Decentralized IoT Solution for Smart Agriculture Using LoRaWAN and Edge Computing

Abstract:

Previous smart irrigation systems face limitations such as dependency on third-party cloud services, limited connectivity range, inefficient water usage, and lack of data privacy. These challenges often hinder the effectiveness and scalability of traditional solutions. To address these issues, this project proposes a decentralized smart irrigation system tailored for agricultural fields. Using a master-slave architecture, the Raspberry Pi acts as the master node while multiple ESP32 nodes serve as slave nodes, each equipped with a soil moisture sensor and a sprinkler. With LoRa communication for long-range, low-power connectivity, the slave nodes monitor soil moisture levels every five minutes and send the data to the master node. The master node hosts a private, decentralized web server for real-time monitoring and decision-making, eliminating the need for third-party cloud services. When the soil moisture falls below a certain threshold, the corresponding slave node activates its sprinkler, ensuring precise water usage and shutting it off when the moisture level is restored. This approach improves data privacy, reduces reliance on external cloud platforms, and enhances irrigation efficiency, contributing to sustainable and autonomous farming practices.

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IoT-based smart irrigation management system to enhance agricultural water security using embedded systems, telemetry data, and cloud computing

Abdennabi Morchid [a,*], Rachid Jebabra [a], Haris M. Khalid [b,c], Rachid El Alami [a], Hassan Qjidaa [a], Mohammed Ouazzani Jamil [d]

[a] Department of Physics, Laboratory of Informatics, Signals, Automation and Cognitivism (LISAC), Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, BP 1796 Fes-Atlas, 30003, Fez, Morocco
[b] College of Engineering and Information Technology, University of Dubai, Academic City, 14143, Dubai, United Arab Emirates
[c] Department of Electrical and Electronic Engineering Science, University of Johannesburg, Aukland Park, 2006, South Africa
[d] Systems and Sustainable Environment Laboratory (SED), Faculty of Engineering Sciences (FSI) Private University of Fez (UPF), Fez, Morocco

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ABSTRACT

Agriculture, the key sector for food production, faces challenges exacerbated by the growing global demand for food and the scarcity of water resources. Traditional irrigation methods often lead to inefficient use of water, resulting in wastage. Moreover, unpredictable weather conditions and the need to adopt sustainable farming practices are driving us to develop advanced irrigation systems. This paper proposed a smart irrigation management system using new technology like 1) embedded systems, 2) Internet of Things (IoT), 3) telemetry data, 4) cloud computing, communication protocol, and 5) sensors to collect and process real-time data of the smart agriculture. This new technology and intelligent algorithm are used in this paper to improve agricultural practices. The architecture of the proposed scheme comprises three layers: 1) IoT devices, 2) ThingsBoard cloud, and 3) the dashboard, each playing a pivotal role in ensuring seamless data flow, secure communication, and enhanced user interaction. The algorithm orchestrates system operations, incorporating sensor data reading, JavaScript Object Syntax (JSON) payload creation, and secure telemetry data transmission via Hypertext Transfer Protocol (HTTP) protocol to the ThingsBoard cloud. Pump activation decisions are governed by predefined thresholds, preventing an over-irrigation system. The evaluation of system performance involves deploying temperature, humidity, moisture, and water level sensors in a testing field. Further, before data is sent to the cloud, sensor values are calibrated using a functional map. Tests carried out with temperature, humidity, and water level sensors demonstrate the system's dynamic efficiency. By visualizing and analyzing environmental information via ThingsBoard, the results provide real-time data on environmental parameters of the system proposed, improving the efficiency of water use and the sustainability of farming practices. In addition, the system features e-mail notifications for alerts. The integration of e-mail notifications reinforces monitoring and management practices by alerting farm owners and users. This study showcases the efficacy of the proposed paper in enhancing sustainability, water usage, and supporting smart agriculture practices. Further, this paper integrates embedded systems, IoT, cloud computing, and advanced algorithms to optimize and enhance crop productivity and contribute to global food and water security.

1. Introduction

Agriculture is a cornerstone of many global economies, playing a pivotal role in significantly contributing to the Gross Domestic Product and ensuring food security [1,2]. However, it is important to realize that agriculture is the only user of water resources; 70 % of the world's freshwater withdrawals are used to irrigate 25 % of the total cultivated land [3–6]. Difficulties caused by population growth and climate change are increasing the demand for vital resources, especially water, needed for agricultural productivity [7]. Recent studies have highlighted the

* Corresponding author.
E-mail address: Abdennabi.morchid@usmba.ac.ma (A. Morchid).

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main obstacles facing agricultural systems, such as urbanization, soil degradation, water shortages, and climate change [8–10]. The growing number of people on the planet is increasing the need for food, putting pressure on water and land resources. Worldwide, there are some 3500 million hectares of degraded land, 80 % of which is affected by erosion [11–13]. By 2050, there will probably be 9.7 billion people on the planet, increasing the demand for water and healthy food [14]. Assuming an increase in water productivity, the Food and Agriculture Organization of the United Nations predicts an increase of more than 50 % in irrigated food production by 2050, which will require a 10 % increase in water abstraction for agriculture [14]. Faced with fixed arable land, agricultural systems must efficiently optimize water and land resources to meet the nutritional needs of growing populations [3]. Understanding and implementing mechanisms to improve water use efficiency is essential to achieve significant water savings and increase productivity, with agronomists defining efficiency in terms of crop productivity per unit of water used [15–19]. With the increasing scarcity of water due to climate change [20], interest in water use efficiency is growing. Competition from other sectors for scarce water is forcing experts and policy-makers to reassess water use practices in agriculture. The adoption of state-of-the-art water management and precision farming techniques is essential to cope with declining land and water allocations [21,22]. Consequently, this study is motivated by the urgent need to tackle the problems associated with global agriculture, particularly those related to water and food security. Innovative solutions are needed due to the confluence of limited water resources and growing food production needs. This study aims to create a smart irrigation system that optimizes water use, increases agricultural production, and supports sustainable farming practices by integrating IoT devices, cloud computing, and sophisticated algorithms. The aim is to provide efficient, intelligent precision farming solutions using cutting-edge technologies, guaranteeing reliable access to the food supply while reducing the impact on the environment.

The use of IoT technologies has given rise to a whole new era in agriculture, known as smart farming, with a particular focus on smart irrigation [23,24]. Many studies focus on the creative use of IoT in agriculture, where sensors and connected devices are used to improve the sustainability, productivity, and efficiency of farming, particularly in the field of irrigation management [25,26]. Smart farming uses automation, sophisticated analytics, and real-time data to transform conventional farming practices [27]. Further, in smart agriculture sensors are essential for collecting real-time data on crop health, soil quality, and weather trends. For example, soil sensors provide accurate information on temperature, water content, and nutrient levels, and fire sensors, enable farmers to make informed decisions on crop management, fire, fertilization, and irrigation [23,28–31]. The authors of this study [32] examined the implementation of application-independent controls in smart irrigation systems. It explores the potential of automated decision-making processes in irrigation control, with a focus on improving efficiency and conserving resources. In addition, this article [33] discusses the integration of IoT and machine learning technologies in the development of smart irrigation systems. The study aims to assess the capabilities of this system to improve water use and enhance irrigation management in general. Focusing on sweet corn cultivation, the authors of this study [34] evaluated the efficiency of an IoT-based smart drip irrigation system. Crop evapotranspiration (ETc) is used to improve irrigation practices, to improve crop productivity, and water use efficiency. In addition, this article [35] conducted experiments to evaluate the practical performance of an IoT-based smart drip irrigation system. The focus is on the use of web applications for remote monitoring and control, providing insight into the actual functionality of the system. Looking at water-saving strategies, this study proposes and evaluates a model-based predictive control strategy for drip irrigation. The authors of this study [36] aimed to improve water use efficiency by using predictive modeling to inform irrigation decisions. Focusing on system design, this study explores the implementation of an agricultural irrigation control system based on a composite controller. The research [37] aims to integrate several control mechanisms to improve the adaptability and response of irrigation management. This case study [38] explores the development and application of a web-based system for remote monitoring and management of precision irrigation in an arid region of Argentina. The research provides insight into the ability of such systems to adapt to specific environmental conditions. Focusing on nano-sensor technology, this paper [39] investigated the potential of a wireless nano-sensor network for irrigation control. The research aims to explore the feasibility and benefits of nanosensors for improving irrigation precision. This research [40] focused on smart irrigation systems developed for greenhouse environments. It presents a proof-of-concept based on real-time soil moisture data, intending to demonstrate the applicability and benefits of these systems in controlled agricultural environments. Further, these studies [41,42], discuss smart sensing methods for sustainable agriculture, focusing on the integration of IoT-based embedded systems, cloud platforms, deep learning, and machine learning for smart agriculture. This article [43] presents an IoT-based smart irrigation system to optimize water management in arid regions, with real-time data analysis and weather forecasting. On the other hand, this article [44] describes a real-time fire detection system for smart agriculture, using IoT and a secure web application to monitor and protect crops. On the other hand, the integration of IoT technologies into agriculture, known as smart farming, has transformed traditional practices by enabling accurate, data-driven decision-making. Sensors, such as the DHT22, moisture sensor, and water level sensor, play a key role in collecting real-time data on crop health, soil moisture, and weather conditions [45]. These data are essential for current research into statistical modeling, enabling the prediction of yields, irrigation requirements, and the optimization of resource use. The use of these models improves decision-making and supports sustainability objectives in agriculture. With a focus on water and food security, this paper concentrates on a smart irrigation system that addresses global agricultural concerns. It combines ThingsBoard cloud, IoT devices, and an intelligent algorithm for best practices. The design ensures secure connectivity and smooth data flow. Sensor placement and e-mail notifications enhance management and monitoring. Promoting water use efficiency and supporting smart agriculture are the objectives. The main contributions of this paper are as follows.

- The paper presents an advanced system integrating embedded systems, IoT, ThingsBoard cloud, and a sophisticated algorithm to optimize agriculture practices.
- The proposed system features a three-tier architecture comprising 1) IoT devices, 2) the ThingsBoard cloud, and 3) a dashboard, guaranteeing efficient data flow, secure communication, and control based on environmental parameters.
- An intelligent algorithm manages tasks such as reading sensor data, creating payloads, and securely transmitting telemetry data via HTTP protocol, preventing over-irrigation. Further, before data is sent to the cloud, sensor values are calibrated using a functional map.
- The study evaluates system performance using sensors and visualizes, and analyzes the information in real-time on ThingsBoard cloud dashboards.
- The study includes email notifications for alert farm owners and users, contributing to effective monitoring, sustainability, and global food security.

The graphical abstract of the proposed scheme can be seen in Fig. 1.

The formation of the rest of the paper is as follows. The material and methods are described in Section 2. Results and discussion of the proposed system are presented in Section 3. The conclusions and future work are presented in Section 4.

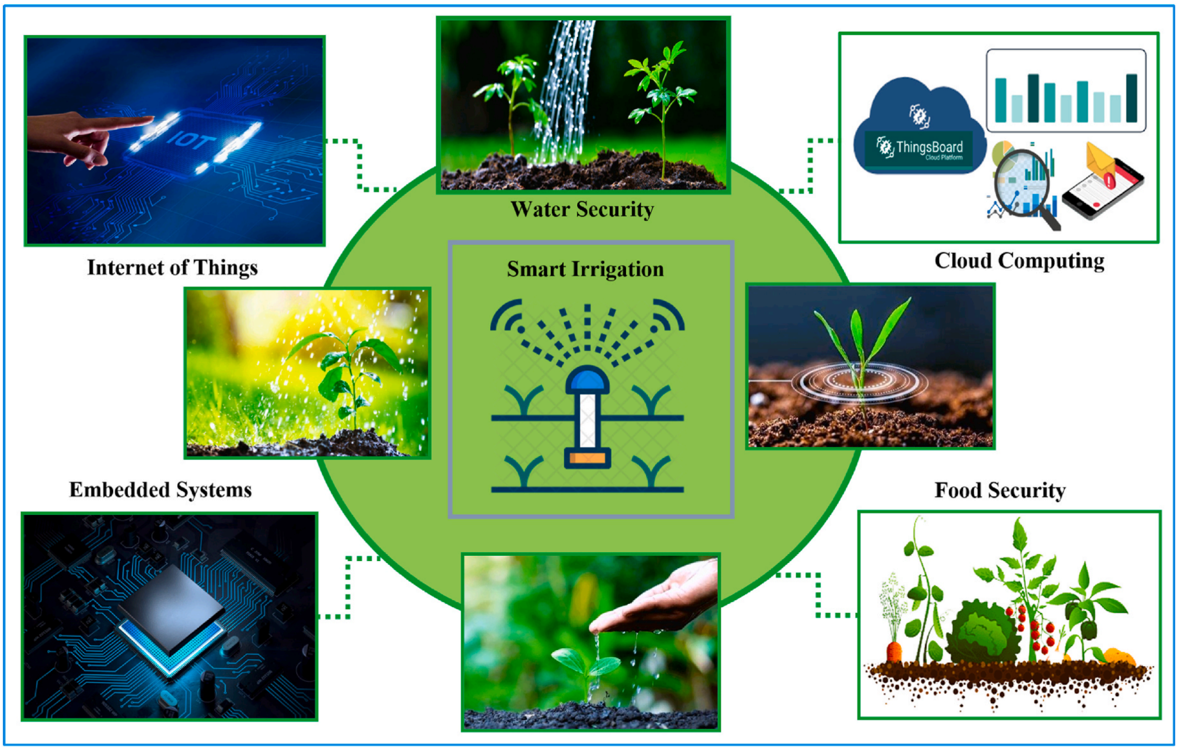

Fig. 1. Graphical abstract of the proposed scheme.

2. Materials and methods

To maximize water use in agriculture, the smart irrigation system management system seamlessly combines cloud computing, IoT devices, and sophisticated algo-rithms. As shown in Fig. 2, its architecture consists of three main layers: the Things-Board cloud, the IoT devices, and the dashboard. The input, procedure, and output of the proposed algorithm are illustrated in Fig. 3. The fundamental element of the system is an algorithm that reads sensor data, initializes components, and securely sends telemetry data to the cloud. To avoid over-irrigation, pump activation decisions are based on predetermined criteria. Deliberate delay and rigorous error management improve overall system reliability. This creative approach enables informed decision-making in contemporary agriculture, environmental sustainability, and resource efficiency. This section deals with the proposed architecture and the proposed scheme algorithm.

2.1. Architecture of the proposed scheme

Fig. 2 shows the architecture of the smart irrigation management

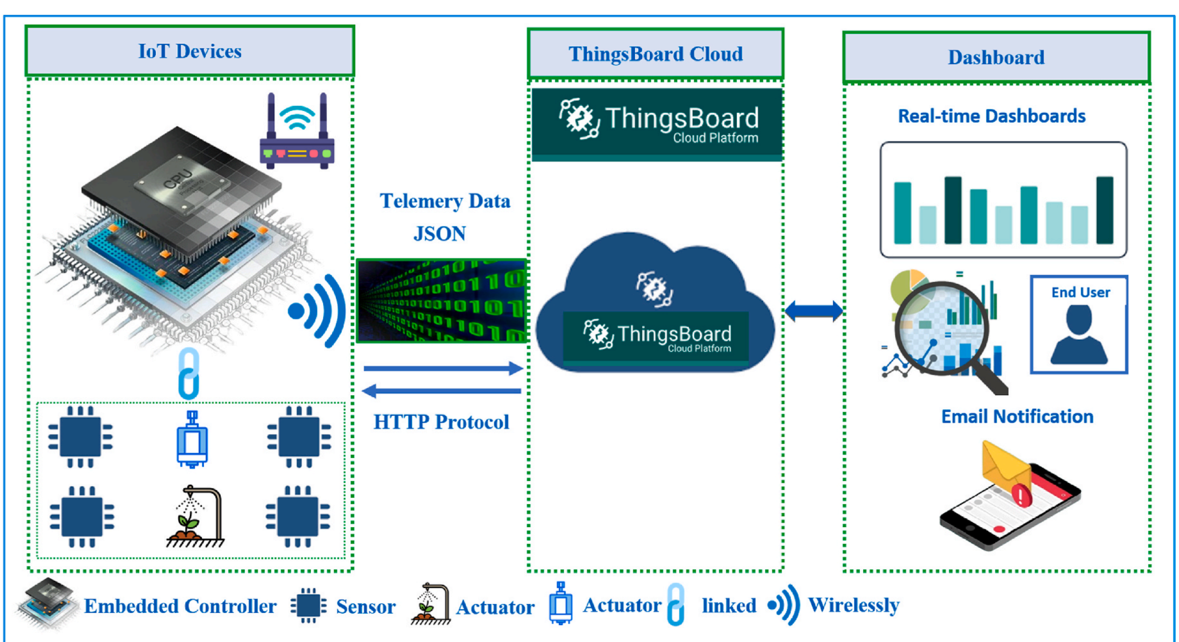

Fig. 2. Architecture of the proposed scheme.

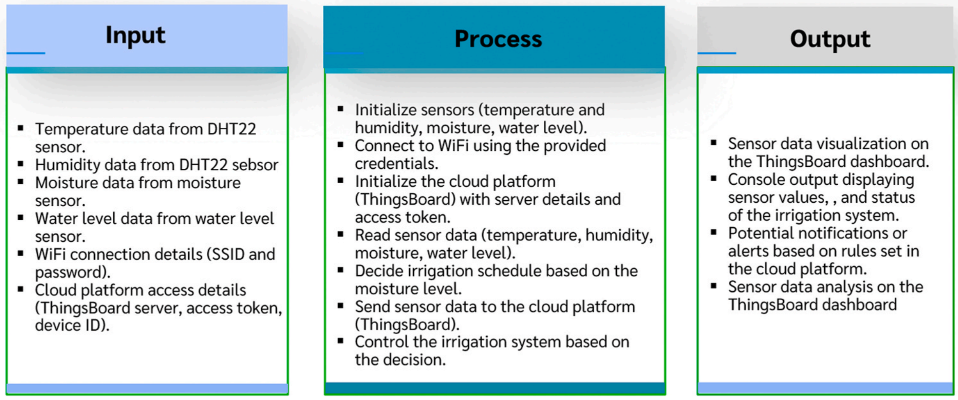

Fig. 3. Input and output of this algorithm.

system proposed to enhance water security, which is set up to collect and process agricultural data effectively and efficiently. The architectural design of the smart irrigation system proposed in this article is structured at three basic levels: 1) IoT devices, 2) ThingsBoard Cloud, and 3) dashboard. This well-designed framework ensures a coherent, synergistic approach that collectively advances the fundamental goals of the proposed system. These objectives include facilitating a smooth flow of data, implementing robust communication protocols, enhancing the interaction experience for the farm owner in particular and the user in general, and introducing advanced real-time data collection and analysis capabilities. These layers are as follows.

2.1.1. IoT devices Layer

This layer serves as the fundamental layer. At the heart of the system is the IoT hard-ware layer, meticulously designed using the latest hardware components. The sensors that support remote measurements are the DHT22, which focuses on precise environ-mental measurements such as air temperature and humidity, the specialized humidity sensor dedicated to measuring soil moisture, and the water level sensor for measuring water levels. form the flexible backbone of the sensory structure. The pumps, including a water pump to irrigate the soil and a water pump to fill the water tank, are perfectly integrated into this framework and are designed to facilitate precise irrigation control. The coordination of these components, sensors, and pumps, is entrusted via actuators to the on-board controller, which is an advanced ESP32 microcontroller. This compact, powerful controller brilliantly manages sensor data capture, actuation control, and secure communications. The wireless gateway, which acts as a wireless communication channel, ensures secure and efficient data transmission. This layer is reinforced by advanced communication protocols, with careful implementation of HTTP to ensure robust, encrypted data exchange. The integration of these components is carefully coordinated, ensuring that data is captured and transmitted smoothly and securely. The creation of a URL to transmit telemetry data to the ThingsBoard Cloud is essential to the data transfer procedure. The following template is used by the system to dynamically generate a URL:

The URL "String url = "https://" + String(thingsboardServer) + "/api/v1/" + String(accessToken) + "/telemetry"; " represents the secure endpoint in ThingsBoard Cloud that will receive the telemetry data. In addition, the system precisely creates the payload in JSON format, which contains the relevant sensor data to be sent. Payload generation is a crucial step in the communication process, ensuring that the data is correctly structured so that ThingsBoard Cloud can process it quickly.

2.1.2. ThingsBoard cloud Layer

This layer serves as the central layer. As an important middleware layer between the IoT devices layer and dashboard layer, ThingsBoard Cloud plays a central role in end-to-end data management, processing, and rule execution. The ThingsBoard server, the cornerstone of this layer, serves as the main repository for essential functions such as device registration, telemetry storage, and rule execution. Device registration management governs the authentication and assignment of unique identifiers to individual IoT devices. To ensure accurate and secure processing of incoming data, the telemetry processing engine is strategically located at this level. At the same time, the rules engine coordinates predefined rules, enhancing automation resulting from conditions such as low soil moisture. Communication within this layer is enhanced by secure HTTPS connections, ensuring not only reliable but also secure communication between the device and the cloud. Superior use of the HTTP protocol optimizes data transmission efficiency, raising the level of telemetry data processing within the cloud computing layer. In addition, e-mail notifications are seamlessly integrated into this dynamic ecosystem, facilitating early warning and contact with stakeholders. This enhancement ensures that relevant staff members are immediately informed of important circumstances or events, improving system responsiveness and encouraging proactive decision-making.

2.1.3. Dashboard Layer

The final layer called the dashboard in ThingsBoard Cloud makes optimal use of the platform's native dashboard functionality for advanced data visualization, analysis, and control in real-time. It provides a responsive interface with high-end dynamic charts and graphs for accurate real-time information, using the ThingsBoard cloud's inherent capabilities. An integrated alert system monitors critical situations and triggers notifications, including e-mail alerts. The user interaction module enables farmers and users to define watering schedules. Secure APIs ensure seamless communication with the ThingsBoard cloud, enhancing the overall user experience with real-time updates of the data.

2.2. Algorithm of the proposed system

The proposed Smart Irrigation System algorithm coordinates smart agricultural irrigation management through seamless integration of advanced sensing technologies, cloud-based data processing, and reactive operation. This algorithm works in a loop, monitoring environmental conditions in real-time and making data-driven decisions to optimize water use. This contributes directly to increasing productivity and saving water. The pseudo-code is presented here to program, develop, and plot the algorithm's structure. Fig. 3 provides the input, process output of this study. Table 1 represents the pseudo-code of the proposed system. This pseudo-code starts by including the libraries required to 1) the WiFi library, 2) the DHT library, and 3) the ThingsBoard library in lines 1 to 3. Initialization and configuration or setup are

Table 1
Algorithm: Smart irrigation system telemetry data.

```
//Input, Process, and Output are described in Fig. 3

//Include Libraries
1:  Include WiFi library.
2:  Include DHT library.
3:  Include ThingsBoard library
//Initialize system
4:  Initialize ESP32.
5:  Initialize sensors (DHT, moisture, ultrasonic).
6:  Set up WiFi connection.
7:  Set ThingsBoard Cloud configuration.
//Main Loop
8:  Main Loop:
//Read sensor data:
9:      Read temperature and humidity from DHT sensor.
10:     Read moisture level from the moisture sensor.
11:     Read water level from ultrasonic sensor.
//Calibration of the sensors and print all data on console:
12:     Calibration of the moisture via function map()
13:     Calibtation of the water level via function map()
14:     Print collected data on the monitor
//Create JSON payload:
15:     Calculate percentage of moisture and water level.
16:     Construct JSON payload with sensor data.
//Send telemetry data to ThingsBoard cloud:
17:     Attempt to connect ESP32 to ThingsBoard cloud.
18:     If connected:
19:        Create secure WiFi client.
20:        Construct ThingsBoard cloud URL.
21:        Send HTTP POST request with JSON payload.
22:        Read and print the response.
23:        Close the connection.
24:     Else:
25:        Print a connection error message.
//Activate Pump (if moisture is below threshold and water level is below tank level):
26:        If the moisture level is below the threshold of 30 %:
27:        Activate the watering pump.
28:     Else:
29:        Deactivate the watering pump.
30:        If the water level is below the threshold of 10 %:
31:        Activate the tank pump.
32:     Else:
33:        Deactivate the tank pump.
34:        Print a message indicating pump activation.
35:     Send email notification
//Delay and Error Handling:
36:     Delay (5 s).
37:     If any sensor reading fails:
38:        Print an error message.
39:     If the connection to ThingsBoard cloud fails:
40:        Print a connection error.
41:  End
```

presented in lines 4 to 7. These are essential components of the proposed system. Creating a solid WiFi connection to enable wireless connectivity setting up a WiFi connection and configuring Set ThingsBoard cloud. In addition, initialize the ESP23 and all sensors. This initialization phase ensures a solid foundation for system operation.

Lines 8–41 represent the main algorithm execution (main loop). Firstly, lines 9–19 in this main loop provide the data sensing and telemetry. The fundamental element of the algorithm is the continuous collection of sensor data. It uses specialized sensors to monitor soil moisture, ultrasonic sensors to assess water levels, and the DHT sensor to read temperature and humidity. The data is then meticulously processed and formatted into a JSON payload for quick and easy transfer to the ThingsBoard cloud. Important details such as temperature, humidity, water content, and water level are included in the telemetry data. Secondly, in the Main loop lines 17–25 represent cloud communication. An essential layer for data storage and rule execution, the ThingsBoard cloud, is connected to the algorithm in an attempt to create a secure link. After a successful connection, it creates the appropriate ThingsBoard cloud URL, establishes a secure WiFi client, and sends an HTTP POST request containing the ready-to-use JSON payload. For monitoring purposes, the cloud response is read and printed. The technique provides a descriptive error report and gracefully resolves the problem if the connection fails. Thirdly, in this main loop line, 26–35 represent pump activation and email notification. The program incorporates a sophisticated pump activation mechanism to ensure efficient use of available water resources. The algorithm determines whether to switch on the irrigation pump and the reservoir pump, taking into account certain water and humidity criteria. This decision-making process improves water security and prevents over-irrigation. An alert signifying the start of irrigation is sent when the pump is activated. In addition, the algorithm includes a function for sending e-mail notifications when critical conditions are detected, so that farm owners and users are quickly informed. Fourthly, in this main loop, lines 36 to 41 represent delay and error handling. The technique introduces a delay before repeating the loop to control system synchronization and avoid data overload. In addition, in-depth error management procedures are implemented to deal with potential problems, ensuring the resilience and reliability of the algorithm. By reporting connectivity problems, these error management systems also offer a proactive approach to system maintenance.

The proposed algorithm is an innovative system of sustainable, data-driven agriculture due to its complex coordination of sensing, cloud communication, actuation, and communication. This algorithm advances precision agriculture by optimizing resource use, water security, environmental sustainability, and rapid decision-making through the use of IoT devices, cloud computing, and proactive alerts. In this context, this article [46] proposed an intelligent, cost-effective irrigation system, integrating real-time monitoring, remote control, and cloud computing of data. The system operated according to predefined parameters, triggering actions such as pump activation. A mobile app and website offer a user-friendly experience, with agricultural information for Bangladesh and a guide to threshold values for different crops.

3. Results and discussion

The implementation of the Smart Irrigation Management System scheme has delivered outstanding results, making it a comprehensive solution at the cutting edge of modern farming practices. The target site for implementation of the proposed IoT-based smart irrigation management system is Fez, Morocco, in North Africa. Although this system is specifically designed for conditions in this region, requirements may vary according to geographical, climatic, and agricultural factors. However, the fundamental principles of real-time monitoring, remote control, and efficient water management can be adapted to other regions, provided the system is customized to meet the specific environmental and agricultural needs of each area based on the algorithm developed. This section examines the results, focusing on the scheme's contributions to water security, food security, smart farming, and its skillful use of advanced technologies. In the results section, the effectiveness of the smart irrigation management system is demonstrated using a simulation scenario that replicates actual farm conditions. The system successfully identifies potential irrigation and collects and sends relevant data in real-time to the ThingsBoard cloud for comprehensive display and analysis. An in-depth implementation of the overall performance of the smart irrigation system is provided in the results section. To provide an overall assessment of the system's effectiveness, the test area was covered by a carefully positioned array of three different sensor types: water level sensors, soil moisture sensors, and temperature and humidity sensors. This systematic evaluation aimed to clarify the system's ability to capture important environmental variables and their implications for irrigation decision-making. A fluid exchange of information between the central server and strategically placed sensors was made possible by the crucial cooperation between algorithmic intelligence and the architectural framework. This complex interaction facilitated methodical data management, enabling relevant information to be shared with the ThingsBoard Cloud computing platform, for example. In this paper, the integration of secure and optimized communication protocols within the ThingsBoard Cloud layer significantly contributes to the development of reliable and precise climate models. This ensures that the study's findings are applicable on a global scale, extending the relevance and impact of our research across different geographic and environmental contexts. In this context, this article [47] explores the use of satellite observations to monitor climate change and the associated uncertainties. It examines the challenges of optimizing precipitation models with binary metrics and proposes a new formulation. evaluation of integrated assessment models reveals inconsistencies in global warming predictions compared with observations, with an increased upward bias in recent climate models for the tropical troposphere.

Fig. 4 shows the sensor mapping process. In this article, sensor calibration is essential for accurate data interpretation. Using the "Map" function with Equation (1), this process translates the sensor readings (Xi) into a defined range on a standardized scale from 0 to 100. This calibration ensures an accurate match between the sensor data and the desired results, enabling informed decisions designed to optimize

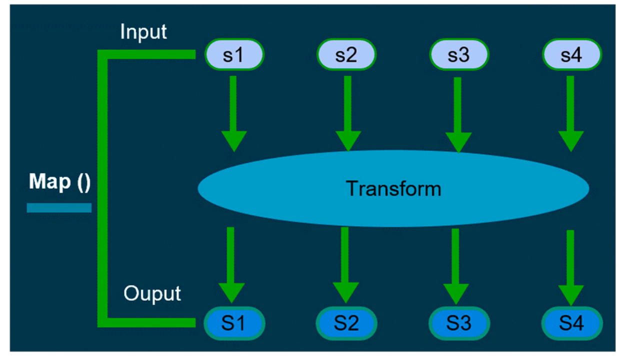

Fig. 4. Map function process.

irrigation. Regular recalibration is recommended to account for environmental influences or sensor drift and to maintain the reliability of calibrated data for efficient water management.

$$\boldsymbol{Y} = \boldsymbol{map}(\mathrm{X_i}, \boldsymbol{Min}\ \mathrm{X_i}, \boldsymbol{Max}\ \mathrm{X_i}, \mathbf{0}, \mathbf{100}) \tag{1}$$

where.

Y: Value of the sensor calibrated.

Xi: This is the sensor value that we want to map.

MinXi: The minimum value of the sensor range.

MaxXi: The maximum value of the sensor range.

0: The minimum value of the desired mapped range.

100: The maximum value of the desired mapped range.

By using the mapping function to normalize the moisture non calibrated from the interval [0, 4095] to the normalized interval [0, 100], this study calculate the percentage moisture calibrated (%) in equation (2). Similarly, equation (3) calculates the water level (Water level calibrated) by normalizing the Water level non calibrated (in cm) from the interval [0, 30] to the normalized interval [0, 100] using the mapping function. These formulas provide a complete and expert description of the moisture and water level calibration procedure.

$$\boldsymbol{Ym} = \boldsymbol{map}(\mathrm{Xm_i}, \mathbf{0}, \mathbf{4095}, \mathbf{0}, \mathbf{100}) \tag{2}$$

$$\boldsymbol{Yw} = \boldsymbol{map}(\mathrm{Xw_i}, \mathbf{0}, \mathbf{30}, \mathbf{0}, \mathbf{100}) \tag{3}$$

where.

Ym: Value of the moisture calibrated in percent.

Yw: Value of the water level calibrated in percent.

Xm_i: Value of the moisture non calibrated.

Xw_i: Value of the water level non-calibrated.

Equations (2) and (3) are an essential calibration procedure for intelligent irrigation systems. Raw sensor data are translated and normalized into understandable and consistent values for percent moisture and water level, respectively, using these formulas. In general, the accuracy and efficiency of smart irrigation systems depend largely on the calibration procedure described by (2) and (3). It ensures that the information gathered by sensors measuring humidity and water level is converted into consistent, useful results, making irrigation techniques smarter and more resource-efficient.

This study is dedicated to the advancement of smart irrigation, showcasing a sophisticated system that seamlessly integrates temperature, humidity, and water level sensors. At the heart of this innovative solution is the powerful ThingsBoard cloud, which orchestrates data management and analysis to improve agricultural practices. The proposed study aggregates crucial environmental data from sensors, including real-time readings of temperature, humidity, soil moisture, and water levels. These vital parameters are efficiently transmitted in real-time to the ThingsBoard cloud, creating a comprehensive repository of actionable information for smart irrigation. Fig. 5 summarizes the system's dynamic response, illustrating its ability to adapt and optimize

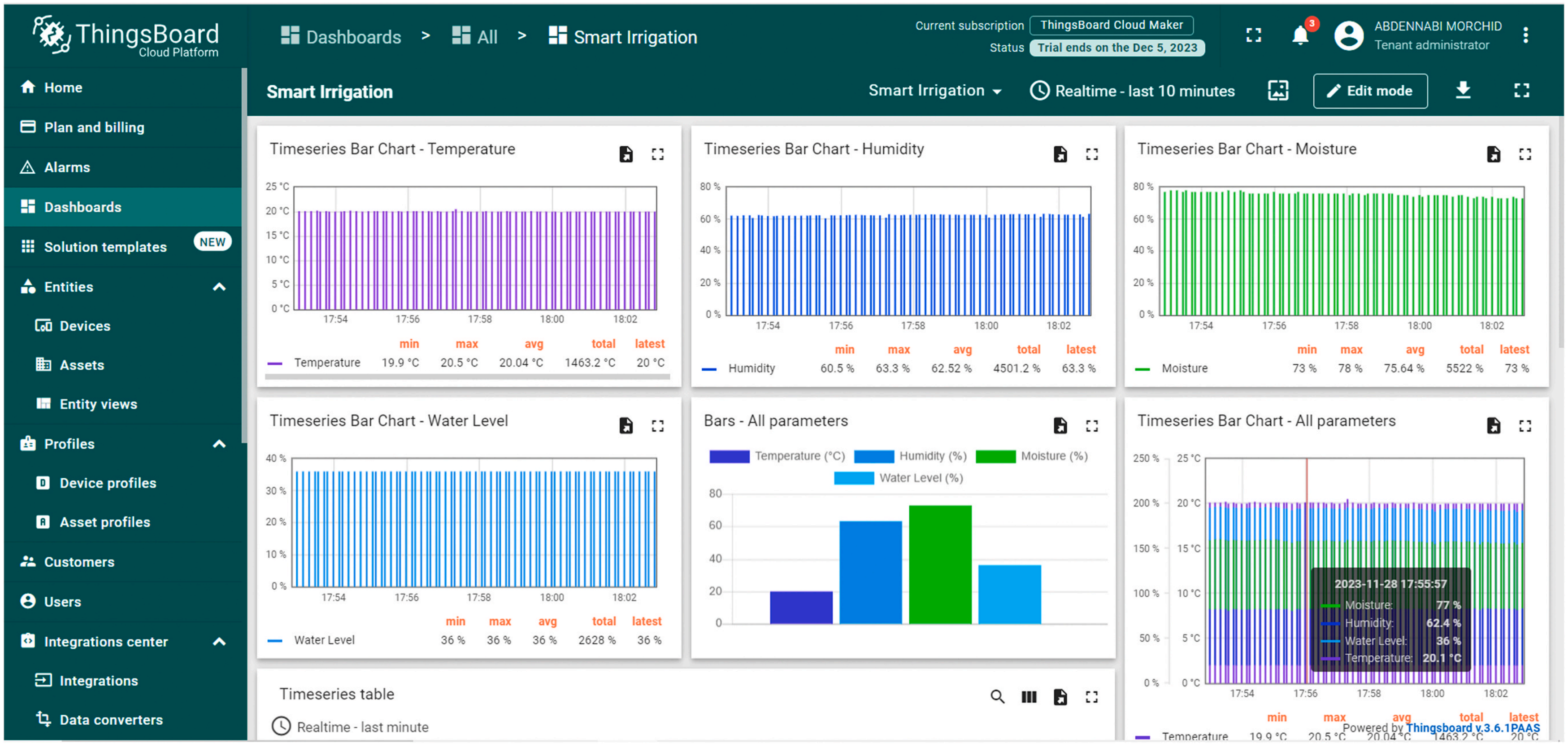

Fig. 5. Dashboard results of the proposed scheme.

irrigation strategies according to the data acquired by the sensors. As shown in Fig. 5, all ThingsBoard output parameters are represented for real-time data visualization and analysis. A key feature of ThingsBoard is its ability to create interactive dashboards for effective monitoring and management. These dashboards are invaluable tools for users, enabling them to visualize and interpret sensor data with unprecedented ease. The flexibility of the system is illustrated by the diversity of widgets integrated into the dashboards, offering users high technology.

In Fig. 6, the actual values of the temperature sensor on the ThingsBoard cloud are meticulously detailed, presenting complete statistical measurements. The temperature data from the DHT22 sensor includes a minimum value of 20 °C, a maximum value of 20.1 °C, an average of 20.1 °C and a cumulative total value sent to the cloud of 602.9 °C. The last recorded value was 20.1 °C. Moving to Fig. 7, the visualization of the DHT22 sensor's humidity readings on the ThingsBoard cloud provides real-time information. The humidity sensor readings show a minimum value of 58.5 %, a maximum of 62 %, an average of 60.73 %, a cumulative total value sent to the cloud of 4311.5 %, and the last humidity sensor reading at 61.8 %. These detailed visualizations provide precise information on the dynamic behavior of the temperature and humidity sensors in the proposed system.

In Fig. 8, the presentation of moisture sensor readings on the ThingsBoard cloud provides dynamic, real-time information. The moisture sensor readings reveal a minimum value of 78 %, a maximum of 79 %, an average of 78.03 %, and a cumulative total value sent to the cloud of 2.341 %, with the last moisture sensor reading recorded at 78 %. This visualization provides a nuanced and accurate representation of the moisture levels detected by the sensor in the proposed system.

In addition, Fig. 9 shows the ultrasonic sensor's water level readings on the ThingsBoard cloud to provide dynamic, real-time information. The water level sensor readings have a minimum of 36 %, a maximum of 36 %, an average of 36 %, and a cumu-lative total value sent to the cloud of 1080 %, with the most recent water level sensor reading recorded at 36 %. These comprehensive visualizations provide precise details of the dynamic behavior of the water level sensors in the proposed system. Before sending the sensor values to cloud computing, the moisture sensor and water level values are calibrated by the mapping function represented in equations (1)–(3).

Fig. 10 serves as a unified representation, capturing a global perspective of all pa-rameters on a unified time-series bar graph. This comprehensive visualization inte-grates temperature and humidity readings from the DHT, as well as humidity and water levels from the ultrasonic sensor. Hosted on the ThingsBoard cloud, the dynamic time-series bar graph provides real-time information, marked by different colors for each parameter. This comprehensive visualization provides not only the minimum, maximum, and average values of the sensor readings but also a cumulative total sent to the cloud. Fig. 10 shows two separate values for the Celsius coordinate: one in Celsius for temperature and one in Celsius for humidity, water content, and water level. This detailed representation provides a better understanding of the dynamic behavior of the entire sensor network within the proposed system. On the other hand, Fig. 11 shows all the parameters, including the water level from the ultrasonic sensor, the temperature and humidity read by the DHT, and the humidity level read by the hygrometer. All the parameters of the proposed system can be read with different colors on the ThingsBoard cloud, providing dynamic information in real-time. In Fig. 12, on the other hand, farmers can visualize water level data from the ultrasonic sensor in a fluid, user-friendly way, thanks to the intelligent visualization of data inside a reservoir. Thanks to this strategic representation, farmers can better understand system dynamics and give visual meaning to water level readings. Farmers can quickly and easily understand water level data through reservoir visualization, enabling them to make informed decisions about cultivation methods.

Fig. 13 shows a visual representation of the real-time sensor data widgets displayed on the ThingsBoard cloud. The distribution of widgets is as follows 1) Fig. 13(a): Widgets for temperature. 2) Fig. 13(b): widgets for humidity. 3) Fig. 13(c): Widgets for moisture control widgets. Fourth, Fig. 13(d): Widgets for water level. This comprehensive illustration makes it quick and easy to visualize the system's current values and guarantees a thorough understanding of the dynamics of each parameter in real-time.

Table 2 reinforces the real-time data perspective by summarizing a series of sensor readings crucial to this study. The structure of Table 2 is as follows. Its tabular representation systematically organizes time stamps with corresponding values for temperature, humidity, and water level. The inclusion of these complete data sets in Table 2 enables detailed analysis of real-time system performance over specific time intervals.

Fig. 6. The value of the temperature sensor on the ThingsBoard cloud.

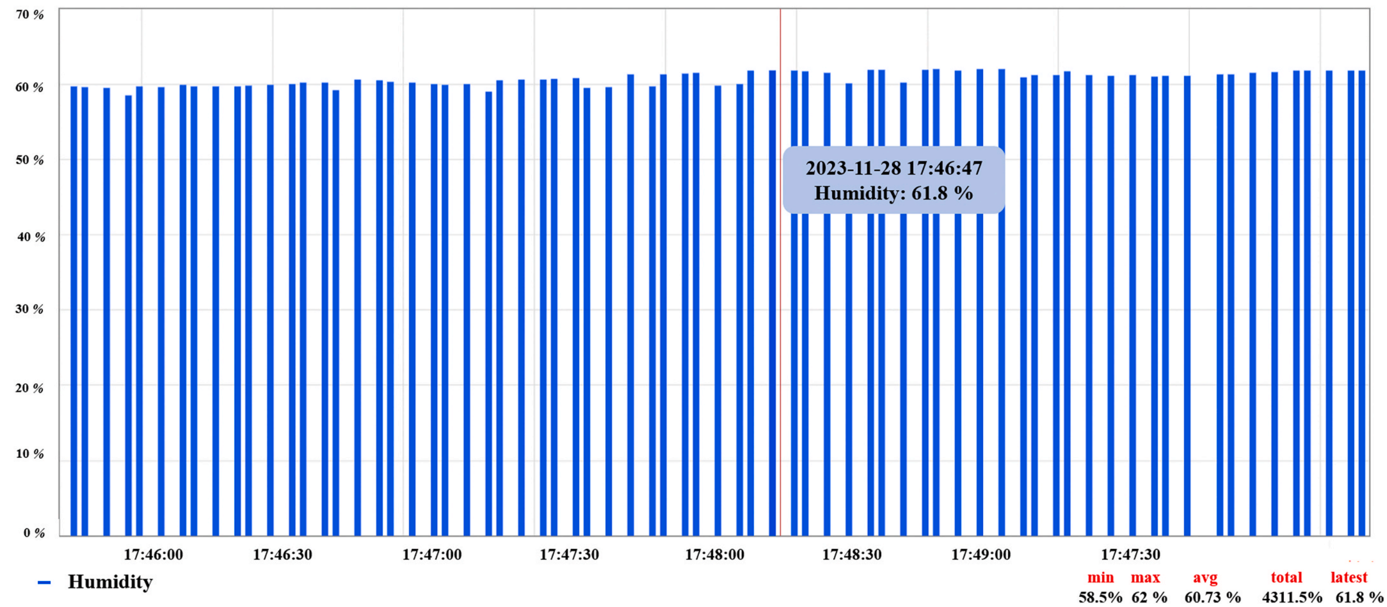

Fig. 7. The value of the humidity sensor on the ThingsBoard cloud.

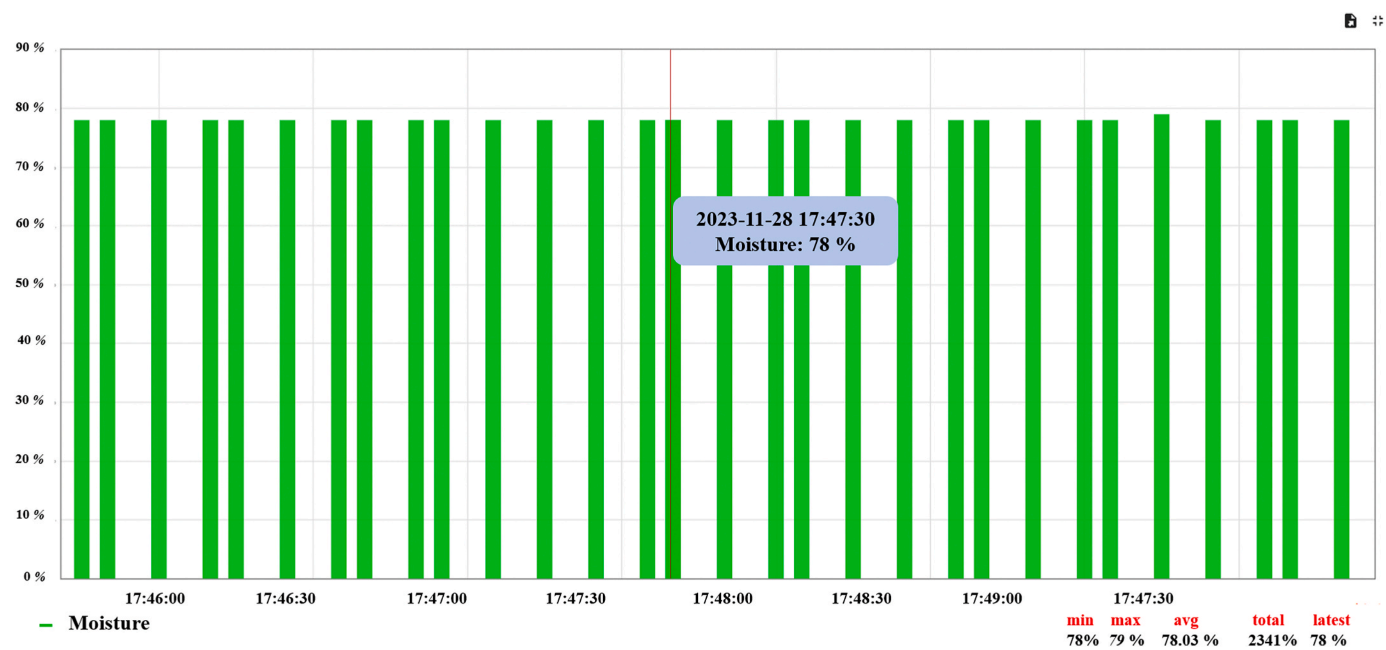

Fig. 8. The value of the moisture sensor on the ThingsBoard cloud.

ThingsBoard, in this article, facilitates the export of widget data and offers seamless interoperability with CSV and XLS formats. This adaptable functionality guarantees compatibility across multiple platforms and targets a wide variety of devices. The parameters described in the dataset configuration are reflected in the column layout of the exported dataset. As shown in Fig. 14, which displays the dashboard widget data export, the generated XLS file includes all relevant system configurations. Thanks to this feature, users can now evaluate, understand, and work more effectively with exported data according to their needs.

In the scenario illustrated in Fig. 15, the system sends e-mail notifications to users. The content of the e-mail includes a detailed overview of telemetry data from the smart irrigation system. Although no anomalies have been reported, users are encouraged to monitor the system. Fig. 16 also shows the status of the notifications. The "Notify again" button is used to resend existing notifications. E-mail notifications require the client administrator to configure the outgoing mail server. Fig. 17 shows an overview of e-mail notifications, including composing, e-mailing, and reviewing. On the other hand, Fig. 18 shows the Recipients tab, which displays a list of notification recipient groups, which can be created or deleted as required. This structured approach ensures efficient communication and management of smart irrigation system notifications to increase water security.

The authors of this study recommendation for this method in practice. The author recommends adapting the IoT-based smart irrigation management system to the specific environmental and agricultural conditions of the location. Although this system is initially designed for the region of Fez, Morocco, its fundamental principles can be effectively applied in other regions, provided that the system is customized according to local needs. For successful implementation, the author suggests focusing on adjusting the system to local particularities, taking into

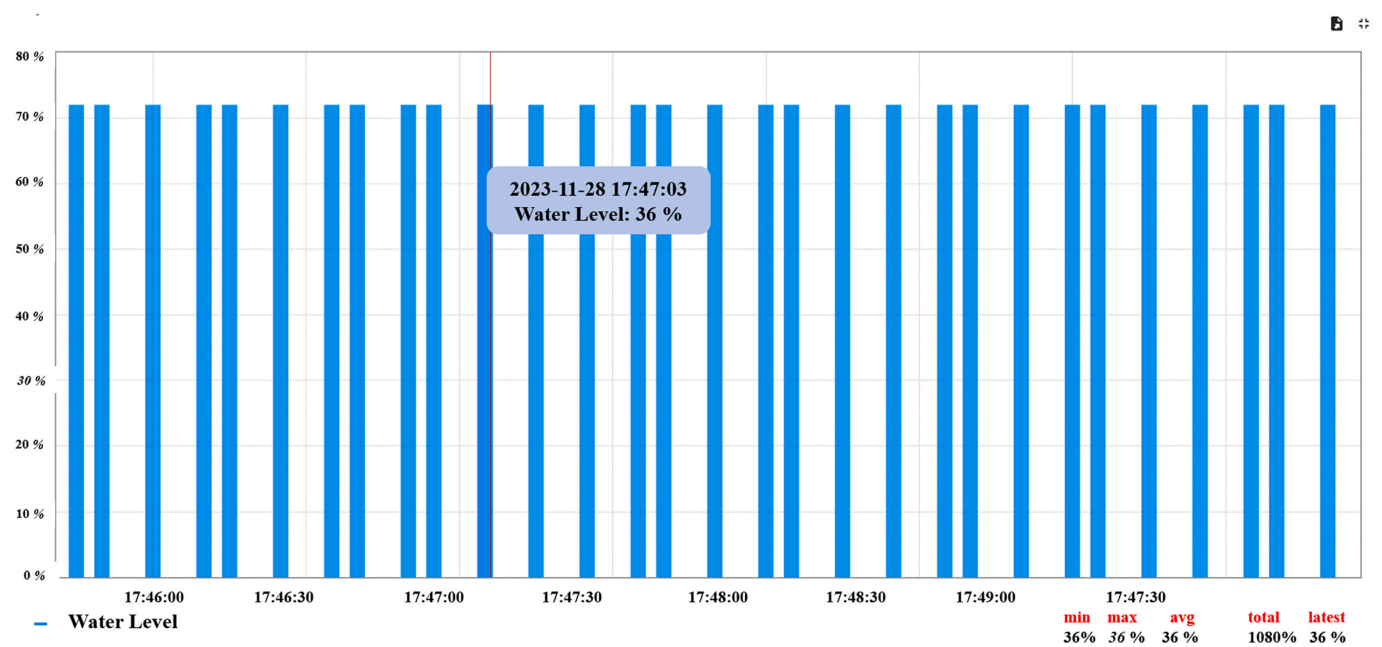

Fig. 9. The value of the water level value sensor on the ThingsBoard cloud.

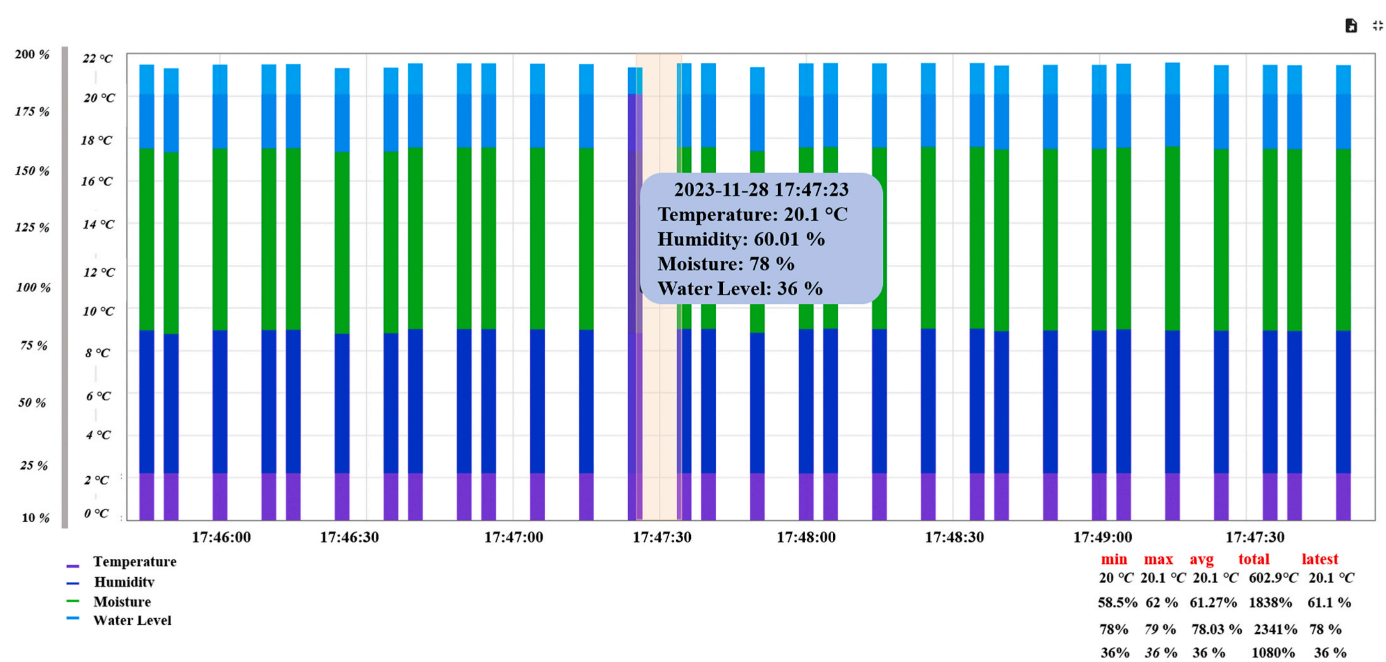

Fig. 10. Time series bar chart of all parameters.

account factors such as climate, soil type, and crop requirements, in order to optimize irrigation management and ensure sustainable agricultural practices. The target site for the implementation of the proposed IoT-based smart irrigation management system is Fez, Morocco, North Africa. Although this system is specifically designed for conditions in this region, requirements may vary according to geographical, climatic, and agricultural factors. However, the fundamental principles of real-time monitoring, remote control, and efficient water management can be adapted to other regions, provided the system is customized to meet the specific environmental and agricultural needs of each area based on the algorithm developed.

The review provided by the authors of this study [22] highlighted the potential, obstacles, and status of smart water technology as it exists today. It highlights the benefits of smart water technologies for the overall management of water resources while drawing attention to certain drawbacks, including high implementation costs, data security concerns, and the need for system stability, particularly in poorer countries. Further, the author's paper [24] presents an IoT-based smart irrigation system for grain corn production, focusing on the evaluation of smart irrigation management. The Institute of Seed and Plant Improvement in Karaj, Iran, served as the research site. Nevertheless, it is important to stress that the research did not make use of cloud computing (such as the ThingsBoard cloud), data analysis methods, email notification systems, communication protocols, or IoT. In addition, the study did not use multiple sensors to detect all the features of the smart irrigation system, nor did it include any technique for

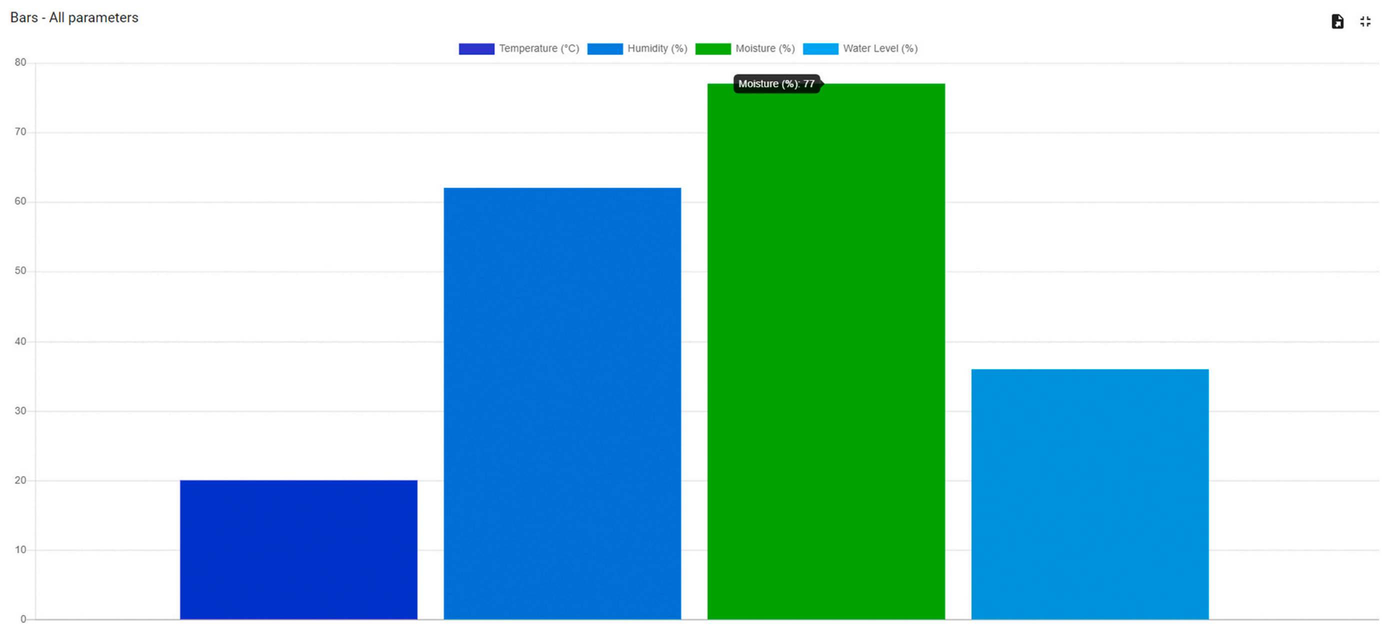

Fig. 11. All parameters.

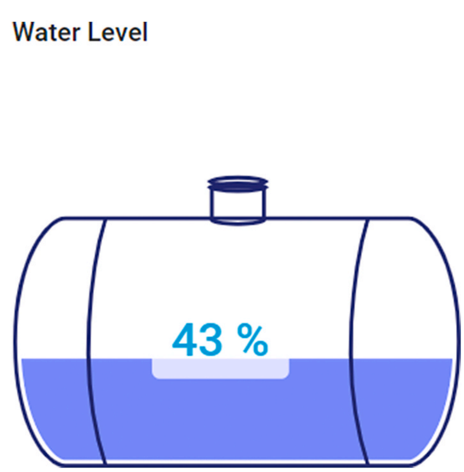

Fig. 12. The water level widget.

calibrating the sensors. On the other hand, the authors' study [25] presents an open-source, low-cost IoT solution for smart irrigation. The system has a strong focus on price and is designed for seamless interaction with multiple platforms and a wide range of sensors. It's important to remember, however, that the study did not include data analysis, communication protocols, email notification capabilities, or cloud computing, such as the ThingsBoard cloud. In addition, the study does not use numerous sensors for in-depth detection of all parameters within the smart irrigation system, nor does it provide a specified technique for sensor calibration. In this study, the authors [27] provide an IoT infrastructure for precision agriculture and measurement, with a particular focus on crop forecasting using machine learning techniques. Crucially, the study does not include data analytics, communication protocols, email notification functions, the IoT, or cloud computing such as the ThingsBoard cloud. In addition, the study does not use numerous sensors to detect all smart irrigation system parameters, nor does it provide a defined procedure for sensor calibration.

Furthermore, the authors' study [30] presents an inexpensive information monitoring system intended for use in smart agricultural applications. Furthermore, different research [31] that focuses on IoT-based sustainable agriculture offers a thorough review of smart farming. In addition, the authors' work [32] suggests independent application controls for intelligent irrigation. It is important to note that these studies do not contain capabilities like data analysis, email notification functionalities, or communication protocols. They also do not include IoT, or cloud computing, such as the ThingsBoard cloud. Furthermore, the smart irrigation system does not use numerous sensors to detect all data, nor is there a clear procedure for sensor calibration offered. Using the Node-RED platform, the authors' study [33] presents an intelligent irrigation system built on the Internet of Things (IoT) and machine learning. But it's essential to remember that, unlike the ThingsBoard platform, the Node-RED platform has certain limits. In addition, this study does not include elements such as e-mail notification functionality, communication methods, or data analysis. In addition, the study does not use numerous sensors to detect all parameters within the smart irrigation system, and no explicit sensor calibration techniques are proposed. Using the ThingSpeak platform, the authors' research [34] provides an evaluation of an IoT-based intelligent drip irrigation and evapotranspiration (ETc) system for sweet corn. Compared with the ThingsBoard platform, the ThingSpeak platform has its limitations. In addition, this study does not include elements such as e-mail notification functionality, communication protocols, or data analysis. In addition, the study does not use numerous sensors to detect all parameters within the smart irrigation system, and no specific sensor calibration techniques are proposed. The study conducted by authors [35] focuses on the functionality of an Android/web application to control an IoT smart drip irrigation system. Authors of this research [36] suggest a system using a dashboard to provide model-based predictive control for drip irrigation that uses less water. Comparing these studies to the more flexible ThingsBoard cloud, however, they rely less on Android/web applications or dashboards. Additionally, neither study uses several sensors to detect every parameter in the smart irrigation system, nor do they give a way for sensor calibration. Other aspects that both studies lack include data analysis, email notifications, and communication protocols. A farm irrigation management system using a composite controller and a web-based platform for remote monitoring is suggested by the authors' investigations [37,38]. On the other hand, the selected platform is not as flexible as ThingsBoard. Data analysis, email notifications, communication protocols, sensor calibration, and the use of several sensors for thorough smart irrigation system detection are all absent from this research. On the other hand, the authors' paper [40] presents a smart irrigation system in a greenhouse that is based on

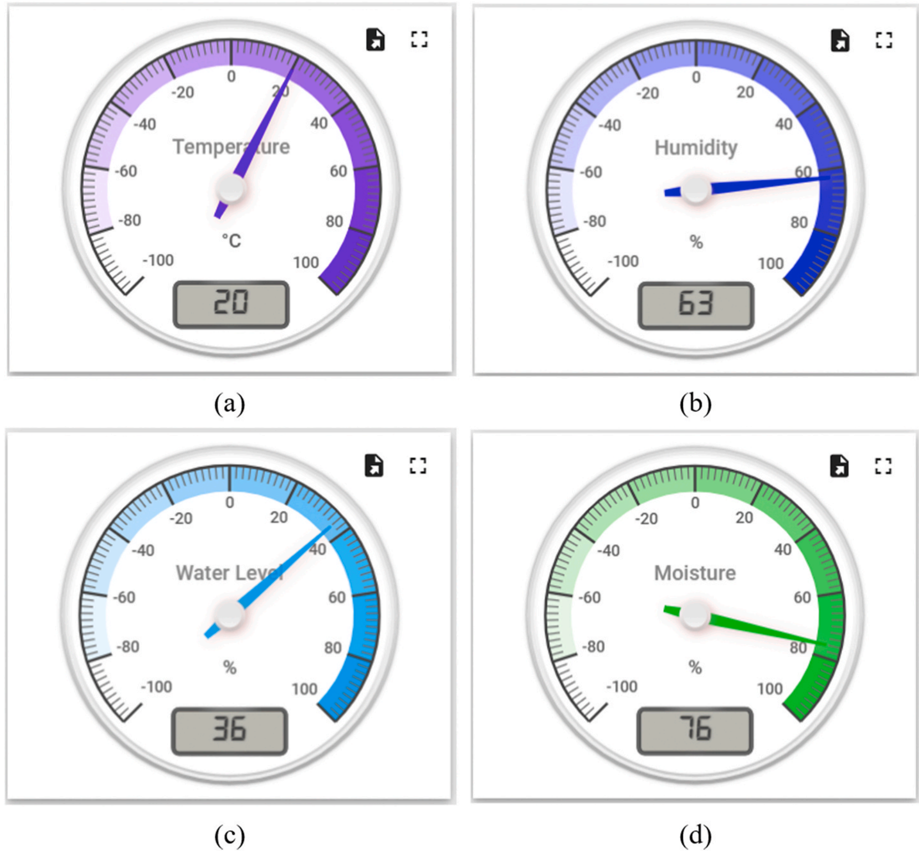

Fig. 13. Real-time sensor data widgets on the ThingsBoard cloud.

Table 2
Time series table in real-time.

Timestap	Temperature	Humidity	Moisture	Water Level
2023-11-28 17:39:27	20.20 °C	59.90 %	79.00 %	36.00 %
2023-11-28 17:39.35	20.10 °C	58.50 %	80.01 %	36.00 %
2023-11-28 17:39:43	20.20 °C	58.70 %	80.01 %	36.00 %
2023-11-28 17:39:51	20.10 °C	60.00 %	79.00 %	36.00 %
2023-11-28 17:39:59	20.10 °C	60.10 %	79.02 %	36.00 %
2023-11-28 17:40:08	20.20 °C	60.20 %	80.00 %	36.00 %
2023-11-28 17:40:19	20.20 °C	60.00 %	80.00 %	36.00 %

real-time soil moisture data. It does not, however, include cloud computing (such as ThingsBoard cloud) or functionalities like email notifications, data analysis, or communication protocols. Furthermore, the study uses several sensors to detect every parameter in the smart irrigation system and does not offer a mechanism for calibrating the sensors.

In contrast, the smart irrigation management system described in this paper is superior in several respects, distinguishing it from existing research by combining advanced features with a comprehensive strategy.

- Integration of new technologies: The core of its superiority lies in the seamless integration of cutting-edge technologies like 1) embedded systems (embedded controllers and sensors), 2) IoT, 3) telemetry data, and 4) cloud computing via the ThingsBoard cloud. 5) communication protocol, and 6) intelligent algorithm. This combination not only increases efficiency and conserves water resources, but also positions the system as a proactive solution.
- Layered architectural precision: IoT devices, the ThingsBoard cloud, and the dashboard make up the three levels of carefully arranged architecture. This layered design raises the bar for the entire user interaction experience, guaranteeing a secure connection in addition to seamless data flow.
- Algorithm management: functioning as the system's central nervous system, the intelligent algorithm plans and coordinates complex tasks, including receiving sensor data, creating JSON payloads, and transmitting secure telemetry data. Thanks to the integration of predefined criteria, over-irrigation is avoided, demonstrating a level of operational intelligence that improves resource efficiency.
- Precise calibration and strategic sensor placement: The system performs exceptionally well in terms of sensor placement, and positioning sensors for water level, temperature, humidity, and wetness throughout a testing area. Interestingly, a strong calibration formula is used, improving accuracy. To ensure accurate readings for efficient smart irrigation management, calibration takes place before data transmission to ThingsBoard Cloud and printing on the console.
- ThingsBoard cloud for real-time visualization and analytics: By utilizing the ThingsBoard Cloud for dynamic charts and real-time visualizations, the solution not only offers quick insights but also makes historical data analytics easier. This function guarantees a comprehensive comprehension of the dynamic behavior of the proposed smart irrigation management system, facilitating efficient irrigation process monitoring and control in real-time.
- Proactive email notification and security: The system features a proactive email notification function that sends out notifications to users promptly, urging them to respond right away. Stakeholders are guaranteed to receive up-to-date information on system

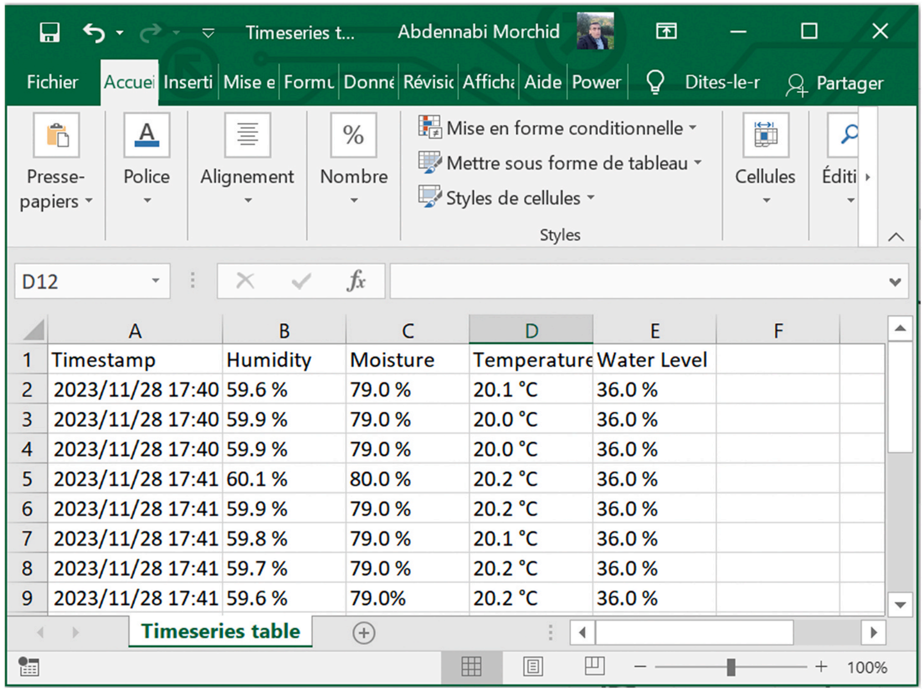

Fig. 14. Data export.

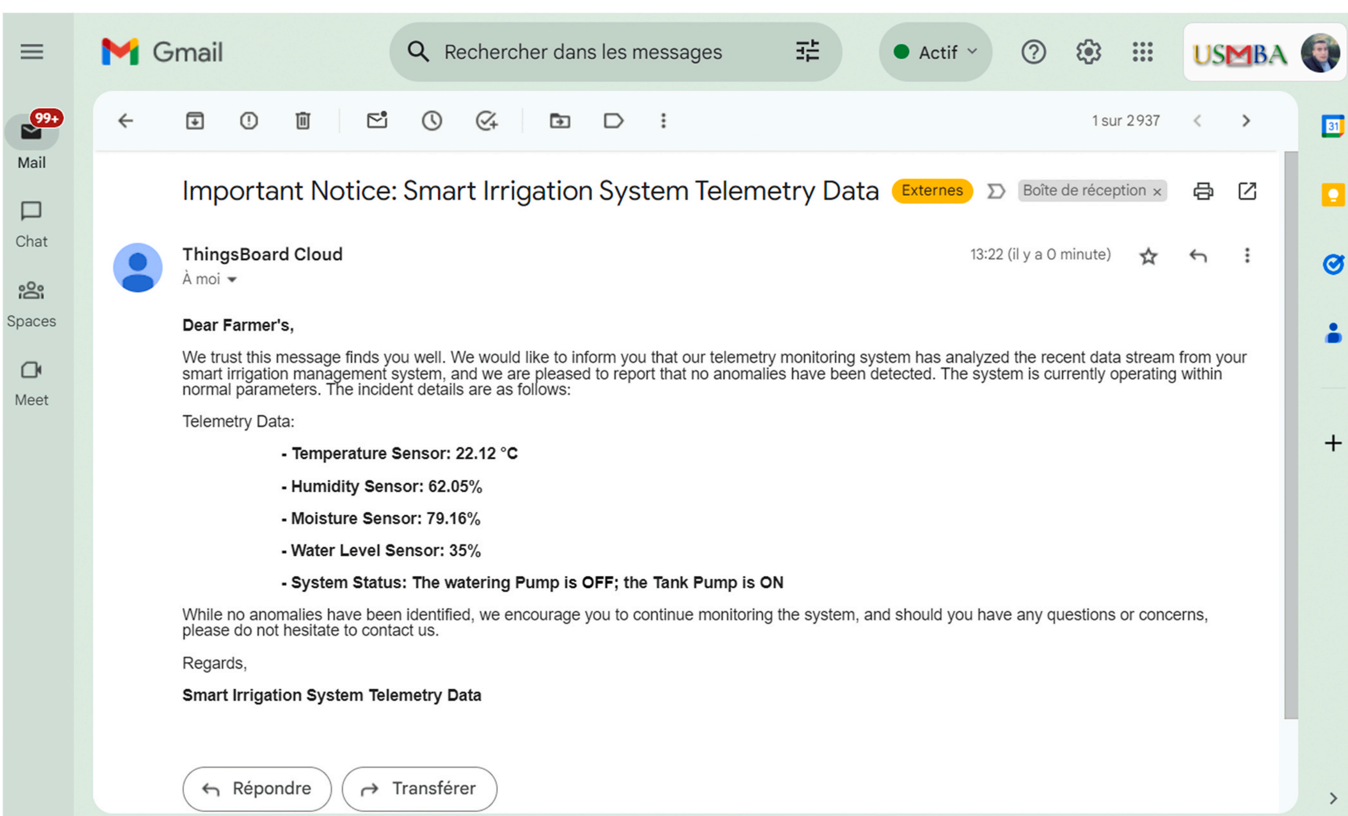

Fig. 15. E-mail notification.

advancements thanks to this user-centric design. Furthermore, the system reinforces device-to-cloud connectivity for improved dependability and vulnerability prevention by prioritizing security through HTTP connections.

Improving sustainable agricultural methods and water security: the proposed smart irrigation system is part of the broader objective of promoting sustainable agriculture and aims to improve water use and increase crop productivity. It is a major player in the field of intelligent agriculture, in line with the global trend towards sustainable

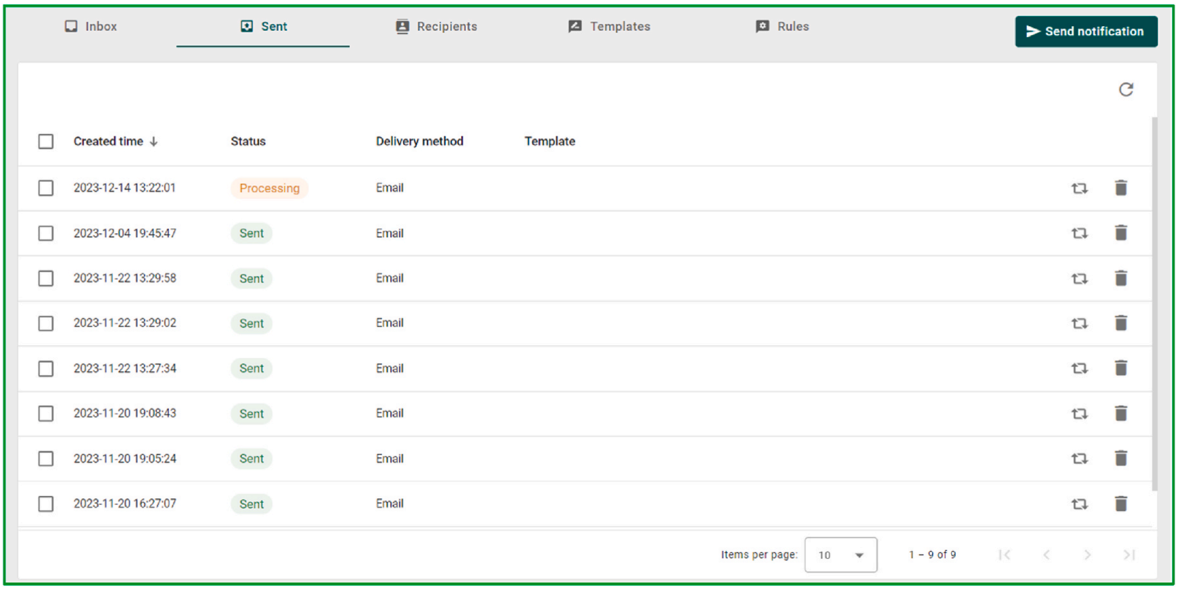

Fig. 16. E-mail notification sent.

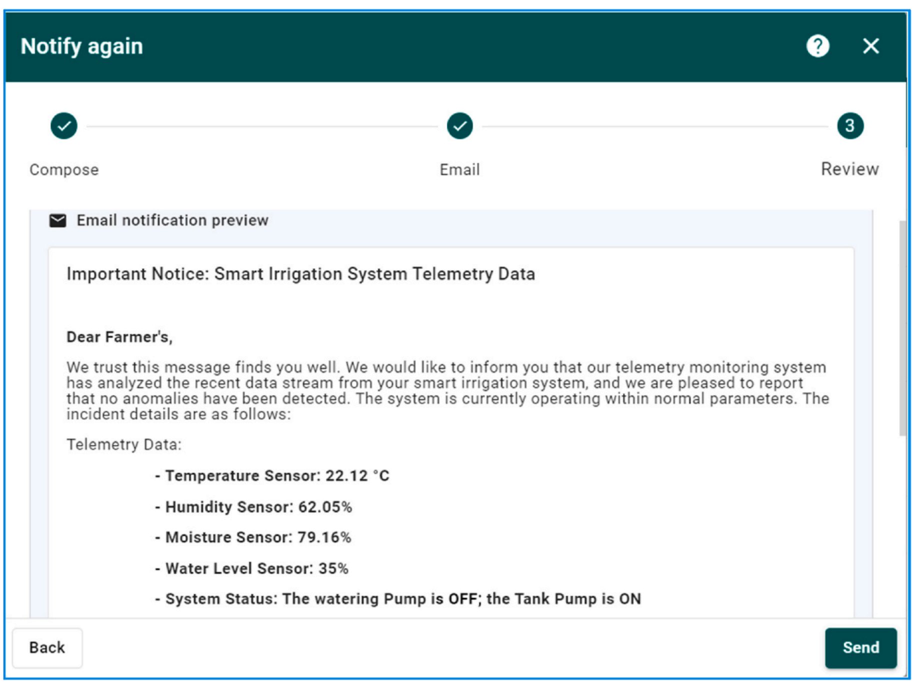

Fig. 17. Overview of e-mail notifications.

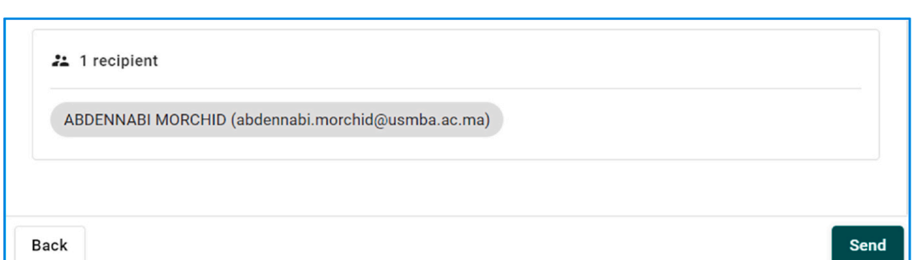

Fig. 18. Recipients of the e-mail notifications.

agricultural practices. In addition, the proposed system helps to ensure food and water security.

4. Conclusion and future work

In conclusion, this paper presents an intelligent irrigation management system that leverages advanced technologies such as 1) embedded systems, 2) the Internet of Things (IoT), 3) telemetry data, 4) cloud computing, as well as 5) sensors for real-time data collection and processing in smart agriculture. The architecture of the proposed system is broken down into three distinct layers: 1) IoT devices, 2) the cloud-based ThingsBoard platform, and 3) a dashboard, ensuring smooth data flow and secure communications. The system's algorithm co-ordinates essential operations, including the reading of sensor data, the creation of JavaScript Object Notation (JSON) payloads, and the secure transmission of telemetry data via HTTP to the ThingsBoard platform. Before data is sent to the cloud, sensor values are calibrated using a functional map. Tests carried out with temperature, humidity, and water level sensors demonstrate the system's dynamic efficiency. By visualizing and analyzing environmental information via ThingsBoard, the results provide real-time data on environmental parameters of the system proposed, improving the efficiency of water use and the sustainability of farming practices. The integration of e-mail notifications reinforces monitoring and management practices by alerting farm owners and users. Overall, this study validates the effectiveness of the proposed system, contributing to global food and water security, promoting sustainability, and supporting smart agriculture practices.

The focus of future development is to integrate intelligent systems, such as smart irrigation and fire detection, into an integrated framework. The use of the publish-and-subscribe model via Message Queuing Telemetry Transport (MQTT) brokers and unified communication protocols is promising. Hosting multiple clients and a master node, the envisaged system aspires to provide a coherent solution to various agricultural challenges. The focus is on creating a scalable framework using advanced technology and algorithms, to improve overall agriculture management solutions. This approach aims to improve resource allocation, enhance real-time monitoring, and promote smart agriculture practices for sustainable and adaptable agriculture in the future.

CRediT authorship contribution statement

Abdennabi Morchid: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rachid Jebabra:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Haris M. Khalid:** Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation. **Rachid El Alami:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Formal analysis, Data curation. **Hassan Qjidaa:** Writing – review & editing, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation. **Mohammed Ouazzani Jamil:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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