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Driving agricultural evolution: implementing agriculture 4.0 with Raspberry Pi and internet of things in Morocco

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ABSTRACT

The purpose of this project was to investigate the use of embedded system and smartphone technologies in conjunction with Raspberry Pi and NodeMCU to create an intelligent system for smart farming (SF). By means of experiments and comparative analysis carried out in several agricultural contexts, the research evaluated the efficacy of the intelligent system. Results showed that the system was able to handle pertinent agricultural activities and effectively monitor important environmental factors including temperature, humidity, soil moisture, and climatic quality. The system's remote accessibility helped farmers by allowing them to effectively oversee agricultural operations at any time and from any location. As a consequence, SF techniques produced more production, lower costs, and maintained assets.

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1. INTRODUCTION

Morocco, renowned for its agricultural production, stands at the brink of a technological transformation that promises to reshape its farming sector. This change is fueled by the incorporation of contemporary technologies into conventional farming methods, leading to the development of the idea of "smart farming" (SF). This study examines how SF can improve Morocco's agricultural production, resilience and sustainability. The country's agricultural sector, which employs a significant proportion of the workforce and underpins the economy, faces a number of challenges, including water scarcity, erratic weather patterns and wasted resources. The livelihoods of many farmers have been undermined by these difficulties, which have resulted in unpredictable crop yields.

The adoption of smart agricultural technology is increasingly essential as Moroccan agriculture develops to address these persistent problems. Farmers may access real-time data through the use of IoT devices, AI-driven analytics, remote sensing, and precision agricultural technologies. This facilitates better resource management, increased production, and the promotion of sustainable farming practices. Morocco hopes to lessen the negative effects of other environmental issues, such as climate change, on agriculture by using this technology.

Numerous studies have explored irrigation systems and highlighted advancements in agricultural technology. One example is the development of an integrated irrigation system that employs Bluetooth technology and microcontroller platforms like the PIC 16F88, along with sensors to monitor soil moisture and temperature in fields [1]. This system sends short-message services (SMS) notifications to manage watering schedules based on predicted rainfall and environmental factors [2], while also providing real-time alerts for detecting plant diseases. Weekly irrigation assessments are conducted by measuring soil and environmental changes through sensor nodes [3].

Automated strategies to improve the quality and quantity of crop production have been combined with machine learning (ML) methods to obtain accurate data and maximize yields [4], [5]. Despite advancements, challenges such as landscape degradation, the spread of pests, and plant diseases continue to impact crop yields. Effective water management remains a critical issue in many cropping systems, as plant diseases can cause significant economic losses [6]. The fact that unplanned water use can lead to significant water waste highlights the need to automate agricultural irrigation to apply the right amount of water, regardless of whether there is labor available to manually adjust valves and monitor crop development [7]. Smart agricultural systems offer farmers a cost-effective way to increase crop productivity [8]. For instance, a soil moisture sensing system using ZigBee wireless technology has been proposed to monitor soil moisture without directly controlling irrigation [9]. The IEEE 802.15.4 standard defines the physical and MAC layer interfaces of ZigBee and facilitates operation in master-slave or peer-to-peer network arrangements [10]. The ZigBee-based soil moisture monitoring system uses solenoid valves to control the moisture content of the soil in the irrigation area, but requires power support. The central ZigBee node connected to the wireless sensor network interacts with the central monitoring station (CMS) using the global system for mobile communications (GSM) or general packet radio service (GPRS) technology. In addition, the system collects field-related data from the global positioning system (GPS) and sends it to the CMS [11], [12].

Although small-scale smart irrigation systems are used to meet the needs of various plant species, they generally cannot comprehensively solve moisture-related problems [13]. To address these challenges, smart agriculture uses environmental sensors and web-based applications to analyze and share information about environmental conditions [14]. Climate-smart agricultural practices are implemented to optimize water use and replenish groundwater levels through effective analysis [15]. User-friendly interfaces are used to simulate irrigation parameters to facilitate decision-making in response to changing climate conditions [16].

El Alaoui *et al.* [17] examines the potential of precision agriculture (PA) and SF using advanced technologies like artificial intelligence (AI), the internet of things (IoT), and unmanned aerial vehicles (UAVs). It addresses global challenges such as food shortages and population growth, focusing on recent developments in data collection, analysis, and visualization. The research highlights the role of IoT and 5G networks and explores the use of robots and UAVs in agriculture, showcasing their integration with AI, deep learning (DL), and ML.

Chamara *et al.* [18] use of agricultural internet of things (Ag-IoT) for crop and environment monitoring, examining its evolution from past to present and providing insights into future developments. It explores how Ag-IoT technologies have advanced over time, focusing on their application in monitoring soil, water, weather, and crop health. The study highlights the integration of sensors, wireless communication, and data analytics to optimize agricultural practices. It also discusses challenges and opportunities for future Ag-IoT systems, including the role of emerging technologies such as 5G, AI, and ML to enhance PA.

One of the main drawbacks of traditional methods is the inefficient use of water, which results in over- or under-watering of crops [16], [19]. In addition, manual irrigation systems lack precision, resulting in inaccurate water distribution. These shortcomings highlight the urgent need to adopt smart agricultural technologies to improve efficiency, conserve resources, and increase overall crop yields [20], [21]. The goal of this research is to create an integrated agricultural system that is especially suited to the requirements and circumstances faced by Moroccan farmers. The main goal is to create a complete system for irrigation control and plant growth monitoring in order to increase Morocco's agricultural output.

Recognizing the challenges faced by traditional farming methods in Morocco, our proposed solution focuses on automation as a practical approach to overcoming these issues. A central aspect of this solution is the development of a plant disease monitoring system that allows for remote observation and control of irrigation in agricultural fields. This approach not only conserves water resources but also significantly reduces labor costs, a major concern for Moroccan farmers [19]. The Figure 1 shows depict a layered framework illustrating the interconnection between various components of smart agriculture.

In order to address the specific needs of Moroccan farmers, this study offers fresh perspectives on the implementation of SF techniques. Through its emphasis on monitoring plant diseases, managing water resources, and using renewable energy, this research adds to the current discussion on sustainable agriculture in poor nations [22]. We propose an integrated agricultural system designed to meet the unique challenges faced by Moroccan farmers. The system utilizes advanced sensors to monitor key parameters, including water flow, temperature, humidity, and soil moisture, increasing efficiency and accuracy. Through knowledge of the unique needs of various crops in terms of water and the soil's ability to retain water, irrigation techniques are adjusted to optimize productivity while reducing waste.

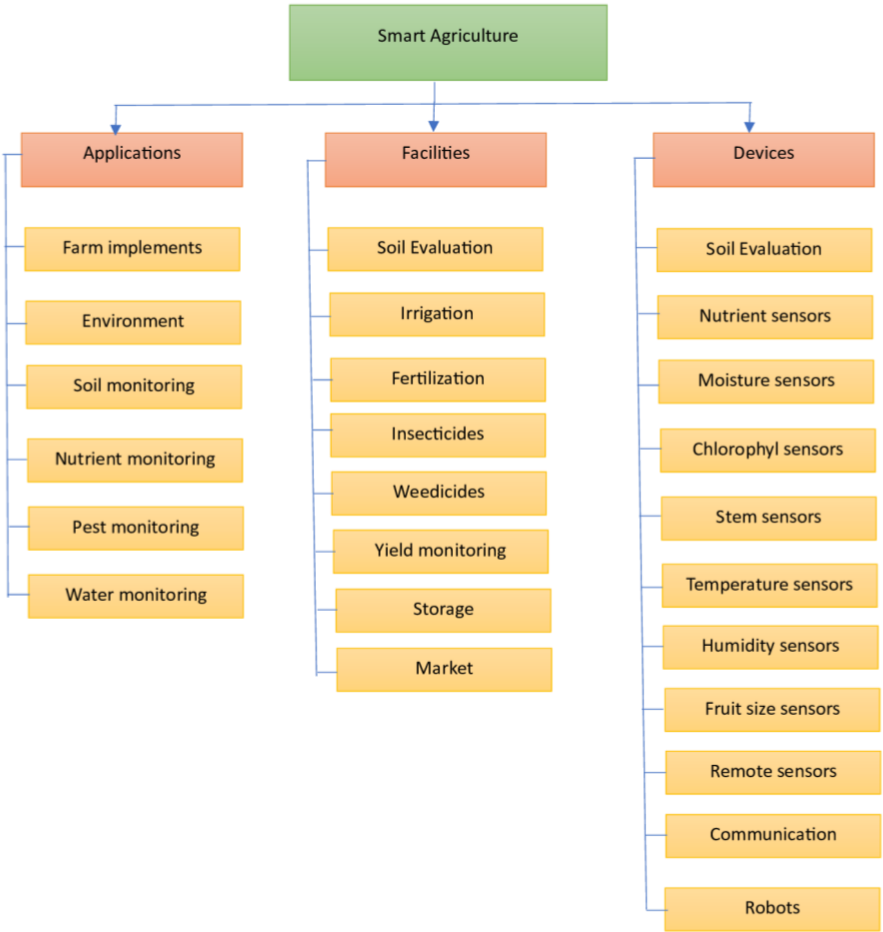

Figure 1. Smart agriculture: a hierarchical overview of applications, facilities, and devices

In addition, the system is powered by solar energy and other renewable sources, lessening its dependency on traditional electricity and enhancing its sustainability for Moroccan agricultural practices. The system can be fully automated through the integration of GSM technology, minimizing the need for human intervention and guaranteeing timely and effective irrigation management. This approach not only optimizes water usage but also conserves energy and lowers operational costs.

The paper offers several noteworthy contributions, including real-time monitoring and feedback based on soil moisture and temperature levels. The system periodically sends out acknowledgment signals, providing farmers with up-to-date information about their fields' conditions. Automatic irrigation control is implemented to prevent over-irrigation, conserving both water and energy by turning the motor on and off according to soil moisture sensor data, thereby reducing manual intervention. Rainfall detection further optimizes resource use by shutting off the motor when rain is detected, while temperature-based energy management adjusts motor operation according to air temperature, enhancing energy efficiency. Together, these contributions highlight how the proposed smart irrigation system improves agricultural practices by offering effective, automated irrigation control while conserving resources and minimizing environmental impact.

The rest of this paper is structured as follows. Section 2 outlines the proposed integrated system, focusing on the implementation of sensors, automation, and renewable energy integration. Section 3 presents the analysis and discussion of the results. While section 4 provides the conclusion, summarizing the key findings and contributions of this research.

2. METHODS AND MATERIALS

2.1. Presentation of the irrigation system

As Figure 2 illustrates, optimal crop growth and resource utilization depend on every component of the intricate irrigation system design. At the heart of this system is a complex configuration that combines data inputs from a weather station with a precisely positioned soil moisture sensor that is located close to the base of the plants. These sensors serve as the vigilant watchdogs of the farming environment by continuously monitoring and sending critical data to the NodeMCU controller, the setup's central nervous system.

As the brains behind the system, the NodeMCU controller orchestrates a symphony of algorithms for data processing and decision-making. After obtaining inputs from the sensors, the NodeMCU carries out a variety of complex calculations to find underlying patterns and trends in the data. However, basic data processing is not enough in the context of smart agriculture; rather, a sophisticated understanding of the dynamic interactions between various environmental elements and crop requirements is needed [20], [23].

This is where the clever application of fuzzy logic comes in handy. Unlike typical binary logic systems that operate in black-and-white, fuzzy logic thrives in the presence of ambiguity and uncertainty, mimicking the intricate decision-making processes of the human mind. Using well-crafted rules and fuzzy sets, the fuzzy controller navigates the challenging terrain of agricultural decision-making with agility and skill. For instance, in the face of fluctuating soil moisture levels, the fuzzy controller does not rely on binary options like "ON" or "OFF" for irrigation. Instead, by considering a range of factors like plant kind, soil type, weather prediction, and historical moisture data, it makes informed decisions that optimize water consumption while ensuring the plant's hydration demands are met.

Black-and-white, mimicking the intricate mental processes involved in making decisions. By employing fuzzy logic, the irrigation system is effectively converted from a mechanical to an intelligent, adaptive system that can respond dynamically to the ever-changing dynamics of the agricultural environment. It embodies the idea of PA, which maximizes crop yields, promotes sustainable farming practices, and optimizes resource allocation by fusing state-of-the-art algorithms with data-driven insights.

The different components of the NodeMCU- and Raspberry Pi Model-B-based automated farming system are shown in Figure 2. The gadget may provide information on the farm's current and daily highs and lows in temperature, humidity, and surrounding weather conditions to smartphones through real-time alerts. Furthermore, users can control the filter fan switches and customize the smartphone's notification system.

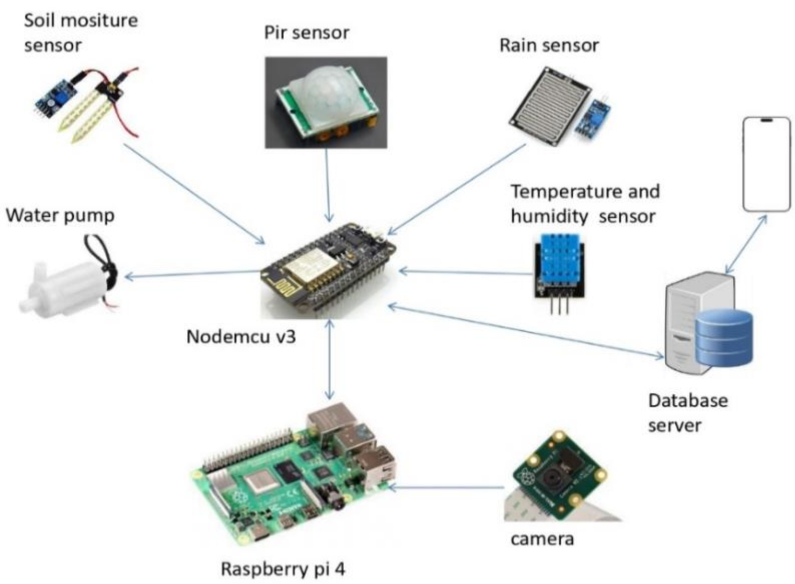

Figure 2. A complete block diagram depicting the entire system

2.1.1. Raspberry Pi 4

The Raspberry Pi 4 is the brains behind our smart agricultural system; it functions as a powerful, tiny Linux-powered computer board [24], [25]. Its versatility enables a seamless integration into networking and electrical architecture, going beyond traditional computer functions. Installing web servers and personal computer software like Apache and MySQL on the Raspberry Pi [26] allows it to perform as a standalone device. Unlike the Arduino, the Raspberry Pi lacks a native analog input feature, despite the fact that its general-purpose input/output (GPIO) pins can be used as digital inputs or outputs. To overcome this limitation, analog sensors are communicated with via communicate boards or external analog-to-digital converters (ADCs).

2.1.2. NodeMCU
NodeMCU is a brilliant example of innovation in the IoT development space. The open-source firmware and development kit for the ESP8266 WiFi module seamlessly blend the flexibility of the Lua scripting language with the power of the ESP8266 WiFi chip [22]. NodeMCU is a user-friendly platform with built-in WiFi and GPIO ports for integrating with sensors and actuators that facilitates rapid prototyping and development of IoT projects. Its compact size, cheap cost, and robust functionality make it a popular choice among makers, hobbyists, and experienced developers when building innovative IoT solutions.

2.1.3. Temperature and humidity sensor module
The DHT22 sensor, a crucial part of our agricultural setup's environmental monitoring system, guarantees that plants grow in optimal conditions. Two environmental factors that directly affect animal lifestyles and raise the risk of chronic epidemics are temperature and humidity. The DHT22 sensor's accurate temperature and humidity detection helps prevent diseases such as hand, foot, and mouth disease, as well as avian influenza.

2.1.4. Soil moisture sensor
When it comes to managing water in modern agriculture, soil moisture sensors are the first to react. These sensors provide real-time data on soil moisture levels. With this information, farmers can implement efficient irrigation techniques, support sustainable farming, and ensure optimal plant health.

2.1.5. Hardware connection
When integrating hardware components in our agricultural system, particular attention to detail is needed because devices such as the Arduino and Raspberry Pi have different electrical potentials. The bidirectional logic level converter isolates and corrects voltage differences to act as a bridge and facilitate seamless communication. Furthermore, establishing a direct connection between the camera and Raspberry Pi via the common system interface (CSI) enables speedy data transfer while consuming less power. A command program called MJPG-streamer can also replicate data from one input to multiple outputs, which facilitates the display of images in a network environment that is accessible through a web browser. All of the sensors are connected by an Arduino board, and data transmission via universal asynchronous receiver/transmitter (UART) is received by the Raspberry Pi, which manages the ventilator system and sends data to a server computer for storing. The smartphone interface gets its real-time updates from the Raspberry Pi as well. Our smart agricultural system's software, which serves as a conduit for data processing, analysis, and end-user presentation, is an equally crucial component. Together with Raspbian Wheezy, Linux, the Raspberry Pi’s primary operating system, offers dependable and efficient resource management. Applications for the Raspberry Pi platform are written in Python, enabling the reading of signals from the Arduino board via a UART connection and the storing of data in a database for later analysis. The Figure 3 illustrates the design and structure of the prototype developed for the project.

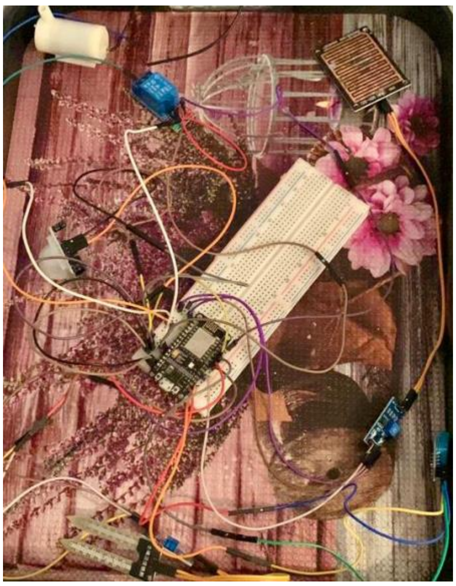

Figure 3. Presentation of the prototype

2.1.6. Software

Our smart agricultural system's software, which serves as a conduit for data processing, analysis, and end-user presentation, is an equally crucial component. Together with Raspbian Wheezy, Linux, the Raspberry Pi's primary operating system, offers dependable and efficient resource management. Applications for the Raspberry Pi platform are written in Python, enabling the reading of signals from the Arduino board via a UART connection and the storing of data in a database for later analysis.

Signals are sent to the GPIO pins at predefined cutoff points, activating associated functions such as ventilator or lamp lighting. Android apps display temperature, humidity, light intensity, and levels of hazardous gases, allowing you to remotely monitor and control the agricultural setup. Wireless network connectivity allows users to interact with the system and ensures optimal conditions for crop development and sustainability.

2.2. Schematic diagram and flowchart

One can comprehend the intricate architecture of a cutting-edge web-based SF system, which aims to revolutionize agricultural practices, by using Figure 4 as a guide. The system's core components are sophisticated sensors that are carefully matched with a microcontroller. The connection of the soil moisture sensor to analog pin A0 and the precise connection of the temperature and humidity sensor (DHT11) to digital pin 5 are two instances of this. These sensors provide vital information on soil moisture content and meteorological factors to decision-makers in crop management. The L293D motor driver IC adds the capability of controlled irrigation methods. Water is effectively distributed over agricultural areas by means of a DC motor. In addition, real-time water level monitoring is provided by the well-submerged wires that make up the water level indication system, which reduces water waste and ensures optimal crop hydration.

Furthermore, the system's receiver module, which comprises the nRF24L01 module and seamlessly interfaces with the Raspberry Pi, enables wireless connectivity for distant data transfer and monitoring. This integration helps farmers control irrigation more precisely and promotes the use of sustainable farming practices by arming them with practical knowledge. By leveraging real-time data and contemporary technology, this SF system represents a paradigm shift toward more ecologically conscious and productive agricultural practices. Its goal is to boost production and sustainability within the agricultural sector.

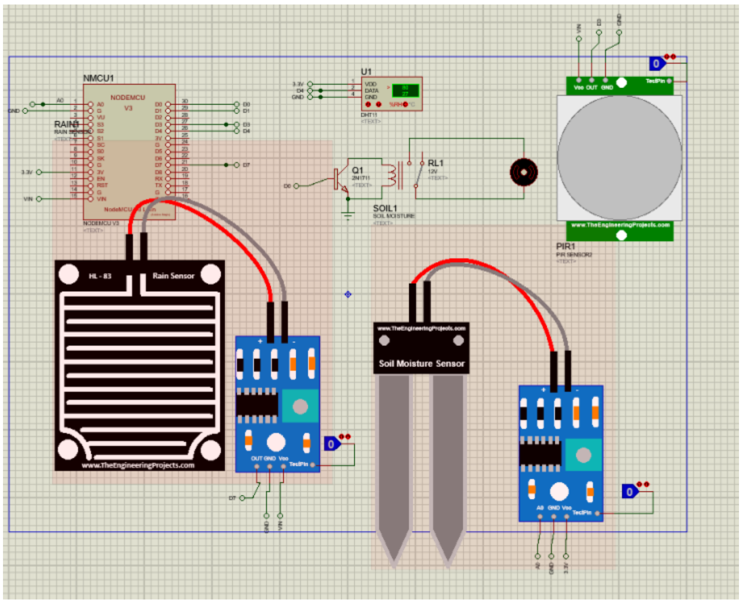

Figure 4. Schematic diagram

The Figure 5 represents the logical flow and operational steps of the proposed irrigation system. The process begins by monitoring the levels of the sensors deployed in the field (humidity, and temperature). If soil moisture is below a predefined threshold, the system checks the availability of the water reservoir. If water is available, the irrigation pump is activated and water is distributed to the crops. The system continues to monitor soil moisture during irrigation and stops the pump when the moisture level reaches the desired value. What's more, if the reservoir is empty, the system sends an alert to signal the need to refill it or solve water supply problems.

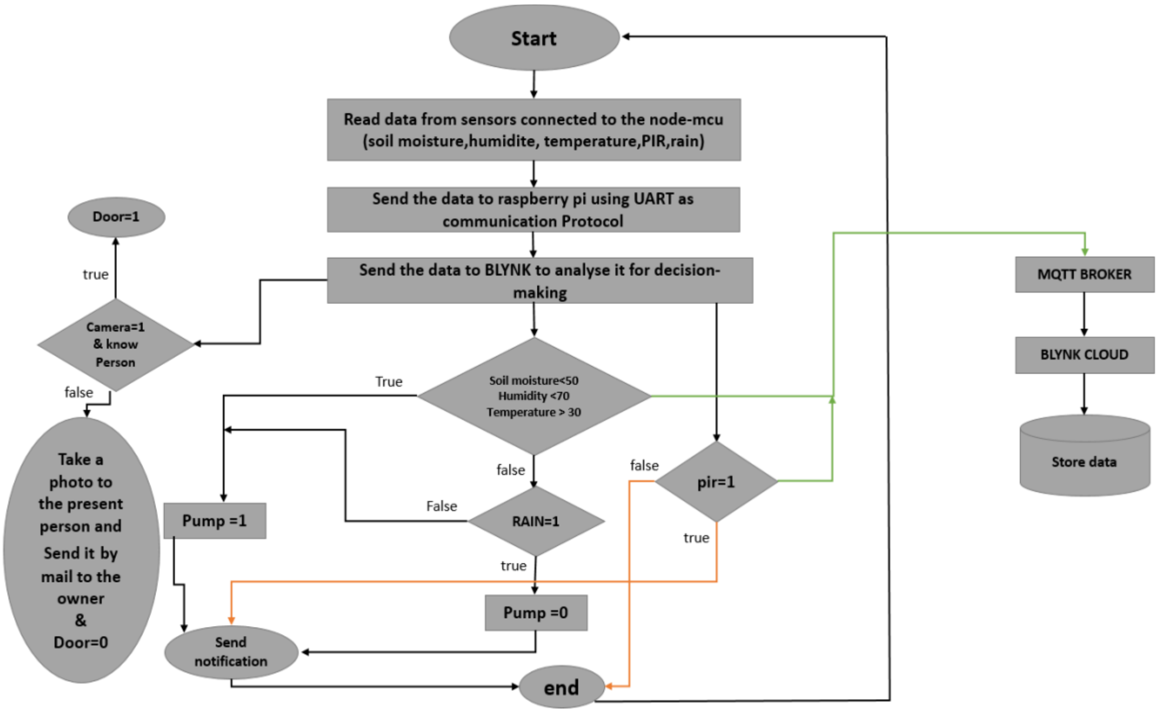

Figure 5. Flowchart software of the proposed irrigation system

The Figure 6 presents a 3D representation of our farms, offering a detailed and immersive view of the agricultural layout. The 3D model visually captures various elements of the farm, including fields, irrigation systems, solar panels, and monitoring stations. The fields are depicted with realistic textures, showcasing different crop zones, each equipped with advanced irrigation lines and soil sensors for precise water and nutrient management.

Figure 6. 3D representation of the proposed irrigation system

3. RESULTS AND DISCUSSION

The results of the model's rigorous testing under the dynamic environmental and meteorological conditions typical of a smart farm are presented in this work. The trial provided invaluable insights into the system's dependability and efficacy through a comprehensive evaluation of its operation and performance in real-world use. The system worked well during the trial period, integrating smartphone interfaces with notifications about default configurations, as shown in Table 1.

Table 1. System alerts based on environmental and operational parameters

List	Nature	Up to the alert (%)
CH4	-	50
NH3	-	50
Maximum temperatures	-	30 °C
Minimum temperatures	-	25 °C
Lighting	-	50
Humidity	Analog	20

This table serves as a comprehensive manual, detailing the exact notifications and alerts generated by the system to ensure timely and proactive response to significant occurrences and alterations in the surrounding environment. Through the integration of default configuration notifications, the system gives poultry farmers vital real-time information, enabling them to quickly address emerging problems and optimize operational efficiency. This study not only validates the robustness of the established model but also shows how, by leveraging state-of-the-art technology and data-driven insights, it might revolutionize SF operations.

Figure 7, which depicts the program's initial interface and provides users with an easier way to access key features, is a crucial visual aid. Four menu options are initially displayed to users by the interface: status, camera control, manual operation, and alert configuration. Each menu item has been thoughtfully designed to address specific aspects of farm management, allowing users total control and oversight over significant duties.

Figure 7. Displays the smartphone's home screen and system status panel

By choosing the "status" option, users can get up-to-date information and insights into a range of traits and situations within the farm environment. This menu serves as the main hub for monitoring the overall state and functionality of the farm infrastructure, including the equipment's functionality, temperature, humidity levels, and ventilation status. With "camera control," users can remotely access and operate security cameras all over the farm. This tool allows users to visually assess different agricultural regions, identify potential issues or anomalies, and manage operations with unparalleled ease and flexibility. Selecting the "manual operation" menu allows users who have direct control over specific agricultural machinery or processes to make the necessary adjustments or step in right away. By using this menu, users can precisely adjust feeding mechanisms, ventilation settings, and irrigation systems in response to operational requirements or real-time situations.

Lastly, users can use the "alert configuration" option to modify the system's alerting features to fit their own preferences and requirements. Using this menu, users can set up equipment fault notifications, define temperature thresholds, and create humidity warnings to match their own operating goals and risk tolerance levels with the system's alerting capabilities. The user-friendly interface ensures strong management and oversight over critical farm activities while providing users with an easy-to-use navigation experience. Users of the application can proactively monitor and improve farm performance, leading to increased productivity, efficiency, and sustainability in agriculture as a whole. It accomplishes this by providing a large selection of menu options and customizable alerting features.

The notification system used to alert users to specific environmental events, such as rainfall, is shown in Figure 8. In this instance, resource management and environmental responsiveness are demonstrated by the system's automatic cessation of water pumping upon receiving a rain warning. The system instantly alerts users when precipitation is detected, enabling them to quickly take appropriate action in response to the current weather conditions. This instantaneous alert serves as an invaluable preventive measure, preventing unnecessary water waste and decreasing the likelihood of over-irrigation during periods of precipitation.

By stopping water pumping in response to precipitation, the system demonstrates an advanced level of flexibility and effectiveness and adapts irrigation techniques to the actual environmental conditions. This preventive approach not only safeguards valuable water resources but also lessens the possibility of soil erosion, fertilizer runoff, and other negative environmental consequences associated with excessive irrigation. All things considered, Figure 8 is a fantastic illustration of the system's commitment to sustainability and environmental protection, showing how it can adapt irrigation methods to changing weather patterns and integrate with natural processes. Through timely and context-sensitive signals, technology promotes water conservation, environmentally friendly agricultural practices, and increased operational efficiency.

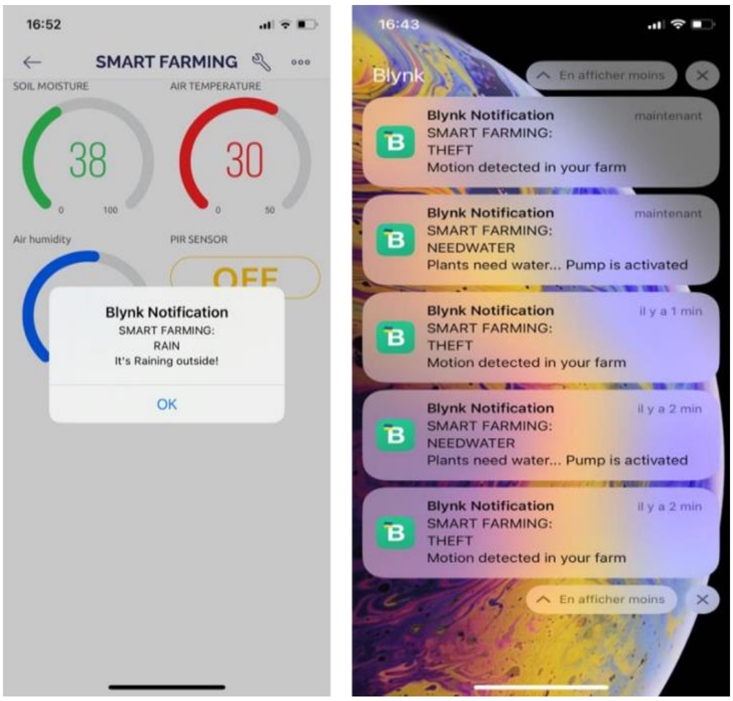

Figure 8. Displays the smartphone's notifications

The intuitive interface and customizable features of this program provide a significant advantage over traditional farm management systems. Unlike the often complex and fragmented interfaces of other systems, this program centralizes all key operations within an accessible menu, simplifying real-time navigation and management. The menu options-such as "status," "camera control," "manual operation," and "alert configuration"-grant users complete and immediate control over agricultural equipment and environmental conditions. With these features, users can quickly intervene to optimize farm performance, enhancing productivity, sustainability, and operational efficiency in agricultural management.

The aim of this project was to investigate the use of embedded systems and smartphone technologies combined with Raspberry Pi and NodeMCU for SF in Morocco. Our results indicate that the smart system significantly improved the monitoring and management of key agricultural parameters, with a strong correlation between system implementation and improved agricultural efficiency. More specifically, the results demonstrated that the use of this technology can lead to a steady improvement in production rates compared with traditional monitoring methods, which will enable agriculture to be assessed at Moroccan level. In addition, our system reduced costs and improved asset maintenance efficiency to a greater extent than conventional manual or digital approaches. This reinforced the idea that integrating remote accessibility through integrated systems contributes to better monitoring and real-time decision-making, which is crucial for modern, scalable farming operations.

4. CONCLUSION

This study presents the results of a comprehensive evaluation of a SF model, rigorously tested under the dynamic environmental and meteorological conditions typical of modern agricultural practices. The trial demonstrated the system's reliability and effectiveness, providing valuable insights into its operation and performance in real-world scenarios. The successful integration of smartphone interfaces ensures that poultry farmers receive crucial real-time information, empowering them to promptly address emerging issues and optimize operational efficiency, thereby enhancing overall farm productivity. The user-friendly interface of the system allows farmers to navigate key features seamlessly. By offering options such as status monitoring, camera control, manual operation, and customizable alert configuration, the system grants users' comprehensive control over critical aspects of farm management. This structured approach enables proactive decision-making, allowing farmers to effectively monitor equipment functionality and environmental conditions. Furthermore, the system's notification capabilities underscore its responsiveness to environmental changes. For instance, the automatic cessation of water pumping upon receiving a rain warning illustrates the system's advanced adaptability, promoting responsible resource management and reducing the risks associated with over-irrigation. This feature not only conserves water but also mitigates potential environmental impacts such as soil. In conclusion, this study validates the robustness of the proposed SF model, highlighting its potential to revolutionize agricultural operations by leveraging advanced technology and data-driven insights. The findings emphasize the importance of integrating cutting-edge solutions into traditional farming practices, ultimately contributing to increased productivity, sustainability, and environmental stewardship in agriculture. As the agriculture sector continues to evolve, embracing such innovations will be vital for addressing the challenges of modern farming and fostering a more sustainable agricultural future. As a future work we propose to explore the integration of AI and ML into the data analysis process can enhance predictive capabilities, allowing farmers to anticipate and respond to agricultural challenges more effectively. Lastly, investigating the long-term environmental impacts of SF practices will be vital to ensure sustainability and resource conservation in Moroccan agriculture.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author, Raja Mouachi., upon reasonable request.

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