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Artificial Intelligence and IoT-Based Precision Irrigation for Energy-Efficient Tropical Agriculture

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ABSTRACT
The growing need for sustainable agriculture has encouraged the adoption of intelligent irrigation technologies to improve water and energy efficiency in tropical farming systems. This study evaluated the effectiveness of integrating Artificial Intelligence (AI) and Internet of Things (IoT) sensors for precision irrigation optimization. A quantitative experimental design was conducted on 24 horticultural plots under tropical conditions over a 60-day period. IoT sensors monitored soil moisture, temperature, humidity, water flow, and energy consumption, while a machine learning model automatically controlled irrigation scheduling and water volume. Results showed that the AI-IoT system reduced water consumption by 31.4% and energy use by 22.7%, while improving crop productivity by 14.2% compared with conventional irrigation. These findings highlight the potential of AI-based precision irrigation to support sustainable and resource-efficient tropical agriculture.

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INTRODUCTION

The agricultural sector faces increasingly complex global challenges due to population growth, climate change, and increasing pressure on natural resources, particularly freshwater availability (Food and Agriculture Organization, 2024; Klerkx et al., 2021). Agriculture remains the largest consumer of freshwater resources worldwide, accounting for approximately 70% of total global freshwater withdrawals, making water-use efficiency a critical component of sustainable agricultural development (Food and Agriculture Organization, 2024). Improving water-use efficiency is essential not only for ensuring food security but also for mitigating the environmental impacts associated with excessive water extraction and energy consumption (Çetin & Yarosh, 2023). Global water-use efficiency increased by approximately 24% between 2015 and 2023; however, substantial disparities remain across regions, particularly in developing countries that rely heavily on agriculture as a primary economic sector (Food and Agriculture Organization, 2024). Consequently, there is an urgent need for innovative irrigation technologies capable of improving agricultural productivity while simultaneously reducing water and energy consumption (Javaid et al., 2023; Talaviya et al., 2020).

Irrigation management in tropical agricultural regions presents unique challenges because of significant fluctuations in rainfall patterns, temperature, humidity, and crop water requirements throughout the growing season (Getahun, 2024). onventional irrigation systems often operate using predetermined schedules without considering actual soil and environmental conditions, resulting in inefficient water distribution, excessive irrigation, and increased energy consumption (Vallejo-Gómez et al., 2023; Owino & Söffker, 2022). Recent advances in digital technologies have accelerated the adoption of precision agriculture, which integrates sensors, Internet of Things (IoT) devices, Artificial Intelligence (AI), cloud computing, and data analytics to optimize agricultural resource management (Wolfert et al., 2021; Zhai et al., 2020). Through continuous monitoring and automated decision-making, these technologies enable irrigation systems to respond dynamically to real-time environmental conditions and crop requirements, thereby improving efficiency and sustainability (Abioye et al., 2022; Liakos et al., 2021).

The integration of Artificial Intelligence and Internet of Things technologies has emerged as one of the most promising innovations in modern agriculture. IoT sensors facilitate continuous monitoring of soil moisture, temperature, humidity, and other environmental parameters, while AI algorithms process these data to support intelligent decision-making (Raja et al., 2024). According to Shahab et al. (2024), IoT-based agricultural management systems significantly improve resource-use efficiency through continuous environmental monitoring, automated data acquisition, and intelligent resource management strategies. Similarly, Delfani et al. (2024) emphasized that machine learning techniques enhance agricultural decision-making through predictive analytics, real-time data interpretation, and adaptive management approaches that improve operational performance under changing environmental conditions. Furthermore, Javaid et al. (2023) argued that AI-driven technologies contribute to sustainable agricultural development by improving operational efficiency, reducing resource waste, and supporting climate-resilient farming practices.

Several previous studies have reported positive outcomes from the application of AI and IoT technologies in irrigation management. Abioye et al. (2022) found that sensor-based precision irrigation systems can improve irrigation scheduling accuracy and reduce water losses. Likewise, Talaviya et al. (2020) reported that AI-assisted irrigation management contributes to optimizing water allocation and minimizing unnecessary irrigation activities. Kour et al. (2023) further demonstrated that the integration of IoT sensors and artificial intelligence enhances monitoring precision and enables autonomous control of agricultural processes. These findings suggest that intelligent irrigation technologies have considerable potential to improve resource efficiency and agricultural productivity under diverse environmental conditions.

Despite these advancements, several research gaps remain. Most existing studies have focused primarily on technical aspects such as sensor development, communication protocols, data transmission mechanisms, or machine learning model accuracy (Sarker et al., 2023; Raja et al., 2024). Research specifically examining the energy-efficiency performance of AI-IoT-based irrigation systems in tropical agricultural environments remains limited (Getahun, 2024). Moreover, studies simultaneously evaluating water consumption, energy usage, soil moisture stability, and crop productivity within a comprehensive assessment framework are relatively scarce (Abioye et al., 2022; Babar & Akan, 2024). Consequently, empirical evidence regarding the overall effectiveness of intelligent irrigation systems in tropical farming conditions remains insufficient, particularly from the perspective of integrated resource optimization.

Based on these issues, this study aims to analyze the effectiveness of integrating Artificial Intelligence (AI) and Internet of Things (IoT) technologies in optimizing energy-efficient precision irrigation systems in tropical agricultural land. Specifically, the study evaluates the effects of AI-IoT-based irrigation on water-use efficiency, energy consumption, soil moisture stability, and crop productivity compared with conventional irrigation methods. The findings are expected to contribute both theoretically and practically. Theoretically, this study expands current knowledge regarding the application of AI and IoT technologies in precision agriculture and sustainable irrigation management (Benos et al., 2021; Khanna & Kaur, 2022; Fountas et al., 2023). Practically, the results may provide valuable guidance for farmers, agricultural managers, technology developers, and policymakers in designing and implementing adaptive, resource-efficient, and environmentally sustainable irrigation systems. Ultimately, this research is expected to support the digital transformation of agriculture and contribute to the development of more productive and sustainable food production systems (Food and Agriculture Organization, 2024; Klerkx et al., 2021).

LITERATURE REVIEW

Artificial Intelligence in Precision Agriculture

Artificial Intelligence (AI) has emerged as one of the most influential technologies in modern agriculture, particularly in supporting data-driven decision-making processes. AI enables agricultural systems to analyze large volumes of environmental and operational data to optimize resource utilization and improve productivity. In precision agriculture, AI techniques such as machine learning, deep learning, and predictive analytics are widely applied for crop monitoring, yield prediction, disease detection, and irrigation management.

According to Liakos et al. (2021), Artificial Intelligence and machine learning technologies have become essential tools in modern agriculture due to their ability to process large datasets and generate accurate predictions for farm management. Similarly, Getahun (2024) emphasized that machine learning algorithms can support decision-making processes by improving the accuracy of agricultural predictions, enhancing resource-use efficiency, and optimizing farm management practices. Furthermore, Talaviya et al. (2020) reported that AI-based agricultural systems contribute to efficient irrigation management by determining water requirements based on environmental and crop conditions, thereby reducing resource wastage while maintaining crop productivity. Klerkx et al. (2021) also highlighted that digital agriculture technologies, including AI-driven systems, play a significant role in enhancing sustainability and operational efficiency in agricultural production. These findings indicate that AI plays a crucial role in developing intelligent agricultural systems capable of adapting to dynamic environmental conditions.

Internet of Things Sensors for Agricultural Monitoring

The Internet of Things (IoT) has transformed agricultural management by facilitating continuous monitoring of environmental and crop conditions through interconnected sensors. IoT devices collect real-time information on soil moisture, temperature, humidity, solar radiation, and water flow, enabling farmers to make informed decisions regarding resource management.

Khanna and Kaur (2022) emphasized that IoT-based sensor networks improve the accuracy of environmental monitoring and provide the foundation for automated agricultural systems. Furthermore, integrating IoT technologies into farming operations allows for remote monitoring and control, reducing labor requirements and improving operational efficiency. Recent studies have demonstrated that sensor-based monitoring systems significantly enhance water management practices by providing precise information about crop water needs and soil conditions (Fountas et al., 2023; Saiz-Rubio & Rovira-Más, 2023).

Precision Irrigation Systems and Water-Use Efficiency

Precision irrigation refers to the application of water according to the specific needs of crops, considering spatial and temporal variability within agricultural fields. Unlike conventional irrigation systems, precision irrigation utilizes environmental data and intelligent control mechanisms to optimize irrigation timing and water volume. Elshaikh et al. (2024) explained that AI-supported precision irrigation systems contribute significantly to water conservation by minimizing excessive irrigation and improving irrigation scheduling.

Likewise, recent research has shown that precision irrigation technologies can improve water-use efficiency while maintaining or increasing crop productivity. The implementation of sensor-driven irrigation management is particularly important in tropical agricultural regions where fluctuations in rainfall and temperature frequently influence crop water demand. Consequently, precision irrigation has become a critical component of sustainable agricultural development.

Integration of Artificial Intelligence and Internet of Things in Smart Irrigation

The convergence of AI and IoT technologies has accelerated the development of smart irrigation systems capable of autonomous operation. IoT sensors continuously collect environmental data, while AI algorithms analyze these data to generate irrigation decisions in real time. This integrated approach enables irrigation systems to respond dynamically to changing field conditions without requiring constant human intervention.

According to Owino and Söffker (2022), the integration of intelligent sensing technologies, automated control systems, and real-time data processing significantly enhances agricultural management by enabling continuous environmental monitoring and adaptive decision-making. Similarly, Vallejo-Gómez et al. (2023) emphasized that smart farming systems based on AI-IoT technologies improve operational efficiency, optimize resource utilization, and support sustainable agricultural production through automated monitoring and control mechanisms. Furthermore, Sharma et al. (2023) highlighted that Artificial Intelligence and machine learning technologies facilitate adaptive agricultural management by improving data integration, predictive analytics, and decision-support capabilities across farming systems. The synergy between AI and IoT represents a significant advancement in precision agriculture and is increasingly recognized as a key driver of agricultural digital transformation.

METHODOLOGY

Research Design

This study employed a quantitative approach using an experimental research design to evaluate the effectiveness of integrating Artificial Intelligence (AI) and Internet of Things (IoT) sensors in optimizing precision irrigation systems based on energy efficiency in tropical agricultural land. Experimental research was selected because it enables the investigation of causal relationships between technological interventions and agricultural outcomes under controlled conditions (Creswell & Creswell, 2023).

The study compared a conventional irrigation system with an AI-IoT-based precision irrigation system to determine differences in water consumption, energy usage, soil moisture stability, and crop productivity. The experiment was conducted over a 60-day observation period, during which environmental and irrigation data were continuously monitored and recorded.

Population, Sample, and Research Instruments

The population of this study consisted of horticultural agricultural plots located in tropical farming environments. A total of 24 agricultural plots were selected using purposive sampling, a non-probability sampling technique, because the plots possessed similar characteristics in terms of soil type, crop variety, irrigation infrastructure, and environmental conditions. This approach was adopted to minimize external influences that could affect the experimental results and to ensure comparability between treatment groups (Campbell & Stanley, 2021). The selected plots were equally divided into two groups, with 12 plots assigned to conventional irrigation and 12 plots assigned to the AI-IoT-based precision irrigation system.

Data were collected using several IoT-based monitoring devices, including soil moisture sensors, temperature and humidity sensors, water flow sensors, and energy consumption monitoring modules. Soil moisture sensors measured the volumetric water content of the soil, while temperature and humidity sensors monitored environmental conditions. Water flow sensors recorded irrigation water usage, and energy monitoring devices measured electricity consumption associated with irrigation activities. Prior to deployment, all instruments were calibrated according to manufacturers' guidelines to ensure data accuracy and reliability. Similar sensor-based monitoring systems have been widely utilized in precision agriculture due to their ability to provide accurate real-time information for irrigation management (Mekonnen et al., 2023).

Research Procedure

The research was conducted in several stages. The first stage involved preparing the agricultural plots, installing IoT sensors, configuring the wireless communication network, and calibrating all monitoring devices. The second stage involved collecting baseline environmental and irrigation data to establish initial field conditions. Subsequently, a machine learning-based AI model was developed using historical and real-time data obtained from the sensors, including soil moisture, temperature, humidity, water flow, and irrigation records. The AI model was designed to automatically determine irrigation timing and water volume according to crop water requirements and prevailing environmental conditions.

During the implementation stage, the treatment plots operated using the AI-IoT-based irrigation system, while the control plots continued to use conventional irrigation practices. Environmental conditions, water consumption, energy usage, and crop performance were continuously monitored throughout the 60-day experimental period. All sensor data were automatically transmitted and stored in a cloud-based database. To maintain data quality, periodic inspections, validation procedures, and anomaly detection processes were conducted throughout the study period, ensuring the reliability and consistency of the collected data (Farooq et al., 2023).

Data Analysis

Data analysis was performed using both descriptive and inferential statistical techniques. Descriptive statistics, including means, standard deviations, percentages, and efficiency indicators, were used to summarize irrigation performance, environmental conditions, and crop productivity. Comparative efficiency analysis was conducted to evaluate the performance differences between conventional irrigation and AI-IoT-based irrigation systems, particularly regarding water consumption, energy utilization, soil moisture stability, and crop yield.

To determine whether statistically significant differences existed between the treatment and control groups, Independent Samples t-tests were conducted at a significance level of 0.05 (Field, 2024). Statistical analyses were performed using IBM SPSS Statistics Version 29, while machine learning model development and sensor data processing were conducted using Python programming language with the Scikit-learn and Panda's libraries. The combination of descriptive and inferential analyses enabled a comprehensive evaluation of the effectiveness of AI-IoT integration in improving irrigation efficiency and supporting sustainable agricultural management in tropical environments.

RESULT AND DISCUSSION

Water Consumption Analysis

The analysis of irrigation water consumption revealed substantial differences between the conventional irrigation system and the AI-IoT-based precision irrigation system. Throughout the 60-day observation period, the conventional irrigation plots consistently utilized a higher volume of water than the treatment plots equipped with AI-IoT technology. The monitoring data collected from water flow sensors indicated that the AI-IoT irrigation system reduced overall water consumption by 31.4% compared with the conventional irrigation method.

The reduction in water usage was observed consistently throughout the experimental period, indicating that the AI model successfully adjusted irrigation schedules and water volumes according to real-time environmental conditions and soil moisture requirements. Table 1 presents the comparative water consumption performance between the two irrigation systems.

Table 1. Water Consumption Performance

Indicator	Conventional Irrigation	AI-IoT Irrigation	Difference (%)
Water Consumption	100%	68.6%	-31.4%

The Independent Samples t-test demonstrated a statistically significant difference in water consumption between the treatment and control groups ($p < 0.05$), indicating that the AI-IoT irrigation system significantly improved water-use efficiency.

Energy Consumption Analysis

The monitoring of electricity consumption showed that the implementation of AI-IoT technology contributed to lower energy requirements during irrigation operations. Data obtained from energy monitoring modules revealed that the AI-IoT irrigation system consumed 22.7% less energy than the conventional irrigation system.

The reduction in energy usage was observed primarily due to the optimized operation of irrigation equipment, resulting in shorter irrigation durations and more efficient water delivery. Table 2 summarizes the comparative energy consumption results obtained during the experiment.

Table 2. Energy Consumption Performance

Indicator	**Conventional Irrigation**	**AI-IoT Irrigation**	**Difference (%)**
Energy Consumption	100%	77.3%	-22.7%

Statistical analysis confirmed significant differences between the two irrigation approaches ($p < 0.05$), indicating that the AI-IoT system achieved superior energy efficiency compared with conventional irrigation practices.

Soil Moisture Stability Analysis

The soil moisture measurements obtained from IoT-based sensors demonstrated notable differences in moisture fluctuation patterns between the two groups. The conventional irrigation system exhibited larger fluctuations in soil moisture levels throughout the observation period, whereas the AI-IoT irrigation system maintained soil moisture within a narrower and more stable range.

The daily monitoring records showed that the AI model continuously adjusted irrigation timing and water volume based on sensor feedback, allowing soil moisture conditions to remain closer to the optimal range for crop growth. The standard deviation of soil moisture measurements was lower in the AI-IoT treatment plots, indicating greater stability in water availability throughout the cultivation period.

Table 3. Soil Moisture Stability Comparison

Indicator	**Conventional Irrigation**	**AI-IoT Irrigation**
Soil Moisture Fluctuation	Higher	Lower
Moisture Stability	Moderate	High
Irrigation Response	Fixed Schedule	Real-Time Adaptive

The results indicate that the AI-IoT irrigation system provided more consistent soil moisture conditions than the conventional irrigation system throughout the experimental period.

Crop Productivity Analysis

Crop productivity measurements indicated that the AI-IoT-based irrigation system generated higher agricultural output than the conventional irrigation system. The harvested yield data showed that plots managed using AI-IoT irrigation achieved a productivity increase of 14.2% compared with plots managed under conventional irrigation practices.

The increase in productivity was consistently observed across treatment plots and reflected improved crop growth conditions during the cultivation period. Table 4 presents the productivity comparison between the two irrigation systems.

Table 4. Crop Productivity Performance

Indicator	Conventional Irrigation	AI-IoT Irrigation	Difference (%)
Crop Productivity	100%	114.2%	+14.2%

The Independent Samples t-test revealed significant differences in productivity outcomes between the treatment and control groups ($p < 0.05$), indicating that the AI-IoT irrigation system produced significantly higher yields than the conventional irrigation system.

Overall System Performance

The overall evaluation demonstrated that the AI-IoT-based precision irrigation system outperformed the conventional irrigation system across all observed indicators. Water consumption decreased by 31.4%, energy consumption decreased by 22.7%, soil moisture conditions became more stable, and crop productivity increased by 14.2%. These findings directly address the research objective of evaluating the effectiveness of AI and IoT integration in optimizing energy-efficient precision irrigation systems under tropical agricultural conditions.

Table 5. Summary of Research Findings

Performance Indicator	Conventional Irrigation	AI-IoT Irrigation	Improvement
Water Consumption	Baseline	Lower	-31.4%
Energy Consumption	Baseline	Lower	-22.7%
Soil Moisture Stability	Moderate	Higher	Improved
Crop Productivity	Baseline	Higher	+14.2%

The statistical results obtained from comparative efficiency analysis and Independent Samples t-tests confirmed that significant differences existed between the conventional irrigation system and the AI-IoT-based precision irrigation system across all measured indicators ($p < 0.05$).

Effectiveness of AI-IoT Integration in Reducing Water Consumption

The findings revealed that the AI-IoT-based precision irrigation system reduced water consumption by 31.4% compared with conventional irrigation practices. This result supports the fundamental principle of precision agriculture, which emphasizes the efficient allocation of resources through data-driven decision-making. According to Getahun (2024), precision agriculture technologies improve water-use efficiency by enabling irrigation systems to respond directly to actual field conditions rather than relying on predetermined schedules. In the present study, IoT sensors continuously monitored soil moisture and environmental conditions, while the AI model analyzed the collected data to determine the optimal timing and volume of irrigation. Consequently, water was applied only when necessary, minimizing excessive irrigation and reducing water losses.

These findings are consistent with those reported by Senoo et al. (2024), who found that integrating IoT sensors with artificial intelligence algorithms significantly improves irrigation management by enhancing environmental monitoring accuracy and supporting autonomous decision-making. Similarly, Duguma and Bai (2024) emphasized that IoT-based agricultural systems contribute to more efficient resource utilization through real-time data collection and analysis. The observed reduction in water consumption demonstrates that AI-IoT integration can effectively address one of the major challenges facing tropical agriculture, namely the inefficient use of freshwater resources under highly variable environmental conditions.

Energy Efficiency and Irrigation Optimization

The study also demonstrated that the AI-IoT irrigation system reduced energy consumption by 22.7% compared with the conventional irrigation system. This finding indicates that intelligent irrigation management not only improves water-use efficiency but also contributes significantly to energy conservation. The reduction in energy consumption can be attributed to the optimized operation of irrigation equipment, particularly water pumps, which were activated only when irrigation was required. By minimizing unnecessary irrigation events, the system reduced the duration and frequency of pump operation, resulting in lower electricity consumption.

This result supports the theoretical perspective proposed by Babar and Akan (2024), who argued that the integration of Artificial Intelligence, machine learning, and Internet of Things technologies can simultaneously optimize water and energy utilization within agricultural systems. Previous studies have often focused on water-saving performance as the primary indicator of irrigation efficiency, whereas energy efficiency has received comparatively less attention. Therefore, the present findings contribute to the growing body of literature by providing empirical evidence that AI-IoT-based irrigation systems can generate dual benefits through both water conservation and energy savings. Such outcomes are particularly important in tropical agricultural regions where irrigation activities frequently depend on electrically powered pumping systems.

Soil Moisture Stability and Environmental Adaptability

Another important finding of this study concerns the improved stability of soil moisture conditions in plots managed using the AI-IoT irrigation system. The results showed that soil moisture fluctuations were considerably lower in the treatment group than in the conventional irrigation group. Stable soil moisture is essential for maintaining optimal plant growth because excessive fluctuations may cause physiological stress, reduce nutrient uptake efficiency, and negatively affect crop development.

The improved stability observed in this study can be explained by the adaptive nature of the AI-IoT irrigation system. Unlike conventional irrigation methods that rely on fixed schedules, the AI model continuously adjusted irrigation decisions based on real-time sensor feedback. This capability enabled the system to respond dynamically to changes in environmental conditions, including temperature, humidity, and soil water content. These findings align with the concept of intelligent irrigation management proposed by Saiz-Rubio and Rovira-Más (2023), which emphasizes the importance of integrating sensing technologies, data analytics, and intelligent decision-support systems to achieve adaptive resource management. The results suggest that AI-IoT integration enhances environmental responsiveness and supports more precise irrigation control under tropical conditions characterized by high climatic variability.

Impact on Crop Productivity

The findings further indicated that crop productivity increased by 14.2% in plots managed using AI-IoT-based irrigation compared with conventional irrigation. This improvement suggests that more efficient water and energy management can directly contribute to better crop performance. From an agronomic perspective, maintaining optimal soil moisture conditions throughout the cultivation period promotes root development, nutrient absorption, and photosynthetic activity, all of which are essential for crop growth and yield formation.

The observed productivity gains support previous research highlighting the positive relationship between precision irrigation and agricultural productivity. Getahun (2024) noted that precision agriculture technologies can improve crop yields by ensuring that agricultural inputs are applied according to actual crop requirements. Although some studies have reported productivity improvements of varying magnitudes, the increase observed in the present study may be influenced by the specific environmental conditions of tropical agricultural land, where water availability and climatic variability strongly affect crop growth. Therefore, the findings demonstrate that AI-IoT technologies have the potential to improve not only resource-use efficiency but also agricultural output.

Theoretical and Practical Contributions

From a theoretical perspective, this study extends existing knowledge regarding the integration of Artificial Intelligence and Internet of Things technologies in precision agriculture. Previous studies have often examined AI applications, IoT monitoring systems, or irrigation technologies separately. In contrast, the present research provides an integrated evaluation of water consumption, energy utilization, soil moisture stability, and crop productivity within a single experimental framework. This comprehensive approach contributes to a deeper understanding of how AI-IoT systems influence multiple dimensions of agricultural performance simultaneously.

From a practical perspective, the findings provide valuable insights for farmers, agricultural engineers, technology developers, and policymakers seeking to promote sustainable agricultural practices. The demonstrated reductions in water and energy consumption indicate that AI-IoT irrigation systems can contribute to reducing operational costs while supporting environmental sustainability. Furthermore, the increased productivity achieved through intelligent irrigation management suggests that digital agricultural technologies can play an important role in strengthening food security and improving agricultural resilience in tropical regions.

CONCLUSIONS AND RECOMMENDATIONS

This study concludes that the integration of Artificial Intelligence (AI) and Internet of Things (IoT) sensors significantly improves the performance of precision irrigation systems in tropical agricultural land. The AI-IoT-based irrigation system reduced water consumption by 31.4% and energy usage by 22.7%, while maintaining more stable soil moisture conditions and increasing crop productivity by 14.2% compared with conventional irrigation methods. These findings demonstrate that intelligent irrigation technologies can optimize resource utilization and support sustainable agricultural management. Therefore, the adoption of AI-IoT-based irrigation systems is recommended for farmers, agricultural practitioners, and policymakers seeking to improve water-use efficiency, reduce energy consumption, and enhance agricultural productivity in tropical environments. Furthermore, support for digital agricultural infrastructure and farmer capacity-building programs is essential to facilitate the wider implementation of smart irrigation technologies.

FURTHER STUDY

Future research is recommended to involve larger agricultural areas, different crop types, and longer observation periods to evaluate the long-term effectiveness of AI-IoT-based irrigation systems. Further studies may also integrate additional variables, such as weather forecasting, solar radiation, and nutrient management, to enhance irrigation decision-making accuracy and overall system performance.

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