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Design of a New IoT Soil Temperature and Moisture Sensor Using LoRa Communication for Smart Agriculture Applications

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Abstract
As the world's population expands and climate change intensifies water shortages, the demand for efficient water management in agriculture is at an all-time high. Although large farms frequently utilize advanced sensor technology for precise soil moisture and temperature monitoring, small to medium-sized farms often lack such resources due to financial limitations. This article explores how Internet of Things (IoT) technology can offer a cost-effective solution for these smaller farms. Specifically, we detail the design and deployment of an affordable IoT system that uses Long Range (LoRa) communication for real-time soil condition monitoring at multiple depths. Through the use of economical electronic components, this system makes precision agriculture accessible to a broader range of farms. Coupled with a user-friendly dashboard, farmers can now make informed, real-time irrigation choices. Following an exhaustive testing and calibration process, the system's effectiveness was confirmed in a pilot farm where it accurately recorded soil conditions at various depths. Our research underscores the equalizing potential of IoT technology in making precision agriculture both affordable and widely accessible, thus facilitating more responsible water usage in agriculture.
Keywords: Internet of Things (IoT), Precision farming, Smart irrigation, Soil moisture, LoRa communication

1. Introduction

With the global population expected to hit 10 billion by 2050 according to UN estimates, the call for increased agricultural production is louder than ever. This rising demand collides with shrinking farmlands and dwindling natural resources, creating a complex challenge. On top of that, the agriculture industry has to grapple with a host of variables such as climate change, deteriorating soil quality, and limited water availability, putting worldwide food security into a critical focus.

Against this backdrop, technological innovations are gaining prominence in agricultural practices, most notably the application of the Internet of Things (IoT) and big data analytics. Cisco anticipates that by 2030, there will be over 500 billion IoT-connected devices, many of which will find a place in agriculture. This technological integration is setting the stage for a new era of "smart agriculture," aimed at boosting efficiency, yield, and sustainability.

Wireless Sensor Networks (WSNs) stand at the forefront of this transformation. Renowned for their self-organizing and adaptive capabilities, WSNs are increasingly applied for environmental monitoring, farm automation, and crop traceability. The proliferation of WSN technology dovetails with the advent of specialized software and decision-making tools, designed to assist farmers in enhancing productivity, optimizing crop quality, and maximizing profitability.

Irrigation, a critical aspect of farming, now hinges on precise measurements of variables like soil moisture, temperature, and plant health. However, state-of-the-art industrial sensors, which offer such precise measurements, are often prohibitively expensive for small to mid-sized farms. This financial barrier can result in inefficient water use, posing yet another threat to sustainable farming.

To address this gap, our article proposes a versatile, cost-effective IoT sensor system capable of measuring soil conditions at multiple depths (10cm to 50cm). Using long-range Radio (LoRa) Peer-to-Peer communication for data transmission, this system avoids recurring costs, making it affordable for smaller farms. The

architecture and utility of this IoT system are elucidated in Section 2. Section 3 offers an in-depth walkthrough of the system's technical specifications and implementation. In Section 4, we delve into the practical applications, detailing measurement results and software components that make up the backbone of this innovation. Finally, Section 5 concludes the paper, summarizing the broader implications for the agricultural sector and advocating for the widespread adoption of such IoT solutions for a more sustainable future.

2. IoT in Smart Agriculture

The Internet of Things (IoT) is a promising smart technology that offers unconventional and practical solutions in many areas, as illustrated in Figure 1, such as smart cities, smart homes, traffic regulation, healthcare, smart agriculture, and more. In the realm of agriculture, IoT technology has led to significant advancements in farm management. This technology connects all agricultural devices and equipment to make informed decisions regarding irrigation and fertilizer provision [16]. Smart systems enhance the accuracy and efficiency of devices monitoring plant growth and even livestock rearing.

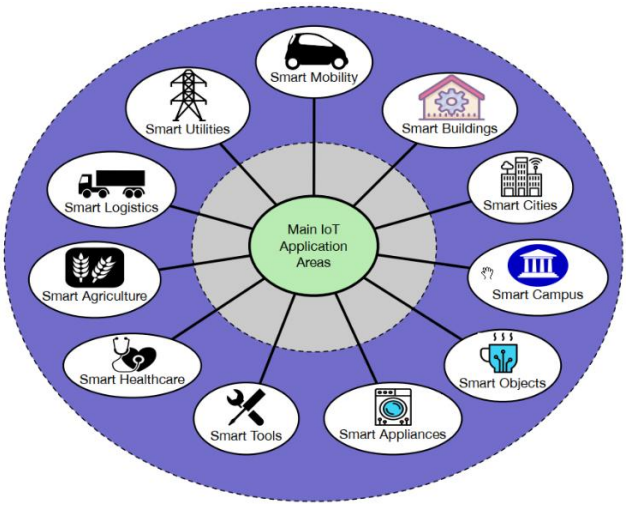


Figure1: Primary Application Areas of Internet of Things (IoT) [17].

2.1 Structure of the IoT Framework for Intelligent Farming

The architecture of the IoT ecosystem designed for smart agriculture is fundamentally built on three core elements: (1) IoT sensors and devices, which are deployed in the field for data collection such as soil moisture levels, temperature, and crop health; (2) communication technologies, which provide the connectivity backbone that allows these devices to transmit data to centralized systems; and (3) data processing and storage mechanisms, which analyze and store the collected data for further use in decision-making processes. Figure 2 illustrates the interconnected nature of these components within the smart agriculture IoT ecosystem.

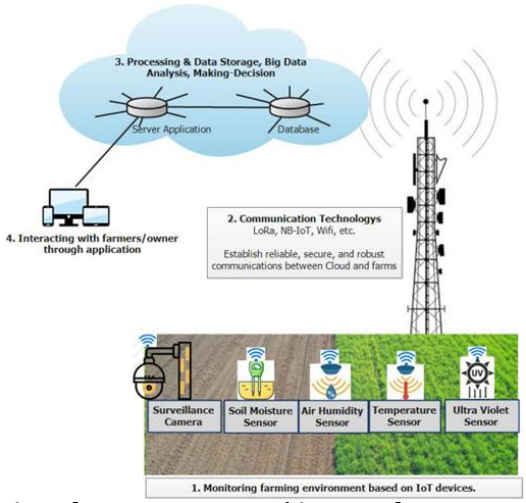


Figure 2: Illustration of IoT Ecosystem Architecture for Smart Agriculture [18].

2.2 IoT Network Nodes in Smart Agriculture

The configuration of communication bands and operational protocols in IoT-based agricultural systems is contingent upon the types of nodes employed—namely, sensor and backhaul nodes [19]. Sensor nodes are generally designed for short-range communication, minimal data transfer, and are optimized for energy efficiency. They are responsible for collecting an array of environmental metrics such as soil moisture, temperature, and air quality. To optimize energy use and minimize costs, these sensors can be set up as Reduced-Function Devices (RFDs), which are programmed to communicate solely with Full-Function Devices (FFDs) [20].

In contrast, backhaul nodes serve a dual purpose. In addition to environmental data collection, they act as relay nodes to funnel this information to a centralized control unit. These nodes are often configured as FFDs and are designed for long-range communication and high data throughput. Figure 3 provides an illustrative example of a low-energy network topology optimized for monitoring various parameters in smart agriculture. This system incorporates:

1- IoT sensor nodes, tasked with environmental data collection such as soil conditions, air humidity, and nutrient composition. These nodes, which may be installed as RFDs, relay this information to backhaul devices.

2-IoT backhaul nodes, which serve not only as data-collecting nodes but also as intermediaries that relay this information to the central control system. They are typically set up as FFDs, enabling them to interface with both other FFDs and RFDs.

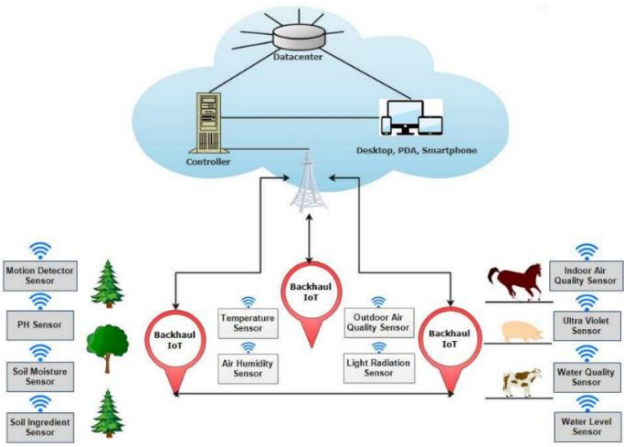


Figure 3: Overview of IoT Network Design in Smart Agriculture [21]

3. Architecture of the deployed IoT system

3.1System Block Diagram

Figure 4 provides an intricate block diagram, breaking down the IoT system module into its two essential parts.

The first part is engineered for real-time environmental monitoring, with a specific focus on capturing soil temperature and moisture metrics at multiple depths. This part iscomprised of several key components :

- A battery serves as the power source to ensure continuous operation.
- A dedicated microcontroller is responsible for data acquisition and initial processing tasks.
- Multiple temperature and moisture sensors are strategically placed at different soil depths to collect comprehensive data.
- An LCD display interface provides real-time readings of soil conditions across multiple depths for instant user feedback.
- A Long Range (LoRa) communication module wirelessly sends the gathered data for further scrutiny.

The second part acts as the data communication center, designed for seamless data reception and forwarding to user-end devices, such as PCs or smartphones. This part encompasses :

- A LoRa module that receives the data and forwards it to an embedded microcontroller.
- A WiFi-enabled microcontroller interfaces with client devices and serves as a data relay, using MQTT protocols for secure and low-latency communication.

This two-part architecture ensures that the system excels in both sophisticated data collection and efficient data transmission, enabling real-time decision-making in the realm of smart agriculture.

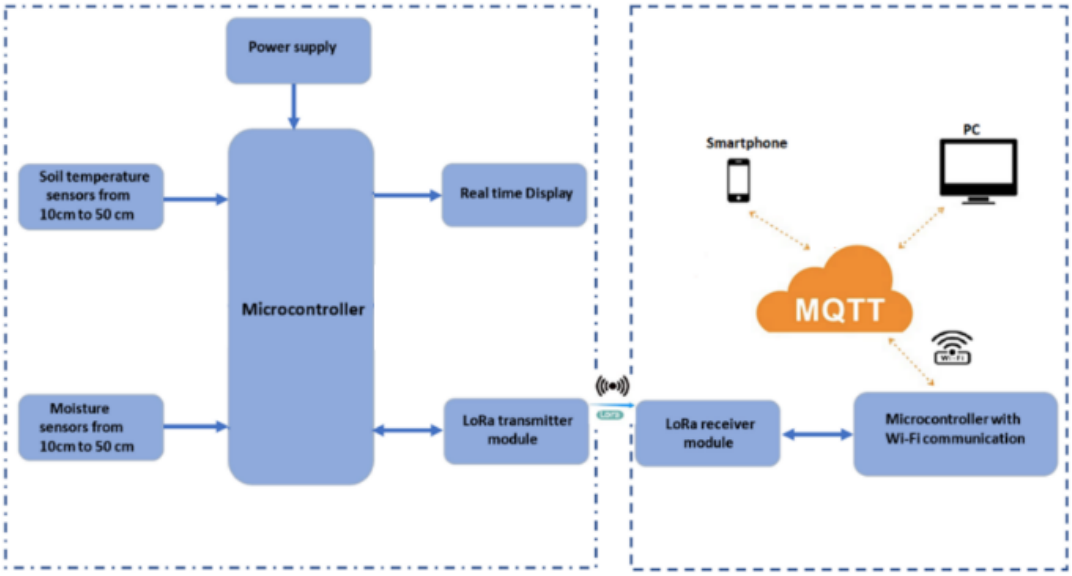


Figure 4: Block Diagram of the IoT Module

3.2Selection of IoT System Components

Figure 5 offers a comprehensive component architecture of the IoT system, strategically organized into two distinct functional domains for optimal performance and usability.

3.2.1. First Functional Domain

This domain specializes in capturing immediate and real-time environmental parameters, with a focus on measuring soil moisture and temperature at multiple depths. The

components and their rationale for selection for this section are:

- **Power Source**: A Lithium-Ion battery is chosen for its long lifespan and capacity to sustain power over prolonged periods, reducing the frequency of replacements or recharges.
- **Microcontroller**: An Arduino microcontroller is selected for its ease of use, robust community support, and ample I/O pins that facilitate multiple sensor connections.
- **Soil Moisture Sensor**: An hygrometer-based sensor is utilized for soil moisture measurement. The choice of an hygrometer sensor is motivated by its accuracy, low power consumption, and ability to work well in various soil types.
- **Temperature Sensor**: A DS18B20 sensor is used for its ability to provide high-accuracy readings, its wide temperature range, and its ease of interfacing with the Arduino microcontroller.
- **Display Unit**: A Liquid Crystal Display (LCD) from renowned vendors like Adafruit provides immediate visualization of data, enabling farmers to take timely actions.
- **Wireless Communication:** A LoRa SX1278 RF transceiver is incorporated for its long-range capabilities, thus overcoming the limitations of shorter-range technologies like Wi-Fi in a sprawling agricultural setting.

3.2.2. Second Functional Domain

This section is responsible for collecting the transmitted data and forwarding it to different user interfaces, such as PCs and smartphones. The chosen components for this domain are:

- **Data Reception**: Another LoRa SX1278 RF transceiver receives the long-range signals from the first domain.
- **User Interface Communication**: An ESP8266 WiFi-enabled microcontroller, chosen for its WiFi capabilities and ease of use, facilitates communication with user interfaces. It employs MQTT protocols, processed through Node-RED, ensuring a secure and efficient data transfer mechanism.

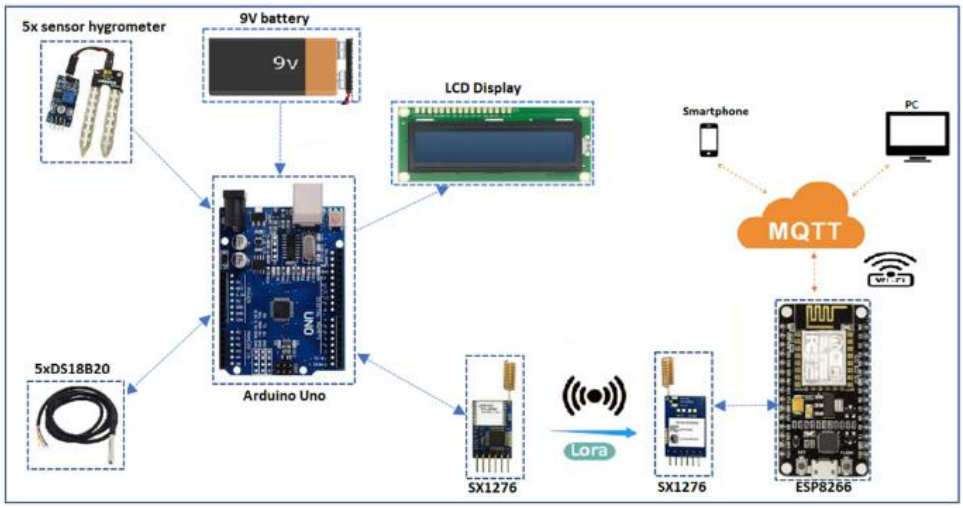


Figure 5: Components of the IoT Module.

4. Practical Implementation

This section provides a comprehensive roadmap for the construction, deployment, and evaluation of our state-of-the-art IoT system designed for modern agriculture. Here, we delineate the meticulous processes we undertook, from preliminary sensor assessments to real-world deployment and subsequent data analysis.

- Phase 1: Sensor Validation and Calibration

During the initial phase, a variety of sensors-including soil moisture hygrometers and DS18B20 temperature gauges-were subjected to comprehensive evaluations. The objective of these tests was to verify the precision and measurement range of each sensor. This was accomplished by comparing their performance to that of industry-recognized instruments, we ensured that the data collected would be both reliable and precise. This step was crucial in eliminating any false readings that could otherwise compromise the system's efficacy.

- Phase 2: System Assembly and Pre-Deployment Tests

After ensuring sensor reliability, we embarked on the system assembly. Each component was connected as per the architecture detailed earlier, ensuring optimal data flow and energy efficiency. The fully assembled system was then subjected to a series of pre-deployment tests, simulating various environmental conditions to evaluate its performance metrics. This helped to fine-tune the system's configurations for optimal results.

- Phase 3: On-Site Deployment at TTC Model Farm

Having completed our lab-based evaluations, the system was deployed at the TTC Model Farm, which serves as a real-world testing ground. Here, the system was installed at strategic locations to monitor various environmental factors including soil moisture at different depths, ambient temperature, and humidity. We ensured that the device's LoRa modules had a clear line of sight for long-range data transmission, and that they were shielded from extreme weather conditions.

- Phase 4: Data Recording and In-Depth Analysis

Once the system was fully operational, we began the data collection phase. Real-time data was recorded and then transmitted to the client interfaces via our secure MQTT-based network. These measurements were meticulously logged and subjected to statistical analysis to assess both the accuracy and reliability of the system. Anomalies, if any, were flagged for further investigation.

By conducting this in-depth, multi-phased implementation approach, we ensured that our IoT system not only met but exceeded the stringent requirements of modern agriculture. The insights derived from the collected data have promising implications for enhancing farm productivity and resource efficiency, paving the way for a new era of smart farming.

4.1 Presentation of the Technology Transfer Center

Our IoT system was rigorously field-tested at the state-of-the-art Technology Transfer Center, strategically located in Khmiss Ait Amirra—a locale approximately 40 kilometers to the south of Agadir, Morocco. This esteemed institution serves as a crucible for cutting-edge technological research, specialized education, and the propagation of modernized agricultural techniques.

Encompassing a sprawling 7.29-hectare campus, the center allocates 4.5 hectares exclusively to advanced greenhouse infrastructures. These greenhouses are designed to simulate diverse agricultural scenarios, thereby providing an ideal testing ground for our system. The center's primary mission revolves around the embracement and operationalization of avant-garde technologies to further agricultural research and development, making it a fitting venue for our IoT system trials.

4.2 System Component Integration and Assembly Various Blocks

The IoT system's temperature and moisture sensors are ingeniously encapsulated within a robust PVC tube with a diameter of 40 mm. Strategically placed at five different vertical layers within the tube, each sensor resides at a depth increment of 10 cm. This multi-level configuration allows for granular, depth-specific soil data collection. All discrete components and subsystems of our IoT device have been skillfully assembled and integrated. A visual representation detailing the final, fully-assembled system can be viewed in Figure 7.

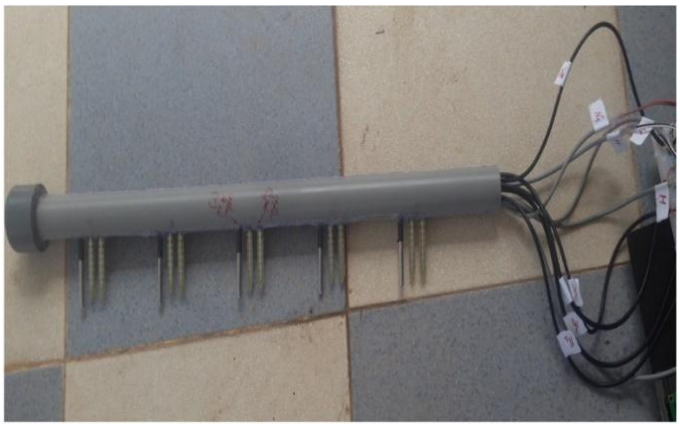


Figure 7: Assembled IoT system

4.3 Implementation of the system

Under the expert supervision of an agronomist, our IoT system underwent rigorous field-testing on the TTC model farm, amid a crop of tomatoes nearing their harvest phase. Figure 8 offers visual insights into the system's strategic positioning in close proximity to the plant root zones. In the final setup, the system was entirely subsumed into the soil, ensuring seamless and continuous data acquisition.

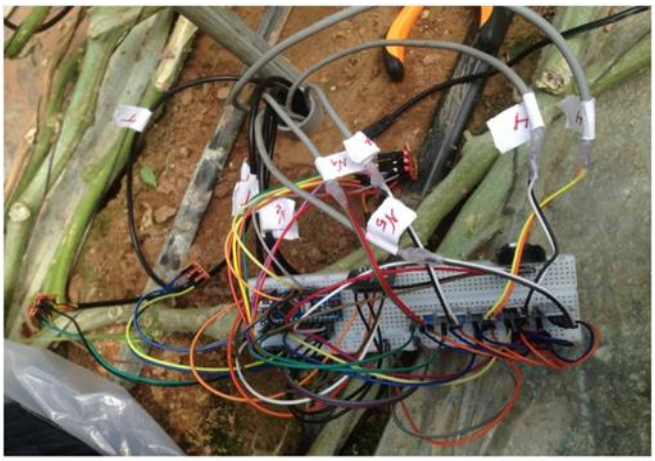


Figure 8: System Implementation.

4.4 Measurement Techniques and Approaches

The IoT system gathers intricate soil data-temperature and moisture levels-at five specific depths: 10cm, 20cm, 30cm, 40cm, and 50cm. Leveraging the MQTT (Message Queuing Telemetry Transport) protocol, these measurements are transmitted securely and efficiently to a dedicated computer for analysis. For ease of data manipulation and subsequent interpretation, the acquired data is stored in an Excel spreadsheet, allowing for robust data analytics tools to be applied. Data collection occurs at 30-minute intervals.

Two data sets, each covering a 24-hour time span, will be presented to shed light on soil condition variations. Figure 9 and Figure 10 outlines the fluctuations in soil temperature and moisture from 10:00 on May 18, 2021, to 10:00 on May 19, 2021. Similarly, Figure 11 and Figure 12 portrays the same variables between 10:00 on May 22, 2021, and 10:00 on May 23, 2021.

For clarity in the data presentation, soil temperatures at respective depths are denoted as Temp_L1 (for 10cm), Temp_L2 (for 20cm),

Temp_L3 (for 30cm), Temp_L4 (for 40cm), and Temp_L5 (for 50cm). Similarly, soil moisture levels

are indicated as Mo_L1, Mo_L2, Mo_L3, Mo_L4, and Mo_L5 for the corresponding depths.

This meticulous methodology ensures that the soil's micro-climatic conditions are comprehensively understood, allowing for precise, data-driven agricultural decision-making.

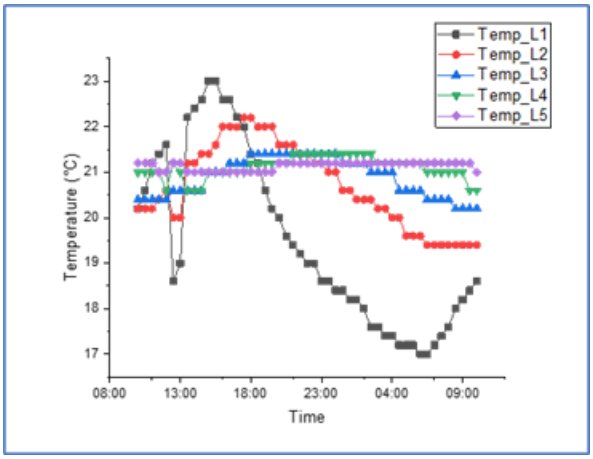


Figure 9: Measurement Results of Soil Temperature across Five Levels (Period 1)

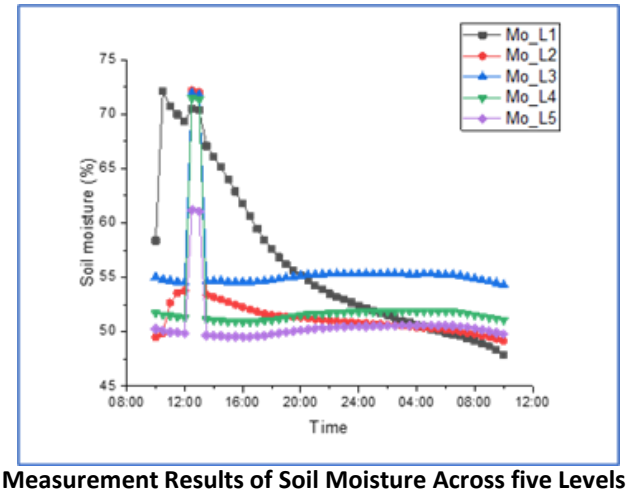


Figure 10: Measurement Results of Soil Moisture Across five Levels (Period 1)

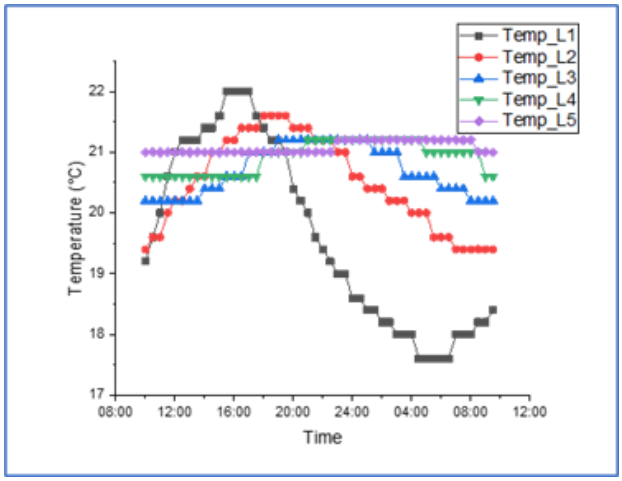


Figure 11: Measurement Results of Soil Temperature Across Five Levels (Period 2)

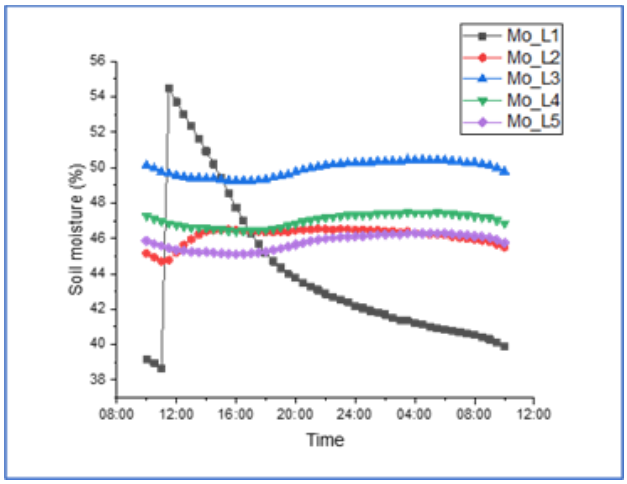


Figure 12: Measurement Results of Soil Moisture Across Five Levels (Period 2)

5. Analysis and Discussion

In our comprehensive data analysis, conducted in collaboration with a specialized agronomist, we found that the soil temperature and moisture readings, as captured by our state-of-the-art sensors, are consistent with industry benchmarks.

During the first observation cycle on May 18, 2021, at exactly 10:00 AM, a significant irrigation event was executed, causing a noticeable uptick in soil moisture at all measured depths. We observed a time-lagged response in moisture levels across varying soil depths. This delay is attributable to soil's natural infiltration rate, which signifies the time required for water to penetrate to deeper soil strata. Simultaneously, a slight decrease in soil temperature was registered during this period.

In a subsequent observation on May 22, 2021, at 11:00 AM, irrigation was conducted using a lower volume of water. This led to only a modest increase in soil moisture, primarily observed at the surface level. The deeper soil layers showed little to no change in moisture levels, a likely result of the reduced volume of water used for this particular irrigation event. Interestingly, the temperature fluctuations during this cycle were analogous to those noted during the initial observation period.

6. Conclusion

The successful deployment of our IoT sensor system at the Transfer & Technology Center near Agadir has demonstrated its potential to revolutionize water management in agriculture. Through meticulous selection and integration of sensors and innovative communication protocols such as MQTT Mosquitto and LoRA Peer-to-Peer (P2P) technology, we have created a robust system capable of delivering reliable, real-time data over long distances while minimizing energy consumption. Most importantly, this low-cost IoT sensor system is designed to be accessible for small to medium-sized farmers. It offers them the critical ability to monitor soil moisture and temperature in real-time, thereby enabling data-driven irrigation decisions that contribute to efficient water usage. This work highlights how IoT technology can level the playing field in agriculture, offering smaller operations an affordable tool for soil analysis and water management, ultimately leading to more sustainable farming practices

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