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An Integrated Paradigm for Advanced Irrigation Systems Leveraging Internet of Things (IoT)

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***Abstract**: As the demand for precision in agriculture and effective sustainable resource management increases, there has been a lot of pressure to have more accurate and efficient soil moisture data-transmission systems. This paper includes the discussion on how machine learning (ML) and deep learning (DL) techniques can be improvise to further accuracy and performance in IoT-based smart irrigation systems. The system is based on the perception of soil moisture using IoT sensors collecting real-time environmental data in fields, such as soil moisture, temperature, humidity, and sunlight, to be transmitted to farmers or end-users using ThingSpeak and Thinger.io platforms for analysis, storage, and visualization. It enables real-time decisions and remote agricultural systems control using web page or mobile applications.*

The WSNs(Wireless sensor network) helps to automate irrigation and water management in agricultural sites. The developed SIS(Smart Irrigation Systems) is based on the sensor network that carries real-time information relating to moisture content in the soil, temperature, and humidity levels as very critical determinants of the proper irrigation schedule. These are analyzed every 15 minutes at the edge server. The system uses deep learning models to predict when the soil moisture falls below a threshold and automatically activates water pumps or sprinklers, which reduces human intervention and optimizes water usage in agriculture. An important part of research forms machine learning algorithms to improvise the performance. The recent advancements relies on several models, among them KNN (K-Nearest neighbors) and TimeGPT models [TimeGPT is a time-series forecasting model that utilizes the power of GPT (Generative Pre-trained Transformer) architecture to predict future values in a sequence.], in the prediction of soil moisture while achieving optimal irrigation schedules from previous available data and weather forecasting. The comparative analyses included an accuracy rate of 97% to 98% in KNN thus describing the high level of accuracy that the system can attain regarding the soil conditions and water requirements.

This research provides the possibility of embedding IoT into machine learning that may form a new age smart agriculture system that, apart from irrigation automation, enhances decision-making in farmer practices. Adoption of such systems could contribute immensely to the sustainability of such agricultural practices mainly due to reduced water wastage, decrease operation costs, and improved crop yield. Integrating real-time environmental data and predictive analytics farmlands can be optimized and maintained even the land has water scarcity or difficult to receive rainfall or other climatic conditions.

***Keywords**: Arduino Mega, Bluetooth Module, Foundation models, Fertilizers, Forecasting, Humidity, IoT (Internet of Things), Microcontroller, Machine Learning Model, Prediction, Sensors, Soil moisture, Solar Panel Time-series, Smart Agriculture, Soil Water Potential, Temperature.*

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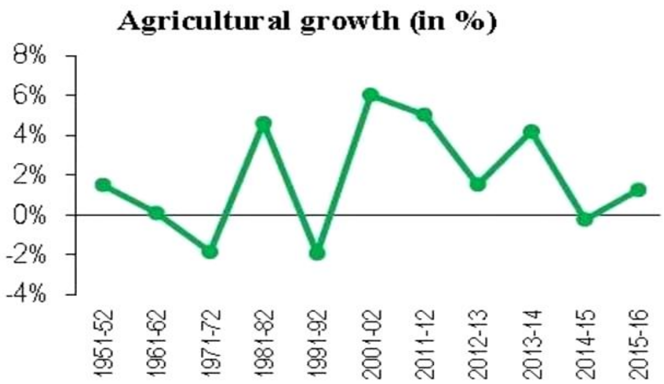
I. INTRODUCTION

The global population is expected to be about 10 billion by 2050, a time when the claim for food creation is anticipated to increase by nearly 70%. This would create heavy challenges, mainly in regions such as Africa, where agricultural practices have to be updated to meet the improved request for food while protecting natural resources. This increases pressure on agricultural systems in terms of climate change, cultivable land, and water scarcity. Here, environmental monitoring is a given that can ensure that agricultural activities do not negatively impact ecosystems or human health.



(Sources: Agricultural Statistics at a Glance, 2015; PRS) [11]

[Fig.1: Agriculture Growth]

Environmental observing is one of the prime important tools applied in monitoring the ecological effects of agriculture. Monitoring can be accomplished by gathering data on a number of environmental parameters, such as soil moisture, temperature, humidity, and pollution levels, in an orderly manner. This will allow farmers and policy makers to take appropriate decisions according to agricultural productivity versus environmental sustainability.

Traditional methods of monitoring usually fail for their manual and time-consuming nature, with little scope to make important events responded to appropriately in time.

II. METHODS

In the IoT, it is finally possible to intervene and alter how agriculture can be used as a potential productivity-building factor through innovative solutions [37]. Through IoT technologies, there is a possibility of real-time monitoring, data collection and its environmental conditions. This new digital agriculture would ensure not only an increase in resource management but also in crop yielding and its quality.

Among the best applications of the IoT in the agricultural sector are the innovations that develop Smart Irrigation Systems (SIS) [38]. Development is built on the use of technologies like WSN and cloud computing, these systems apply the technologies for optimization in irrigation. Most cases usually witness wastage of water during fixed scheduled irrigation by human beings due to either excess application or inefficiency of water. Avoiding such factors is possible with SIS by making automatic irrigation based on real-time data presentation about the correct amount of water that crops require at the correct time [39].

Major constituents of SIS are moisture sensors, temperature sensors and a central processing unit (CPU), preferably a microcontroller. These sensors gather data on soil status and weather, which were used to determine the schedule for irrigation. For example, whenever the level of water in the soil hits a pre-set threshold limit, then the system switches on the irrigation system, thus saving water and energy. Moreover, SIS can also be designed with consideration of weather forecasting; so that the system can automatically stop irrigation when it rains.

A. Advantages Offered by SIS During Implementation

- Water Conservation: It saves water by optimizing the use of water. This is highly essential in regions where water is scarce, and each drop is treasured.
- Cost Efficiency: These computerized systems decrease labor expenses and bring down the level of human intervention required on the construction site. Whatever little water and energy it saves in the long time period is equal to the investment cost it takes to implement technology.
- Environmental Protection: The SIS minimizes runoff and saves the local ecosystem from the devastating consequences of the same. More water runs off the site and prevents more nutrients and pesticides into the nearby water bodies. This in turn prevents the killing of aqua life and keeps the water quality good.

B. The Mass-Scale Adoption of SIS Includes a Few Issues

- Capital Expenditure Costs: The advanced sensors and automated systems are relatively expensive for small-scale farmers. Although long-term savings are considerable, this is still a cost that deters the farmers.
- Issues related to technical knowledge: Small farmers may not have the technical knowledge on how to run and manage IoT-based technology. Education and training are important to using it effectively.
- No Connectivity: The internet would not be available in rural setups most of the time. This would naturally hinder the cloud solution deployment, though it also affects fast data transfer abilities.
- Data Privacy and Security: Similar to any other IoT solution, data privacy and security concerns should be addressed. Data should be secured and not compromised by third parties, especially for farmers.
- Considering these problems, this study focuses on the design and development of an economical SIS controller for drip irrigation. As stated above, the developed system will be made accessible to small-scale farmers through its technology, not meant to be, strictly speaking, reserved for larger agricultural enterprises.

C. SIS

The proposed SIS employs a microcontroller, ESP8266, as a central processing unit that connects to moisture and temperature sensors. Data coming from these sensors on environmental conditions is then transmitted through for further storage and analysis in a cloud computing platform called ThingSpeak. The whole system uses open-source technologies to decrease costs but still confirm proper functionality.

The SIS is designed to continuously read soil moisture levels. Should the moisture levels reduce below a selected threshold value, the system will turn on the irrigation pumps. Besides that, the system can use weather conditions to further optimize an irrigation schedule by withholding applications during periods of rain. Besides saving water, automation saves energy and reduces labor costs.

Introduction of IoT in agriculture is an important step toward creating a sustainable farming culture. With increasing concerns related to climate change and growing population, pressure over food production, thereby calling for efficient resource management. Employment of Smart Irrigation Systems would benefit farmers respond to changes in agriculture conditions fast, making it productive and environment-friendly.

Moreover, this study draws kindness to the importance of taking into account of contextual factors in an agriculture system. Different regions face different challenges and needs, so customized solutions are needed. Such flexibility can best be assured in the proposed SIS (in the recent development): it should be flexible to be adapted according to local environmental conditions and farmer preferences.

III. LITERATURE REVIEW

The weather forecasts, soil moisture sensors, and automated irrigation systems can highly benefit smart agriculture, using microcontrollers and relays as aids [1]. Using such IoT-based solutions as studied from the paper, farmers may monitor real-time conditions of the soil and optimize the usage of water for crops. Let, soil moisture sensors is very necessary to a microcontroller that, in turn, can transmit a signal through a relay to turn on a water pump, for example, in most experiments performed with such sensors [4]. More complex models, such as TimeGPT, can forecast the soil

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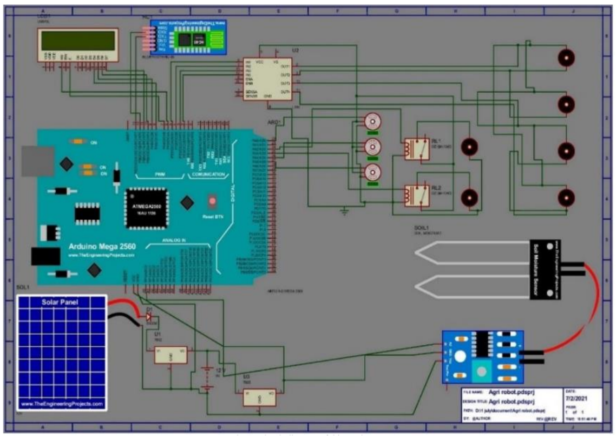
water potential, thus allowing more effective irrigation techniques, like when to irrigate the crops, as such models and prior data with a plot can forecast [5]. For example, using the software platform like Blynk to monitor and control water systems remotely can help farmers effectively to manage their resources by responding changes in the weather [2]. In this regard, this integrated approach saves water and supports sustainable agriculture [3].



[Fig.2: Circuit Diagram of Smart Agriculture][2]

Weather forecasting, soil moisture sensors, and microcontroller-based systems can advance upon smart agriculture significantly [5]. Using a microcontroller as NodeMCU, the farmer will be able to automate the irrigation process with real-time data from soil moisture sensors to obtain the level of moisture and the raising of water pumps by relays whenever there is a need [6]. These additions of weather forecasts support better irrigation decisions and serve to enhance the use of water without wasting it [8]. More than this, means such as Blynk software allow for remote monitoring and control of the irrigation system, whereby a farmer is able to operate his resources perfectly from the mobile device [7]. These technologies, in this combination, not only enhance crop yield but ensure that the consumption of water is sustainable while trying to reduce the issues of scarcity of water within agricultural regions [9]. Integration with weather forecasting, soil moisture sensors, and microcontroller-based systems could improve agriculture in relation to irrigation optimization [10]. Thus, the soil moisture sensor YL-69 could be used to monitor the state of soil in real time as water would be supplied only when there is a need so it conserves resources and increases crop yields [15]. By the usage of the microcontroller, such as the PIC16f876A, the system would be capable to take independent decisions regarding irrigation with consideration of the values threshold for rainfall and soil moisture [12]. Additionally, the relays can be used for controlling the pump supplying water wherein the relays are engaged once soil moisture levels are less than the threshold value and disengaged when satisfactory moisture levels are realized [14]. Data from the weather forecast can further improve irrigation scheduling. Rainfall prediction allow farmers to change their irrigation techniques well in advance [13]. This integrated approach saves labour and water, among other things. In addition, there is easy approach for sustainable agriculture [11].

Smart agriculture applies technology usage to optimize irrigation and improve crop management and with the help of weather forecasting along with the use of soil moisture sensors, and automatic systems. As a result, it makes water usage highly efficient and increases crop output.

A. Integration of Soil Moisture Sensors

These are essential in helping monitor the levels of moisture present hence, this helps to automatically regulate the turn-on condition of water pumps through real-time data information [16]. Systems like NodeMCU is able to share moisture information on mobile apps to the users, and will be able to give more irrigation remotely [17].

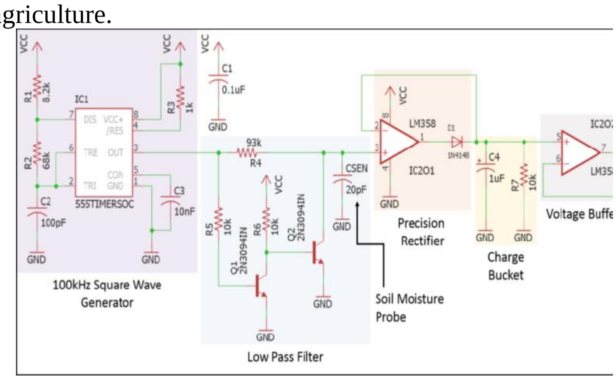
[Fig.3: Solid State Soil Moisture Sensor][36]

B. Integration of Weather Forecasting

Accurate weather forecasts will enable efficient irrigation management. Machine learning algorithms can predict rain and other weather-related events; hence farmers will also be in a better position to make decisions [18]. Weather information coupled with soil moisture can provide accurate control over irrigation hence less water waste while enhancing crop health [20].

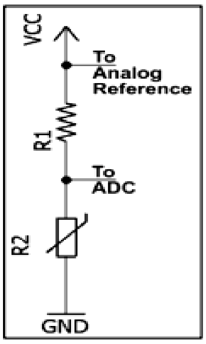
C. Integration of Automation and Control Systems

For instance, using microcontrollers and relays [16], automated systems could close or open pumps based on moisture levels or inputs from the weather forecast, hence avoiding some of the human intervention [20]. IoT technologies provide access to real-time data, thereby enhancing decision-making and promoting sustainability practices [19]. Though these technologies offer many benefits, they present initial problems that include the initial setup costs and the requirement for specific knowledge, hence not yet commonly found in all farmer's fields. Still, there is promise for more efficiency and sustainability in agriculture.

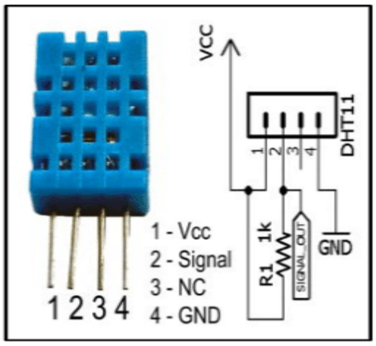


[Fig.4: Soil Moisture Sensor Signal Conditioning Circuit][35]

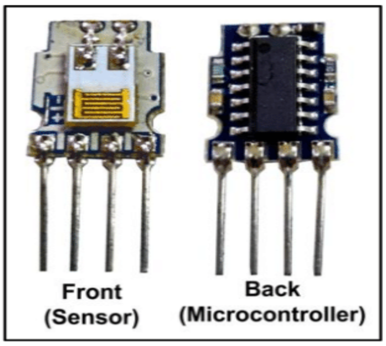
Smart agriculture employs up to date with various technologies such as weather forecasts, soil moisture sensors, microcontrollers, and relays in making proper use of water resources and achieving proper crop yield [11]. This can be achieved by integrating a microcontroller into a soil moisture sensor device where one can regularly monitor the moist condition of the soil for proper control of irrigation [23]. This on activation acts a relay that control the water pump in such a way that only when moisture levels are at a particular threshold, it will hydrate the crops, meaning the crops would not be overwatered [21]. Another advantage is weather forecasting, which enables the informing of farmers about rainfalls that are due to fall, thus one can act in adjusting irrigation schedules of such water. This saves on the use of water resources. The availability of IoT platforms such as Blynk software enables remote monitoring and control, which informs the farmer about their agricultural practices [22]. The level of human intervention is reduced, good farming practices are improved, and soil health and productivity in agriculture are enhanced [24].



[Fig.5: Thermistor Microcontroller Interfacing][35]



[Fig.6: DHT11 Microcontroller Interfacing][35]



[Fig.7: DHT11 Internals][35]

Smart agriculture now uses advanced technologies such as weather forecasting, and soil moisture sensors, combined with microcontrollers to optimize the activity of irrigation along with crop management [25]. With a system that has incorporated the soil moisture sensor together with a microcontroller like Arduino, an application in this regard can automatically control a water pump based on real-time moisture levels without human intervention [26]. Implementation of a relay will maximize the switching of the water pump while Blynk software will enable remote monitoring and control by permitting farmers to remotely check, monitor, and control their mobile irrigation devices [27]. The ability also doubles up as weather forecasting, which can be used to prevent over-irrigation by stopping water flow during raining in order to conserve the available water resources [28]. That is, the integration of these technologies will not only promote more efficiency in irrigation but also help sustain agricultural practices, therefore increasing crop yield and doing better resource management [29].

This would greatly improve smart agriculture, if weather forecasts, soil moisture sensors, and microcontrollers were put together in a device to ensure that the irrigation practices were conducted optimally [30]. By attaching the soil moisture sensor with a microcontroller like NodeMCU or 8051, farmers can work in real time to monitor soil conditions and automate the water pumps' operation by making use of relays according to the prevailing moisture levels [34]. This would further allow better information when trying to predict rainfall, which can then alter the irrigation schedule, thus preventing over- or under-irrigation [32]. Acquisition of this data and transfer into a user-friendly application by the IoT systems will allow proper management and sustainable use of resources by farmers [33]. This integrated approach preserves water besides improving crop production and encouraging sustainable agricultural practices [31].

IV. RESULTS AND DISCUSSIONS

The crop prediction and fertilizer recommendation system are modelled using machine learning on datasets feature engineering in regard to temperature, humidity, pH, rainfall, and nutrients in the soil, including nitrogen, phosphorus, and potassium. The crop prediction considers all these features, whereas the fertilizer recommendation mainly focuses on the moisture of the soil and the degree to which nutrient availability is abundant. Various algorithms were experimented, such as Random Forest, Decision Tree, Naive Bayes, SVM, Logistic Regression, and XGBoost: The highest yielding one was Random Forest. The system gives farmers tailored crop recommendations based on environmental and soil conditions as well as fertilizer suggestions based on nutrient and moisture levels.

Table 1: Comparison of Various ML Techniques and its Achieved Accuracy for Crop Recommendation Model

Sl.No	Machine Learning Techniques Used	Accuracy Achieved in %
1.	Decision Tree	90
2.	Naïve Bayes	99.0909
3.	SVM	97.9545
4.	Logistic Regression	95.2272
5.	RF	99.0909
6.	XGBoost	99.0909

V. CONCLUSION

Climate change, increase in population, and limited availability of resources are forming a hail of storms for the agricultural sector. Since agriculture acts as the backbone of most countries economies, innovative solutions need to be presented to enhance productivity while sustaining it. This paper has discussed the transformational potential of SIS based on the idea of IoT and advanced analytics and provided a comprehensive framework on how agricultural activities can be improved.

The main purpose of this study has been to introduce how modern technology, especially IoT and big data analytics, could be a tool for improving the efficiency of irrigation of crops. The findings of the study are that in the agricultural practice, by introducing real-time monitoring of environmental variables such as soil moisture, air temperature, humidity, and sunlight, water usage can be optimized extensively. With sensor data, farmers can take some decision regarding the schedule of irrigation and its practice, which at the end will involve optimal resource utilization.

The big part of this paper is the development of an intelligent weather data management platform to serve Moroccan agriculture. Of course, through clear applications, such an endeavor shows how big data can be used in outlining information on the patterns of rains and enabling farmers to modify their irrigation activities in order to enhance production. It was found that the combination of ERA5-Land reanalysis data with advanced deep learning algorithms predicts air temperature and evapotranspiration with fair accuracy for farmers to predict water requirements by their crops. Such irrigation practices in traditional farming systems have inefficiencies and increased labor costs since most of them are done manually. In this proposed study, the automated smart irrigation system addresses the aforementioned drawbacks by using sensors that monitor real-time soil moisture levels and environmental conditions. This system involves irrigation done at the right time with the right amount of water according to crops. The results obtained show that the system greatly reduces waste water usage while improving crop quality and yield simultaneously. Integrating an Android application further makes it easy to have data received by farmers, whom they can then use to override the system settings according to their specific needs with regards to certain crops, hence making the system user-friendly and adaptable. A critical aspect that makes the automated system more viable for farmers, especially small-holding ones, is the cost-effectiveness of it. With minimal operating costs and a reduced maintenance schedule of SIS, it is an inexpensive means of optimizing agricultural practices. This fact that the system can operate at low power and on low-cost components guarantees its place in a wide spectrum of farmers reach to promote fairness in innovations in agriculture.

This has profound implications much beyond the immediate agricultural practice. Showing promise for revolution in irrigation patterns through IoT and big data analytics, this study advocates a shift in the approach of agriculture across the world. With water looming as a scarce commodity over an ever-growing proportion of population, adoption of smart irrigation techniques could go a long way in helping sustainable water management practices. This can minimize over-irrigation and under-irrigation, thereby also preserving valuable water resources supporting the broader aims of environmental sustainability. The findings of this paper also highlight the need to do extensive awareness and training of farmers because these are evolving technologies. The majority of the farmers may not be aware of IoT and related smart farming concepts, proper schooling is required; hence they would know how to implement them accordingly and reap its benefits. Interactions between the government, education, and agriculture sectors can facilitate the sharing of knowledge and empower farmers to be more productive and sustainable.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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