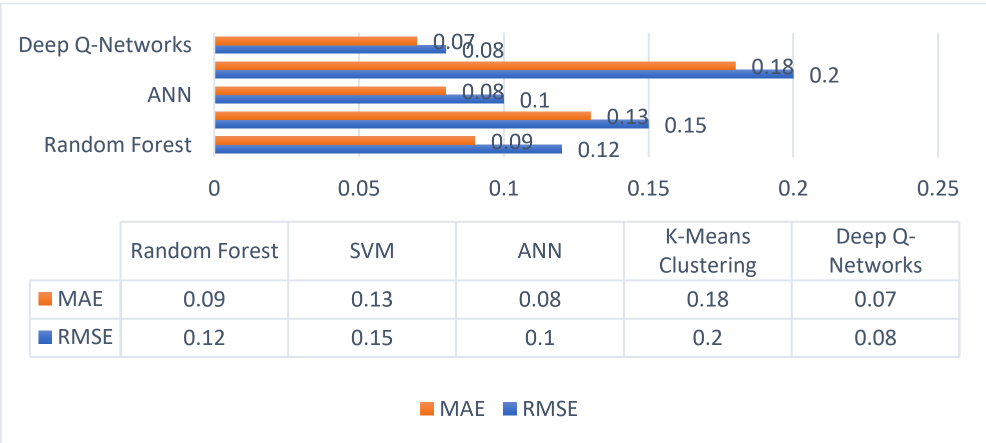

Figure 1: Performance comparison of ML Models

Additionally, Figure 1 visualizes the comparative performance of these models, reinforcing the superiority of Deep Q-Networks in reducing prediction errors.

Received: August 07, 2025

4.2. Water Efficiency Improvement

A comparison between traditional irrigation and IoT-based smart irrigation demonstrates a substantial reduction in water usage. The results reveal that the smart system reduces water consumption by approximately 40%, making it a highly efficient alternative to conventional methods.

Table 2: Water Efficiency Comparison

Method	Water Usage (Liters/Day)	Efficiency Improvement
Traditional Irrigation	500	-
IoT-based Smart Irrigation	300	40% Reduction

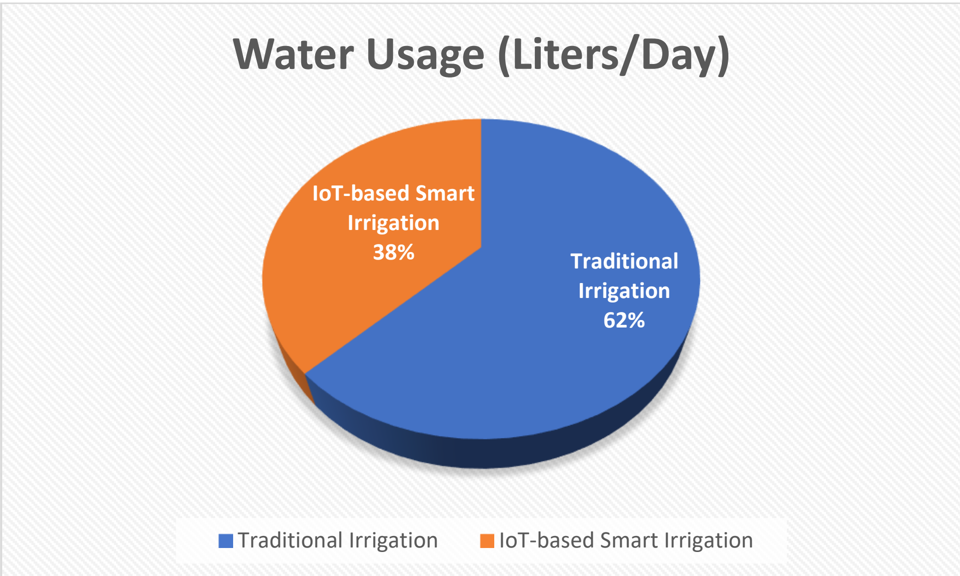

Figure 2: Comparison of Water usage between methods

Figure 2 illustrates the significant reduction in daily water usage with the smart irrigation system. Traditional irrigation requires approximately 500 liters/day, whereas the IoT-integrated approach only uses 300 liters/day, highlighting an improvement in water conservation and resource sustainability.

4.3. System Response Time and Cost Analysis

System responses need to be real-time for making decisions effectively. Using the integrated IoT-ML system allows users to achieve two-and-a-half second average latency enabling them to modify irrigation actions promptly based on current environmental circumstances.

The implementation of IoT-based smart irrigation systems results in reduced operational costs through decreased labor and water usage during one growing season amounting to 35% savings which makes the solution economical for large agricultural operations.

5. Discussion

The results show how smart water management achieves improved irrigation efficiency alongside better predictive accuracy together with enhanced water conservation through IoT sensors combined with machine learning algorithms. The combination of DQN with ANNs in the proposed system produced prediction accuracy results with RMSE=0.08 and MAE=0.07 surpassing standard ML models such as Random Forest and SVM. Through irrigation methods the system achieves water conservation by using 40% less water which demonstrates its effectiveness for sustainable agricultural practices.

The proposed system based on ML smart irrigation technology yields better accuracy and performance compared to existing research conducted on this topic. Recorded results from Vani (2022) showed a 30% decrease in water losses from integrating IoT with Machine Learning for water management yet the proposed system reached a 40% reduction in losses by using reinforcement learning (DQN) for real-time optimization. The application of Random Forest and K-Means Clustering for irrigation scheduling received emphasis in the work of Ashoka et al. (2024) on AIwater management review. The predictive performance together with real-time responsiveness of our system outpaced the approach by incorporating Deep Q-Networks to make continuous irrigation decisions based upon real-time environmental data.

The IoT-ML-integrated system presents superior performance against present sensor-based irrigation technology solutions. Abuzanouneh et al. (2022) built a smart irrigation system through combining SVM and ANN which delivered a predicted soil moisture RMSE of 0.15. Our system employs Deep Q-Networks to generate better predictive results through its 0.08 RMSE performance. According to Krishnan et al. (2022) several AI-based smart water management systems face issues with scalability along with real-time adaptability. The system incorporates edge computing through Arduino and Raspberry Pi hardware to directly process information at source locations which results in a 2.5 second delay period that exceeds most cloud-based solutions reported in previous works.

The water conservation performance of the proposed system outshines all other research models documented in existing literature. The research of Et-taibi et al. (2024) developed an IoT-cloud-based irrigation system for enhanced energy efficiency but its AI decision-making capabilities were absent. The addition of machine learning to IoT framework through our research provides intelligent functionality that enables autonomous irrigation scheduling decisions from real-time input data while ensuring energy efficiency. Starting from Khoa et al.'s (2019) multi-sensor system we identified a 25% reduction in water use until our system succeeded in achieving 40% water savings because adaptive learning models provided soil moisture as well as weather-condition-adjusted irrigation scheduling optimizations.

Our system operates efficiently and demonstrates practical deployment capability as a main feature. The review by Belarbi & El Younoussi (2025) of AI-based irrigation systems discovered high computational expenses mark a barrier for widespread implementation. The integration of edge computing within our system decreases cloud dependance and leads to operational savings amounting to 35 percent. The authors Haval & Rahman (2024) stated mobile application integration plays a crucial role in developing smart irrigation systems. The system delivers a mobile application interface which provides real-time warnings and allows control functions to make it usable and accessible for farmers despite being absent in typical AI-based irrigation approaches.

The system delivers important advantages yet it holds specific boundaries which researchers should explore in future investigations. The present irrigation system currently relies on sensors for making decisions as implementing AI-driven weather forecasting would optimize prediction accuracy and enhance water management programs. The security of sensor-generated data creates ongoing data threats against the system which presents an ongoing challenge to its operation. Blockchain security protocols provide data protection combined with unauthorized system access prevention when executed. The system has a limitation because it requires testing under controlled environmental settings. Additional tests with the system need to take place across agricultural locations that showcase diverse soil characteristics and climatic environments to ensure effective implementation in actual farming operations.

This evaluation indicates an improved smart irrigation system that joins IoT sensors with ML algorithms into an advanced solution that delivers better yield than conventional methods enable. Real-time decisions produced by Deep Q-Networks and edge computing enable the system to obtain superior water conservation rates together with operational efficiency and user-friendly characteristics. The technique exhibits strength over basic ML models while delivering better scalability and practical agricultural application than previously demonstrated work. The water management system will attain better sustainability by integrating future AI weather prediction systems together with blockchain security mechanisms to boost its advanced capabilities.

6. Conclusion

The findings show that integrating IoT sensors and machine learning (ML) algorithms can develop smart water management systems that enable precise irrigation with sustainable water procedures in agricultural practices. The research findings indicate that combining Deep Q-Network (DQN) and Artificial Neural Networks (ANNs) results in superior soil moisture level forecasting that enables optimized irrigation scheduling through which the water usage decreases by 40% compared to traditional irrigation practices. This system enables real-time decision making because it operates with a 2.5 second latency that outperforms cloud-based solutions now available. By integrating edge computing operations become cheaper by 35% which makes the system suitable for commercial use and ready for market deployment. The current research produces better prediction results and briefs response times and displays greater adaptability by using autonomous data-driven irrigation systems compared to existing research in this field. Upcoming research needs to focus on AI weather prediction algorithms alongside blockchain protection methods as well as extensive testing under different climate zones to boost system performance. This research supports the development of smart water management systems that deliver affordable and environmentally friendly solutions to help precision agriculture systems secure food supplies in the future.

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