STATISTICS, OPTIMIZATION AND INFORMATION COMPUTING
Stat., Optim. Inf. Comput., Vol. **16**, September 2026, pp 2348–2368.
Published online in International Academic Press (www.IAPress.org)

An IoT-Enabled Smart System for Real-Time Environmental Monitoring and Automated Threshold-Based Irrigation for Water Stress Testing in Precision Agriculture

Mohamed Walid Hajoub*, Hicham Touil, Mohammed Achkari Begdouri

Information System and Software Engineering Laboratory, National School of Applied Sciences of Tetouan, Abdelmalek Essaadi University, Tetouan, Morocco

Abstract Internet of Things is a major technology for improving agricultural practices and developing intelligent research environments dedicated to biologists. Real-time monitoring of environmental parameters promotes efficient crop management and data-driven decision-making. Nonetheless, the majority of existing IoT systems are limited to data visualization or alert generation, they rarely exploit the full potential of measurements for automation. In this context, this study proposes an intelligent system enabling not only real-time monitoring of environmental parameters but also automated irrigation management through water stress scenarios defined by biologists in a controlled environment. Our system integrates an IoT measurement unit and a microservices-based web application for advanced management and analysis. The evaluation results after the deployment of a single unit in an agricultural field indicate that our IoT system provides measurements with effective stability, reflected by a low variance of 0.0721 for soil moisture, 0.0552 for soil temperature, 0.0081 for air temperature and 0.0023 for air humidity, and executes 50000 water stress scenarios in 872 ms without any error. These results highlight the system's capability for data-driven automation, decision support and environmental sustainability in precision agriculture.

Keywords Precision Agriculture, Water Stress, Environmental parameter, Internet of Things, Web application

DOI: 10.19139/soic-2310-5070-3485

1. Introduction

Agriculture is considered an essential sector and contributes significantly to the economy of many countries including Morocco [1]. The Green Plan a project launched in 2008 by the Moroccan Minister of Agriculture has played a pivotal role in the development and strengthening of the agricultural sector positioning it as the main contributor to the gross domestic product and constituting more than 40% of the overall economic production of the country [2]. Despite the efforts made to achieve the project objectives there are difficulties and obstacles that continue to hinder food production thereby contributing to the worsening of food insecurity [3].

Climate change constitutes a critical global challenge marked by abrupt temperature fluctuations and rising humidity levels, leading to substantial instability in agricultural yields and a consequent decline in farmers' income and overall economic resilience [4].

Environmental parameters of a field such as temperature, soil moisture, wind speed and direction can influence crops from planting to harvest [5]. It is therefore essential to monitor these environmental conditions to improve and maintain production quality [6]. The process of monitoring environmental parameters can assist biologist in deci-sion-making regarding pesticide and fertilizer selection [7].

*Correspondence to: Mohamed Walid Hajoub (Email: mohamedwalid.hajoub@etu.uae.ac.ma). Information System and Software Engineering Laboratory, National School of Applied Sciences of Tetouan, Abdelmalek Essaadi University, Tetouan, Morocco.

ISSN 2310-5070 (online) ISSN 2311-004X (print)

Water stress in agriculture refers to a condition characterized by limited water availability affecting plant physiological processes, and it is widely used to study plant responses under controlled environmental constraints [8]. Furthermore, this practice provides biologists with the opportunity to conduct experiments to identify the ideal environmental conditions for crop growth according to weather patterns specific to the cultivated geographical area [9].

Traditional methods that rely on biologists' manual monitoring of these parameters and the application of water stress remain inefficient [10], particularly in vast cultivated geographical areas, since they require substantial effort and considerable time [11]. On the other hand, with manual water stress, irrigation is carried out based on a predefined duration without accounting for environmental factors such as humidity and solely based on estimates, which can negatively impact plant growth as well as water wastage [12].

With the integration of recent technologies within precision agriculture, the agricultural sector is undergoing significant evolution through the emergence of innovative solutions that enhance farming practices [13]. In recent years, Internet of Things (IoT) has become an essential pillar for improving agricultural operations [14]. Numerous scientific studies propose using sensor networks to collect data on environmental parameters, which allow biologists to observe and manage their fields in real time in a more effective manner. However, the majority of proposed solutions based on IoT and are coupled with mobile or web platform whose functionalities are mostly confined to visualizing the data collected or sending alerts. These systems enable biologists to make rapid decisions in case of anomalies, such as when temperature or humidity exceeds predetermined thresholds.

Despite the existence of these solutions, data measured by sensors in agricultural fields remains largely underutilized. It is not fully leveraged to automate water stress or conduct experiments. This limitation hinders the ability to exploit the collected data to automate agricultural operations, such as irrigation and water stress scenarios, in order to reduce crop losses and improve both the quality and quantity of production. This observation paves the way for the present study, which focuses on the design and implementation of a technical system for the acquisition, monitoring and exploitation of environmental data to automate agricultural practices driven by biologists.

The purpose of this study is to build and implement an intelligent research environment for biologists, enabling them to monitor in real time important environmental factors related to climate change such as air and soil temperature and humidity, and to remotely apply configurable experimental water stress scenarios defined by biologists through the exploitation of real-time collected data. This provides the possibility to conduct precise experiments based on specific water stress scenarios in order to support controlled agricultural testing and improve environmental data utilization in farming systems. We intend to approach the subsequent investigative question: To what extent can IoT-based automation of water stress support the design and execution of controlled irrigation experiments in agricultural systems? The main contribution of this work is:

Develop and design a modular IoT-enabled measurement unit that integrates sensors for environmental data acquisition, communication protocols for reliable data transmission and control components for automated irrigation management to implement predefined water stress scenarios in a controlled agricultural environment.

Set up a service-oriented web application with high availability and scalability, offering a set of options for administrators and biologists to supervise, track in real-time and apply water stress scenarios.

Conduct a comprehensive technical evaluation of the proposed system to assess its effectiveness, stability and operational performance.

Perform a comparative study with other existing systems to evaluate the effectiveness of the proposed system.

The remainder of this article is organized as follows: Section 2 provides an overview of recent literature on real-time monitoring systems in precision agriculture. Section 3 provides a detailed description of the proposed system's architecture. Section 4 presents a detailed discussion and analysis of results, including comparisons with benchmark systems and state-of-the-art approaches. Finally, Section 5 concludes the study and highlights potential directions for future research.

2. Literature review

2.1. IoT in Smart agriculture

Monitoring environmental parameters in real time in agricultural fields has now become an essential process aimed at preserving agricultural yields in the face of impacts and threats related to climate change [15], [16]. As such, it stands as a fundamental pillar of precision agriculture. This section presents a review of existing work, highlighting its advantages and limitations.

Visconti et al. [17] propose a real-time monitoring and control system for the environmental parameters of an agricultural field with the aim of optimizing the management of the quantity and type of fertilizer applied. The system relies on collecting environmental data using dedicated sensors. More specifically, the DHT22 sensor is used to measure air temperature and humidity, while the SEN0193 sensor monitors soil moisture. All sensors are connected to an ESP8266 microcontroller. The collected data is transmitted via a Wi-Fi communication module to an open-source cloud platform, where it is stored and visualized in real time. This work devotes special attention to the system's energy autonomy, proposing a power supply solution based on the use of solar panels.

Sandeep et al. [18] present a low-cost and efficient system comprising three layers, an IoT device capable of collecting agricultural field data such as air and soil temperature and humidity using DHT11 and LM393 sensors, which utilizes a geolocation module to uniquely identify each device in the field. The study employs an Arduino Uno microcontroller equipped with a Wi-Fi module of ESP8266 to transfer collected data to a mobile application integrating an advanced dashboard for real-time information visualization.

Dayananda et al. [19] developed a low-cost real-time weather monitoring system for agricultural farm tracking, based on IoT. It uses a set of sensors to detect temperature, humidity, pressure, rainfall and CO2 level. A GSM900A module is used to send data to a mobile phone in the form of a message. Kathole et al. [20] introduce a wireless sensor network for real-time monitoring of environmental parameters in an onion agricultural field. This study specifically focuses on soil moisture, measured using the LM393 sensor. The collected measurements are transmitted to a mobile application that enables farmers to receive alerts and make decisions.

Vivekrabinson et al. [21] present an IoT system for real-time monitoring of soil parameters such as pH, moisture, and temperature via a mobile application. The proposed system uses a Raspberry Pi controller connected to sensors to collect data and send parameter measurements to the mobile application. Furthermore, an irrigation system is automatically triggered when soil moisture falls below a certain threshold and a rain sensor prevents irrigation during rainfall.

Akter et al. [22] developed an intelligent IoT and image processing-based system to monitor environmental parameters with the aim of detecting and identifying diseases in potato plants. The system uses temperature sensors along with an ESP32-CAM module to capture leaf images, which are subsequently used to train an image classification model. A GSM/GPRS module is integrated to send real-time notifications to farmers.

Radzi et al. [23] presented an automated solution for real-time control and monitoring of environmental parameters. This solution aims to optimize irrigation practices for farmers in Malaysia. The system uses the NodeMCU ESP32 microcontroller coupled with electrical conductivity and pH sensors to accurately measure nutrient concentration and pH levels in the fertilizer mixture. The collected data is then displayed on a dedicated web platform, providing farmers with real-time visualization and dynamic control of agronomic conditions to improve agricultural productivity.

Morchid et al. [24] presented an IoT architecture for proactive monitoring comprising smoke sensors and Raspberry Pi for handling data. These sensors collect real-time environmental information that is subsequently transmitted to the ThingSpeak open-source system for archiving and representation. The latter is integrated with MATLAB representation tools for uninterrupted observation and detailed analysis.

Narayana et al. [25] developed an innovative system for efficiently instantaneous management of agricultural field parameters. The proposed solution uses sensors such as the MQ135 for air quality, MQ2 for gas detection and DHT11 for measuring air temperature and humidity. An Arduino Uno microcontroller is used for data processing, while a GSM module ensures transmission of measurements to remote platforms where they are stored in a database and visualized through a dedicated interface.

Table 1 presents various existing systems for the real-time monitoring of agricultural environmental parameters, specifying their objectives, advantages and limitations. From this table, it appears that the majority of real-time environmental parameter monitoring systems are generally composed of two main components, an IoT measurement unit consisting of sensors deployed in the agricultural environment to collect and transmit data, and a web or mobile application responsible for receiving these measurements to analyze and store them. Each system uses sensors, microcontrollers and technologies suited to its needs. However, a common limitation appears, the collected data is often simply visualized and stored without advanced processing. Although some offer alert or decision-support functions, none fully leverage this data to automate water stress. Some studies, like Vivekrabinson et al. [21] present traditional automatic irrigation systems. Nonetheless, the merits of our study lie in the proposal of a biologist-driven experimental platform, which is not limited to an automatic irrigation system but constitutes a system enabling the implementation of configurable experimental water stress scenarios. Other studies fail to address the issue of water stress, probably due to the lack of collaboration between biology laboratories and engineering teams, which limits the development of systems dedicated to the automated management of water stress in experimental settings. Furthermore, the biological risk associated with the automated application of stress represents a significant constraint, due to the potentially irreversible impact on crops. This article aims to overcome this limitation by proposing an advanced data utilization approach through intelligent automation of water stress and development of a robust application integrating smart features for early and effective decision-making.

3. Materials and methods

The purpose of this work is to build an intelligent research environment for biologists, enabling them not only to monitor agricultural field parameters in real time but also to automatically execute configurable experimental water stress scenarios. The proposed system supports the execution of predefined experimental scenarios under controlled conditions and enables structured data collection on environmental parameters. This approach enables real-time agricultural monitoring aimed at enhancing agricultural productivity and ensuring food security.

Generally, our system consists of two essential elements. The prototype or measurement unit is the core of our IoT-based system designed to regularly collect air and soil temperature and humidity parameters in the agricultural field and to execute water stress scenarios defined through the system's actuators. The web application, which constitutes a crucial component of our system, offers essential functionalities for managing measurement units, real-time monitoring, storage of collected information and allows biologists to create and launch water stress scenarios. Figure 1 illustrates the architecture of our proposed system.

Information transfer between the proposed IoT system and the web application is achieved through the ESP8266 Wi-Fi module, a choice motivated by the need to combine cost-effectiveness with optimal performance. Although alternatives such as Bluetooth or GSM modules can technically fulfill this function, Bluetooth has notable limitations in terms of range and transmission speed, while GSM involves recurring costs linked to Internet subscriptions. The following sub-sections provide a detailed presentation of our measurement unit and its operation, as well as the application and its functionalities.

3.1. Measurement unit architecture design

The measurement unit is an essential component of our system. It comprises three main sensors connected to a microcontroller, a 16x2 LCD display, a water pump and relay module. Detailed information about the components used is presented in Table 2.

The DHT22 sensor is responsible for measuring air temperature in the range of -40 °C to 80 °C and relative humidity in the range of 0% to 100%. The FC28 sensor measures soil moisture level, while the DS18B20 sensor with a probe is used to measure soil temperature. The ESP8266 microcontroller acts as the orchestrator, periodically reading and interpreting the digital or analog signals from the sensors every ten seconds. It then sends the measured environmental values to our platform via the Wi-Fi module through an HTTP request for storage and analysis.

Our ESP8266 microcontroller also displays the measurements on a 16x2 LCD screen, providing real-time monitoring either directly or remotely through the web application. The relay module functions as a switch in

Table 1. Literature overview of existing real-time monitoring systems proposed in previous studies.

Reference	Objective	Advantages	Limitations
Visconti et al. [17] (2020)	Proposes a real-time monitoring system for three environmental parameters to manage irrigation and fertilizer selection.	Provides a platform for real-time visualization and decision-making, along with the design of an efficient solar panel-based power supply solution.	Insufficient utilization of measured data and lack of experimental validation in a real field.
Sandeep et al. [18] (2021)	Introduce an IoT based real-time monitoring system with a mobile application to ensure advanced monitoring against the effects of climate change.	Incorporates a mobile application providing charts and features that support decision-making.	Insufficient utilization of measured data, focus only on display and storage.
Dayananda et al. [19] (2021)	Develop a real-time monitoring system for environmental factors to help biologists and farmers respond swiftly to emerging issues.	Tracks a wide range of parameters, enabling a comprehensive overview of agricultural field conditions.	Inadequate utilization of measurements; the data are transmitted exclusively as mobile messages to farmers.
Kathole et al. [20] (2024)	Propose an IoT solution for real-time monitoring of soil moisture in an onion field.	Enables farmers to adjust irrigation based on data displayed through the mobile application.	Tracks a minimal number of parameters and exhibits inadequate utilization of measurements.
Vivekrabinson et al. [21] (2024)	Develop an IoT solution for real-time monitoring of soil parameters through a mobile application.	Provides comprehensive monitoring via integrated sensors and enables remote irrigation.	High implementation cost and exclusive focus on data visualization.
Akter et al. [22] (2022)	Propose a real-time monitoring system aimed at increasing agricultural yield.	Combines collected measurements with image processing techniques to enable early disease identification.	High implementation cost.
Radzi et al. [23] (2025)	Establishment of a real-time monitoring system to optimize fertilization and irrigation practices.	Provides comprehensive surveillance of soil nutrient-related parameters through a web application.	Insufficient utilization of measured data, limited to display and storage only.
Morchid et al. [24] (2024)	Propose an IoT solution for real-time control of environmental parameters.	Provides biologists with a platform for statistical visualization and analysis of collected measurements.	Focuses only on data visualization.
Narayana et al. [25] (2024)	Propose a solution for efficient monitoring of environmental parameters in an agricultural field.	Simple solution tailored to farmers' capabilities.	Exclusively focuses on data storage and visualization.

our system, allowing the control of the current flow to the water pump. Our proposal enables biologists to apply water stress automatically by defining scenarios predefined as conditional thresholds. When these conditions are

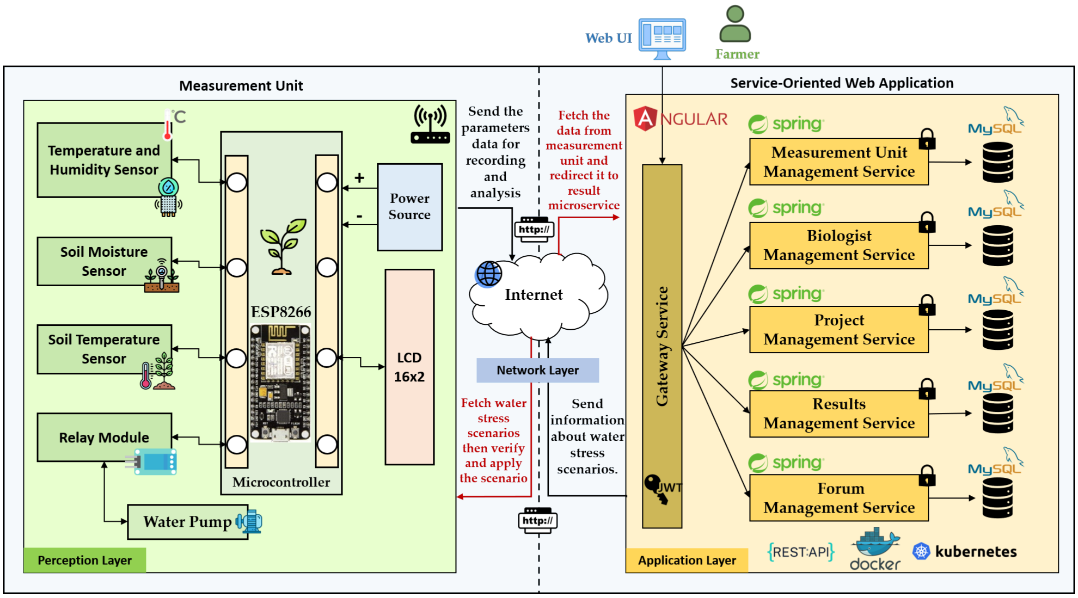

Figure 1. Architecture and Conceptual Framework of Our Proposed IoT-Based System.

satisfied, the relay module closes the electrical circuit, thereby activating the water pump for irrigation. Conversely, if the predefined conditions are not met, the circuit remains open and the pump remains deactivated.

Each measurement unit has a private serial, which facilitates its assignment to biologists so that each has their own units to conduct experiments. This serial number is also transmitted along with the environmental parameters to characterize the measurement results and is used to retrieve information on the water stress scenarios defined by the biologist.

The full circuit and associated modules are placed in a plastic casing to create a measurement unit. Our microcontroller firmware is developed in C++ using the Arduino IDE. Internet connectivity is provided through a mobile phone's access point. The connection details are embedded in the Arduino code. Figure 2 depicts the structure and implementation of our proposed measurement unit.

3.2. Data Preprocessing

The preprocessing of data collected by the sensors is a crucial step to ensure the validity of measurements and minimize the risk of errors likely to disrupt the execution of water stress scenarios.

This study adopts a simple yet effective preprocessing pipeline. After acquisition, each sensor reading is first verified to ensure it falls within the operating range specified by the sensor manufacturer, as presented in Table 2. If the measurement is valid, it is then compared to the conditions defined by the water stress scenarios. Compliant measurements are transmitted for storage in the database via an HTTP request. Conversely, if a value exceeds the validity range or is missing, the proposed system performs up to five consecutive readings to rule out any momentary error. If the anomaly persists after these attempts, the missing value is automatically replaced by the average of the last five valid measurements from the corresponding sensor. Simultaneously, a notification message is immediately sent to the responsible biologists to inform them of the potential sensor malfunction or an environmental issue. The following formula presents the average calculation used to replace missing values.

$$V_t = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{1}$$

Where V_t is the average value that will replace the missing measurement at time t, x_i represents the i-th last valid measurement from the sensor and N is the number of last measurements considered, in our case $N = 5$. This

Table 2. Information of used hardware components.

Components	Model Reference	Voltage	Sensor Output	Accuracy and Dimension	Manufacturer
Air temperature sensor	DHT22	3.3-6 V	Digital	±0.5 °C Measurement: -40 to 80 °C	Aosong Electronics
Air humidity sensor	DHT22	3.3-6 V	Digital	±2–5 % RH Measurement: 0–100% RH	Aosong Electronics
Soil moisture sensor	FC-28	3.3-5 V	Analog and Digital	Approx. 3.2 cm × 1.4 cm Measurement: 0–100% RH	Seeed Studio
Soil temperature sensor	DS18B20	3–5.5 V	Digital	±0.5 °C Measurement: -10 to +85 °C	MicroPlanet
Relay module	SPDT	5 V	Digital	Dimension: 92 × 46 × 20 mm	Phenovo
Water Pump	MD014	3.3-6 V	Digital	Capacity: 80–120 L/H	MicroPlanet
LCD 16 × 2	HD44780U	5 V	Digital	Dimension: 36 × 79 × 20 mm	Hitachi

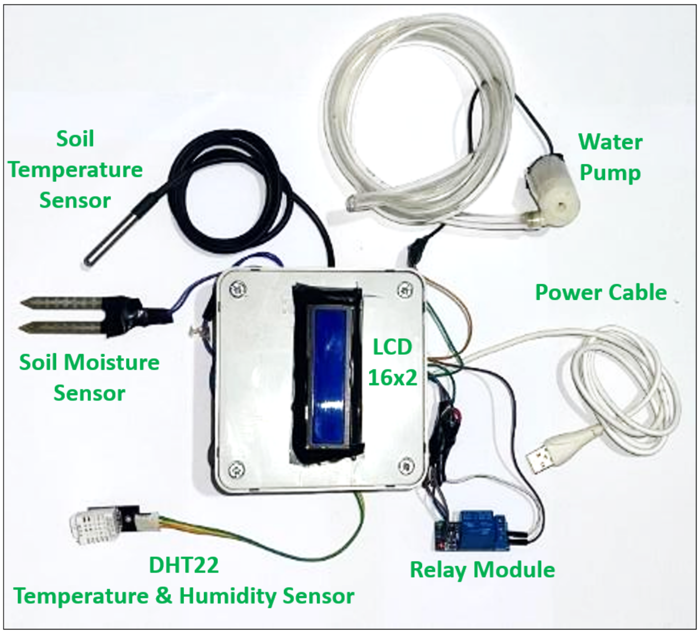

Figure 2. The structural design of our IoT monitoring unit.

processing approach both preserves data continuity and maintains the reliability of real-time monitoring, while ensuring traceability and a rapid reaction in case of an incident.

3.3. Automation of water stress application

Water stress application is an important operation in agriculture used to study plant responses to variations in water availability. Moreover, it facilitates irrigation control and contributes to combating water wastage [26]. In this study, water stress is considered as a controlled threshold-based condition defined by biologists using collected environmental parameters. Our system enables biologists to apply water stress in an automated manner by defining test scenarios based on environmental variables. These scenarios, defined as criteria or conditions established by biologists, once met, trigger the relay module to command the water pump and regulate irrigation. This system enables biologists to create and manage water stress conditions based on three environmental factors such as air temperature, soil moisture and soil temperature.

Typically, when a biologist wishes to implement a water stress scenario for an experiment, they must first define three project-specific thresholds, maximum air temperature, maximum soil temperature and minimum soil moisture. Once these thresholds are set, our system manages the scenario processing according to the following formula.

$$P(t) = \begin{cases} 0 & \text{if } T_a^{\max} = \text{NULL} \wedge H_s^{\min} = \text{NULL} \wedge T_s^{\max} = \text{NULL} \\ 1 & \text{if } T_a(t) \geq T_a^{\max} \vee H_s(t) \leq H_s^{\min} \vee T_s(t) \geq T_s^{\max} \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Let $T_a(t)$ denote the air temperature measured at time t, $T_s(t)$ the soil temperature measured at time t and $H_s(t)$ the soil humidity measured at time t. $T_a^{\max}$, $H_s^{\min}$ and $T_s^{\max}$ respectively correspond to the threshold values of air temperature, soil moisture, and soil temperature, as defined by the biologist for a specific experimental project. $P(t) \in \{0, 1\}$ denotes the irrigation pump control signal, where $P(t) = 1$ corresponds to the pump activation, while $P(t) = 0$ indicates its deactivation. Irrigation stops automatically when all real-time measurements of air temperature, soil humidity and soil temperature fall below the defined thresholds for the project.

Water stress scenario processing occurs at the measurement unit level, specifically on the ESP8266 microcontroller, in accordance with the logic described in Algorithm 1. Once the hardware prototype is powered on, it retrieves the project scenario data from the project microservice to which the measurement unit is assigned, then regularly executes tests according to the defined principle.

Algorithm 1 describes the data transmission mechanism as well as the management of water stress within the proposed IoT system. Its operation is based on a sequential polling of the sensors at regular intervals of ten seconds, an interval that can be adjusted according to needs. This temporal organization ensures sufficient time for the reliable collection and acquisition of environmental parameters. The adopted approach ensures a continuous and consistent data transmission, while limiting the risk of errors such as loss of information or communication bus blockage, which may occur when multiple sensors share microcontrollers.

3.4. Experimental study areas

To assess the effectiveness of the proposed system, real-world experiments were carried out on a small agricultural field. The purpose is to enable biologists to apply water stress remotely and monitor their agricultural fields easily in order to collect data and make observations. In this study, the deployment field is located in the province of Larache, in northern Morocco (35°15′48″N, 5°32′42″W) specifically in the village of Tazroute, Beni-Arouss. This study area is known for its climate characterized by hot summers often exceeding 30 degrees Celsius as well as humid winters. Furthermore, during the autumn and winter seasons, precipitation is high, whereas the summer period extending from June to September, is marked by an almost complete absence of rain. The impacts of climate change are clearly observable in this study area, disrupting growth cycles and negatively affecting the yield of major crops such as wheat and tomato. For this reason, the automatic application of water stress scenarios offers biologists effective real-time environmental monitoring and control. In this study, an example of a mockup was deployed during the spring period to evaluate the operation and capabilities our system. The experimental field is presented in Figure 3.

Algorithm 1 IoT-based agricultural data transmission and Water Stress Management

Input: Wi-Fi credentials ($ssid$, $password$), device identifier ($port$)
Output: Sensor data sent to server and irrigation pump control $P(t)$

Initialize sensors: DHT22 (*air temp/humidity*), soil moisture, soil temperature
Initialize actuators: pump
$Duration\_start\_time \leftarrow Current\_time$
$Duration\_time \leftarrow$ 10000ms // data transmission interval
Retrieve thresholds from server: Ta^{max}, Hs^{min} and Ts^{max}
While True **do**
  If $Current\_time - Duration\_start\_time \geq Duration\_time$ **then**
    Try
      Read $AirHumidity\ Ha(t) \leftarrow$ DHT22 humidity
      Read $AirTemperature\ Ta(t) \leftarrow$ DHT22 temperature
      Read $SoilTemperature\ Ts(t) \leftarrow$ Soil temperature sensor
      Read $SoilMoisture\ Hs(t) \leftarrow$ Soil moisture sensor
      Send sensor data $(Ha(t), Ta(t), Ts(t), Hs(t))$ to server via HTTP POST
    Catch sensor/read error **OR** network failure **then**
      Send alert notification to server/biologist
      Skip current transmission cycle
    End Try
    $Duration\_start\_time \leftarrow Current\_time$
  End If
  If Ta^{max} = Null **AND** Hs^{min} = Null **AND** Ts^{max} = Null **then**
    $P(t) \leftarrow 0$ // pump OFF
  Else If $(Ta(t) \geq Ta^{max})$ **OR** $(Hs(t) \leq Hs^{min})$ **OR** $(Ts(t) \geq Ts^{max})$ **then**
    $P(t) \leftarrow 1$ // pump ON
  Else
    $P(t) \leftarrow 0$ // pump OFF
  End If
  Apply $P(t)$ to irrigation pump // apply water stress
End While

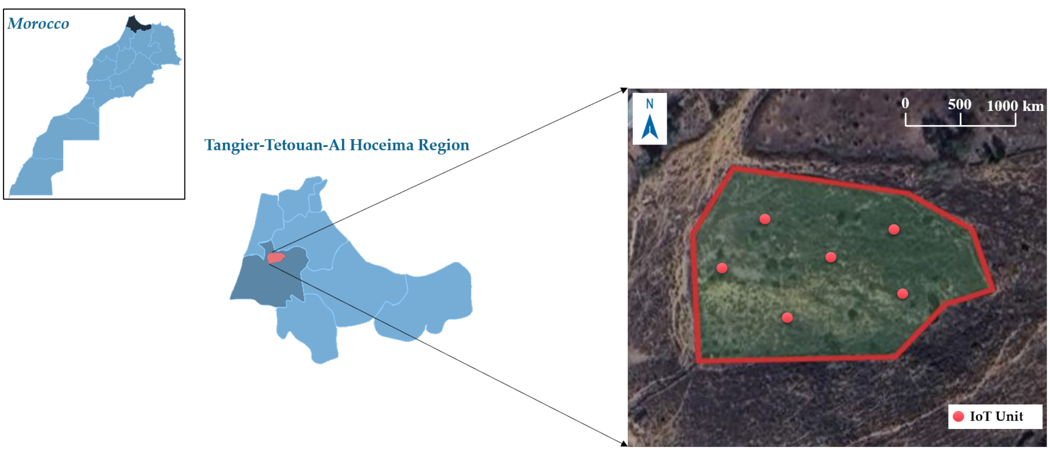

Figure 3. The agricultural field studied in the experimental study.

3.5. Sensor evaluation

Sensor evaluation constitutes an essential step in this study to analyze the stability of measurements recorded over time by the sensors used. Due to the unavailability of a calibrated reference probe during the experimental deployment, no direct comparison with a ground truth could be performed. Consequently, the evaluation carried out does not aim to estimate the absolute accuracy of the measurements, but rather to examine their stability as well as their temporal consistency.

In this study, a statistical analysis was performed on a dataset collected by the proposed IoT measurement unit in a real deployment environment over three days during the spring period, in order to evaluate the stability of the sensors as well as the dispersion of measurements under real conditions. In addition, the physical consistency of the data was verified by ensuring that the recorded values remain within plausible environmental ranges reported in the literature and in the technical datasheets.

The mean (μ), variance (σ^2) and standard deviation (σ) constitute statistical indicators used in our analysis to obtain a clear view of the sensors' stability and the dispersion of measurements over a given period. These indicators thus make it possible to evaluate the operational behavior of the sensors under real deployment conditions, in particular their ability to provide continuous, consistent and stable measurements for irrigation monitoring and water stress control. The following equations represent the calculation of the statistical indicators used in this study.

$$\mu = \frac{1}{N}\sum_{i=1}^{N} s_i \tag{3}$$

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(s_i - \mu)^2 \tag{4}$$

$$\sigma = \sum_{i=1}^{N}\sqrt{\sigma^2} \tag{5}$$

where s_i represents a sensor measurement and N the total number of collected data.

In general, periodic recalibration strategies as well as sensor replacement are recommended for long-term deployments. Future work will include the integration of reference instruments and the implementation of in-field calibration procedures in order to improve measurement accuracy and enable a more rigorous quantitative validation of the acquired data.

3.6. Service-oriented web application

In this research, an advanced web application is developed to provide a set of robust and relevant services to the two main stakeholders, the administrator and the biologist.

The administrator serves as the system manager of the proposed solution. They have the capability to add and manage measurement units through the measurement unit management microservice.

Each IoT unit has a private serial number. Biologists wishing to monitor agricultural fields in real time and perform water stress tests must have an account. The administrator, via biologist management microservice, is responsible for creating an account for each biologist and assigning available IoT measurement units to each biologist account to conduct experiments and enable the reception of measurement results. Furthermore, our web application services provide the administrator with the capability to generate statistical reports like the number of registered measurement units, the number of unused units, the count of biologists and the number of created agricultural projects.

Biologists can access their account, view and modify their own information through the biologist management microservice. When a biologist wishes to conduct an experiment, they must create a project via the project management microservice. During project creation, the biologist assigns a series of unused measurement units to the project. In reality, the assigned measurement unit has been deployed in an agricultural field. Once activated, it begins to collect and periodically send environmental parameters to the biologist's account, in the form of the created project's results for real-time monitoring.

The measurement unit is programmed to send an HTTP request to the results management microservice API to save the data. The HTTP request body includes the measured data and the serial number of the measurement unit transmitting the results. This property ensures that each project receives its own dedicated data.

Through the application services, biologists can monitor and analyze real-time data for each created project. Upon selecting a project in the project management interface, the application provides a dashboard featuring time-based graphical representations of each measured environmental parameter. These graphical representations are automatically updated to display all newly obtained real-time results. The dashboard delivers two core functionalities of proposed system, it enables biologists to either remotely start and stop the water pump manually for irrigation or create water stress scenarios according to their experimental requirements. Defined scenarios directly control the water pump for irrigation.

Our web application is divided into two components, Back-end and Front-end. The back-end is based on a microservices architecture. The application comprises five microservices, each with its own database. This study employs a MySQL database for data storage and manipulation. All microservices are developed in Java using the Spring Boot framework. Each microservice exposes a RESTful API to enable access to and utilization of the developed services.

Our study integrates several security mechanisms to ensure data confidentiality and secure access control. At the level of our web application, an RSA asymmetric encryption algorithm is used to secure data transmission between the IoT measurement unit and our application. An RSA public and private key is generated and managed within our application. The IoT measurement unit encrypts the collected environmental data using the RSA public key before transmission. Upon reception, the encrypted data are saved and then securely decrypted within our application using the associated private key before being viewed by authorized biologists. In addition, the platform integrates Spring Security with JWT-based authentication to ensure user access security and secure session management. Each biologist receives authenticated access credentials when their account is created by the system administrator. These mechanisms jointly contribute to protecting transmitted data as well as system access against unauthorized access and potential security threats. Furthermore, fault tolerance mechanisms are implemented via the Resilience4j framework to prevent incorrect responses. Finally, the back-end is deployed in Docker containers and orchestrated using Kubernetes. The front-end is developed with the Angular framework. The Communication between the two components of the application occurs via the HTTP protocol using the JSON format.

In this section, we present our work methodology, which aligns with existing works regarding the IoT measurement unit and web application. However, our approach introduces controlled water stress for experimental scenarios in an agricultural environment. The following subsection presents the results and evaluation of our work.

4. System Evaluation and Discussion

4.1. Evaluation results

This section presents the technical evaluation of the proposed system. The evaluation was carried out after the deployment of a single IoT unit in an agricultural field to collect real data, as illustrated in Figure 4. During a deployment period of three days, 759 measurements were collected to ensure real-time monitoring. Table 3 presents a sample of the measurements recorded by our IoT unit in the field. First, we present the developed web application to illustrate the operation of our system, particularly with regard to the collection and exploitation of data measured in real time and then the application of water stress tests. The operation of our web application is presented as follows.

First, the administrator authenticates their account using their email address and password. In case of a forgotten password, they can reset it via their email address. If authentication is successful, they are redirected to a dashboard, illustrated in Figure 5, which allows them to administer our application. Each IoT measurement unit is declared in the system with a unique identifier. The administrator can add new units after their construction using the option

Figure 4. Deployment of our IoT measurement unit in an agricultural field for validation.

Table 3. IoT-based system results for air temperature, humidity, soil moisture and soil temperature.

Air temperature (°C)	**Air humidity (%)**	**Soil temperature (°C)**	**Soil moisture (%)**	**Time**	**IoT Unit Serial**	**Project ID**
17.70	99.9	25.36	12.51	2025-02-03 02:03:04	MWH1	49
17.71	99.9	25.38	12.51	2025-02-03 02:02:48	MWH1	49
17.71	99.9	25.38	12.51	2025-02-03 02:02:37	MWH1	49
17.71	99.9	25.38	12.52	2025-02-03 02:02:27	MWH1	49
17.71	99.9	25.37	12.51	2025-02-03 02:02:17	MWH1	49

available in the dashboard illustrated in Figure 6. The serial number always begins with the prefix "MWH" followed by an incremented number based on the total number of registered units.

Biologists use these IoT measurement units to monitor their agricultural fields and conduct experiments. To do so, they request access from the administrator to create an account and be assigned measurement units. The administrator then creates the account by entering the biologist's name, specialty, email address and password, thereby granting access to their personal workspace. During this process, the administrator allocates a specific number of measurement units by selecting from those available, as illustrated in the figure 7. Once the account is created, the administrator provides the biologist with the assigned units, enabling them to begin their work. Furthermore, the administrator is authorized to manage and monitor measurement units and biologists, including modifying or deleting these entities and generating statistical reports in PDF and Excel formats.

The most important part of our web application is biologist's space. Once authenticated in the application, the biologist accesses an advanced dashboard that allows them to create projects for monitoring agricultural field parameters or initiating water stress treatments. Before activating the measurement unit in the field to collect, analyze and monitor in real time, it is necessary to create a project, as shown in Figure 8. In this context, the biologist defines the project name, description and most importantly, links the project to the measurement unit deployed in the agricultural field. Once activated, the unit starts sending results every ten seconds to the biologist's account.

The project management option in the biologist's dashboard, presented in figure 9 is the core of our study. It offers a set of essential features such as editing, deleting and most importantly is real-time monitoring of environmental

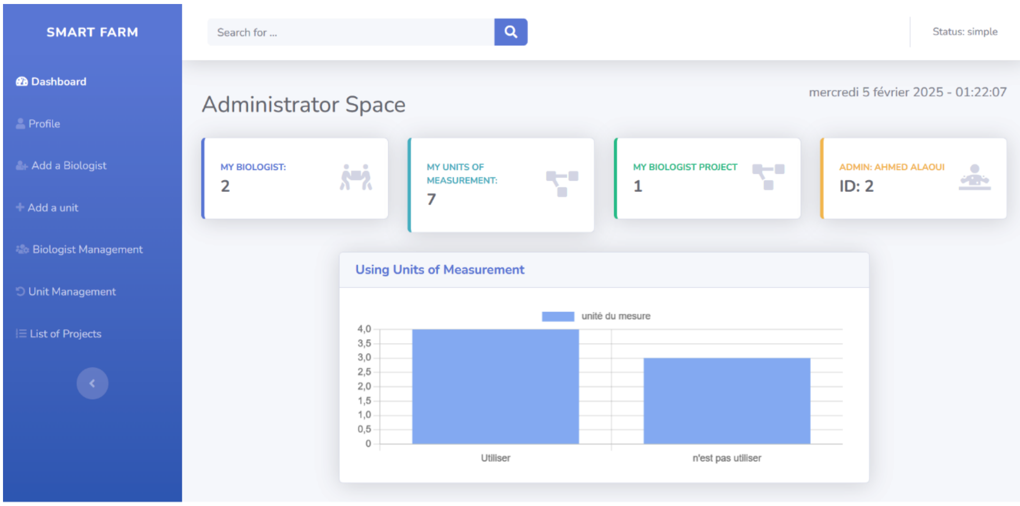

Figure 5. Administrator dashboard for managing our application system.

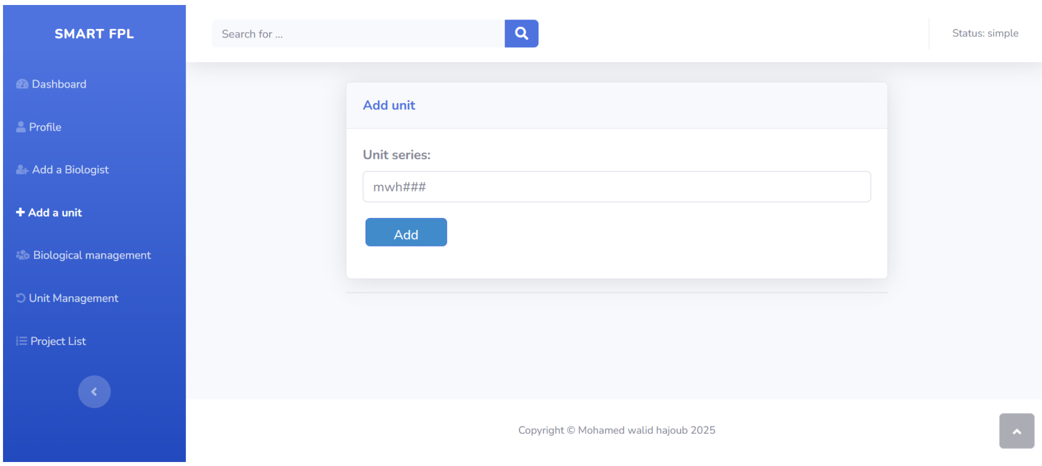

Figure 6. Process of adding an IoT measurement unit.

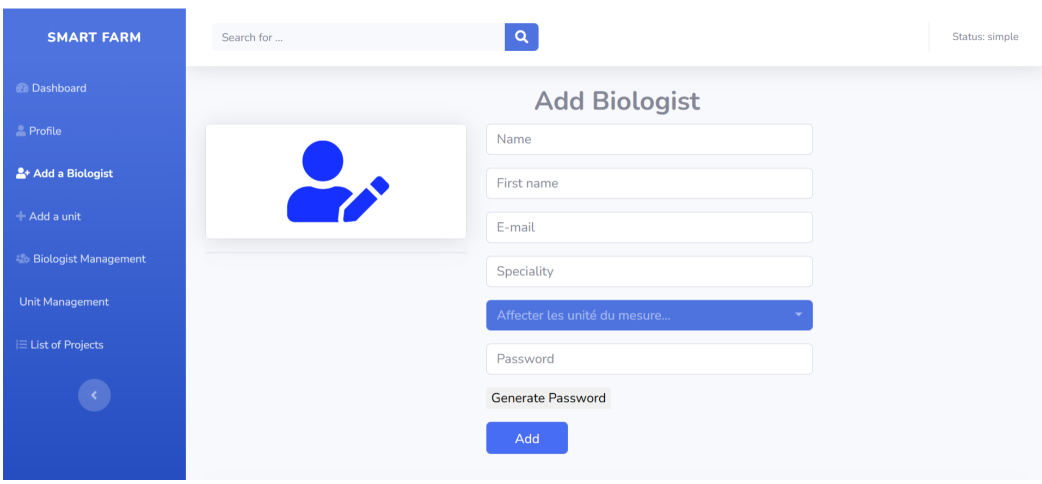

Figure 7. Process of adding a biologist by the administrator.

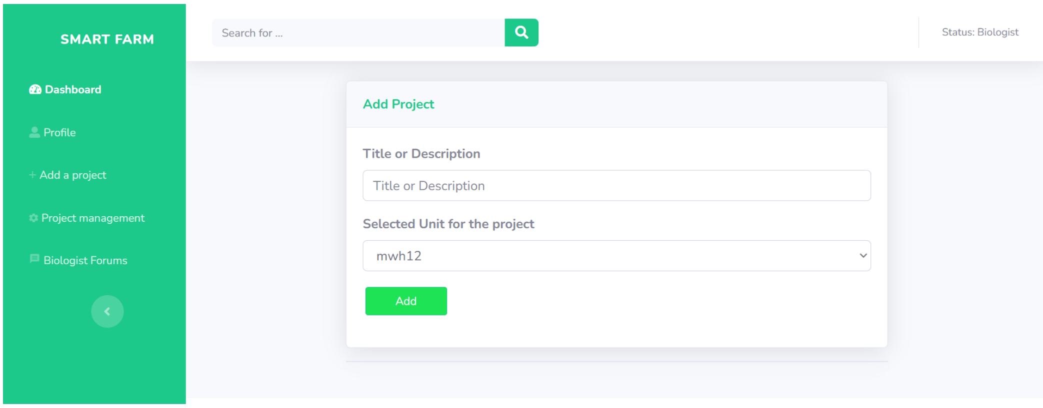

Figure 8. Process of creating an agricultural project by the biologist.

parameters measured by the unit, in the form of interactive graphs. Once the biologist selects the project monitoring option, a monitoring interface appears, comprising two graphical representations, as presented in Figure 10. The first graph displays the real-time measured values of air and soil temperature, while the second shows air and soil humidity.

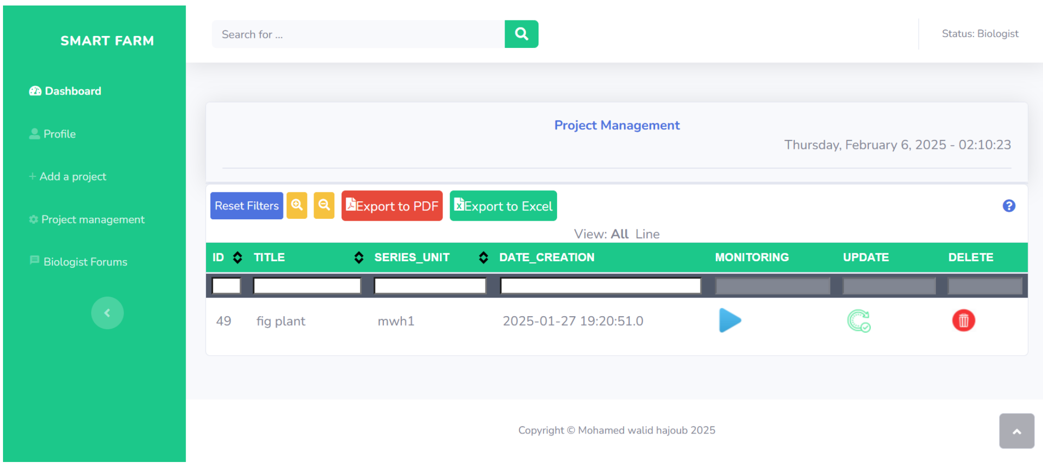

Figure 9. Project management interface.

The data are transmitted from the microcontroller to our application via the Wi-Fi module. By default, the monitoring interface displays environmental parameter values from the last five days. It also provides biologists with the capability to search and display measurements within a user-defined time interval. Additionally, it shows the most recent measurement values, identical to those displayed on the unit's LCD screen. The graphical representations consist of linearly arranged scatter plots. When a data point is selected, its corresponding numerical value is displayed. New results are automatically added to the graphs, enabling real-time monitoring and early detection of changes.

The creation of water stress scenarios in an agricultural field, where the measurement unit is deployed, is performed through the monitoring interface. The biologist defines the maximum and minimum thresholds for the environmental parameters to be used in the stress test, as shown in Figure 11. A threshold value of null indicates that the parameter is excluded from the water stress test. Once the scenario is applied, it is recorded in our database.

The IoT unit's microcontroller retrieves the scenario information via an HTTP request to our application's API, then initiates water stress processing. The water pump is activated by the relay module when the defined conditions

Figure 10. Monitoring and water stress application space of a project.

are met. Upon pump activation, an email is sent to signal the start of irrigation. Furthermore, in Figure 10 illustrating the project's monitoring interface, two indicator lights are displayed, a green lamp blinks when the scenario is active, while a red lamp blinks in the opposite case. Also, our solution enables biologists to remotely start and stop the water pump based on requirements and for a specified period.

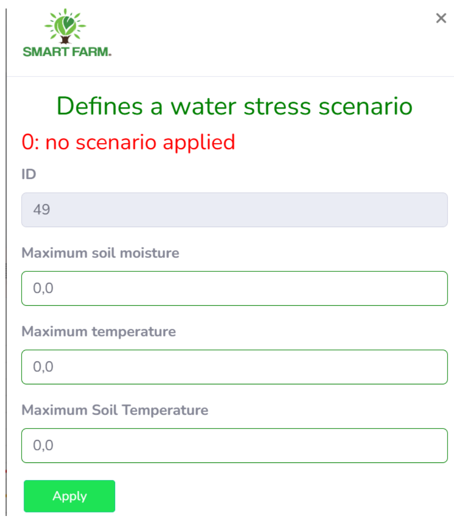

Figure 11. Creation of water stress scenario by the biologist.

4.2. Sensor stability analysis

Sensor stability is an essential element in the practice of real-time monitoring within the framework of precision agriculture. In this work, we study the stability of the sensors of our IoT unit using a test dataset collected during the deployment period in an agricultural field, during the spring season. The dataset comprises 200 measurements, each containing four values of environmental parameters recorded by our IoT unit, collected successively over 2 hours. In order to study sensor stability in depth, we perform an ablation study to obtain a clear view of the stability of the sensors used. Table 4 presents a statistical analysis of the environmental parameters collected for different sample sizes N = 50, 100, 150 and 200.

Concerning air temperature, the mean values remain relatively stable, varying from 17.50 °C to 17.61 °C as the number of samples increases. The low values of variance and standard deviation indicate limited dispersion of the measurements, which reflects good stability of the collected data and consistent sensor behavior over time. Air humidity exhibits very high and almost constant mean values, ranging between 99.81% and 99.89%. The very low values of variance and standard deviation confirm strong sensor stability.

For soil temperature, the mean values increase slightly with the number of samples, rising from 15.61 °C to 15.83 °C. At the same time, the variance and standard deviation gradually decrease, which indicates a reduction in data dispersion and an improvement in the statistical stability of the measurements as acquisition proceeds. Soil moisture also presents a relatively stable evolution with mean values between 12.49% and 12.82%. Although some fluctuations in variance and standard deviation are observed, the values remain overall low, reflecting acceptable consistency of the measurements and satisfactory stability of the soil water conditions. Overall, all the results highlight a stable behavior of the environmental parameters measured by the sensors of our proposed IoT unit. The low levels of variance and standard deviation observed for all sensors suggest good consistency of the collected data as well as operational stability of the proposed IoT system under real agricultural deployment conditions.

Table 4. Statistical analysis for evaluating the stability of the sensors used in our IoT unit.

Number of samples	**Air temperature (°C)**			**Air Humidity (%)**			**Soil temperature (°C)**			**Soil Moisture (%)**		
	Mean (μ)	**variance** (σ^2)	**Standard** deviation (σ)	**Mean** (μ)	**Variance** (σ^2)	**Standard** deviation (σ)	**Mean** (μ)	**Variance** (σ^2)	**Standard** deviation (σ)	**Mean** (μ)	**Variance** (σ^2)	**Standard** deviation (σ)
50	17.50	0.00	0.00	99.81	0.0023	0.0487	15.61	0.1703	0.4127	12.49	0.1203	0.3469
100	17.52	0.0021	0.0450	99.89	0.0508	0.0241	15.76	0.0995	0.3154	12.74	0.1236	0.3517
150	17.58	0.0074	0.0861	99.89	0.0341	0.0184	15.81	0.0710	0.2665	12.82	0.0954	0.3889
200	17.61	0.0081	0.0900	99.89	0.0023	0.0029	15.83	0.0552	0.2305	12.82	0.0721	0.2602

Table 5. Results of performance tests of the automated water stress functionality.

Indicator	**Value**
Number of requests	50000
Average response time (ms)	872
Minimum response time (ms)	6.625
Maximum response time (ms)	9
Error percentage (%)	0.000
Throughput (requests/sec)	453.72

To evaluate the execution of water stress scenarios, we carried out performance tests using the JMeter platform in order to assess the efficiency of the proposed web application. The tests were performed by simulating 50000 HTTP requests with JMeter, representing the transmission of IoT data and the triggering of scenarios to the system's REST API under controlled load conditions. The load was generated using concurrent virtual users with a defined ramp-up strategy in order to reproduce simultaneous connections. According to Table 5, a total of 50000 HTTP requests containing water stress test data were sent to evaluate the water stress functionality. The results indicate that our system successfully processed 100% of the requests, achieving a throughput of 453.72 requests per second and an average response time of 872 ms under load conditions, with response times varying between 9 ms in low-latency cases and 6625 ms during peak congestion under high concurrency. These results were obtained in a controlled test environment executed on a local computer equipped with an Intel Core i5 8350U processor with 8 threads operating at approximately 1.70 to 1.90 GHz and 8 GB of RAM running Windows. These results reflect the system performance under simulated operational conditions typical of IoT-based environmental monitoring systems. However, stress testing under extreme overload conditions and system failure threshold analysis were not included in this study and are identified as important future work.

4.3. Analysis and discussion

This research presents an innovative solution that enables not only the real-time monitoring of environmental parameters but also the implementation of configurable experimental water stress scenarios, which contributes to the development of advanced agricultural monitoring and water management systems based on the Internet of Things.

Recently, several researchers have explored the use of the Internet of Things to develop real-time monitoring systems for agricultural fields [27]. Although these systems have produced promising results, they also present significant limitations. Through a literature review, it appears that the majority of proposed systems utilize predefined platforms to display only the environmental parameters values in graphical form or send these values as alert messages. In this context, the role of the biologist remains complex, as decision-making and the execution of water stress experiments must still be performed manually.

This study work proposes an intelligent monitoring and water stress application system, providing biologists with the ability to control, test and manage agricultural fields. Our system is built on two robust and complementary components, an IoT measurement unit capable of collecting and transmitting measurements as well as applying the water stress defined by biologists, and a modern web application, which offers advanced services to receive, store, analyze and display measurements, along with creating water stress tests. To demonstrate the performance and robustness of our proposed system, we analyzed and interpreted the evaluation results in terms of IoT unit stability, cost and functionality.

In terms of stability and cost, our IoT measurement unit is composed of sensors, a microcontroller and actuators. Its design is based on two essential objectives, to guarantee measurement stability and to reduce installation costs. To this end, this work selected three sensors offering consistent quality and stability, while maintaining a significantly lower cost. The statistical analysis and ablation study show that our IoT unit exhibits effective stability, characterized by low variance and low drift for all sensors under study, notably a variance of 0.0081 for air temperature, 0.0552 for soil temperature, and 0.0721 for soil moisture. These results indicate that the measurements provided by the sensors remain stable during the testing phase, in the absence of disturbances.

Sensor calibration is an essential step, as it allows comparing and evaluating the effectiveness of the most commonly used sensors against reference sensors. According to our literature review, several studies have performed this calibration process. The works of [28], [29] and [30] carried out this calibration and report a strong agreement between the DS18B20 sensor and the THERM200 reference sensor. Behmanesh et al. [28] indicate a strong correlation between the two sensors with a coefficient of determination (R^2) close to 0.974 under experimental conditions, while studies [29] and [30] confirm a low deviation between the two sensors, reflecting consistent temperature measurements during field deployments. Furthermore, the cost of the THERM200 sensor is 40 dollars, which is significantly higher than that of the DS18B20, priced at 2 dollars, thus demonstrating the low cost of our unit. This reinforces the relevance of our choice combining stability and economy.

Our study does not include a calibration process or direct comparison with reference sensors, it relies on existing calibration studies for the selection of sensors for our IoT unit. In order to validate the measurement accuracy of our IoT unit, we plan to carry out a calibration process in future work, with the aim of improving and continuing the contribution of our system.

In terms of functionality, our biologist-driven web application provides useful and efficient services, particularly for the exploitation of measured data. It enables biologists to make informed decisions. The automation of water stress constitutes the core functionality of our application. It allows the controlled execution of experimental scenarios via predefined parameters, enabling remote control of irrigation systems without field intervention. This reduces operational efforts and facilitates the implementation of structured experiments on plant response to water availability. Thanks to these functionalities, biologists can make real-time decisions in order to improve agricultural practices. Thus, our solution helps reduce negative impacts on agricultural production while improving quality and yield. Furthermore, the automation of water stress aims to enhance irrigation control by biologists in order to effectively combat water waste.

The features offered by our application, such as interval-based search, results filtering and project management, facilitate the work of biologists and allow them to focus on real-time decision-making. The design of our web application emphasizes software quality by ensuring reduced response time, high availability, optimal scalability, effective management of massive data, simplified maintenance and fault tolerance. To achieve these objectives, we adopted a Microservices architecture combined with modern technologies like Docker and Kubernetes. Furthermore, the separation of databases enhances the speed and efficiency of our solution. In contrast, the majority of existing works developing their own platform rely on a tightly coupled monolithic architecture, where a failure in one part of the application leads to the failure of the whole. The use of the Microservices architecture constitutes a major asset in precision agriculture. The results of the performance tests illustrate this advantage. Our application processed 50000 user requests without issue and with a maximum response time of 9ms representing a significant software improvement. Furthermore, the performance tests of the water stress functionality revealed no errors on the IoT measurement unit, with the tests being correctly executed and interpreted by the microcontroller, proof that all requests were processed successfully.

Water stress automation is the heart of proposed research environment and constitutes an essential functionality of our solution. This aspect represents a major advantage, as most existing systems do not support this functionality. Table 5 presents a comparative analysis between existing real-time agricultural monitoring systems and our proposed system.

Table 6. A comparative analysis between existing systems and our proposed system.

Author/Ref.	**Parameters**	**Application**	**Data management Dashboard**	**Water Stress Application**
Omar et al. [31] (2020)	Soil moisture, Soil temperature, Air Temperature and Humidity	Yes	Yes	No
Vivekrabinson et al. [21] (2024)	Soil moisture, Air temperature and humidity	Yes	Yes	No
Narayana et al. [25] (2024)	Air quality, Gas detection, Air temperature and humidity	No	No	No
Radzi et al. [23] (2025)	pH Value and Electrical conductivity	No	No	No
Our approach	**Air temperature and Humidity, Soil moisture, Soil temperature**	**Yes**	**Yes**	**Yes**

The comparative study presented in Table 5 shows that the majority of the proposed systems, as well as our system, ensure the monitoring of the same environmental parameters in order to cope with environmental variations. Nevertheless, our proposal stands out through a biologist-driven system, enabling the implementation of configurable experimental water stress scenarios, not merely automatic irrigation, but a platform dedicated to scientific testing. More specifically, the automation of water stress constitutes a functionality that has not yet been reported in the literature.

The research by Omar et al. [31] presents a real-time monitoring system for air and soil temperature and humidity. However, it is limited to displaying measured data on an open-source platform and does not propose water stress automation. Similarly, the approach by Vivekrabinson et al. [21] focuses mainly on a conventional irrigation system and real-time monitoring of air temperature and humidity as well as soil temperature, without providing advanced functionalities for data processing and exploitation. The approach by Narayana et al. [25] covers a broader range of parameters, such as air quality and gas detection, but does not offer any visualization application; data are transmitted in the form of messages, which limits their exploitation, while accuracy remains average. Radzi et al. [23] use pH and electrical conductivity sensors for monitoring soil nutrients via an open-source display platform, Bylink. Generally, existing systems are mainly oriented towards environmental monitoring and traditional irrigation automation. However, these approaches remain limited by the absence of configurable water stress scenarios, the lack of experimental control mechanisms and the non-integration of thresholds defined by the biologist for the management of environmental conditions. In contrast, the main contribution of this work lies in the development of an experimental system driven by the biologist. This introduces a configurable framework within which the biologist explicitly defines environmental thresholds such as air temperature, soil temperature, and soil moisture. The proposed system then applies automated control based on these parameters, enabling both real-time monitoring and the implementation of controlled experimental water stress scenarios. Compared to existing systems, our proposal offers a complete solution integrating monitoring, data visualization, alert generation, remote control and advanced experimentation. This integration provides a more flexible agricultural platform, promoting the improvement of agricultural practices and contributing to the development of smart agriculture.

The use of a Wi-Fi module in our design was prioritized in order to reduce costs and avoid subscription fees associated with GSM or LoRa services. Generally, our IoT measurement unit uses a local Wi-Fi connection without Internet access, solely to transmit measurement data to a MySQL database and to receive water stress thresholds locally. In the event of Wi-Fi connection loss during a measurement cycle, the system continues to operate normally and perform acquisitions, but data are not stored locally during this period. To address this issue, a notification is generated in the event of a prolonged absence of data in order to alert the biologist to intervene and resolve the problem.

After the initial deployment of the proposed system in an agricultural field, preliminary feedback was collected from seven biologists who remotely tested the water stress automation functionality. The preliminary feedback indicates that our system enables more controlled irrigation management. The results also suggest that the system can facilitate the collection of structured datasets under different irrigation scenarios. Overall, our proposed system is considered a tool for data acquisition and environmental monitoring, capable of supporting analysis and decision-making in agricultural contexts.

This study is primarily focused on the design and implementation of a technical IoT-based system for environmental monitoring and automated water stress control. No biological experiments on real crops were conducted in this work, and therefore no direct physiological or agronomic outcomes are reported. As a result, the impact of the proposed system on plant development and crop productivity cannot be empirically validated within the scope of this study. Furthermore, the evaluation is limited to system-level performance metrics.

In this study, a set of points is taken into consideration in order to address the limitations encountered during the realization of this work. Future work aimed at continuing the development of our contribution is as follows. First, the deployment of high-precision sensors in order to carry out a calibration process to validate the measurement accuracy of our IoT unit against reference sensors. Second, the conduct of biological experiments on real crops such as tomato and wheat, as well as on different soil types, in order to evaluate plant responses under different automated water stress scenarios to measure physiological and agronomic parameters such as growth, biomass, yield, and stress indicators. Third, the improvement of the robustness and performance of the proposed solution by adding sensor fault detection methods and advanced data imputation techniques, as well as the integration of a hysteresis mechanism aimed at improving stability around the thresholds of water stress scenarios. Finally, the performance of extreme stress tests will allow analyzing the system's failure thresholds. These directions will improve the contribution and make it more suitable for smart agriculture practices.

5. Conclusion

Intelligent environmental monitoring is an essential component of modern agriculture, particularly in the context of ongoing environmental changes. Water stress represents an important research framework for biologists, enabling the development of configurable water stress scenarios and supporting real-time decision-making.

This study proposes an intelligent research environment for agricultural biologists based on IoT technology. The proposed environment integrates an IoT measurement unit capable of collecting environmental parameters, including air temperature, air humidity, soil temperature and soil moisture. It is also able to execute the automatic water stress tests defined by biologists. In parallel, a modern and robust web application has been developed to ensure the management, real-time monitoring and execution of water stress tests related to irrigation. The evaluation results obtained after deploying a sample of our measurement unit in an area of an agricultural field show that our solution executes the water stress scenarios defined by the biologists without errors and with a reduced execution time. Indeed, our application processed 50000 scenario requests in only 872 ms. Furthermore, the statistical analysis performed on a sample of collected data shows that our IoT unit exhibits a low variance of 0.0721 for soil moisture, 0.0552 for soil temperature, 0.0081 for air temperature, and 0.0023 for air humidity, which reflects effective stability and consistent sensor behavior over time within our proposal.

In future work, we focus on improving our proposal by adding and implementing all the specified points, such as biological experiments on real crops to study the impact of our proposed solution, performing calibration to validate measurement accuracy, as well as implementing all technical and functional requirements to make our proposal more stable, efficient, and secure. With these improvements, we aim to make our proposal a robust solution in the practice of smart agriculture.

Author Contributions: The authors confirm their contributions to the paper as follows: Conceptualization, M.W.H.; methodology, M.W.H.; software, M.W.H.; validation, H.T. and M.W.H.; formal analysis, M.W.H.; writing—original draft preparation, M.W.H.; writing—review and editing, H.T. and M.A.B.; visualization, H.T. and M.A.B.; supervision, H.T. and M.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Data availability statement: The data that support the evaluation of this study are openly available in Zenodo at the following DOI: https://doi.org/10.5281/zenodo.20645177.

REFERENCES

1. M. W. Hajoub, H. Touil, A. Arouijal, and M. Achkari Begdouri, *Integration of IoT sensing and spatial interpolation for optimized agricultural monitoring: a case study in Larache, Morocco*, Systems Science & Control Engineering, vol. 14, no. 1, p. 2657113, Apr. 2026, doi: 10.1080/21642583.2026.2657113.
2. M. W. Hajoub, H. Touil, and M. A. Begdouri, *Sustainable IoT-Based System for Real-Time Environmental Control in Precision Agriculture*, in *Smart Technologies for a Sustainable Environment*, M. Azrour, A. Guezzaz, and S. Jabbour, Eds., CRC Press, 2026, pp. 10–19, doi: 10.1201/9781003671602-2.
3. Z. E. Mohamed, M. K. Afify, M. M. Badr, and O. A. Omar, *IoT-driven smart irrigation system to improve water use efficiency*, Sci. Rep., vol. 16, no. 1, 2026, doi: 10.1038/s41598-025-33826-6.
4. S. Lahrache, M. E. Kassimi, and A. E. Qadi, *Cross-Modal Federated Learning for Robust Plant Disease Classification*, Statistics, Optimization & Information Computing, Nov. 2025, doi: 10.19139/soic-2310-5070-3048.
5. S. Lagnaoui, K. Boumais, Z. En-naimani, and K. Haddouch, *Automated Initialization Method in Convolutional Neural Networks using BO Applied to Plant Disease Classification*, Statistics, Optimization & Information Computing, vol. 14, no. 5, pp. 2487–2502, Sep. 2025, doi: 10.19139/soic-2310-5070-2380.
6. A. R. Jangam, K. V. Kale, S. Gaikwad, and A. D. Vibhute, *Design and Development of IoT based System for Retrieval of Agrometeorological Parameters*, in *2018 International Conference on Recent Innovations in Electrical, Electronics & Communication Engineering (ICRIEECE)*, Jul. 2018, pp. 804–809, doi: 10.1109/ICRIEECE44171.2018.9008636.
7. B. Oduro, O. O. Apenteng, and H. Nkansah, *Assessing the effect of fungicide treatment on Cocoa black pod disease in Ghana: Insight from mathematical modeling*, Statistics, Optimization & Information Computing, vol. 8, no. 2, pp. 374–385, May 2020, doi: 10.19139/soic-2310-5070-686.
8. A. Oliveira-Jr, K. Cardoso, F. Sousa, and W. Moreira, *A Lightweight Slice-Based Quality of Service Manager for IoT*, IoT, vol. 1, no. 1, pp. 49–75, Aug. 2020, doi: 10.3390/iot1010004.
9. Z. Zhou, Y. Majeed, G. Diverres Naranjo, and E. M. T. Gambacorta, *Assessment for crop water stress with infrared thermal imagery in precision agriculture: A review and future prospects for deep learning applications*, Computers and Electronics in Agriculture, vol. 182, p. 106019, Mar. 2021, doi: 10.1016/j.compag.2021.106019.

10. H. Touil, M. Achkari Begdouri, and M. W. Hajoub, *Innovative Hybrid Approach for Efficient Lightweight Vision Transformer Networks in Plant Disease Detection*, International Journal of Intelligent Engineering and Systems, vol. 18, no. 5, pp. 329–346, 2025, doi: 10.22266/ijies2025.0630.24.
11. S. S and R. G. K, *Digital Image Forgery Detection Using Cyclic Symmetry Convolutional Neural Network*, International Journal of Intelligent Engineering and Systems, vol. 18, no. 1, pp. 368–379, 2025, doi: 10.22266/ijies2025.0229.27.
12. F. M. S and B. Booba, *A Novel Deep Learning Architecture for Irrigation Prediction Using 1D-CNN-Bidirectional GRU-Fusion Model*, Int. J. Intelligent Eng. Syst., vol. 18, no. 5, pp. 310–328, 2025, doi: 10.22266/ijies2025.0630.23.
13. M. walid Hajoub, H. Touil, and M. Achkari Begdouri, *Plant Disease Detection Using a Hybrid Approach Based on Vision Neural Network Transformers*, in *Proceedings of the 7th International Conference on Networking, Intelligent Systems and Security*, in NISS '24. New York, NY, USA: Association for Computing Machinery, Aug. 2024, pp. 1–6, doi: 10.1145/3659677.3659685.
14. Y.-L. Huang, J.-Y. Tian, and T.-Q. Shang, *Design of Monitoring System in Smart Agriculture Environment*, DEStech Transactions on Social Science, Education and Human Science, vol. 0, no. icesd, 2020, doi: 10.12783/dtssehs/icesd2020/34560.
15. A. Hessane, A. El Youssefi, Y. Farhaoui, B. Aghoutane, and F. Amounas, *A Machine Learning Based Framework for a Stage-Wise Classification of Date Palm White Scale Disease*, Big Data Mining and Analytics, vol. 6, no. 3, pp. 263–272, 2023, doi: 10.26599/BDMA.2022.9020022.
16. P. D. W. Ayu, G. A. Pradipta, I. M. D. Susila, D. P. Hostiadi, and M. Liandana, *Deep Learning Based Detection and Classification of Amniotic Fluid Echogenicity Type for Enhanced Prenatal Diagnosis*, International Journal of Intelligent Engineering and Systems, vol. 18, no. 1, pp. 246–267, 2025, doi: 10.22266/ijies2025.0229.18.
17. P. Visconti, R. de Fazio, P. Primiceri, D. Cafagna, S. Strazzella, and N. I. Giannoccaro, *A solar-powered fertigation system based on low-cost wireless sensor network remotely controlled by farmer for irrigation cycles and crops growth optimization*, Int. J. Electron. Telecommun., vol. 66, no. 1, pp. 59–68, 2020, doi: 10.24425/ijet.2019.130266.
18. S. V. Gaikwad, A. D. Vibhute, K. V. Kale, and S. C. Mehrotra, *An innovative IoT based system for precision farming*, Computers and Electronics in Agriculture, vol. 187, p. 106291, Aug. 2021, doi: 10.1016/j.compag.2021.106291.
19. L. Dayananda, N. Amarasingam, and P. Ponnampalam, *An IoT based Low-cost Weather Monitoring System for Smart Farming*, Agricultural Science Digest - A Research Journal, Oct. 2021, doi: 10.18805/ag.D-370.
20. A. B. Kathole, K. N. Vhatkar, S. Kumbhare, J. Katti, and V. V. Kimbahune, *IoT-Based Smart Agriculture for Onion Plant Disease Management: A Comprehensive Approach*, Internat. J. Intel. Syst. Appl. Eng., vol. 12, no. 13, pp. 472–476, 2024, doi: 2-s2.0-85186859749.
21. K. Vivekrabinson, A. Vishnu, S. Jeya Aravinth, and P. Sundara Mahalingam, *An IOT Based Smart Agriculture Monitoring System for Precision Farming*, in *Artificial Intelligence and Digital Twin Technology*, V. K., R. A., S. Seeni, U. Kose, B. T. Hung, and K. Kottursamy, Eds., Cham: Springer Nature Switzerland, 2024, pp. 103–111, doi: 10.1007/978-3-031-77799-8_9.
22. Md. A. R. Nishad, M. A. Mitu, and N. Jahan, *Predicting and Classifying Potato Leaf Disease using K-means Segmentation Techniques and Deep Learning Networks*, Procedia Computer Science, vol. 212, pp. 220–229, Jan. 2022, doi: 10.1016/j.procs.2022.11.006.
23. N. S. A. Mahmudin and N. H. M. Radzi, *Application of Internet of Things (IoT) on Monitoring EC and pH Values for Fertigation System*, Journal of Advanced Research in Applied Mechanics, vol. 126, no. 1, pp. 188–206, 2025, doi: 10.37934/aram.126.1.188206.
24. A. Morchid, R. El Alami, A. A. Raezah, and Y. Sabbar, *Applications of internet of things (IoT) and sensors technology to increase food security and agricultural Sustainability: Benefits and challenges*, Ain Shams Engineering Journal, vol. 15, no. 3, 2024, doi: 10.1016/j.asej.2023.102509.
25. T. L. Narayana *et al.*, *Advances in real time smart monitoring of environmental parameters using IoT and sensors*, Heliyon, vol. 10, no. 7, p. e28195, Apr. 2024, doi: 10.1016/j.heliyon.2024.e28195.
26. S. Mukherjee, S. Paul, S. Bhattacharya, A. Islam, S. Mahammad, and E. Alam, *Optimizing water resource management in tropical drought-prone regions through hybrid MCDM techniques: A water-stress mapping approach*, Journal of Hydrology: Regional Studies, vol. 57, p. 102171, Feb. 2025, doi: 10.1016/j.ejrh.2024.102171.
27. T. Saranya, C. Deisy, S. Sridevi, and K. S. M. Anbananthen, *A comparative study of deep learning and Internet of Things for precision agriculture*, Engineering Applications of Artificial Intelligence, vol. 122, p. 106034, Jun. 2023, doi: 10.1016/j.engappai.2023.106034.
28. J. Behmanesh and S. Mehdizadeh, *Estimation of soil temperature using gene expression programming and artificial neural networks in a semiarid region*, Environ Earth Sci, vol. 76, no. 2, p. 76, Jan. 2017, doi: 10.1007/s12665-017-6395-1.
29. K. N. Bhanu, T. B. Reddy, and M. Hanumanthappa, *Multi-agent based context aware information gathering for agriculture using Wireless Multimedia Sensor Networks*, Egyptian Informatics Journal, vol. 20, no. 1, pp. 33–44, Mar. 2019, doi: 10.1016/j.eij.2018.07.001.
30. A.-F. Jimenez, P.-F. Cardenas, F. Jimenez, A. Ruiz-Canales, and A. López, *A cyber-physical intelligent agent for irrigation scheduling in horticultural crops*, Computers and Electronics in Agriculture, vol. 178, p. 105777, Nov. 2020, doi: 10.1016/j.compag.2020.105777.
31. N. Omar, H. Zen, N. N. A. A. A. Aldrin, W. Waluyo, and F. Hadiatna, *Accuracy and Reliability of Data in IoT System for Smart Agriculture*, International Journal of Integrated Engineering, vol. 12, no. 6, Art. no. 6, Jun. 2020, doi: 10.30880/ijie.2020.12.06.013.