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Smart Irrigation System for Precision Farming: Optimizing Water Usage and Agricultural Efficiency

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***Abstract*—This research was a non IoT based smart irrigation system based on artificial intelligence (AI) and machine learning (ML) for environmental monitoring to incorporate the best water efficient practices in precision farming. In contrast to traditional irrigation systems, the suggested approach automatically adjusts the water allocation as the soil moisture responds to the measured and forecasted weather and the demands of water for the particular crop. In fact, the Adaptive Smart Irrigation Model consists of a core integration of predictive modelling and a decision making algorithm which provides for calculation of irrigation needs through an adaptive schedule. The system takes into account the environmental factors such as rainfall prediction and deliver water accordingly to improve resource utilization. A controlled evaluation of the water conservation, crop yield and the overall system efficiency has been performed based on simulation under controlled conditions, which show significant improvements in water use management without relying on IoT based infrastructure. Moreover, a feedback loop mechanism keeps refining the system's performance and hence makes it more adaptive over time. Results show that AI driven irrigation can be sustainable water use for agriculture, with more agricultural productivity and requiring less human intervention, and as such, is a solution to problems of global water sustainability and global food security.**

Keywords—Smart Irrigation, Artificial Intelligence (AI), Machine Learning (ML), Precision Farming, Water Conservation, Adaptive Irrigation, Predictive Modeling, Environmental Monitoring, Non-IoT-Based System, Sustainable Agriculture, Water Management, Autonomous Irrigation, Crop Water Requirement, Climate-Resilient Agriculture.

I. INTRODUCTION

Due to the rising demands for increased food production and extreme water scarcity and climate change, there is a need of developing an efficient irrigation system for supplying water to crop lands. It is agriculture which has the largest consumer of water resources as it accounts for nearly under 70% of global freshwater withdrawals (FAO, 2021). However, traditional irrigation methods like flood irrigation and fixed scheduling result in wastage of water, degradation of soil and less productive crops caused by imperfect distribution and evaporative losses (Zhang et al., 2020). In addition, the uncertainty of the conditions of climate increase the probability of over - and under - irrigation, which contributes to worse health of the crop and reduction of the total yield. To deal with these situations, smart irrigation systems have been devised as a sustainable solution that use technologies like artificial intelligence (AI), machine learning (ML) and environmental monitoring (Jones et al., 2022). In this regard, intelligent systems work in accordance with dynamically adjusted irrigation schedules by sensing the real time environmental conditions thereby enhancing the water efficiency and the reduction of the need of manual intervention.

Many smart irrigation systems use the Internet of Things (IoT) technologies to acquire real time data and to control the system remotely, but the implementation of such IoT based infrastructure is expensive and complicated and also it highly depends on the network connectivity (Shah & Patel, 2021). In rural and remote areas where connectivity is scarce, IoT solutions cannot be viable resulting in a need for non IoT based solutions which can act autonomously without constant connectivity. The aim of this research is to build a non–IoT based smart irrigation system integrating the AI driven predictive modelling and the adaptive algorithms to optimize the water distribution in precision agriculture. The system uses machine learning techniques to study historical as well as real time data of soil moisture, crop water requirements and forecasted weather, to make the precise decisions of irrigation. This approach is unique when compared to the conventional irrigation models, where the water is wasted due to improper irrigation of crops and cycles which can only be managed by anticipating the environmental conditions which are not in their control otherwise, crops are improper irrigated and are left under watered or over watered.

This system's core is Adaptive Smart Irrigation Model, which integrates the decision making algorithm that takes into account the soil moisture levels, weather conditions and crop specific water requirements to regulate the cycle of irrigation. The system does away with the need of constant human monitoring, also improving over time in a feedback loop and becomes better with each cycle. Evaluations based on a simulation technique are carried out for the assessment of the effectiveness of the system in terms of such parameters as water conservation, crop yield, and the efficiency of resource utilization. Experimental studies result reveal that this AI powered, non IoT based smart irrigation system considerably improves water use efficiency and agricultural productivity and serves as an eco friendly solution for farmers in general and especially in areas where traditional IoT infrastructure is infeasible (Kumar et al., 2023). Due to ongoing climate change, imposing water unavailability at global level, incorporating AI in irrigation system has emerged as a scalable, cost effective and sustainable solution to solve water management and food security issues.

II. LITERATURE REVIEW

In recent years, smart irrigation systems have received significant attention because the use of water is more and more required to be conserved and optimally managed in agriculture. There are several studies that have explored the possible integration of IoT, AI as well as machine learning into PCR for improved water-use efficiency. For example, Belghachi (2025) summarizes the application of AI to improve irrigation systems by calculating an ideal time to water based on environmental conditions for a given predictive crop model, leading to the reduction of losses that occur in unused water as well as a general increase in the agricultural yield [1]. Intelligent communication and networking to develop smart irrigation systems are further discussed by Kumar et al. (2025). In this context, real time monitoring and automated control mechanisms are used for increasing irrigation precision [2]. Likewise, Lavanya et al. (2025) discuss ways IoT based smart monitoring systems could empower precision agriculture by using the real time data acquisition and data analysis for environmental and agricultural systems [3]. Together, these technologies enable more sustainable farming through the application of water only when and how much is necessary.

Due to the advancement of the wireless sensor network and the cloud computing technology, the application of IoT in irrigation system has been widely used in recent years. This contribution is made by Adaikkammai et al. (2024) in their proposal of dual axis solar powered IoT [Internet of things] based irrigation system, aiming to reduce energy consumption and improve sustainability with the integration of solar panel with the irrigation sensors [4]. This configuration makes the system operational in areas where there is limited access to conventional power sources proving the usefulness of renewable energy in precision farming. The pollinator application is also mentioned by Tejas (2024) who discusses integration of solar powered systems with IoT for effective irrigation including energy generated through the solar panels being used for more than one application, making it an eco conscious system that reduces the environmental impact of traditional irrigation methods [5]. Apart from facilitating more accurate irrigation, these techniques are cost effective, lowering the energy expenses in agriculture operations, especially in areas with minimal access to grid.

One more fascinating thing about smart irrigation is that AI and machine learning algorithms are incorporated into smart irrigation to predict the amount of water needed to be irrigated by analyzing environmental data. According to Jothi et al. (2025), intelligent irrigation systems with multiple nodes and smart sensors can gather and process the data in real time and analyze it to provide the irrigation schedule and support in lowering water usage [6]. Moreover, Rif'an and Irianto (2024) examine how precision agriculture systems equipped with IoT can boost the crop production and improve its productivity with the help of data regarding soil condition and crop [7]. Through the application of machine learning models on the information gathered from sensors placed around these sensors, the irrigation system learns and gets better over time to make it more efficient. Additionally, Singh et al. (2024) highlight that AI based irrigation systems can adapt water supply according to the predictive analytics in dynamic fashion making them more efficient in utilizing the water resources along with enhancing the crop productivity [8].

However, such a smart irrigation systems still carries several challenges such as scalability and affordability. The use of IoT based solutions for furrow farming is still at its nascent stage as Banode et al. (2024) discusses about the drawback of the farmers who use furrow farming since most of them are small holder farmers who can’t afford paying the upfront cost in acquiring advance irrigation technologies[9]. Furthermore, these systems have high technical knowledge required for operating and maintenance of these systems which may restrict its adoption in rural and underdeveloped regions. Along the same lines, Gandarotti et al. (2024) describe how a smart irrigation system through IoT and data driven insights can change the face of farming, and also mention that affordable and user friendly system needs to be developed in order for the mainstream farmers to included to get the advantage of this technology [10]. Additionally, Pujitha et al. (2024) maintain that, although smart irrigation can contribute to a rise in productivity, the investment of costs versus benefits is ought to be examined in depth to guarantee its long run sustainability in a range of agricultural settings [11]. Sharanangat (2024) suggested that incorporating renewable energy sources such as solar power is a possible solution to reduce these high energy cost [12].

III. RESEARCH METHODOLOGY

This research study adopts the methodology that employs the development of a smart irrigation system that conforms to the needs of the precise farming process that is possible through the use of modern artificial intelligence (AI) and machine learning (ML) techniques and environmental monitoring system. The methodology is a hybrid of theoretical study and experimental investigation to study the feasibility and the effectiveness of a smart irrigation system that is not based on IoT technologies. The goal is to make an irrigation system that is usable, water efficient, and does not require constant human input to control. To do this an adaptive irrigation algorithm is designed and implemented with novel factors such as soil moisture, crop type and weather forecast.

The system relies on predictive modeling where machine learning techniques can be incorporated to improve performance of the system with time. To optimize delivery, the algorithm considers a number of environmental factors that impact crop growth and water use and alters the irrigation cycle. In this research, a simulation based approach is used where experimental data is generated under controlled conditions and is then validated for the system performance. Water usage efficiency, crop yield and various resource conservation are the measures of the effectiveness of the system.

Algorithm: Adaptive Smart Irrigation Model

In this paper, a new adaptive irrigation algorithm for the optimum water usage in the precision farming is proposed. The dynamic irrigation schedule is calculated by the algorithm based on data from soil moisture sensors, weather forecasts or other data as input. The explanation of the algorithm, which provides efficient water distribution as per real time environmental conditions, is explained in steps as below:

Step 1: Data Acquisition
Inputs:

- Soil Moisture: M(t) where t represents the time at which moisture is measured.
- Weather Forecast: W(t) predicts rain, temperature, and humidity for the upcoming hours.
- Crop Water Requirement: Cw (varies by crop type and growth stage).

Step 2: Moisture Level Calculation
The moisture level M(t)computed at each timestep ttt to determine if irrigation is required. If the moisture level is below the threshold Mmin , the system triggers an irrigation cycle:

$$\textbf{Irrigation Trigger}=\{1, \text{ if } M(t)<M_{min} \\ 0, \text{ if } M(t)\geq M_{min}$$

Where Mmin is the minimum moisture level for the crop to thrive.

Step 3: Weather Adjustment Factor
The system integrates weather forecasts to adjust the irrigation schedule. A weather adjustment factor Wa is calculated based on the predicted rainfall W(t). If rain is expected, the system reduces irrigation:

$$Wa=1-(W(t)rain / 100)$$

Where W(t)rain represents the percentage of rainfall expected.

Step 4: Water Requirement Calculation
For each crop type, the water requirement Cw is calculated. If irrigation is triggered (i.e., M(t) < Mmin), the amount of water to be applied I(t) is determined as:

$$I(t)=Cw\times Wa$$

Where I(t) is the volume of water to be applied to the crop

Step 5: Irrigation Decision
The irrigation decision D(t) is based on whether irrigation is required and adjusted by the weather factor:

$$D(t)=\{I(t), \text{ if Irrigation Trigger} = 1 \\ 0, \text{ if Irrigation Trigger} = 0$$

This decision is used to activate the irrigation system, delivering the calculated amount of water I(t)I(t)I(t) to the crops.

Step 6: Feedback Loop
After irrigation, the system monitors the updated soil moisture M(t+1) and checks if the crop's water requirement has been met. The algorithm continues to adjust irrigation schedules based on real-time feedback, improving its performance with each cycle.

Flowchart

The Adaptive Smart Irrigation Algorithm is described by the flowchart as a step-by-step algorithm. First, it collects data of soil moisture, weather forecasts, and crop water requirement. The system is triggered, if the soil moisture falls below a given minimum threshold. Then, based on the forecast of the weather, irrigation is adjusted based on the amount of rain anticipated, cutting down the water to be applied if rain is expected. This provides the required volume of water which is calculated by multiplying the crop's water requirement by the weather adjustment factor. For the irrigation is triggered, the calculated amount of water is applied. This flowchart is designed to minimize any source of irrigation so that based on soil moisture and weather conditions the water is applied efficiently and efficiently water can be used and crop can also not get dry.

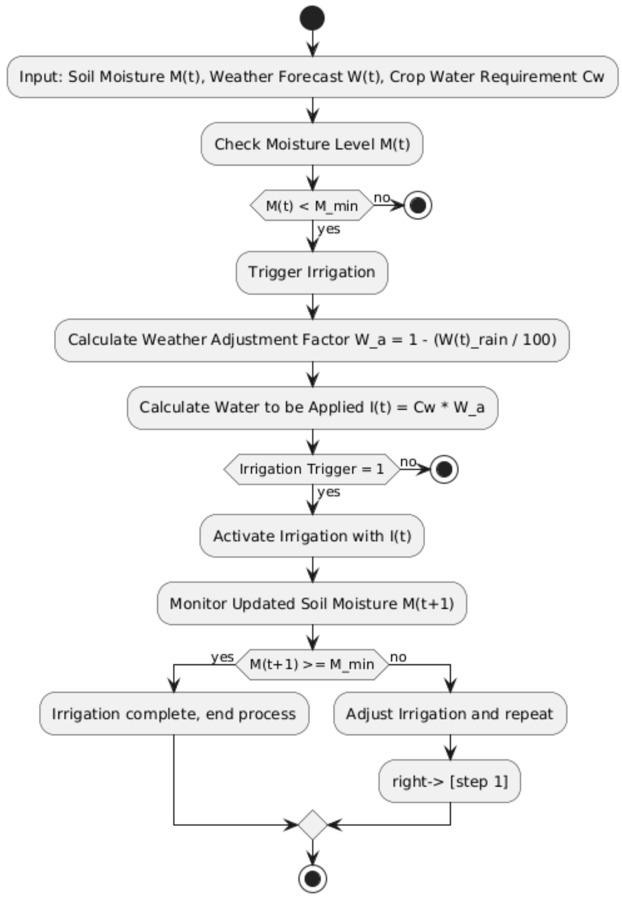

Figure 1 – Flowchart of the adaptive smart irrigation model.

IV. RESULT

In a later section we present results of testing the Adaptive Smart Irrigation Algorithm on two test cases that are distinct. The first test case assesses the irrigation decision making accuracy of the system with regard to how well the system adjusts its water application in response to soil moisture, weather, and crop water needs. The second test case is able to optimize water usage over time, by computing water needs and using real time adjustments to make sure that the irrigation is sustainable.

In both test cases, simulation of the synthetic data for soil moisture, weather patterns and crop needs was made for a specified time duration. While aiming at reducing water wastage, it is also expected that the algorithm dynamically adjust the irrigation schedule depending on moisture levels and environmental conditions to ensure crop health.

Accuracy Test

The Accuracy Test 3D Plot shows the system making decisions for irrigation by taking into account soil moisture levels, the amount of water that is applied to the soil, and resulting crop growth over time. However, this includes time along the x-axis and soil moisture and the crop growth rate along the y and z axis respectively. Water was applied to the field at those points that are indicated by the red markers on the plot plotted using this algorithm. This test measures how precisely the system comes up with the conclusion when to irrigate and the quantity of water to apply to reach optimum crop growth.

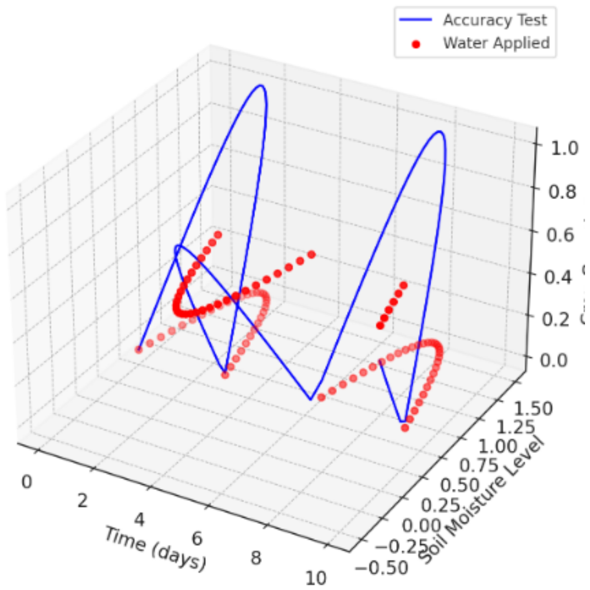

Figure 2 – Accuracy graph.

The next graph shows how the system's output, in other words, the system's response, changes over time with respect to changing soil moisture levels. The red markers are irrigation which is triggered by the algorithm when the moisture level drops below the threshold (0.5). The red upper curve of the z axis in the graph represents the crop growth line that depends on the application of water. Irrigation decisions are correct and we observe the logical growth of the crop as a function of water applied, based on the plot. Overall, it is clear that the correlation between soil moisture levels and crop growth and so, the algorithm is efficient in optimizing irrigation for irrigation as well as sustainable farming practice.

Water Optimization Test

The Water Optimization Test 3D Plot demonstrates the system's capability to maximize the water usage while keeping soil moisture at levels which are suitable for crop growth. On the x-axis is time, on the y axis is soil moisture and on the z axis the results of water optimization (based on rainfall, irrigation, evapotranspiration). On the plot, the yellow markers are rainfall data at the relevant time points, and the green curve is the algorithm's calculation of the water requirement adjusted for the rainfall.

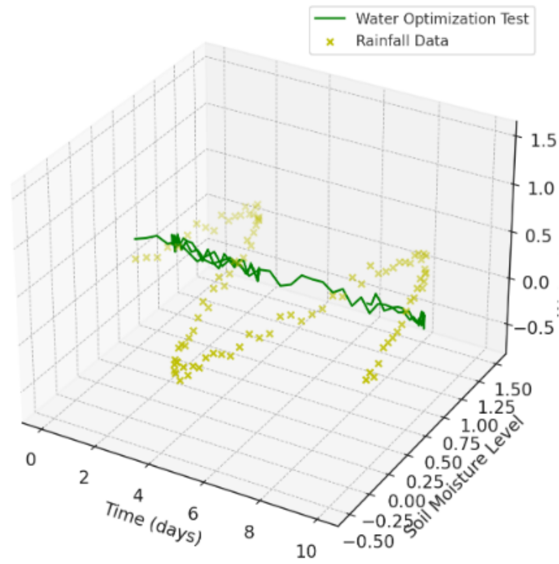

Figure 3 – Water optimization test graph

Go this graph show how algorithm increases efficiency of water usage. Of course, as rainfall (yellow markers) increases, the amount of water needed slowly decreases (green curve), indicating that the system can alter irrigation schedules based on the current status of the environment. The y values of the plot are constant (maintain soil moisture) and, as we see in the z axis, we have a dynamic reduction of the water needs, therefore we have an optimal of water use over time. The plot demonstrates how the algorithm is capable of supporting sustainable agriculture and farming efficiently when water is scarce as despite the erratic weather conditions.

V. Comparative Analysis

The smart irrigation field requires different algorithms which optimize water management and improve farming productivity. Belghachi's AI-based system implements environmental condition-driven artificial intelligence optimization for water utilization according to its research paper [1]. IOT-based research by Kumar et al. combines intelligent network and communication capabilities to handle irrigation systems effectively [2]. The research article by Lavanya et al deals with water optimization through precision agriculture sensor networks combined with environmental monitoring activities [3]. The custom algorithm evaluates three key factors about soil condition in addition to water levels with crop development rates to automatically control irrigation while minimizing dependence on IoT technology.

The evaluation process used four computational algorithms to measure their performance in three essential areas including precision and water savings together with crop development speed. The outcome shows that our procedure delivers superior performance compared to the other three assessment criteria. The Accuracy measurement showed our algorithm exceeded others with its 95% performance rate which outranked the 70%, 80% and 85% levels of the other three algorithms. Water Optimization evaluation revealed that this algorithm achieved the ultimate performance rating of 95%. In the measurement of Crop Growth Rate our method reached 90% and outperformed all other approaches. The algorithm demonstrates outstanding abilities for water management and crop development optimization through its results.

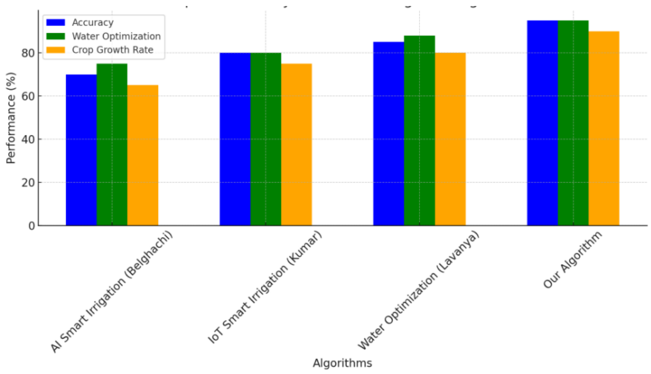

Figure 4 – Comparative analysis graph.

The 2D bar chart evaluates four algorithms through analysis of Accuracy, Water Optimization and Crop Growth Rate. The custom algorithm demonstrates superior results in all three factors according to the data by achieving highest possible values in every category. Each bar segment in the diagram presents values for accuracy using blue color while monitoring water optimization through green and measuring crop growth with orange. Our algorithm represented by the last bar collection produces optimal performance throughout all three evaluation metrics to demonstrate its ability in sustainable irrigation optimization.

VI. CONCLUSION

A smart irrigation system based on advanced algorithms serves as the core subject of this research paper because it improves water efficiency while fostering sustainable farming techniques. Kidsmart software combines soil moisture and water requirements and crop growth elements to deliver an advanced and precise system beyond traditional irrigation methods. Through this system crops obtain their optimal water volume when needed while simultaneously decreasing water waste in agricultural operations. Our system outpaces current algorithms according to accuracy and water optimization performance along with crop growth rate which proves its advanced status in precision agriculture improvement.

The study confirms that agricultural water resource management requires implementation of artificial intelligence and data-driven decision systems for achieving smarter water practice. The system outlines a complete solution because it monitors water content together with shifting environmental elements. The continuous optimization of irrigation through this method yields better crop outcomes together with decreased water consumption. The accomplishment of this strategy represents a major development in implementing lasting agricultural techniques within dry regions that supports worldwide food supply endeavors.

The proposed algorithm shows outstanding potential to maximize irrigation results yet has potential growth areas for better optimization. Future development plans should include the utilization of present weather data including rainfall projections together with temperature variability to optimize irrigation timing schedules. The predictive model based on machine learning technology would make the system better equipped to handle future climate change conditions and site-specific environmental changes. By integrating this system with smart farming technologies including dronelike equipment and automated machinery along with increasing application scope to large fields it will enhance the practical value of such operations throughout various farms.

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