Agris on-line Papers in Economics and Informatics

Volume XVIII Number 2, 2026

Optimization of Water Use in Precision Agriculture Through IoT-Enabled Multi-Sensor Fusion and Machine Learning-Based Smart Irrigation Scheduling

Amritpal Kaur, Devershi Pallavi Bhatt, Linesh Raja

Department of Computer Applications, Manipal University Jaipur, India

Abstract

This research presents a smart irrigation system that integrates Internet of Things (IoT) and machine learning (ML) to optimize water usage in agriculture. The system consists of a wireless sensor network that continuously monitors real-time environmental parameters such as soil moisture, temperature, humidity, wind speed, and rainfall. A Node-MCU microcontroller processes sensor data and transmits it to the Thing-Speak cloud for predictive analysis. The system follows a structured irrigation scheduling method, dynamically adjusting water distribution based on sensor feedback and environmental conditions. The proposed irrigation framework integrates an inverted U-shaped structure with a T-shaped hybrid irrigation system, enabling efficient water management through solenoid valves and sub-pipelines. This system, previously developed for sprinkler irrigation, was evaluated using machine learning models to assess its performance based on soil moisture and temperature parameters. In the present study, several machine learning algorithms, including Decision Tree, XG-Boost, Gradient Boosting, and Random Forest, were employed to predict irrigation requirements. The models consider multiple factors, such as soil moisture, rainfall, wind speed, and water availability, to forecast future irrigation demands, thereby facilitating optimal water utilization. Gradient Boosting achieved the highest accuracy (98.38%) and the lowest RMSE (0.1272), while Decision Tree and XG-Boost also performed strongly, with accuracy of 98.24% each. For controlling and monitoring the developed system, an android-based mobile application developed, allowing farmers to monitor and control irrigation remotely. The results demonstrate significant improvements in water conservation, reduced manual intervention, and enhanced crop yield. Future work will focus on refining predictive models, integrating additional environmental factors, and expanding system capabilities for broader adoption in precision agriculture..

Keywords

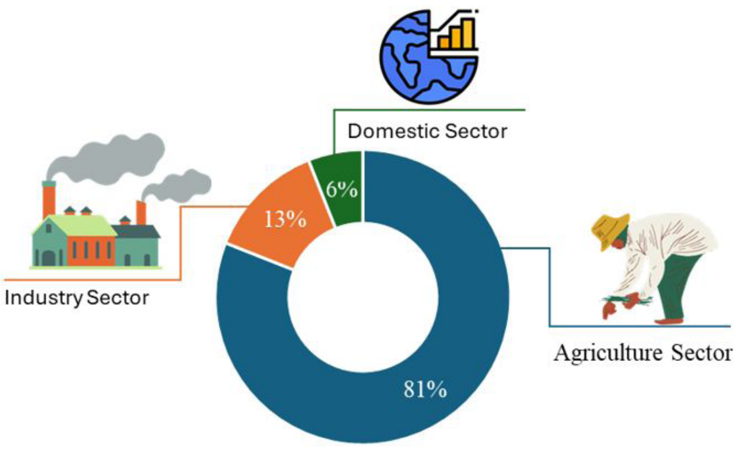
Internet of Things, water use efficiency, water management, sensors, soil moisture monitoring, smart irrigation system.

Kaur, A., Bhatt, D. P. and Raja, L. (2026) "Optimization of Water Use in Precision Agriculture Through IoT-Enabled Multi-Sensor Fusion and Machine Learning-Based Smart Irrigation Scheduling", *AGRIS on-line Papers in Economics and Informatics*, Vol. 18, No. 2, pp. 33-45. ISSN 1804-1930. DOI 10.7160/aol.2026.180203.

Introduction

Farming and agriculture contribute significantly to the GDP (gross domestic product) of both emerging and developed countries. Hence, it is important to improve and optimize current agricultural technologies. Currently, as it has been the case for the last few centuries, agriculture serves as the primary source of food for society, accounting for over 74% of the daily intake of populations from agricultural fields (Glória et al.,2021). Agriculture is not only crucial for sustaining people, but it also ranks as one of the primary sectors in terms of water usage, accounting for about 81% of global freshwater consumption. Furthermore, despite the need to meet growing consumer demands and address the global problem of water scarcity, 30% of water is wasted for a variety of reasons, such as poor water management, leaky systems, and outdated methods (Kaur et al., 2022). To address these issues, sustainability and the integration of technology in agriculture have emerged as significant factors. The world is currently experiencing water scarcity in certain regions, and this problem is worsening due to the growing global population and the increasing demand for fresh water (Goap et al., 2018). During the early 1900s, irrigation was undoubtedly the most important technology that needed to be used effectively. Farmers must anticipate the water requirements for their crops, either by verifying the information from agricultural weather stations or by acquiring knowledge of the evaporation rate of water surfaces in lakes or dams. Scheduling agricultural irrigation is an essential administrative activity that aims to achieve efficient and effective water utilization. Effective irrigation scheduling focuses on applying the right amount of water at the right time. Irrigation scheduling enhances water usage efficiency by using evapotranspiration (ET) estimate techniques to comprehend geographical changes of ET (Das, 2003). To identify irrigation applications, the water balance component must be detected. Various sensing technologies must be integrated into irrigation scheduling models and control. Furthermore, water quality restrictions will be connected to irrigation scheduling and management, and new, improved sensor technologies will be used. It is anticipated that India can irrigate 139.5 million hectares in total. This comprises 15 million hectares from small irrigation systems, 66 million hectares from groundwater extraction, 58.5 million hectares from big and medium irrigation schemes, and an expected 77 million hectares from freshwater usage for irrigation after 2025 (Saggi et al., 2025). It is estimated that ar,ound 50% of the total farmed area will remain rain-fed after the irrigation system reaches its maximum capability. Irrigation is the primary determinant for increasing the agricultural yield of plants. To maximize the benefits of irrigation, it is crucial to accurately assess the amount of water needed. This assessment is affected by the crop's kind, environment, subsurface geo-hydrological conditions, and stage of development. When scheduling irrigation, the following questions arise: (i) What is the procedure for applying irrigation water? (ii) What is the appropriate amount of water to use for irrigation? (iii) When is the optimal time to irrigate? (Thomson et al., 2007). Figure 1 shows that the agriculture sector in India uses 81 percent of fresh water, the industry sector 13 percent, and the domestic sector 6 percent. It is expected that human water consumption will increase to up to 26% by 2025 according to (Phasinam et al., 2022).

In smart agriculture, Internet of Things (IoT)-based irrigation systems represent a modern approach that utilizes real-time environmental data to automate and optimize irrigation practices. It uses connected devices, such as sensors and actuators, to assess major soil and environmental parameters, like moisture in the soil, humidity, wind speed, temperature, and rainfall (Kaur et al., 2023). Appropriate water distribution is possible with the help of smart irrigation methods; this all can be achieved with the help of sensors and continuous gathering of real-time field data. These methods help conserve water, reduce costs, and improve crop health and production by preventing both over- and under-irrigation. Integrating these systems with machine learning algorithms enhances decision-making by predicting



Source: Different sectors water consumption. Authors identification, 2025

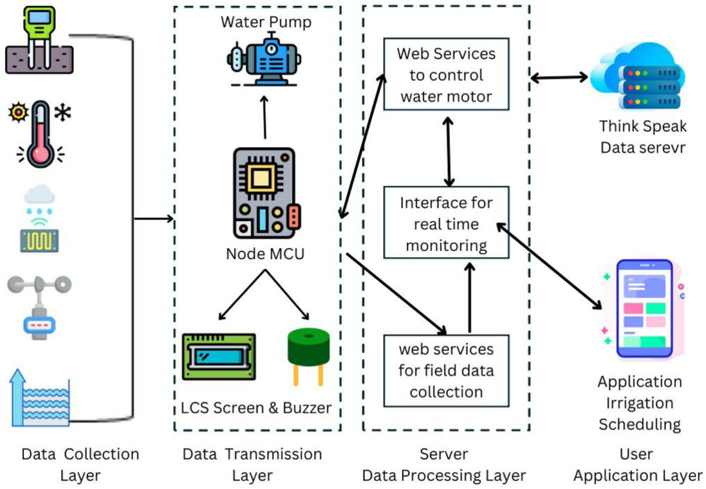
Figure 1: Fresh water consumption by different sectors.

future irrigation needs based on historical data and current field conditions (Vij et al., 2020). This research developed a smart irrigation system using multiple sensors and the Node MCU ESP8266. Sensors employed in fields collect real-time data and automatically control and monitor irrigation from remote locations using mobile or web applications (Scarlatache et al., 2024). This research developed an advanced smart sprinkler irrigation system, utilizing internet of things technologies to optimize irrigation, reduce water utilization, and improve crop productivity. An irrigation system is developed using multiple sensors and microcontrollers, such as Node MCU, soil moisture sensors, temperature sensors, and solenoid valves, to effectively control the system based on field parameters like soil moisture and temperature. By integrating fuzzy logic, the system efficiently adjusts field irrigation and ensures real-time optimization of water utilization (Marathe et al., 2024). In this research work, different irrigation methods are compared by the author to identify the best strategies to enhance sweet corn production while decreasing water use and energy consumption. The researcher compares two methods: soil moisture monitoring (IoT-SM) and the evapotranspiration (ET)-based irrigation method. Soil moisture sensors are part of IoT-SM, which irrigates at two levels: 43.5% and 34.8% of the soil's capacity, while the ET-based method uses the total amount of water needed for crop evapotranspiration (ET). Crop height, yield production, and water productivity determined the effectiveness of these methods. The research revealed that the IOT-SM methods at 43.5% field capacity produce approximately 12.5% higher production and decrease 11% water consumption compared to the ET-based method (Kumar et al., 2023). This research uses machine learning algorithms to develop an automated hybrid irrigation system. Researchers gather on-field data regarding soil moisture and temperature to optimize the irrigation timing in real time. The SVM algorithm provides the highest accuracy for irrigation prediction compared to other models, enabling better irrigation scheduling. The proposed model enhances irrigation efficiency using real-time environmental data for automatic irrigation systems, which will help in reducing water use and improving crop production and sustainable agriculture practices (Sarjerao and Sudhagar, 2024). Arduino Nano microcontrollers manage off-grid wind and solar power smart irrigation system. To enhance irrigation efficiency, the system monitors soil moisture level and water conditions. Integrating renewable energy sources reduces the demand for commercial electricity in the agriculture sector. The proposed system motivates farmers to adopt smart irrigation systems, enhancing resource efficiency and lowering operation expenses, based on renewable energy systems (Ghosh et al., 2023). In this research, a smart irrigation system is developed using deep learning techniques to predict soil moisture content based on real-time environmental factors like temperature and humidity, as well as light intensity. Real-time collected data from the field is integrated with machine learning to schedule the irrigation and improve water efficiency. Crop production, health, and water uses are improved by integrating the internet of things, neural networks, and predictive analytics to predict the requirements for irrigation (Maira Sami et al., 2022). In this research (DADP-LP), SA and OD-DADP, two different hybrid algorithms, are proposed to solve the complex nonlinear optimization problems of the optimal allocation of resources like water and land for irrigation. In this proposed model, decomposition-aggregation dynamic programming is integrated with linear programming and orthogonal design methods. The model was used in the irrigation area of Gao'a in Jiangsu Province, China, and it worked better than older methods like Real-Coded Genetic Algorithm (RGA) and Particle Swarm Optimization (PSO) by giving higher quality and more reliable solutions for managing water and land resources (Wei et al., 2023). This research develops an IoT-based smart irrigation system to enhance the sustainable management of water resources in the agricultural sector. IoT sensors are employed in the field to gather real-time sensor data on soil moisture, temperature, humidity, and TDS (total dissolved solids) to determine real-time irrigation requirements and classify crop varieties like wheat, rice, and corn in combination with K-Nearest Neighbors. This data-driven methodology allows accurate irrigation scheduling autonomously, maximizing water efficiency and supporting sustainable agricultural practices such as reducing the usage of fossil fuels for extracting water, preserving essential water resources, and improving crop production— all while handling issues related to water scarcity and climate change while promoting sustainable agriculture (Sharan et al., 2025). A smart irrigation system is proposed by researchers and introduced as the ROWIA method to decrease the use of fresh water by reusing reverse osmosis (RO) wastewater for agricultural field irrigation. To optimize irrigation time, an ESP32 microprocessor and DHT22 sensors are used for monitoring environmental data such as soil moisture, humidity, and temperature. A mobile application is developed using the Blynk cloud platform to monitor and control the real-time data from agriculture to optimize the resources. This method handles water shortage problems and improves sustainable agriculture practices via an efficient irrigation management system and less dependence on freshwater resources (Panah and Taghizadeh, 2024). In this research, the author developed a hybrid dynamical systems approach to the drip irrigation system that takes into consideration the binary nature of the control input. It analyses the influence of transients in the irrigation pipe on uniformity and derives an intuitive policy of irrigation based on existing farmer operations. The model is verified by simulation using parameters derived from field farm measurements, with the aim of enhancing irrigation effectiveness and efficiency by this new approach (Bertollo et al., 2022). The hybrid irrigation system designed in the study combines solar and wind energy to power a standalone drip irrigation system for 1 acre of banana plantation in Kalangala district, Uganda. It utilizes 14 solar panels and a wind turbine to meet the water requirement of 33.73 m^3 per day. The system operates efficiently at wind speeds of 20 m/s, ensuring sustainable irrigation while minimizing costs and environmental impact compared to traditional motorized methods (Ssenyimba et al., 2020). The hybrid irrigation system described in the paper combines photovoltaic (PV) panels and a diesel generator to supply power for irrigation on fruit-growing farms without grid connection. It features a 7.5 kW pump powered by 11.04 kW PV panels, capable of delivering 80 m^3 of water daily. The system includes lead storage batteries for up to 37 kWh of electricity and a 20-kW diesel generator as backup during periods of low solar radiation, ensuring continuous operation throughout the year (Ševaljević and Nikolić, 2017). The paper discusses a hybrid irrigation system that combines wind and photovoltaic (PV) generation with water tank storage for efficient water pumping. This system addresses the variability of renewable energy sources, providing a reliable solution for irrigation in off-grid, arid areas. The methodology includes a one-year operation simulation and evaluates different combinations of PV technologies, wind types, and water tank capacities based on investment costs, crop requirements, and system oversizing, making it adaptable for various agricultural sites in Bulgaria (Stoyanov et al., 2021). The hybrid irrigation system designed in the paper combines wireless sensor networks (WSN) and wireless underground sensor networks (WUSN) to achieve precision irrigation. It utilizes ARM9 microprocessor and GPRS module for remote monitoring and control. The system collects soil temperature, humidity, and water content data at varying depths, enabling automatic irrigation based on real-time soil conditions. This innovative approach can save approximately 25% more water compared to traditional irrigation methods, enhancing water efficiency in agriculture (Yu et al.,2015). In this research, the focus is on addressing the challenges faced by small-scale farmers in developing and underdeveloped nations, particularly in India, where traditional farming methods are still prevalent. Despite agriculture being the primary income source for 58% of the population, many farmers struggle with low income, inefficient irrigation practices, and the high cost of modern equipment. The study proposes a cost-effective smart irrigation system utilizing Node-MCU and IoT technology to automate irrigation based on real-time soil moisture levels. Additionally, the system includes plant monitoring through camera input and ensures data integrity using encryption techniques. The proposed solution aims to offer an affordable, efficient, and reliable alternative to conventional farming methods, tailored to the needs of resource-constrained farmers (Badotra et al., 2021). In this research, a communication protocol for smart irrigation systems within the framework of Smart City initiatives is proposed, with a focus on efficient water management in urban areas facing water scarcity. The study emphasizes the potential of using non-potable water sources, such as treated sewage or rainwater, for irrigating urban gardens and green spaces. The proposed protocol facilitates communication between devices using both LoRa and Wi-Fi technologies, aiming for effective data transmission and system coordination. Implemented with low-cost hardware in an urban environment, the system demonstrated strong performance, achieving minimal packet loss through the introduction of a 500 ms delay at the central hub (CH) during message transmission (Aldegheishem et al., 2022). In this research, Smart and Green framework is proposed to enhance irrigation efficiency through intelligent data handling and prediction techniques in smart agriculture systems. Recognizing that irrigation is one of the most water-intensive agricultural practices, the study highlights the need for accurate and synchronized data across multiple sources for optimal irrigation management. The framework provides integrated services including data monitoring, preprocessing, fusion, synchronization, storage, and soil moisture prediction. To improve data reliability, outlier removal techniques such as Z-score, Modified Z-score, and Chauvenet's criterion are applied, significantly increasing the precision of irrigation decisions. For areas lacking soil moisture sensors, the system estimates matric potential using weather, crop, and irrigation data, applying the Van Genuchten model to calculate moisture levels. The results show that this approach can reduce water usage by 56.4% to 90%, demonstrating its effectiveness in supporting sustainable irrigation practices (Campos et al., 2019). In this research, the feasibility and potential impact of implementing smart irrigation systems in Malaysia's oil palm plantations are examined in the context of Industry 4.0 technologies. Recognizing that the palm oil industry is the second largest globally but still heavily reliant on labor-intensive practices, the study evaluates smart irrigation as a strategy to enhance efficiency, economic performance, and sustainability. The analysis incorporates key factors such as return on investment (ROI), water footprint, plantation size, and server setup configurations. Results indicate that smart irrigation becomes economically viable for plantations larger than 1.5 hectares, offering substantial water savings and reduced operational costs while maintaining optimal soil moisture conditions. These findings provide valuable guidance for stakeholders considering technological transformation in the oil palm sector through the adoption of smart agricultural practices (Chalvantharan et al., 2023). In this research, a low-cost, autonomous Internet of Things (IoT)-based irrigation monitoring and control system is developed to address challenges posed by rising global food demand, population growth, and climate change. The system is designed to optimize water usage in remote agricultural areas by automating irrigation through the integration of sensors, actuators, and a pumping mechanism. Using the system development lifecycle and the waterfall model, the prototype was built with tools such as the Proteus 8.5 design suite, Arduino IDE, and embedded C programming. The resulting system provides sensing, monitoring, control, power supply, and internet connectivity, enabling efficient water delivery from a reservoir to crops. Experimental and simulation results confirm the system's flexibility and practical applicability, highlighting its potential to reduce manual supervision, support remote access, and contribute to the broader economic advancement of irrigation farming (Abba et al., 2019). In our research we integrated machine learning and the Internet of Things to develop a smart irrigation system to automate the irrigation system. Different types of sensors are deployed in the field to calculate real-time environmental data. Sensors such as soil moisture sensors, humidity and temperature sensors, and wind speed sensors are used. Machine learning algorithms are used to process data and to forecast the irrigation requirements to regulate the irrigation system according to real-time conditions. The developed system will help to optimize water use by automating the irrigation system, reducing the labor requirements, and increasing crop production due to automated irrigation according to climate and environmental conditions. A wireless sensor network is developed using microcontrollers such as Arduino UNO and Node MCU, which will help farmers to automatically control and monitor irrigation requirements from a remote location from a mobile application. The motivation behind this research is to develop an efficient irrigation system that optimizes water use, reduces expenditure, and enhances crop production. The research work is divided into different sections: In section 2, the smart irrigation system is discussed; in section 3, the results and discussion of the implemented work; and in section 4, the research findings are concluded.

Material and methods

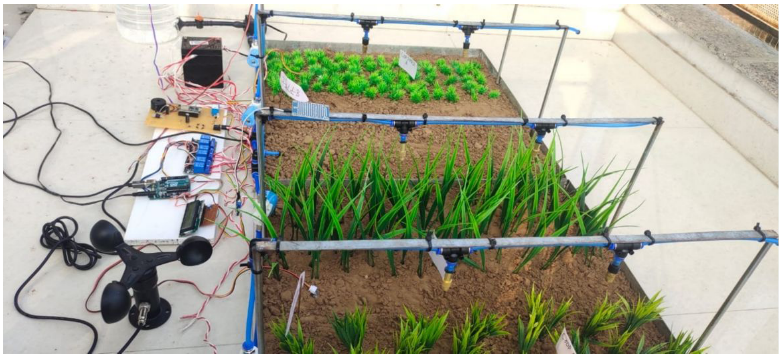
In this section, smart irrigation system implementation procedure is discussed. Smart Irrigation System Architecture is shown in Figure 2.

This model framework is made up of many key components, such as a soil moisture sensor, wind speed sensor, rain detection sensor, water level sensor, temperature and humidity sensor, Node-MCU, LCD display, buzzer, cloud storage, machine learning algorithms, and mobile application. Based on real-time data collection from the field, the system aims to optimize water use in the agricultural sector. The main component of this system is the Node-MCU microcontroller, which develops wireless connectivity using



Source: System architecture illustrating sensor connectivity in the field, integration with the microcontroller, and interaction with the web application. Authors identification, 2025

Figure 2: Smart irrigation system architecture.



Source: Smart sprinkler irrigation System harware protoype. Authors identification, 2025

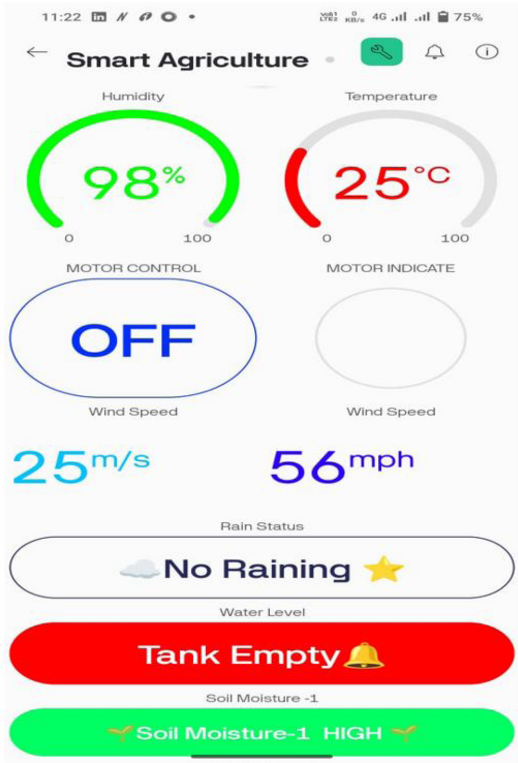
Figure 3: Smart irrigation system prototype.

its versatile ESP8266 chip and manages data processing. It helps in increasing crop production, maintaining soil conditions, and ensuring effective water utilization. Node-MCU performs sensor interconnectivity and real-time data transfer over Wi-Fi and to mobile applications, making it perfect for remotely monitoring and controlling irrigation. Various sensors are deployed to monitor environmental conditions such as soil moisture levels, wind speed, water levels, and rainfall. A soil moisture sensor is used in this model to detect moisture levels in the soil. If the moisture level falls below the required threshold, it notifies the farmer to remotely adjust irrigation settings. A water level sensor is used to monitor the reservoir; if the reservoir is empty, the system updates the status to indicate a low or empty water level. A wind speed sensor is used to measure wind velocity. If the wind speed is too high, the application alerts the farmer, as high wind speeds can reduce the water use efficiency of sprinkler irrigation systems. Solenoid valves manage water flow by activating only in fields where moisture levels are low, leaving adequately moist areas untouched. Real-time updates are displayed on an LCD panel for easy monitoring. The system uses the Thing-Speak cloud server to store and process the collected data. It analyzes historical datasets to generate insights, enabling predictive irrigation based on environmental trends. The setup involves programming the sensors and integrating them with a microcontroller to ensure easy data transmission and control operations. Once deployed, the system provides a responsive and adaptive irrigation solution that enhances agricultural productivity while promoting resource efficiency and sustainability. Figure 3 Smart irrigation system prototype (above).

The material has been precisely cut into the required length dimensions of the construction, ranging from 1.2 to 0.17 to 0.4 metres. The project design has an inverted U-shaped structure integrated with a T-shaped hybrid irrigation system. An eight-millimetre water pipe serves as the primary supply pipe. Sub pipelines are constructed using six-millimetre water pipes to give water to fields. The sub pipe is connected to main pipes and solenoid valves using T and L form pipe connections (Kaur et al., 2024).

In previous research, we considered only the soil moisture level to activate the irrigation system and, based on this, evaluated the system's accuracy. However, in this study, we aim to predict the irrigation time by considering multiple factors, including soil moisture, air temperature, wind speed, and rainfall status. Based on these parameters, the results for scheduling irrigation are significantly improved and are discussed in detail in the Results section. This smart irrigation system was developed to overcome the problems of existing irrigation models. The model will help farmers to grow different crops according to their choice under the smart irrigation system and to perform interculture activities like harvesting, sawing new crops, pesticides without any hustle of removing or re installing the project after these kinds of activities.

The model is designed in vertical t shape structure. The development of an Android application is underway to enable farmers to effectively monitor and manage the smart irrigation system. The program presents input metrics like soil moisture, wind speed, rain status, water, temperature, and humidity. Farmers will have the capability to continuously monitor and regulate field conditions from any location and at any time. This enables the farmer to manipulate the motor switch and schedule irrigation for the crop based on the specific needs and water availability. In Figure 4 mobile applications developed for smart irrigation systems are shown.



Source: Mobile application for farmers to monitor and control the smart irrigation system automatically. Authors identification, 2025

Figure 4: Smart irrigation system mobile application.

Data collection and analysis

The smart irrigation system utilizes Internet of Things (IoT) technology to automate irrigation by continuously collecting real-time environmental data. Key parameters monitored include soil moisture, air temperature, humidity, rainfall status, wind speed, and pump activity. Sensor data is centrally stored and analyzed on the Thing-Speak cloud server. To validate the system, devices were deployed across diverse soil conditions and environmental settings, leveraging IoT technology. These autonomous sensors form a self-organizing network, efficiently collecting and transmitting data for precise irrigation control. An algorithm processes the gathered data, enabling optimal water distribution and providing real-time insights. A total of 7,000 dataset, encompassing all monitored parameters, has been collected from the field.

Data interpretation from sensor readings

Soil moisture data

The capacitive soil moisture sensor is used to monitor the soil moisture level. Real time soil moisture gathered from field range between 315 and 920, indicating diverse field conditions. Table 1 shows the real time sensor measurements from the field.

Temperature data

Using the DHT11 sensor, air temperature was recorded in degrees Celsius. The monitored months revealed a mean temperature of 26.24°C. The lowest temperature observed was 18.00°C, while the maximum reached 42.2°C, highlighting seasonal variations.

Air humidity data

The DHT11 sensor also provided air humidity readings, with values ranging from 38% to 81.26%. The average humidity during the observation period was 66.4.

Wind speed data

Wind speed data was collected and updated on application to make decision on irrigation process on high-speed wind condition. The wind speed sensor collect data in between range of 1 m/s 50m/s or in mph.

Rain status

The rain sensor is used to collect data on raining condition if it is raining then mobile application is updated with the help of rain sensor farmer can avoid over irrigation. The sensor will store rain or not raining condition in the form cm. Table 1 show the data collected sample from field.

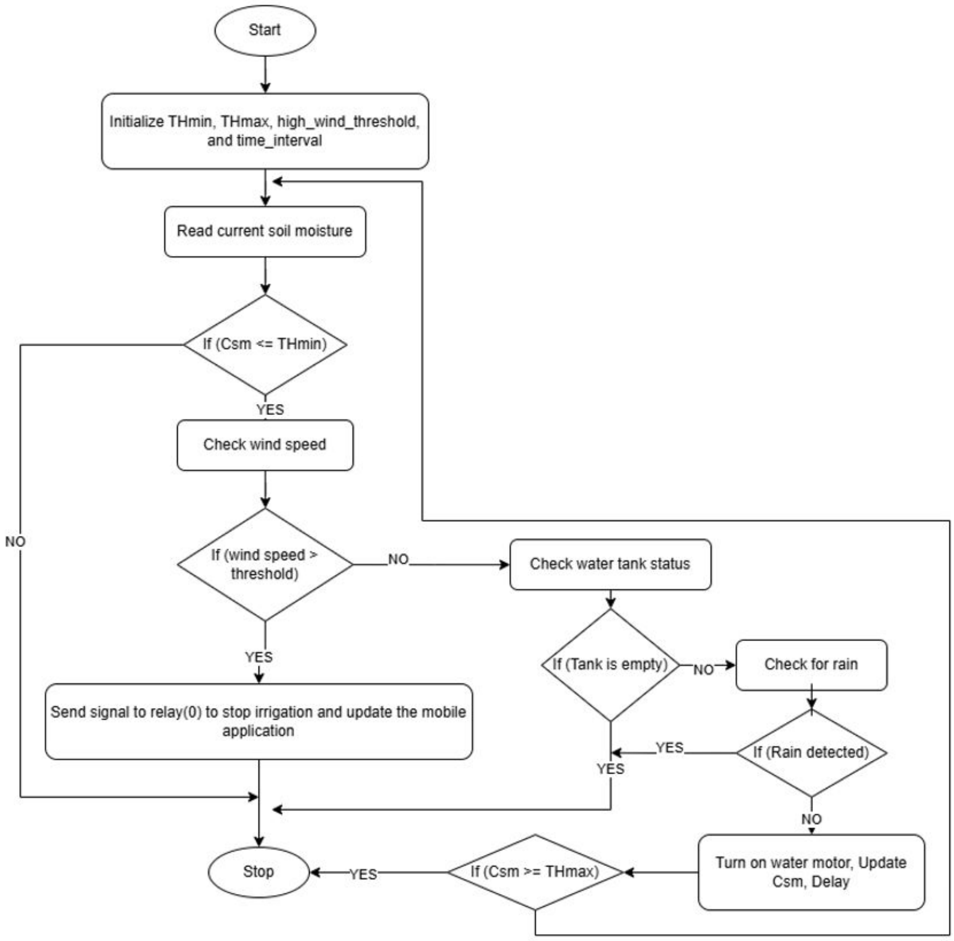
Irrigation scheduling algorithm

The irrigation control algorithm is designed to optimize water usage in smart agriculture by automating the irrigation process based on real-time soil moisture data and environmental conditions such as wind speed, rain status, and water tank levels. Initially, the algorithm sets two key thresholds: a minimum soil moisture level (TH-min) to trigger irrigation and a maximum level (TH-max) to stop it. The system continuously monitors the current soil moisture (Csm) using sensors. When soil moisture falls below TH-min, the system initiates irrigation, and when TH-max indicates sufficient soil moisture, it stops irrigation operations. To avoid over-irrigating crops and provide appropriate irrigation, the system dynamically adjusts TH-max based on conditions such as predicted soil moisture, temperature, humidity, and weather. The wind speed sensor is used to detect the wind speed and prevent irrigation during high wind speed to minimize the water loss due to evaporation. Water level sensors monitor the water dam, sending notifications when it becomes empty. Rain detection sensors are used to detect the rain status; if it is raining, then the system sends information to the mobile app about the rain, and the system prevents irrigation. The system is collected and monitored in a continuous loop, constantly checking moisture levels and adjusting irrigation as necessary to maintain an optimal irrigation requirement of crops. The system collects real-time environmental data, and automated decisions are made to control and monitor the irrigation system. The system helps reduce water usage and labour while implementing sustainable and efficient irrigation methods tailored to current weather conditions and soil requirements. This approach offers a robust and adaptable solution for water management in precision agriculture. The Figure 5 depicts the algorithm's flowchart.

S. No.	Soil Moisture	Air Temperature (°C)	Air Humidity (%)	Wind Speed (mph)	Rain Status	Pump Status
1	583.78	35.53	38.66	10	0	1
2	333.35	22.18	58.06	13	0	0
3	474.84	36.13	55.85	11	0	0
4	612.01	21.12	43.27	8	0	1
5	846.75	33.64	41.80	4	0	0

Source: The values represent real-time monitoring of field parameters, including soil moisture, wind speed, temperature, rainfall status, and pump status. Authors identification, 2025

Table 1: Real-time sensor measurements from the field.



Source: Irrigation scheduling algorithm flowchart. Authors identification, 2025

Figure 5:Irrigation scheduling algorithm flowchart.

Irrigation scheduling algorithm steps

Step 1: Initialization

THmin = (Minimum threshold of soil moisture)

THmax = (Maximum threshold of soil moisture)

High wind threshold = (Threshold for wind speed)

Step 2: Continuous monitoring loop while system is powered on:

Step 3: Read current soil moisture

Csm = read soil moisture sensor()

Step 4: Soil moisture evaluate

if Csm <= THmin:

Step 5: Adjust THmax if necessary

THmax = adjust THmax based on conditions()

Step 6: Start irrigation if Csm < THmax

while Csm < THmax:

Check wind speed

wind speed = read wind speed sensor()

if wind speed > high wind threshold:

send_notification("High wind speed detected.")

Check water tank status

if check water tank status() == "empty":

send_notification("Water tank is empty. Stopping irrigation.")

send signal to relay(0) # Stop irrigation

break # Exit the loop

Check for rain

if read rain sensor() == "raining":

send notification("Rain detected. Stopping irrigation.")

send signal to relay(0) # Stop irrigation

break # Exit the loop

If conditions are normal, start irrigation

send signal to relay(1) # Turn on the water motor

Csm = read soil moisture sensor() # Update current soil moisture level

delay(<time_interval>) # Add a delay for system stability

Step 7: Stop irrigation if Csm reaches THmax

if Csm >= THmax:

send_signal_to_relay(0) # Turn off the water motor

else: # If Csm is above THmin, no irrigation is needed

send_signal_to_relay(0) # Ensure irrigation remains off

Optional delay before repeating the loop

delay(<time_interval>)

Result and discussion

To enhance water management for agricultural areas, the smart irrigation system suggested in this study combines machine learning algorithms with Internet of Things technology. The system uses a variety of sensors to gather environmental data in real time, including wind speed, humidity, soil moisture, air temperature, and rain status. In this smart irrigation system machine learning plays an important role in optimizing irrigation management by gathering real-time environmental data. To determine the irrigation requirements in real time the soil moisture and temperature are the important factors. If soil moisture drops below the required threshold, then sensors send signals to microcontrollers to activate the irrigation pump and soil moisture updated on mobile applications. Field temperature also plays important role in scheduling the irrigation because higher temperatures can cause high evaporation and crop water requirements are increased. Machine learning models are trained to predict the irrigation timing and requirements based on gathered data from the field on various parameters such as soil moisture, air temperature, wind speed, and rain status. The system will help to manage the over and under irrigation by integrating real-time data with predictive analytics, the system automates the irrigation process, thereby minimizing both over-irrigation and under-irrigation. This method enhances water use efficiency and supports optimal soil conditions for improved crop health and production. Furthermore, a graphical analysis compares the performance of various machine learning models in forecasting irrigation requirements.

Performance analysis of machine learning models

In this study, we evaluated the performance of various machine learning models for optimizing smart irrigation systems. Accurate prediction of irrigation requirements is crucial to conserve water resources and maximize crop yield. To this end, models including Decision Tree (DT), Random Forest (RF), Gradient Boosting (GB), and XG-Boost were implemented, each employing distinct approaches to learn from environmental data. Decision Tree (DT): A supervised learning method that recursively splits data based on feature values. Its hierarchical structure allows it to capture nonlinear patterns while maintaining interpretability. Random Forest (RF): An ensemble of decision trees that combines multiple classifiers to improve generalization and reduce overfitting. Gradient Boosting (GB): Builds models sequentially, where each new model attempts to correct the errors of the previous ones, enhancing predictive accuracy. XG-Boost: An optimized gradient boosting framework designed for efficiency and performance, incorporating regularization to reduce overfitting and improve robustness. The models were evaluated using standard performance metrics, including Accuracy, Precision, Recall, F1-score, and Root Mean Squared Error (RMSE). These metrics provide a comprehensive assessment of the models' ability to predict irrigation requirements reliably.

Comparative results

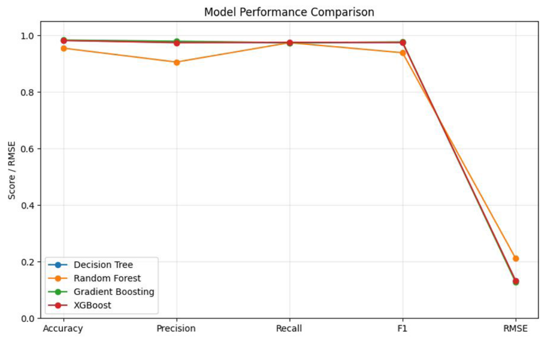
The performance results of each model are summarized in Table 2.

Algorithm	Accuracy	Precision	Recall	F1	RMSE
Decision Tree	0.982381	0.975709	0.974394	0.975051	0.132737
Random Forest	0.955238	0.906015	0.974394	0.938961	0.211570
Gradient Boosting	0.983810	0.979675	0.974394	0.977027	0.127242
XGBoost	0.982381	0.974428	0.975741	0.975084	0.132737

Source: Performance evaluation of machine learning models for irrigation system. Authors Identification, 2025

Table 2: Performance results of each model.

- Gradient Boosting emerged as the best-performing model, achieving the highest accuracy (98.38%) and F1-score (97.70%), along with the lowest RMSE (0.1272). These results demonstrate their superior ability to balance precision and recall while minimizing prediction errors.
- The Decision Tree and XG-Boost models also showed strong performance, with accuracies above 98% and F1-scores exceeding 97%, making them reliable alternatives. The Decision Tree model offers greater interpretability, which is valuable for understanding feature importance, while XG-Boost provides computational efficiency for larger datasets.
- Random Forest, although robust in handling data variability, displayed slightly lower precision (90.60%), indicating a higher rate of false positives in irrigation prediction. Performance comparison of machine learning models for irrigation optimization is shown in Figure 6.



Source: Model performance evaluation based on real-time field data. Authors Identification, 2025

Figure 6: Performance comparison of machine learning models for irrigation optimization.

Conclusion

The proposed research work confirms that when we integrate IoT sensors with machine learning, it will significantly enhance water use efficiency in agriculture. Analysis of the gathered data shows that Gradient Boosting performed best, with 98.38% accuracy and the lowest RMSE (0.1272). Decision Tree and XG-Boost also performed well, each with 98.24% accuracy and F1-scores above 97.5%, while Random Forest had lower precision (90.60%) and higher RMSE (0.2116). These models are well-suited for handling the complexities of real-time irrigation data, providing precise predictions and enabling efficient water management. The automated irrigation system offers a practical solution for farmers, allowing for real-time monitoring and control of irrigation based on environmental conditions. The system reduces water waste and decreases the need for manual workers, contributing to more sustainable and productive agricultural practices. Future work will focus on enhancing the system's capabilities by incorporating additional environmental factors, refining predictive algorithms, and improving the user interface for better farmer accessibility.

Corresponding author:
Dr. Amritpal Kaur, Ph.D.,
Department of Computer Applications, Manipal University Jaipur
Jaipur-Ajmer Express Highway, Dehmi Kalan, Near GVK Toll Plaza
Jaipur, Rajasthan 303007, India
Phone: +91 8769169023, E-mail: amritpal.kaur@jaipur.manipal.edu

References

[1] Abba, S., Wadumi Namkusong, J., Lee, J. A. and Liz Crespo, M. (2019) "Design and performance evaluation of a low-cost autonomous sensor interface for a smart IoT-based irrigation monitoring and control system", *Sensors*, Vol. 19, No. 17, p. 3643. ISSN 1424-8220. DOI 10.3390/s19173643.

[2] Aldegheishem, A., Alrajeh, N., García, L. and Lloret, J. (2022) "SWAP: Smart water protocol for the irrigation of urban gardens in smart cities", *IEEE Access*, Vol. 10, No. 1, pp. 39239-39247. ISSN 2169-3536. DOI 10.1109/ACCESS.2022.3165579.

[3] Badotra, S., Gundaboina, L., Trehan, A., Mishra, D., Srivastava, P., Dhaiya, A. K. and Anwar, S. (2021) "Smart irrigation system using Internet of Things (IoT) and machine learning", *Proceedings of the 2021 9th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO),* Vol. 1, No. 1, pp. 1-4. DOI 10.1109/ICRITO51393.2021.9596139.

[4] Bertollo, R., Cáceres, G. B., Millán, P., Pereira, M. and Zaccarian, L. (2022) "A hybrid dynamical systems approach to smart irrigation", *IFAC-PapersOnLine*, Vol. 55, No. 32, pp. 188-193. ISSN 2405-8963. DOI 10.1016/j.ifacol.2022.11.137.

[5] Campos, N. G. S., Rocha, A. R., Gondim, R., Coelho da Silva, T. L. and Gomes, D. G. (2019) "Smart & green: An Internet-of-Things framework for smart irrigation", *Sensors*, Vol. 20, No. 1, p. 190. ISSN 1424-8220. DOI 10.3390/s20010190.

[6] Chalvantharan, A., Lim, C. H. and Ng, D. K. (2023) "Economic feasibility and water footprint analysis for smart irrigation systems in palm oil industry", *Sustainability,* Vol. 15, No. 10, p. 8069. ISSN 2071-1050. DOI 10.3390/su15108069.

[7] Ghosh, D., Saha, A., Rashid, H. A., Shafin, M. N. S., Sadhu, P. and Ahmed, K. F. (2023) "Design and development of hybrid renewable energy based smart irrigation system", *Proceedings of the 2023 IEEE 11th International Conference on Smart Energy Grid Engineering (SEGE)*, Vol.1, No. 1, pp. 224-229. E-ISBN 979-8-3503-4557-5. DOI 10.1109/SEGE59172.2023.10274546.

[8] Glória, A., Cardoso, J., and Sebastião, P. (2021) "Sustainable irrigation system for farming supported by machine learning and real-time sensor data", *Sensors*, Vol. 21, No. 9, p. 3079. ISSN 1424-8220. DOI 10.3390/s21093079.

[9] Goap, A., Sharma, D., Shukla, A. K. and Krishna, C. R. (2018) "An IoT-based smart irrigation management system using machine learning and open-source technologies", *Computers and Electronics in Agriculture*, Vol. 155, No. 1, pp. 41-49. ISSN 0168-1699. DOI 10.1016/j.compag.2018.09.040.

[10] Kaur, A., Bhatt, D. P. and Raja, L. (2022) "Applications of nanotechnology in agriculture, with a focus on insect pest management", *NanoWorld Journal*, Vol. 8, No. 1, pp. 76-82. ISSN 2379-1101. DOI 10.17756/nwj.2022-s1-015.

[11] Kaur, A., Bhatt, D. P. and Raja, L. (2023) "Applications of smart agriculture and an automated irrigation system based on the Internet of Things", Proceedings of the International Conference on Data Science and Applications, *Springer Nature*, Vol. 1, No. 1, pp. 475-487. ISSN 2193-1801. DOI 10.1007/978-981-99-7862-5_36.

[12] Kaur, A., Bhatt, D. P. and Kaur, V. (2024a) "Hybrid smart irrigation systems using IoT and machine learning: A precision farming approach", *Proceedings of the International Conference on Communication and Intelligent Systems*, Vol. 1, No. 1, pp. 433-443. E-ISSN 2367-3389. DOI 10.1007/978-981-96-5723-0_32.

[13] Kaur, A., Bhatt, D. P. and Raja, L. (2024b) "Developing a hybrid irrigation system for smart agriculture using IoT sensors and machine learning in Sri Ganganagar, Rajasthan", *Journal of Sensors*, Vol. 2024, No. 1, pp. 1-15. ISSN 1687-725X. DOI 10.1155/2024/6676907.

[14] Kaur, A., Bhatt, D. P. and Raja, L. (2025) "Major crops water requirements and automated irrigation scheduling system", *AGRIS on-line Papers in Economics and Informatics*, Vol. 17, No. 1, pp. 41-50. ISSN 1804-1930. DOI 10.7160/aol.2025.170104.

[15] Kumar, V., Singh, C. D., Rao, K. R., Kumar, M., Rajwade, Y. A., Babu, B. and Singh, K. (2023) "Evaluation of IoT-based smart drip irrigation and ETc-based system for sweet corn", *Smart Agricultural Technology*, Vol. 5, No. 1, p. 100248. E-ISSN 2772-3755. DOI 10.1016/j.atech.2023.100248.

[16] Marathe, A., Ughade, J., Jungade, T., Kalamkar, K., Katepallewar, P. and Kamble, A. (2024) "Enhancing agriculture with smart sprinkler systems", *Proceedings of the 2024 8th International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)*, Vol. 1, No. 1, pp. 269-272. ISSN 2768-0673. DOI 10.1109/I-SMAC61858.2024.10714876.

[17] Panah, A. H. and Taghizadeh, S. (2024) "ROWIA: A smart IoT-based reverse osmosis wastewater irrigation system for agriculture", *Proceedings of the 2024 International Conference on Engineering Management of Communication and Technology (EMCTECH)*, Vol. 1, No. 1, pp. 1-9. E-ISSN 3064-9382. DOI 10.1109/EMCTECH63049.2024.10741619.

[18] Phasinam, K., Kassanuk, T., Shinde, P. P., Thakar, C. M., Sharma, D. K., Mohiddin, M. K. and Rahmani, A. W. (2022) "Application of IoT and cloud computing in automation of agriculture irrigation", *Journal of Food Quality*, Vol. 2022, No. 1, pp. 1-8. E-ISSN 1745-4557. DOI 10.1155/2022/8285969.

[19] Saggi, M. K. and Jain, S. (2025) "A survey towards decision support system on smart irrigation scheduling using machine learning approaches", *Archives of Computational Methods in Engineering*, Vol. 29, No. 6, pp. 4455-4478. E-ISSN 1886-1784. DOI 10.1007/s11831-022-09746-3.

[20] Sami, M., Khan, S. Q., Khurram, M., Farooq, M. U., Anjum, R., Aziz, S., and Sadak, F. (2022) "A deep learning-based sensor modeling for smart irrigation system", *Agrnomy*, Vol. 12, No. 1, p. 212. ISSN 2073-4395. DOI 10.3390/agronomy12010212.

[21] Sarjerao, J. S. and Sudhagar, G. (2024) "Hybrid ABC-WOA-based machine learning approach for smart irrigation system", *Proceedings of the 2024 2nd International Conference on Networking and Communications (ICNWC)*, Vol. 1, No. 1, pp. 1-8. E-ISBN 979-8-3503-6526-9. DOI 10.1109/ICNWC60771.2024.10537592.

[22] Scarlatache, F., Grigoras, G., Scarlatache, V. A., Neagu, B. C. and Ivanov, O. (2021) "A hybrid methodology based on smart management energy consumption in irrigation systems", *Electronics*, Vol. 10, No. 22, p. 2864. ISSN 2079-9292. DOI 10.3390/electronics10222864.

[23] Sharan, M. S., Shivani, D. and Ramprasath, M. (2025) "Enhancing crop prediction and resource management: A KNN-based approach coupled with IoT-driven smart irrigation for rice, wheat, and corn cultivation", In: *Challenges in Information, Communication and Computing Technology*, 1st ed. ISBN 9781003559092. DOI 10.1201/9781003559092-41.

[24] Ssenyimba, S., Kiggundu, N. and Banadda, N. (2020) "Designing a solar and wind hybrid system for small-scale irrigation: a case study for Kalangala district in Uganda", *Energy, Sustainability and Society*, Vol. 10, No. 1, pp. 1-18. E-ISSN 2192-0567. DOI 10.1186/s13705-020-0240-1.

[25] Stoyanov, L., Bachev, I., Zarkov, Z., Lazarov, V. and Notton, G. (2021) "Multivariate analysis of a Wind-PV-based water pumping hybrid system for irrigation purposes", *Energies*, Vol. 14, No. 11, p. 3231. ISSN 1996-1073. DOI 10.3390/en14113231.

[26] Thompson, R. B., Gallardo, M., Valdez, L. C. and Fernández, M. D. (2007) "Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors", *Agricultural Water Management*, Vol. 88, No. 1-3, pp. 147-158. ISSN 1873-2283. DOI 10.1016/j.agwat.2006.10.007.

[27] Vij, A., Vijendra, S., Jain, A., Bajaj, S., Bassi, A. and Sharma, A. (2020) "IoT and machine learning approaches for automation of farm irrigation system", *Procedia Computer Science*, Vol. 167, No. 1, pp. 1250-1257. ISSN 1877-0509. DOI 10.1016/j.procs.2020.03.440.

[28] Wei, C., Cheng, J. and Jiang, Y. (2023) "Application of hybrid algorithms in an optimal allocation model of water and land resources", *Journal of Hydroinformatics*, Vol. 25, No. 5, pp. 1547-1564. E-ISSN 1465-1734. DOI 10.2166/hydro.2023.060.

[29] Yu, X., Han, W. and Zhang, Z. (2015) "Remote monitoring system for intelligent irrigation in hybrid wireless sensor networks", *International Journal of Control and Automation*, Vol. 8, No. 3, pp. 185-196. E-ISSN 2207-6387. DOI 10.14257/ijca.2015.8.3.20.