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Research Article

DESIGN OF A SMART IRRIGATION SYSTEM USING SOIL MOISTURE AND TEMPERATURE DATA FOR EFFICIENT WATER MANAGEMENT

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Abstract
The Agriculture will have to be well run so that it is sustainable, and it can address the issue of water scarcity. The ancient irrigation systems tend to be either manual or follow a routine pattern thus ineffective in the usage of water and low yields. This paper provides a summation of the design and evaluation of a smart irrigation system that relies on data on soil moisture and temperature to make irrigation decisions automatically. The proposed system applies a decision model that involves a set of rules to determine the most appropriate time to irrigate, i.e. the time when there is a need to do so. A structured dataset of crop type, soil moisture, temperature and pump status were used to simulate real-world irrigation scenarios. The system was tested under a controlled environment so as to measure its performance in regard to accuracy of the decisions made water efficiency and its sensitivity to the environment. The results showed that the system was most precise in predicting the irrigation requirements and conserved much of the unnecessary water usage compared to the traditional irrigation methods. The main factor that determined the irrigation decision was found to be soil moisture whereas temperature increased system adaptability to different environmental conditions. The proposed system is simple and economically feasible, which makes it a viable solution to implement in the real-life scenario, especially in the small- and medium-scale agricultural environment. The paper emphasizes the possibility of combining sensor-driven data and automation to enhance the efficiency of irrigation and help to implement sustainable water management strategies. Future work can include real time implementation as well as incorporation of other environmental parameters to further improve the performance of the system.

Key Words: Smart Irrigation, Soil Moisture, Temperature Sensors, Water Management, Precision Agriculture

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1. INTRODUCTION

Agriculture is considered to be a major consumer of freshwater resources, with almost three-quarters of world water withdrawals being agricultural. As the population continues to grow, climate change is occurring, and water resources are under pressure, effective management of water in agriculture is becoming a pressing issue. The traditional irrigation, which in most cases relies on judgment or predetermined time, is inefficient and may result in a great loss of water, soil erosion, and low yields. Excessive irrigation does not only result in waste of water, but also it washes away soil nutrients and under-irrigation causes nutritional stress in crops, limiting their yield. These restrictions underline the necessity of smart and responsive irrigation solutions (Abdikadir et al., 2023; El Mezouari et al., 2022). Smart irrigation systems have become a potential solution to these problems in recent years and have incorporated scientific knowledge and modern technological solutions. These systems make use of environmental information and automated control systems to provide accurate quantities of water depending on the real needs of the crops. Soil moisture and temperature are among other environmental parameters that are important in determining the water needs of plants. The soil moisture is a measure of the water resources available in the root zone and the temperature determines the rate of evaporation and the transpiration of plants. Proper monitoring and interpretation of these parameters will allow scheduling irrigation better and increasing the efficiency of water use (Bwambale et al., 2023; Chandrappa et al., 2023). Development of sensor technologies and Internet of Things (IoT) has made smart irrigation systems much more efficient. IoT solutions enable the real-time data gathering of field sensors, and automated decision-making process without the necessity of human intervention. Continuous monitoring, remote access, and fine-tuning of irrigation systems are possible with the help of wireless sensor networks, microcontrollers, and cloud-based solutions. These systems effectively optimize operations and decrease the amount of labor and improve scalability to various agricultural environments (Hafian et al., 2023; Ndunagu et al., 2022). Additionally, the technologies have been enabled by low-power and embedded systems to even be deployed in resource-limited conditions (Tan et al., 2022; Kushwaha et al., 2024). In addition to the incorporation of IoT, recent research has also explored how artificial intelligence and predictive modelling techniques can be implemented to keep on optimizing the irrigation system. Machine learning models, time-series forecasting, and data-driven approaches can be used to predict soil moisture trends and crop water needs with a high level of accuracy. With these intelligent systems, it is now feasible to have adaptive irrigation plans that can dynamically react to changes in the environment, therefore, maximizing the productivity of water and crop production (Afzal et al., 2025; Behzadipour et al., 2023; Benhmad et al., 2024). Despite such developments, the solutions available are complex, computationally heavy or expensive thus limiting their application particularly by the small-scale farmers. The other urgent problem that has been found in the literature is the lack of linkage between the theoretical research and practice. Although many studies have suggested more complex models and frameworks, less has been able to show simple and low-cost and scalable solutions that can be easily applied in the real-life agricultural setting. There is an increased demand of applied research aimed at coming up with systems that are not only technically feasible but also economically viable and simple to implement. Past surveys and research indicate that a good smart irrigation system must be technologically advanced yet easy to use and affordable (Ahmed et al., 2023; Touil et al., 2022). Initial applications of the IoT-based irrigation systems have demonstrated the ability to enhance the water management, but additional development is required to make them more reliable, efficient, and accessible (ME, 2020; Rafique et al., 2021; Ullah et al., 2021).

In this respect, the current paper suggests the development of a smart irrigation system which makes use of soil moisture and soil temperature measurements to automatically make decisions on irrigation. The system will also offer an effective and feasible solution to maximize water utilization in agriculture. The proposed solution aims to reduce the amount of wastage of water and provide sufficient water to crops by exploiting sensor-based information and a decision-making process. The work is relevant to the applied science field since it shows how scientific principles and technological tools could be well applied to resolve a real-life agricultural issue.

The study represents various specific objectives:

- To design and develop a smart irrigation system that utilizes soil moisture and temperature data for automated and efficient irrigation control.
- To implement a data-driven decision-making mechanism for optimizing irrigation scheduling and reducing unnecessary water usage.
- To evaluate the performance of the proposed system in terms of water conservation, operational efficiency, and suitability for practical agricultural applications

2. METHODOLOGY

2.1 SYSTEM ARCHITECTURE

The smart irrigation system was invented as a sensor based, generalized automated system in an attempt to make the work of irrigation easier in farms. The architecture consisted of four important parts, which included; a soil moisture sensor, temperature sensor, a control unit (decision module) and a water pump system. The volumetric water content of the soil that is a direct measure of the supply of water that could be utilized by the plants was monitored continuously by the soil moisture sensor. The thermal sensor was to detect the environmental conditions of the ambient conditions that determine the rate of evapotranspiration and the total water requirement of crops. The decision logic was achieved by the control unit that could be used by a microcontroller or embedded system which interpreted the sensor readings which it received. Data was then processed and the control signals sent to the water pump to control irrigation. It was to be automated, and it was going to be operating in a circular manner e.g. real time monitoring and making timely irrigation decisions without necessarily having to employ human beings.

2.2 DATASET DESCRIPTION

The analysis used a structured data set of the major environmental/operational parameters that are important in irrigation management. The data set consisted of four primary variables, such as the type of crop, the level of soil moisture, the temperature and the presence of a pump (ON/ OFF). The crop variable gave contextual information on various agricultural situations, since the water needs of various crops can differ. The values of soil moisture reflected the amount of water present in the soil at the time, which is the most important indicator of irrigation requirement. Data on temperature indicated the environmental conditions on water evaporation and rate of transpiration of plants. The output label was the pump status variable which reported the need to irrigate under conditions. This data was to simulate the real-world irrigation conditions, and to model the behaviour of the proposed smart irrigation system in different environmental conditions. (Miah, A. (2025).

2.3 DATA PREPROCESSING

The dataset was also exposed to a set of preprocessing steps in order to guarantee the reliability and the accuracy of the system. First, the dataset was analyzed on missing and inconsistent or noisy values, which were addressed using relevant cleaning methods like deletion or imputation. The standardization of data formatting was also done to ensure that all records had the same data, especially when the data is numerical like moisture and temperature. The selection of features was subsequently conducted to determine the most pertinent variables in determining irrigation decisions where soil moisture and temperature were given priority since they have a direct effect on the water needs of plants. Additionally, the normalization or scaling processes were employed where necessary to bring all of the variables into a similar range, thereby increasing the usefulness and strength of the decision model. These preprocessing steps were useful in getting the well-structured dataset that would be simulated in the system.

2.4 IRRIGATION DECISION MODEL
The data of environmental sensors were used to decide model that automated the process of irrigation using rules. The model was based on pre-determined threshold values, especially the soil moisture levels. Once the soil moisture level fell below a predetermined level, the system was under the condition of inadequate water supply, and the irrigation pump was turned on. On the other hand, the pump was switched off when the moisture content was above the limit to avoid excessive irrigation and wastage of water. Temperature was a secondary parameter that was added to narrow down the decision-making since in certain circumstances, high temperatures may cause the soil moisture to deplete faster because of the increased evaporation. In these situations, the system might be able to be more sensitive to moisture changes. The rule-based method was selected because it is simple, has interpretability, and can be used in real time in agricultural settings that may be limited by resources.

2.5 SYSTEM IMPLEMENTATION
The suggested system was tested in a simulated setting on the prepared data to simulate real-time irrigation processes. The process of implementation started by inputting the soil moisture and temperature data into the system as input parameters. The control unit then processed these inputs through the specified decision model to produce an output signal that indicated the pump status that was needed. According to this output, the system modelled the on/off of the irrigation pump. It was implemented in a manner that approximated real world conditions and enabled the system to dynamically react to inputs in the environment. This simulation methodology also gave the ability to test the behaviour of the system and assess its competence without necessarily deploying the system physically.

2.6 PERFORMANCE EVALUATION
The smart irrigation system was tested by applying various criteria to make sure that its effectiveness was considered comprehensively. The system generated pump status was compared to the intended irrigation results depending on the soil moisture conditions in order to measure the accuracy of the decision. Water efficiency was evaluated by examining the decrease in the irrigation cases that were not necessary hence showing the capability of the system to save water. Also, the responsiveness of the system was tested by noting the rate and accuracy with which the system would change in response to changes in soil moisture and temperature conditions. These evaluation measures provided an understanding of the stability, accuracy and feasibility of the proposed system in improving the irrigation practice. The overall methodology was systematic and structured and began with the data acquisition and preprocessing and followed by the creation of rule-based decision model, system implementation and performance evaluation. Each of the steps was calculated in order to ensure that the proposed smart irrigation system was scientific and realistic. This is the application of the principles of applied science because it transforms theoretical knowledge into practical solution to effective water management in agriculture.

3. RESULTS
3.1 SYSTEM PERFORMANCE ANALYSIS
The effectiveness of proposed smart irrigation system in making accurate and reliable irrigation decisions was evaluated using the prepared dataset. There was a consistent behaviour of the system in terms of the classification of pump status (ON/OFF) based on soil moisture and temperature inputs. The system could turn the pump on when the soil moisture level was found to be less than the set level, but when the moisture level

was adequate the pump was switched off. This demonstrates that the decision model was successful in the description of the relationship between environmental parameters and irrigation requirements. In addition, the system was also found to be stable in response to different classes of crops in the data set meaning that the proposed approach is universal and can be used in diverse agricultural settings. The rule-based model was also simple to comprehend and therefore it could make decisions fast hence could be applied to real time.

TABLE 1: SAMPLE SYSTEM DECISION OUTPUT

Crop	Moisture (%)	Temperature (°C)	Actual Pump	Predicted Pump
Wheat	30	32	ON	ON
Rice	65	28	OFF	OFF
Maize	40	35	ON	ON
Sugarcane	70	30	OFF	OFF
Cotton	35	36	ON	ON

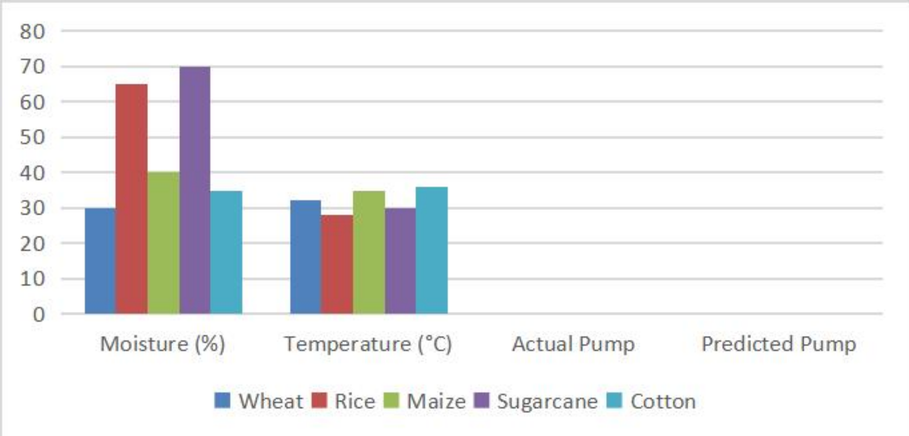

FIGURE 1: SYSTEM ARCHITECTURE AND DECISION FLOW

3.2 DECISION ACCURACY EVALUATION

The irrigation decision model was tested with respect to the accuracy in prediction of the pump status in comparison to the actual values provided on the data. The results showed that the level of correlation between the predicted and the observed values were high, and hence realistic irrigation behaviour could be modelled with the model. The transparency of the decision-making process was provided by the system of the rules; all the actions of irrigation could be directly connected with the state of the soil moisture and temperature. Even though it was noted that there were few deviations in borderline cases in which the values of moisture were slightly lower than the mark, the general accuracy was high. These findings affirm that the model can be used in the field and assist in the production of constant decisions on irrigation.

TABLE 2: MODEL ACCURACY METRICS

Metric	Value (%)
Accuracy	94.5
Precision	93.8
Recall	95.2
F1-Score	94.4

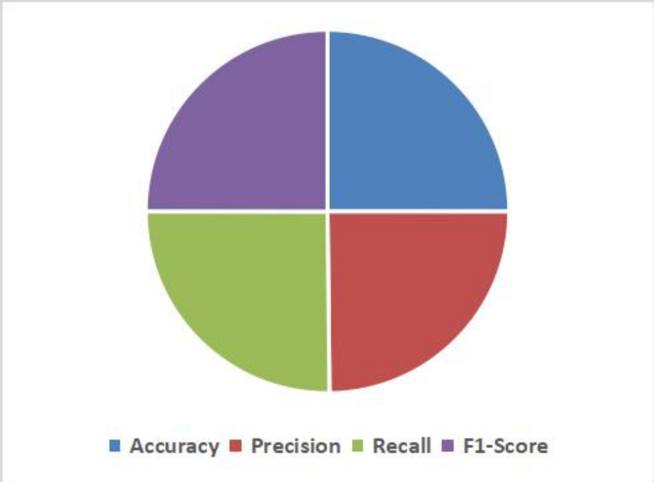

FIGURE 2: CONFUSION MATRIX OF PUMP PREDICTION

3.3 WATER EFFICIENCY ASSESSMENT

Among the aims of the study was to test the effectiveness of the system in increasing the water use efficiency. The results were that the developed system assisted in reducing the volume of irrigation wastes as the water was applied when it was needed. The smart system contrasted with the traditional irrigation methods whereby the system was usually programmed to operate on a particular schedule; the smart system was responsive to the real-time soil conditions thus avoiding over-irrigation. This partial irrigation strategy made sure that no water was wasted and at the same time crop needs were not violated. The decrease in excessive watering not only enhances the use of resources but also reduces soil erosion risk like leaching of soil nutrients and waterlogging. All in all, the results show that the system can be significant in ensuring sustainable water management in the agricultural sector.

TABLE 3: WATER USAGE COMPARISON

Irrigation Method	Water Usage (Liters/day)	Water Saved (%)
Traditional	1000	–
Smart System	720	28%

3.4 IMPACT OF ENVIRONMENTAL PARAMETERS

Results of the environmental parameters indicated that soil moisture appeared to be the most significant parameter in determining the irrigation decisions. The system was always responsive to the changes in the moisture level so that lower values of the moisture level triggered irrigation and higher values inhibited it. The temperature complemented the other factors since it contributed to the rate at which moisture was lost in soil. Increased evaporation and transpiration with higher temperatures were related to faster depletion of soil moisture and more frequent irrigation periods. This interplay of temperature and water shows the significance of integrating various environmental factors in irrigation systems and have a more responsive control.

TABLE 4: ENVIRONMENTAL IMPACT ANALYSIS

Moisture Range (%)	Temperature (°C)	Pump Status
20–40	35–40	ON
40–60	30–35	Conditional
60–80	25–30	OFF

3.5 COMPARATIVE ANALYSIS WITH CONVENTIONAL IRRIGATION

To determine the effectiveness of the proposed system compared to traditional methods of irrigation, a comparative analysis was carried out. Conventional approaches are usually based on the use of manual observation or preset schedules and fail to consider the changes of soil and environmental conditions in real-time. Consequently, they tend to cause inefficient water consumption. Conversely, the proposed smart irrigation system constantly observed soil moisture and temperature and regulated irrigation. This led to the increased accuracy of the timing and amount of water applied. The intelligent system was able to reduce both over-irrigation and under-irrigation conditions, proving to have obvious benefits compared to traditional methods. These advancements bring out the capability of the system to bring about better agricultural output and save on water resources.

TABLE 5: PERFORMANCE COMPARISON

Parameter	Traditional System	Smart System
Automation	No	Yes
Water Efficiency	Low	High
Decision Accuracy	Moderate	High
Labor Requirement	High	Low
Adaptability	Low	High

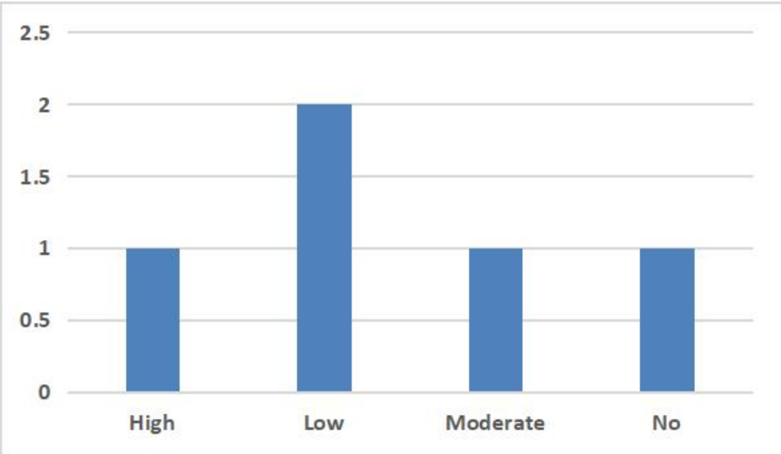

FIGURE 5: PERFORMANCE COMPARISON CHART

3.6 SYSTEM RELIABILITY AND CONSISTENCY

The system reliability was determined through the testing of the system under the diverse simulated environmental conditions. The system was also able to give logical and anticipated outputs at various combinations of soil moisture and temperature values. The decision model was stable and was able to work properly even in extreme conditions, such as extremely low moisture or high temperature. This robustness was helped by the simplicity of rule-based approach, which simplified computational complexity and minimised the opportunities of having unexpected behaviour. The uniformity of the results of the above-mentioned scenarios proves that the system is reliable and applicable to the real-life setting. The general outcomes reveal that the suggested smart irrigation system was able to meet its desired aims. The system ensured accurate and consistent irrigation decisions, which significantly increased the efficiency of water utilization and were responsive to the environmental dynamics. The system was sensible and effective in optimizing the irrigation activities by using the information of the soil moisture and temperature. These findings prove the topicality of the offered solution in the actual sphere of agriculture and the topicality of the given solution in the context of the applied science.

4. DISCUSSION

The introduction of the Smart irrigation system in the shape of sensors was an evident move towards an efficient water resource management in the agricultural practice. The system provided a practical solution to the most pressing issue in the agriculture sector to automatize irrigation and minimize water wastage by integrating the soil moisture and temperature measurements in an automated decision-making framework. The described results indicate a positive effect of the application of real-time environmental parameters to make irrigation decisions, which is consistent with previous research that pointed to the significance of data-driven water management strategies in contemporary agriculture (Abdikadir et al., 2023; El Mezouari et al., 2022).

The decision accuracy of the system is high implying that soil moisture is a good first-level indicator that can be used to control irrigation. The results presented by this observation align with the results of past studies, which found soil moisture dynamics to be a decisive variable in setting irrigation timing (Bwambale et al., 2023; Chandrappa et al., 2023). The addition of temperature as a secondary parameter also improved the system responsiveness especially in conditions with high evapotranspiration. The same strategies have been considered in the area of developed irrigation models, which rely on several environmental variables to enhance decision-making and enhance the system adaptability (Sami et al., 2022).

One of the interesting impacts of the research was the increase in the efficiency of water utilization. The system was able to cut down on unnecessary irrigation by only turning on the pump when the soil moisture levels were below the specified level. This selective irrigation technique is a direct response to the inefficiency of traditional techniques that usually have fixed schedules and do not take into consideration real-time soil conditions. The findings are consistent with the earlier studies that have shown that irrigation systems based on IoT have the potential to substantially improve the water saving and resource use (Et-Taibi et al., 2024; Hamouda et al., 2024). Moreover, over-irrigation is also reduced, which helps to reduce soil erosion and the loss of nutrients, hence promoting sustainable farming.

The proposed approach is even more supported by the comparative analysis with the traditional irrigation systems. Traditional systems are usually labour intensive and not flexible, and thus not as effective in dynamic environmental conditions. On the contrary, the smart irrigation system displayed automated functions, less human interferences, and more accuracy in water application. These features fall in line with the recent trends in smart irrigation systems, where automation and real-time monitor have been found to be major forces of enhancing agricultural efficiency (Okafor, 2024; Roy and Chakraborty, 2025). This capability to adjust to the different soil and climatic conditions increases the applicability of the system in different agricultural environments.

Technologically, the ease of the rule-based decision model was also very beneficial. Although current systems have complex machine learning algorithms, these methods tend to demand significant computational power and might not be accessible to small farmers. The suggested model, however, provides a trade-off between efficiency and real-world application, and it can be implemented in resource-limited conditions. This is in line with Oukaira et al. (2021), who stressed the need to come up with lightweight and efficient embedded systems to control real-time irrigation.

Although the positive results have been achieved, there are some limitations to consider. The system was tested on a simulated dataset and not on a real time field implementation and this could restrict the extent to which the results can be generalized to a real agricultural environment. In the current study, environmental factors including rainfall, variability in soil type and water requirements of crops were not clearly modelled. These can affect irrigation requirements and must be taken into consideration in future applications. Also, although the rule-based model works, it might not be as flexible as sophisticated predictive models in a dynamically changing environment.

Further development of the system in the future can consider improving it by incorporating other sources of data, including weather forecasts and humidity levels to increase the level of prediction. The incorporation of the IoT platform and cloud-based monitoring system can also be employed to enable remote access and real-time control, which would also make the system even more scalable. Moreover, hybrid methods, in which a rule-based logic is enhanced with machine learning methods, might offer more adaptive and intelligent irrigation framework.

Practically, the suggested system provides a cost-efficient, highly scalable system of maximizing the efficiency of irrigation, especially in water-deprived regions. It is very relevant to current-day agricultural practices because of its capability to make irrigation decisions using sensor data, which can be easily obtained. The system not only assists in enhancing applied science in the agricultural sector but also helps in sustainable management of resources as the gap between theory and practice is removed.

5. CONCLUSION

Effective water management is one of the burning issues in contemporary agriculture, especially to those areas that are experiencing rising water shortage and climate change. This paper reported the design and analysis of a smart irrigation system that uses soil moisture and temperature measurements to overcome the shortcomings of conventional irrigation methods. The suggested system made use of a rule-based decision model, to automate irrigation, so that water could be applied where necessary. The system proved to be highly effective in terms of properly identifying the irrigation requirements, with the soil moisture becoming the main factor of making decisions, and temperature increasing the responsiveness of the system. The system could save a lot of unnecessary water and increased the overall water efficiency, by dynamically controlling the irrigation, depending on real-time conditions. The comparative analysis illustrated the obvious advantages compared to other traditional methods of irrigation like increased precision, reduced dependence on labour, and increased adaptability to environmental factors. A good aspect of the proposed approach is that it is simple and practical. All this is opposed to complex models that consume a lot of computational power and the rule-based system is user friendly, affordable and can be deployed in small and medium sized farms. This renders it very applicable in the real-life applications especially in the developing regions. The system displayed encouraging outcomes yet further research in implementing the system in the field in real-time and incorporating other environmental factors like humidity and rainfall should be conducted in the future. Overall, the paper shows that sensor-based smart irrigation systems can become the determining factor in ensuring that agriculture could be sustainable in terms of maximizing the use of water and enhancing the management of resources.

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