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Hybrid Data-Fusion Model for Solar-Powered Smart Irrigation with Predictive Decision-Making

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The proposed system addresses inefficient water use in agriculture by integrating an Arduino microcontroller, sensors, and data analysis. It irrigates only when needed, using weather forecasts and soil moisture sensors to optimize water delivery. The system conserves water, improves irrigation and resource management, enhances crop productivity, and reduces environmental impact. It features a user-friendly interface for remote monitoring and control and uses a Weather Forecast API to obtain real-time and forecast data from Open Weather via the REST protocol, including temperature, humidity, wind speed, and rain probability. This weather data is combined with soil moisture sensor readings in a Hybrid Fusion Algorithm, which checks both current and predicted conditions to decide when to irrigate. For instance, if the soil is dry but rain is likely, the system delays irrigation to save water. If the soil is dry and no rain is expected, irrigation starts automatically. By combining soil and weather data, the system can make more informed and sustainable decisions. In tests, this approach reduced water use by 27 % and cut unnecessary operations by 18 % compared to traditional systems. The system operates on solar energy, ensuring a sustainable and self-sufficient solution. This system represents an innovative advancement in agricultural technology, supporting more efficient and sustainable farming practices.

1. Introduction

Plants are vital for human beings in numerous ways. They maintain equilibrium and give access to a multitude of natural resources. Addressing problems related to conservation issues brings these topics to the forefront. There is an increase in food product demand and a stagnant supply, as a lack of water and poor farming techniques used by many farmers lead to market inefficiencies. Considering all these recent problems, modern solutions can be adopted that allow cultivation to take place over short periods, provided a proper water supply and continuous oversight of the crops are maintained. Crops will also fail if the wrong amount is supplied. Constant surveillance is pivotal. Automated irrigation systems designed for modern farming, equipped with advanced self-monitoring devices for soil parameters, would provide instantaneous solutions to basic problems hindering farmers' productivity/work. IoT plays an important role in automated irrigation systems employing Arduino technology. Other IoT components include sensors and microcontrollers. Sensors can assess the soil's moisture levels, indicating how much water the plants require, and can collaboratively detect, gather, and transmit data to microcontrollers (Abbas et al., 2024), such as Arduino boards, which can collect data from sensors, making decisions to regulate water flow to crops through motors. This system adjusts watering schedules based on real-time data, eliminating the need for human intervention (Klerkx et al., 2019) . The

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Internet of Things (IoT) encompasses a comprehensive implementation of modern technologies, including information technology, field PC systems, telecommunications, and remote control. Today, it is widely used in healthcare, medicine, transportation, technological industries, and agriculture (Lv et al., 2021). Smart agriculture deeply integrates IoT-based technologies, helping to improve the yield and efficiency of farm work while conserving resources and ensuring crop quality. Smart Agriculture based on IoT encompasses information gathering for agricultural services, Logistics, Data collection, data storage and management, data mining, analysis, and modeling (Sundaravadivel et al., 2018). The advent of Data Analytics, Machine Learning, IoT, and mobile application development has been widely recognized as a significant driving force in the successful design and implementation of many precision agriculture and smart farming systems (Gharrawi and Al-Joda, 2024). The concept of precision agriculture relies on the use of advanced technologies, such as the Global Positioning System (GPS), Geographic Information Systems (GIS), Remote Sensing, and Variable Rate Technology, to optimise and improve farm yields. The farm management process is enhanced through automated, precise, and effective fertilizer application, smart irrigation, and waste reduction, among others (Kamilaris et al., 2017).

2. Review of Related Works

Different IoT-related approaches have been utilized in various ways to obtain automated irrigation solutions. These solutions have varying levels of complexity, and the build modules, such as Arduino and Raspberry Pi, as well as the types of sensors used, are associated with the type of problems solved and the goals. The authors provide a review of the literature, which is mostly recent and related to the proposed system. Anbarasi et al. (Nagendhiran, 2019). presented an IoT-based smart irrigation framework to enhance crop yield. The framework provides real-time decisions based on readings from the land. A soil moisture sensor measures the moisture level, activating or deactivating the pump motor according to the readings. A web application allows farmers to monitor soil moisture and temperature at selected intervals. Hassan et al. (2018) developed an automated irrigation system using the Arduino microcontroller. The system includes a soil moisture sensor to monitor the soil humidity of the plant. Based on the sensed soil moisture level, the system will automatically irrigate the plant when the soil is too dry and stop the water pump when the soil is sufficiently wet. This solution consists of only one sensing node and is relatively simple in its operation, implying that it does not process the collected data. It operates solely as a monitoring system, allowing users to ensure that soil moisture is monitored with readings displayed on the Liquid Crystal Display (LCD).

In 2018, Al-Omary et al. proposed a smart cloud-based IoT technique for monitoring and controlling the irrigation process in gardens using Arduino Uno. To do this, the authors assisted in monitoring and keeping within the right values of the garden soil moisture and light intensity quantities by using two sensors (soil moisture and light intensity). Those quantities are constantly sent to Thing, a cloud-based framework in which the collected data are analyzed and visualized. The cloud makes the proper decision and automatically sends the irrigation system to water the garden. However, the authors did not take into account some other irrigation parameters, such as air humidity and temperature. In addition, transferring all the collected data to the cloud will require considerable amounts of data storage, introduce latency, and exacerbate privacy problems (Al-Omary et al., 2018). (Morenikeji Dele et al., 2025) employed an IoT approach using WSNs in the design and implementation of a smart irrigation system. They used the WSN to collect, save, and share sensor data. They used two sensors: the Telosb sensor and the VH400 soil moisture sensor. The Telosb sensor measured light, temperature, humidity, and energy, and the VH400 sensor measured soil moisture. The collected data is sent to a cloud server, where it is analyzed and processed. The WSN using a cloud server does not use the concept of fog computing. In other words, all collected data is sent to a cloud server, where the data is analysed and decisions made.

Okoye et al. (2018) established an automated irrigation system based on Arduino, which differed from Fawzi and Jalal. The goal of the study was to determine the irrigation time for three soils in Nigeria. For this reason, they used an Arduino Uno integrated with a soil moisture sensor to control the irrigation. The water level and other important data statuses are displayed on an LCD. This system is straightforward and was designed specifically to study the relationship between irrigation time and soil type. It did not consider the primary concept of IoT, as the data collected is not shared via the internet (Okoye, et al., 2018). Based on the reviewed studies, it is obvious that most of them used Arduino Uno, and some have deployed WSNs and cloud-based systems. (Kadhim and Al-Safi, 2025) focuses on how Wireless Sensor Networks (WSNs) have revolutionized precision farming, enabling smarter and more efficient crop monitoring and management. Yet, traditional WSNs often struggle with limited reach and flexibility. In this study, the authors introduce an innovative WSN design that unites ground-based sensors with agile, drone-mounted nodes, creating a dynamic network for smart agriculture. Ground sensors deliver detailed, on-the-spot data, while drones swiftly scan fields for rapid environmental shifts. Traditional irrigation wastes water and gives uneven crop yields because it depends on guesswork. The proposed automated systems save water but often lack stable power, making them less effective in remote areas or bad weather. This project develops an automatic irrigation system using Arduino and solar power to improve water use in farming. Using weather monitoring, the system focuses on saving water, supporting plant health, and using renewable energy. This system combines real-time soil moisture data with weather forecasts to change irrigation times based on current and expected conditions. It runs on solar power with a backup battery to work reliably in different weather. These features make it different from older IoT irrigation systems that used only cloud processing or fixed schedules, providing a simpler and more sustainable farming solution.

3. Methodology

Arduino was used to build a simple IoT irrigation system. The aim is to create a system to manage irrigation. A soil moisture sensor connected to the Arduino measures moisture levels. This lets the Arduino turn a water pump on or off for automatic watering based on soil moisture and weather data from an API. An LCD shows sensor readings in real time. Arduino serves as a central hub, handling computation, communication, and control, and acts as a bridge between sensors and the web server for monitoring. Moisture sensors are placed in the field to collect soil data, and a weather API provides forecasting. With these inputs, the system dynamically controls irrigation to optimize water usage and promote crop health, rather than relying on preset schedules. Cloud computing enables data storage and remote access to data. Farmers can monitor, analyze, and adjust the system remotely using a web application. The system components are: Resistive Soil Moisture Sensor, 9V 220mA Solar Panel with Aluminium frame, Lithium Battery Charging Mppt Solar Panel Regulator, 5200mAh 3S 11.1V 35C LIPO Battery XT60, Arduino UNO, L298N 2A Dual Motor Driver Module with PWM Control, LCD 20 x4 model, Micro Submersible Water Pump DC 3V-5V, temperature and humidity DHT11 sensor, Jumper wires, Pipes, Data cable, ESP-Wifi and ESP32 cam. (Okoye et al., 2018; Sunehra, 2019; Morchid et al., 2024). The system block diagram of the smart irrigation system is shown in Figure 1.

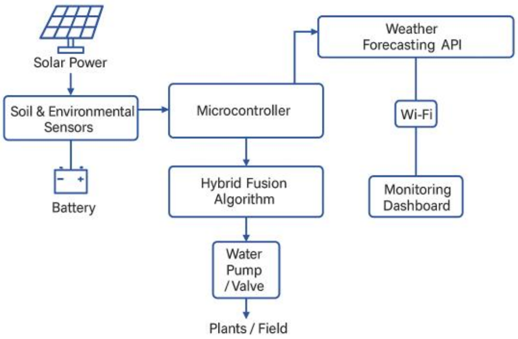

Figure 1: The block diagram of the smart irrigation system

The resistive sensor, which measures changes in electrical resistance as soil moisture levels vary, was chosen because it is affordable, compact, and energy efficient. These qualities fit well with the system's solar-powered and low-maintenance design. To mitigate the effects of temperature and salinity, the calibrated sensor was tested at several points using gravimetric soil moisture data, which involves weighing soil samples before and after drying, across a range of moisture levels and temperatures from 15 to 35 °C for 20 days. The calibration curve showed a strong fit. We placed the probes 10 to 15 cm deep, about one-third of the crop root zone, and 10 cm from the emitters to avoid areas that might be too wet. To minimize errors from placement, the authors took repeated readings and used median filtering, which helps reduce the impact of outliers. This confirmed that it is a good fit for the smart irrigation system. Field reference points for 0 % (dry, Analog-to-Digital Converter ADC = 1023), and 100 % (saturated, ADC = 400) were used to recalibrate the soil moisture sensor. The following is the expression for the resulting linear relationship between ADC and volumetric water content (VWC, %):$\mathrm{VWC} = -0.160 \times \mathrm{ADC} + 164$

Real-time soil water content estimation is made possible by this calibration, which also helps the Hybrid Fusion Algorithm make accurate irrigation decisions. A practical comparison was conducted between a conventional irrigation system (based on a fixed schedule) and a proposed fusion system that integrates soil moisture data with weather forecasts. Water consumption and pump operation frequency were recorded during a two-week test period under identical environmental and soil conditions. The results showed that the proposed system consumed 27 % less water than the conventional system by postponing irrigation when API data predicted rainfall or high humidity. If the water consumption in the traditional system is 100 L and the consumption in the proposed system is 73 L, then the savings percentage is calculated as follows:

$$\eta_{water} = \frac{W_{Traditional} - W_{Proposed}}{W_{Traditiona}} \text{X}100\ \%$$

Where η_{water} : water saving (%), $W_{Traditional}$:water consumption in the traditional system ,and $W_{Proposed}$: water in the proposed fusion system.

The number of unnecessary pump operations was also reduced by 18 % which is calculated based on the following equation:

$$\eta_{pump} = \frac{N_{Traditional} - N_{Proposed}}{N_{Traditiona}} \text{X}100\ \%$$

where η_{pump} reduction in pump activations, $N_{Traditional}$: pump activations in the traditional system and $N_{Proposed}$: pump activations in the proposed fusion system.

The proposed algorithm is shown below:

1. Start the system.
2. Read soil moisture value from the soil moisture sensor.
3. Check the soil moisture level:
    - If the moisture value is greater than 400, go to Step 4.
    - Otherwise, if the moisture is less than or equal to 400, skip irrigation and end the process.
4. Check the weather condition from the Weather Forecasting API.
5. Evaluate weather condition:
    - If the weather is Partly Cloudy, Mostly Cloudy, Overcast, Snow, Hail, Rain, Drizzle, or Thunderstorm, turn OFF the pump and end the process.
    - If the weather is Heat Wave or Storm, irrigate for one extra hour and then end the process.
    - If the weather is Clear or Sunny, irrigate based on the plant's needs (according to programmed time or soil type).
6. After irrigation, update the system status and return to monitoring mode for the next reading cycle.
7. End the process.

Before implementation begins, the various components are assembled, and instructions are written for each element. The water pump's soil sensor is calibrated to ensure it is up to standard, and the moisture level within the soil is monitored during pumping. Additionally, an interfacing LCD provides real-time data measuring.

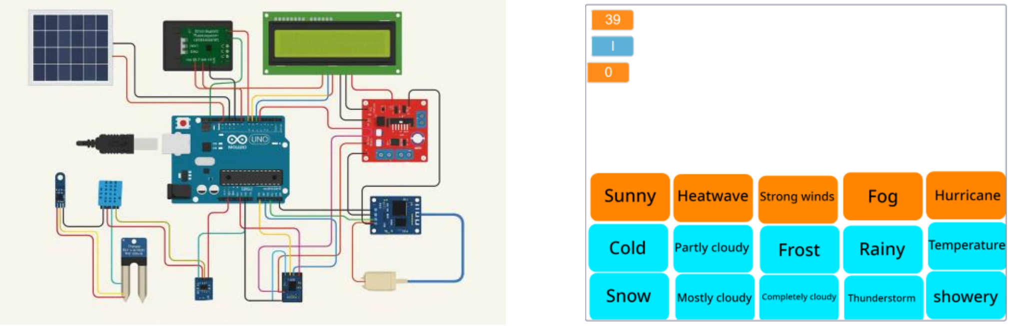

Figure 2: Circuit connection of the proposed system

Figure 3: System Implementation

Figure 2 shows the circuit connection. The whole system is dependent on a power source, which must be turned on. Once the power is turned on, the soil moisture sensor reads the moisture level of the soil. If the moisture level is higher than 400, the API weather checks to see if it is cloudy, and the motor will turn off, or the system will check to see if the API weather check was a heat wave or storm, and if so, will irrigate the soil for an additional hour. A solar cell is used to charge the Battery. The system implementation is shown in Figure 3.
The application interface shown in Figure 2 is the main point of interaction between users and the intelligent irrigation system. It is designed to be simple and responsive, so farmers can easily check real-time sensor data like soil moisture, temperature, humidity, and system status. The interface also shows visual indicators and graphs to help users see how environmental data has changed over time, making it easier to understand the field's condition. The authors developed a mobile app using Python that enables users to monitor and control the system from anywhere. The app lets you pick manual or automatic mode, set soil moisture levels, and get instant alerts. It connects to the system via Wi-Fi, so you can control it from your phone or computer. This makes the system simple to use and practical for farming.

4. Results and Discussion

An IoT irrigation system uses parts like an Arduino Uno, a soil moisture sensor, a water pump, a DHT11 sensor, an ESP Wi-Fi module, and an LCD to water plants automatically. The soil moisture sensor is placed in the soil to check moisture levels and send the data to the Arduino Uno. The Arduino Uno processes this information to decide when to turn the water pump on. To turn the water pump on and off, depends on API weather forecasting. The LCD is used to display the moisture levels and status. Model tests of the intelligent, solar-powered system showed it could use water more efficiently by adjusting to changing environmental conditions. By analyzing soil moisture, temperature, and air humidity together, the system's algorithm successfully combined real-time sensor data with weather forecasts to guide irrigation. Figure 4 show the relation between these values.

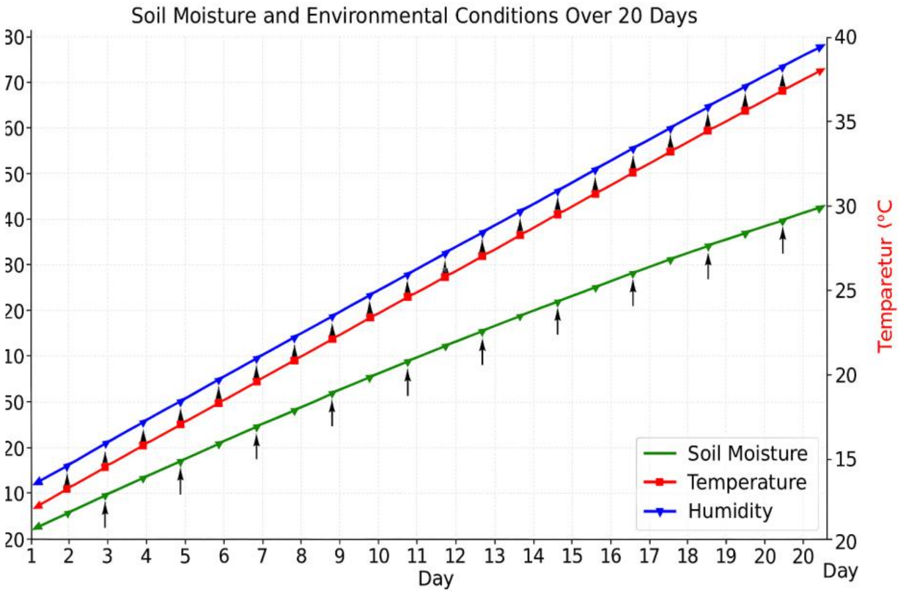

Figure 4: Relationship between soil moisture, temperature, and relative humidity

Figure 4 illustrates the uniform variation of soil moisture, temperature, and relative humidity over 20 days, providing a comprehensive view of the environmental interactions within the proposed intelligent irrigation system. The soil moisture curve is represented in green, while the temperature and air humidity curves are depicted in red and blue. The chart illustrates a clear inverse relationship between soil moisture and temperature, where an increase in temperature typically results in a gradual decrease in soil moisture due to increased evaporation rates. Conversely, air humidity shows a partial direct correlation with soil moisture, as an increase in humidity helps reduce water loss from the soil surface.
These combined patterns show that the hybrid integration algorithm works well to control irrigation based on changing environmental conditions. The balance between the three factors shows the system can keep soil moisture at good levels while using less water, making it practical and adaptable for farming. Tests showed water use dropped by 27 % and unnecessary pump activity fell by 18 % compared to traditional fixed-schedule

systems. This came from changing irrigation times based on soil and weather conditions, which cut water loss from evaporation and stopped overwatering. Sensors and control worked reliably with consistent results. Using solar power made the system self-sufficient and able to work in remote areas. Overall, the results show the system can save water and support eco-friendly farming.

5. Conclusion

For reliable and sustainable irrigation management, the proposed smart IoT system incorporates forecasting that is both efficient and policy-sensitive. Based on learning, the system dynamically modifies irrigation schedules by fusing data on soil moisture, temperature, and humidity with forecasted weather inputs from an application programming interface (API). According to experimental results, real-time irrigation reduced overall water consumption by 27 % and unnecessary indicator activations by 18 %. The system operated independently on solar power and showed dependable performance, preserving ideal soil conditions in a range of climatic conditions. Its initial design permits flexibility and scalability to meet different budgets in a range of settings. All things considered, the new findings validate that the suggested AI-enhanced, solar-powered planning system offers a useful, eco-friendly, and clever precision agriculture solution.

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