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Intelligent Valve Control Mechanism for Irrigation in Precision Agriculture

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Abstract
Precision agriculture, powered by IoT and machine learning, offers a promising solution to optimize water usage and enhance crop yields. This research presents an innovative Intelligent Irrigation System (IIS) that leverages real-time sensor data, predictive analytics, and mobile app interaction to achieve efficient and sustainable water management. Unlike traditional systems, our IIS employs a Raspberry Pi to collect critical data, including soil moisture, temperature, humidity, and rainfall. Advanced machine learning algorithms, such as Random Forest, analyze this data to accurately predict irrigation needs. The system's predictive capabilities enable precise valve control, delivering water to plants based on their specific requirements.By integrating IoT and machine learning, our IIS surpasses the limitations of existing solutions. It empowers farmers to make informed decisions, reduce water waste, and improve crop productivity. The system's user-friendly mobile app interface facilitates remote monitoring and control, enhancing accessibility and convenience. Our research aligns with the findings of previous studies (Abuzanouneh et al., 2022),(S, n.d.) (Water and Agriculture in India, n.d.)which demonstrate the potential of IoT-based irrigation systems in optimizing water usage. However, our IIS distinguishes itself by incorporating a comprehensive approach that combines sensor data, predictive analytics, and mobile app interaction. By adopting this intelligent irrigation solution, farmers can contribute to sustainable agriculture and address the challenges posed by climate change and water scarcity.
Keywords: *Raspberry PI, Machine Learning, Precision Agriculture, Irrigation in Agriculture*

1. Introduction
India, an agrarian economy supporting 17% of the global population with only 4% of the world's freshwater resources, faces a dire challenge of managing its water scarcity effectively. Agriculture, which accounts for 80% of India's freshwater consumption, continues to rely heavily on inefficient irrigation practices such as flood irrigation, which result in significant wastage. Alarmingly, irrigation efficiency across India remains below 40%, contributing to the rapid depletion of groundwater reserves(Water and Agriculture in India, n.d.). India is the largest global user of groundwater, withdrawing approximately 245 billion cubic meters annually. Over 54% of India's groundwater wells are declining, particularly in regions such as Punjab, Rajasthan, and Maharashtra. These areas are on the brink of becoming drought-prone zones if unsustainable water extraction persists. Additionally, monsoon irregularities, exacerbated by climate change, affect the 54% of agricultural land dependent on rainfall, further threatening food security and rural livelihoods. Economic losses caused by inefficient water management in agriculture exceed $10 billion annually, highlighting the urgent need for sustainable solutions. Research indicates that adopting water-efficient technologies, such as IoT-integrated systems and AI-based analytics, can mitigate these challenges. Such systems improve water-use efficiency by 30-50% while simultaneously boosting crop yields by up to 30%. Drip irrigation and automation have demonstrated the potential to reduce water usage by 60%, showcasing the promise of smart irrigation systems for sustainable agriculture(Water and Agriculture in India, n.d.).This research presents an intelligent irrigation system that integrates IoT sensors, AI-driven predictive models,

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and a mobile application interface. Utilizing a Raspberry Pi, the system collects real-time soil moisture and weather data, predicts optimal water requirements, and minimizes wastage. Sensor readings and predictions are stored in Firebase and visualized on a Flutter-based app, offering farmers actionable insights for precision irrigation. Aligned with India's initiatives for sustainable agricultural practices, the proposed system addresses critical challenges such as groundwater depletion, low irrigation efficiency, and water resource mismanagement [1]. By leveraging advanced technologies, this project aims to set a benchmark for integrating innovative solutions into traditional farming methods, contributing to long-term water sustainability and enhanced agricultural productivity.

1.1. Methods

The intelligent irrigation system aims to optimize water usage by leveraging real-time environmental data and predictive analytics. The system employs a Raspberry Pi for data acquisition, which gathers sensor readings such as soil moisture, temperature, and humidity. These data points are then stored in Firebase for further analysis and visualization through a Flutter-based mobile app. Due to the relatively small size of the dataset (only a few hundred rows), a machine learning model capable of handling such limited data efficiently is required. In this context, a Random Forest model is chosen for its robustness in situations where the available data is not extensive. Random Forest is an ensemble learning method that generates multiple decision trees during training, each trained on different subsets of the data. This technique is particularly suitable for small datasets as it helps to reduce overfitting by averaging the predictions across various trees, providing better generalization to unseen data. The model is used to predict water requirements by analyzing the environmental conditions (e.g., soil moisture, temperature, and humidity) and deriving insights that drive automated irrigation decisions. Despite the limited dataset, Random Forest's ability to effectively handle overfitting and provide reliable predictions with relatively few data points makes it an ideal choice for this application. In addition, the system integrates the use of Firebase for cloud storage and data management, ensuring seamless access and retrieval of historical data to further refine the model's predictions. The results are visualized on a mobile app, which allows users to monitor sensor readings and adjust irrigation schedules based on the model's recommendations. This methodology combines hardware and machine learning in a compact, efficient solution for precision irrigation, optimizing water usage while addressing the challenges posed by small-scale datasets [2].

2. Dataset

A dataset according to requirements was searched for and found [12]. Data scarcity remains the biggest problem in the agriculture domain. The dataset consists of the following attributes: Crop Type, Soil Type, Region, Weather, Minimum Temperature, Maximum Temperature and Water Requirement [3].

SR NO.	CROP TYPE	SOIL TYPE	REGION	WEATHER	TEMP_MIN	TEMP.MAX	WATER REQUIREMENT
0	POTATO	DRY	DESERT	NORMAL	10	20	8.500
1	POTATO	DRY	DESERT	SUNNY	10	20	10.000
2	POTATO	DRY	DESERT	WINDY	10	20	9.500
3	POTATO	DRY	DESERT	RAINY	10	20	0.500
4	POTATO	DRY	DESERT	NORMAL	20	30	9.500

Figure 1 Dataset

From the dataset the crop type 'POTATO' was specifically chosen to make the prototype of the project due its optimal water requirement which was found after carrying out exploratory data analysis and visualization, shown in Figure 1 [4].

3. System Architecture

In our proposed system, initially, Data acquisition is done from various sensors we have used to get features for classification which are stored in CSV format and are then ingested to the Firebase database i.e. cloud. At this stage, the data cleaning takes place and thereafter analysis is performed on the received data. This mainly focuses on our ML model i.e. Random Forest. The model is trained with a pre-existing dataset according to our requirements, was searched for and the model is evaluated using an

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accuracy score metric and 98 % achieved. Water quantity forecasting is done using the extracted features and the trained model whose output is then stored on the cloud and used by raspberry pi to start the valve control mechanism as to dispense the exact quantity of water. The table provides the specifications for various hardware components used in the intelligent irrigation system. It includes details about the Raspberry Pi 4b, which serves as the central processing unit, and sensors such as the moisture sensor, temperature sensor, and rain sensor, which monitor environmental conditions. Additionally, it lists the solenoid valve, which controls water flow, and outlines the voltage, current, and operational characteristics of each component. These components work together to enable data collection, processing, and intelligent irrigation management, shown in Figure 2 [5]

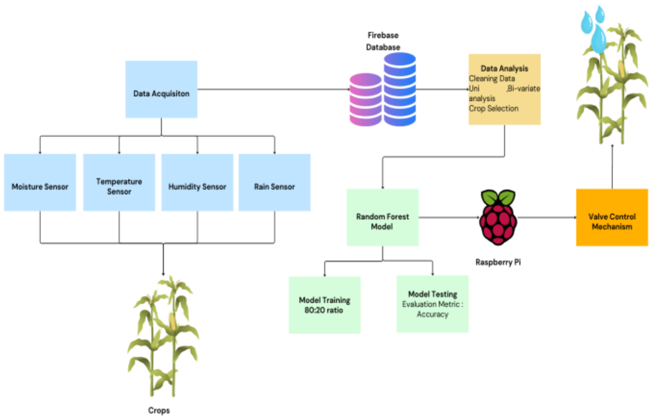

Figure 2 Overall System Architecture

4. Random Forest Model

The Random Forest model is an ensemble learning technique used for both classification and regression tasks. It works by constructing multiple decision trees during training and outputs the mode or mean prediction of the individual trees. In the context of the intelligent irrigation system, Random Forest is used to predict water requirements based on various environmental parameters, such as soil moisture, temperature, and humidity. Random Forest is particularly suited for this project due to the relatively small size of the dataset (a few hundred rows), which can lead to overfitting in more complex models. The strength of Random Forest lies in its ability to handle such situations, shown in Table 1 [6].

Table 1 Used Hardware and its Specifications

Hardware Components	Specifications
Raspberry Pi 4b	1GB RAM Bluetooth 5.0 2x micro HDMI port 2-lane MIPI DSI display port 2-lane MIPI DSI cam port Micro SD card slot
Moisture sensor	3.3V to 5V DC Vtg 15mA operating current 0V to 5V operating digital 0V to 5V operating analog LM393 based design
Temperature sensor	3.5V to 5.5V operating voltage 0.3mA operating current serial o/p data 0-50^C temperature range 20-90% humidity range 16-bit revolution both
Rain sensor	30mm x 16mm pcb size Rain detection & rainfall intensity measurement & monitoring
Solenoid Valve	Rated Operating Voltage: 12V DC Rated Current: 1A Operation Mode: NC (Normally Closed) Pressure: 0.02 – 0.8MPa Max fluid temperature: 100°C

By averaging predictions from multiple decision trees, it reduces variance and improves generalization, thus making reliable predictions even with limited data. Each tree in the forest is trained on a random subset of the dataset with a random selection of features, ensuring diversity in the trees and enhancing the model's robustness. This approach makes the Random Forest model less prone to overfitting compared to single decision trees, providing a reliable solution for predicting irrigation needs and automating water usage efficiently, shown in Figure 3 [7].

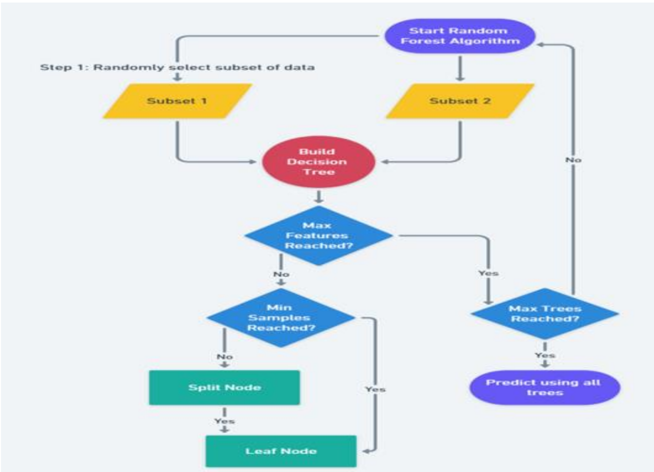

Figure 3 **Random Forest Algorithm**

5. Flutter App

5.1. Flow Chart

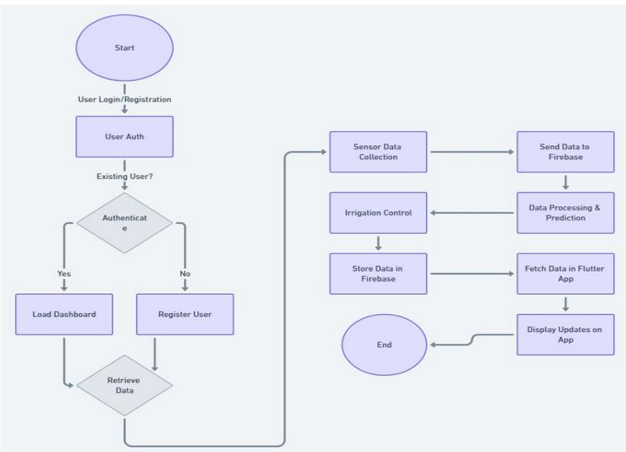

Figure 4 **Flutter App Data Flow Diagram**

The flowchart outlines the processes involved in user authentication and data management for the application. It starts with the user's login or registration followed by authentication If there is an existing user the dashboard will be loaded. Otherwise the user will be registered. Data is collected from sensors and sent to Firebase for storage and processing. The processed data is then imported into the Flutter app, where the updates are displayed. This process includes controlling irrigation based on the collected data, shown in Figure 4 [8].

6. Results and Discussion

This Intelligent irrigation system combines advanced analytics with advanced operations to optimize water use in agriculture. The Table 2 accuracy of the system was estimated using a random forest regression model. It gives the following results:

Table 2 **Model Evaluation Results**

Model	Training Score	Testing Score
Random Forest	99.63536765703 54	98.047427441568 74
Gradient Boosting	99.984193	94.436213
XGBoost	99.999994	93.736450
LightGB M	99.367424	96.588048
CatBoost	100.000000	97.814790
Neural Network	96.863742	96.918830

High training and testing scores demonstrate the model's ability to generalize well while minimizing generalizations. These results demonstrate that the prediction method can reliably estimate water quality under various conditions ensuring water quality and accuracy. This excellent accuracy indicates that the system can use resources more efficiently, reduce water loss, and increase crop yields combined with real-time sensor data and seamless app integration. This discovery proves to be a powerful and scalable solution for modern sustainable farming systems [9]. After processing sensor readings (e.g., soil moisture, temperature, humidity), the Raspberry Pi displays real-time water requirement predictions. This on-site display ensures farmers can access actionable insights even without continuous internet connectivity, shown in Figure 5 [10].

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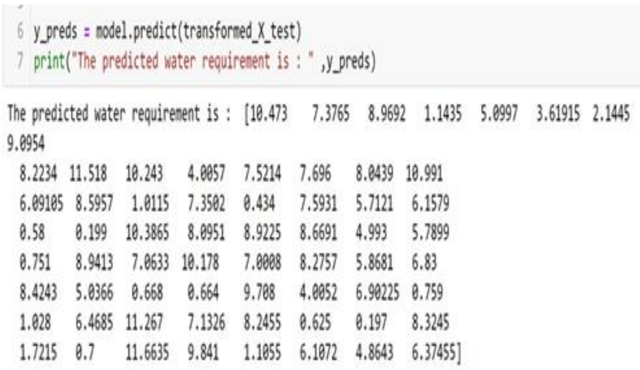

Figure 5 Testing Water Prediction

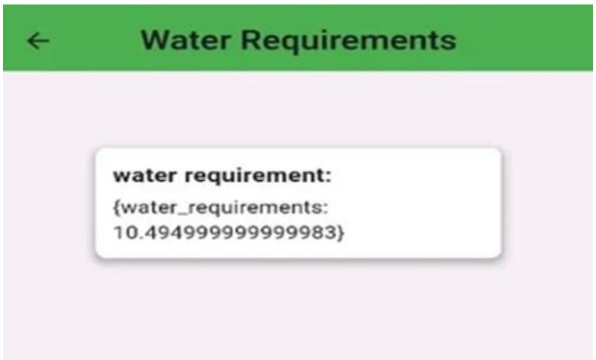

Figure 6 Quantity of Water Predicted and Dispensed to Crop

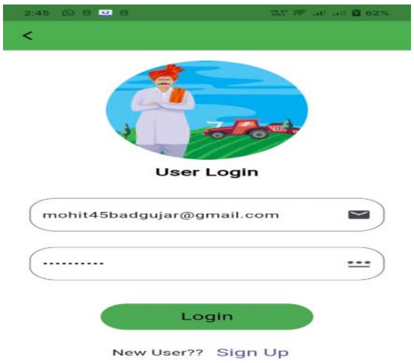

Figure 7 Login Page

Displays detailed water predictions, enabling precise irrigation planning.The farmer can easily view the quantity of water predicted and dispensed for the day. The login page is designed to provide farmers with an easy and secure starting point to access the app. It has a clean and easy-to-use interface with fields for entering your email ID and password. While the option "New user? Register" allows easy access for first-time users. This page focuses on availability and functionality. It sets the tone for a smooth app experience, shown in Figure 6, Figure 7, Figure 8.

Figure 8 App Home Page

The Home Page of the application, Sejal, is designed to provide users with an intuitive and functional interface while reflecting the core purpose of the project. The app name "Sejal," derived from the Sanskrit word meaning "pure water", underscores the project’s focus on sustainable water management in agriculture. This nomenclature directly aligns with the overarching goal of addressing the global challenge of water scarcity and promoting resource-efficient irrigation practices.The home page prominently features two functional modules: Sensors Readings: This section displays real-time data collected from IoT-enabled sensors, such as soil moisture, temperature, and humidity levels, providing users with actionable insights into current field conditions. Water Requirements: This module showcases precise water requirement predictions generated through the machine learning model, enabling farmers to adopt data-driven irrigation practices, shown in Figure 9.

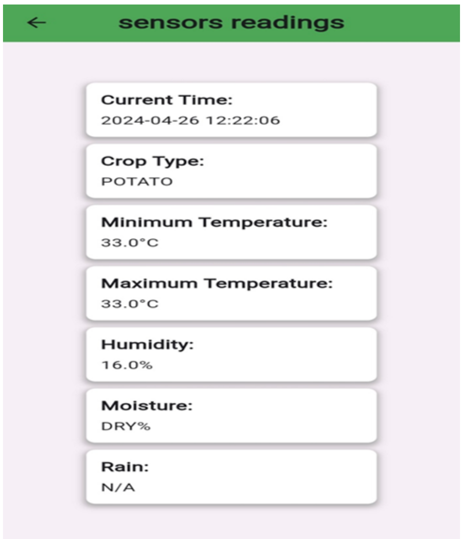

Figure 9 Sensor Reading Display for User

The Sensors Readings Page provides real-time environmental data crucial for informed decision-making in irrigation. This interface captures and displays sensor inputs, including:

- **Current Time:** Timestamp of the data collection for real-time monitoring.
- **Crop Type:** The specific crop being monitored, enabling tailored water predictions.
- **Minimum and Maximum Temperature:** Ambient temperature ranges affect evapotranspiration rates.
- **Humidity:** Percentage of air moisture, a key factor in determining irrigation needs.
- **Soil Moisture:** Current soil moisture levels indicate the need for water.
- **Rain:** Presence or absence of rainfall, helping to avoid over-irrigation.

Conclusion

The results and discussions confirm the effectiveness of the proposed solution in addressing the critical problem of inefficient water management in agriculture. By analyzing real-time environmental data such as soil moisture, temperature, and humidity, the system accurately predicts water requirements for crops. This ensures that irrigation is performed optimally, addressing the issue of over-irrigation and water wastage. The high model accuracy, demonstrated by the training score of 99.64% and testing score of 98.05%, validates the robustness of the machine learning model in diverse environmental scenarios. These outcomes confirm that the system effectively resolves the identified problem of imprecise irrigation practices. Additionally, the user-friendly mobile and Raspberry Pi interfaces bridge the gap between technological advancements and practical implementation, making the solution accessible to farmers. The project conclusively demonstrates that integrating machine learning with IoT technologies is a viable and efficient approach to achieving sustainable water management in agriculture.

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