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AgriLink: an innovative real-time data monitoring and connectivity platform for an orange orchard in Morocco

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Sustainable and digital agriculture, grounded in robust scientific research, is crucial to addressing the challenges related to the water-food-energy Nexus (WFE). Ensuring global food security, particularly for small-scale farms, presents a major challenge for the scientific community in the coming decades. Despite occupying only 12% of agricultural land, small-scale farms are responsible for around 35% of the world's food production. In this context, digital and smart farming solutions, including low-cost, energy-efficient technologies, offer a promising way forward. Low-power wide-area networks (LPWAN), such as LoRa, Sigfox, and NB-IoT, are particularly well-suited for Internet of Things (IoT)-enabled agriculture due to their affordable deployment, energy efficiency, and optimal transmission range for agricultural applications. In contrast, existing systems—often based on expensive technologies such as artificial intelligence (AI) or satellite imagery—are not suitable for smallholder farmers for several reasons (high costs, technical complexity, and insufficient resolution for small-scale plots). Therefore, this paper introduces a new IoT-based agricultural platform utilizing LoRaWAN technology, designed to provide an affordable and effective solution within the Moroccan agriculture context, suffering from severe water scarcity in the last decades. The platform, called AgriLink, uses sensors to collect data and transmit it to a gateway via LoRaWAN. The data is then processed and transferred to a server using Python, SQLite, and InfluxDB. Once the server confirms the receipt of the data, it is promptly deleted from the gateway. This approach allows farmers to monitor and manage their irrigation and fertilization systems in real-time, enhancing both efficiency and ease of use, while overcoming the limitations of existing systems. The objective of using this platform is primarily to save more water and fertilizers in fruit tree crop orchards, which consequently serve to promote sustainable agriculture.

KEYWORDS

digital agriculture, Internet of Things, LoRaWAN, LORA, fruit tree crops, remote sensing, water management

1 Introduction

The world's population is projected to increase continuously through the end of the century, reaching 9.7 billion people in 2050 and potentially peaking at nearly 11 billion around 2,100, according to recent projections by the United Nations organization (Vollset et al., 2020). The agricultural sector, which is already impacted by alterations in the hydrological cycle due to climate change, will require significant changes to meet the food needs of the global market (Hatfield et al., 2020). Small-scale agriculture, which operates on only 12% of the world's agricultural land, contributes significantly to food security by producing 35% of the world's total food (Paloma et al., 2020; Bartol, 2023; Moreno-Pérez et al., 2024). By adopting modern practices, these farms can easily meet the demands of a growing population. Small-scale farmers face various challenges, including drought, climate change-driven water scarcity, scarce arable land, rising global temperatures, and extreme weather (Moreno-Pérez et al., 2024). However, these challenges can be faced with proper planning and implementation of sustainable farming practices (Bartol, 2023; Tessier et al., 2021). By utilizing innovative techniques and technologies, crop yields can be increased and the long-term effects of these challenges can be mitigated (Tallou et al., 2023; Abbatantuono et al., 2024). To address the global problem of food security, small-scale farmers should adopt new technologies to optimize water and fertilization for increased food production (Diao et al., 2023). This will preserve water resources and prevent groundwater pollution. These technologies provide real-time data that helps small farmers make informed decisions at every stage of the agricultural cycle (Balasundram et al., 2023; Papadopoulos et al., 2024). Regarding the Citrus sector, Morocco is an important player in the global orange production market, ranking as the third-largest producer in Africa. Orange production was projected to reach 820,000 metric tons in 2024, with a 5% increase from 2022, primarily attributed to improved weather conditions and increased adoption of drip irrigation methods and smart farming practices. Despite this growth, production remains about 24% lower than in optimal years due to ongoing drought conditions affecting the region (Fardaoussi, 2023).

More specifically, the use of smart technologies, particularly sensor systems, is not new in agriculture and has recently attracted considerable attention for its ability to balance the optimization of irrigation and fertilization and the increase of crop yields, guaranteeing a substantial income for farmers (Ahmad et al., 2022; Giannoccaro et al., 2020; Papadopoulos et al., 2024). In this regard, several digital platforms have been developed, mostly based on satellites, artificial intelligence (AI), unmanned aerial vehicles (UAVs) images and sensors, to provide better real-time data for precise decision-making (Tallou et al., 2023; Abbatantuono et al., 2024; Balasundram et al., 2023). However, it has been stated that the overall improvement record by introducing these innovative technologies among small farmers is not very encouraging and thus has a partial success due to several factors: sensors are costly and more complicated to use by farmers, the problem of the resolution of small farms' images, the processing of data which requires a well-trained staff, and the actual commercial products for smart farming which rely on cloud servers and proprietary software platforms that cost several thousand euros (Wei et al., 2024; Dhanaraju et al., 2022). In addition, because of their dependence on satellites, these solutions can be applied only to outdoor farmers and are not extendable to greenhouse farming, which is starting to grow rapidly, particularly in the south of Morocco, due to its ability to increase crop production by creating the optimal climatic conditions needed for plant growth (Meng et al., 2021; Et-taibi et al., 2024). Aware of these challenges, the proposed solutions must be more attractive in terms of the use of low-cost sensors, simplicity of use in the field and, above all, their ability to be integrated into existing agricultural practices, especially within a context of countries that suffer more from water scarcity and climate change impact (Et-taibi et al., 2024; Alharbi et al., 2024).

In this regard, the development of the Internet of Things (IoT), which is a connection of small, cheap and disposable sensors through IoT platforms, has created numerous opportunities to improve the management of irrigation water and fertilization plans (Tallou et al., 2023; Balasundram et al., 2023; Dhanaraju et al., 2022). Moreover, the average price of an IoT sensor has decreased from $1.30 in 2004 to $0.44 in 2018, which promotes its increasing use, especially by smallholder farmers. It's also more suitable for both greenhouse and open-field farming (Meng et al., 2021; Pascoal et al., 2024). In general, the use of IoT technologies in agriculture can significantly contribute to the development of smart agriculture instead of traditional one, by helping farmers to smartly control and manage the soil and vegetation parameters of their fields (Pascoal et al., 2024; Dhanaraju et al., 2022). In fact, it helps to collect real-time data, which enables farmers to get all the information at once, instead of waiting until the end, when everything has already occurred (Dhanaraju et al., 2022; Lin et al., 2020). IoT is used to monitor a large area of farmland and increase productivity with the help of various devices, sensor nodes, IoT protocols and other different tools. The devices are connected using a Low-Power Wide Area Network (LPWAN), which is considered a suitable technology for IoT applications. It allows the transmission and reception of small messages over long distances, with the major advantage of using low-cost devices that are highly energy efficient. Therefore, with a simple battery, sending and receive the collected information for many years is possible (Dhanaraju et al., 2022; Matetić et al., 2022).

More recently, several LPWAN technologies have been developed, such as SigFox, NB-IoT and Lo-RaWAN (Meng et al., 2021). Founded in 2009, SigFox is both a French company and an LPWAN network operator. It is a low-bandwidth network based on the use of unlicensed ISM (Industrial, Scientific, Medical) frequency bands. The frequency bands used in Europe and the United States are 868 MHz and 902 MHz, respectively, (Pagano et al., 2023; Pablo Becoña et al., 2024; Soy, 2023). Although their use does not require a license and the number of messages transmitted is limited to 140. The second technology is NB-IoT or Narrow-band Internet of Things technology, standardized by the 3rd Generation Partnership Project (3GPP). It is based on existing mobile telephony infrastructures. This technology can deliver unlimited messages but requires a license to use (Meng et al., 2021; Soy, 2023; Hu et al., 2021). In order to overcome these problems related to the number of messages delivered and the license, the American company Semtech has developed a LoRa (Long Range) technology, which has been deployed through its LoRa Alliance platform. LoRa enables long-range communications, from five kilometers in urban areas to 15 km or more in rural areas. Another key feature of LoRa-based solutions is their ultra-low power consumption, which allows the creation of battery-powered devices that can last up to 10 years (Kökten et al., 2020). All these advantages make LoRa technology very attractive and economical for the end user (Pagano et al., 2023; Pablo Becoña et al., 2024; Soy, 2023; Kökten et al., 2020).

This paper describes the AgriLink platform, an IoT-based platform designed for smart agriculture using LoRaWAN technology. However, similar systems have already been widely explored in the literature. The primary challenge with these existing systems lies in their cost, complexity, and applicability for smallholder farmers. Here's what is lacking in these systems: (1) High Cost and Complexity: Many existing smart farming technologies involve expensive sensors and systems that are difficult for smallholder farmers to use, as they require specialized training and infrastructure. For instance, satellite-based solutions and cloud-based platforms often involve high deployment and operational costs; (2) Limited accessibility for small farms: Many systems are tailored for large-scale operations, and the spatial resolution of free satellite images often does not align well with small plot sizes typical of smallholder farms. Furthermore, these technologies tend to favor open-field farming over greenhouse farming, which is growing in popularity, especially in regions like southern Morocco; (3) Dependence on Cloud Servers and Proprietary Software: Current systems are frequently tied to commercial solutions that rely on cloud servers and proprietary software, which not only increases costs but also makes these technologies less flexible and harder to adapt to local contexts.

For the above-mentioned reasons, the novelty of the AgriLink platform resides in addressing these gaps by providing a low-cost and easy-to-use alternative, with a focus on LoRaWAN technology for small-scale, real-time data monitoring. It emphasizes simplicity and the use of open-source software like Python, SQLite, and InfluxDB. This makes it a more accessible and viable option for smallholder farmers, enabling more efficient irrigation and fertilization management at a lower cost. The paper is structured as follows: Section 2 provide a comprehensive overview of LoRa technology. Section 3 presents a description of the proposed AgriLink architecture followed by a description of experimental setup in section 4, while section 5 presents AgriLink's preliminary test results.

2 Overview of LoRa technology

LoRa (Long Range) is a network protocol that enables long-range communication at low speeds ranging from 0.3 to 50 Kbps. This technology finds wide application in several areas, including connected objects, M2M, intelligent buildings, and particularly in agriculture. The purpose of this technology is to effectively address issues related to the IoT by establishing bidirectional communication between the object and the collection network over long distances with low power consumption (Pagano et al., 2023; Rybak and Strzecha, 2021). The system utilizes frequency modulation to transmit small data packets from sensors that can travel over longer distances than traditional telecommunications networks. With LoRa, a device can operate for up to 10 years on a small battery without requiring any human intervention to replace it. For this reason, it was used in the present study to establish the Agrilink platform (Kökten et al., 2020; Rybak and Strzecha, 2021).

The LoRa Alliance standardized the LoRaWAN protocol in 2015, which allows any company to deploy its own network. Unlike SigFox, which uses Ultra Narrow Band, LoRa uses Chirp Spread Spectrum modulation (CSS), a technology originally developed in the 1940s for radar applications (Pablo Becoña et al., 2024; Kökten et al., 2020). LoRaWAN offers six Spreading Factors (SF7–SF12) to regulate data rate, improve range, and reduce energy consumption. Increasing the spreading factor results in an increase in transmission range, but a decrease in data rate. It is important to note that LoRa operates in the ISM bands 169, 433, 868, and 915 MHz. To limit interference, a duty cycle of 0.1–1% must be respected depending on the sub-band used to limit interference (Miles et al., 2020; Correia et al., 2023). Table 1 shows a comparison between these three LPWAN technologies.

Figure 1 describes the LoRaWAN network architecture, which consists of four components: (1) End devices, that are able to send and receive from the gateways. They contain sensing capabilities, some processing power, and a radio module to translate the data into a radio signal. These devices can work for many years on a small battery and also the user can put into deep sleep mode to optimize power consumption; (2) The gateways act as a transparent bridge, relaying bi-directional data between end nodes and servers; (3) Network Server connects to multiple gateways via a secure TCP/IP connection, either wired or wireless, then eliminates duplicate messages, identifies the gateway that must respond to the end-node message, and manages end-node data flows through an adaptive data flow scheme to optimize network capacity and extend node battery life; (4) Application Server serves to collect and analyzes data from end nodes and determines their actions.

The network has a star topology where each end node connects to one or more gateways that communicate with the network server. The gateways act as a bridge, routing raw data packets from the end-devices to the network server, which encapsulates them in UDP/IP packets.

LoRaWAN defines three communication classes for end-devices. Class A enables bidirectional communication, allowing for two-way communication. After sending an uplink message, the device allocates two short downlink message reception windows from the gateway. This is the most energy-efficient solution for devices whose application does not require any downlink message reception advantage. Class B, on the other hand, defines bidirectional end-devices with planned receiving slots. Class C pertains to end-devices that continuously listen to the network. Devices in this class have no energy consumption constraints and offer the lowest latency.

3 Description of the AgriLink scheme

The AgriLink project optimizes the production of targeted vegetables through the deployment of connected objects. The implementation of

TABLE 1 Comparison between the three LPWAN technologies.

Standards	SigFox	LoRa	NB-IoT
Bandwidth	100 Hz (unlicensed ISM)	125 KHz (unlicensed ISM)	200 KHz (licensed LTE)
Number of messages/days	140	Unlimited	Unlimited
Data rate	100 bps	0.3–50 kbps	200 kbps
Coverage	Good	Good	Excellent
Battery life	Very high	Very high	High
Cost of IoT products	Low	Low	Low

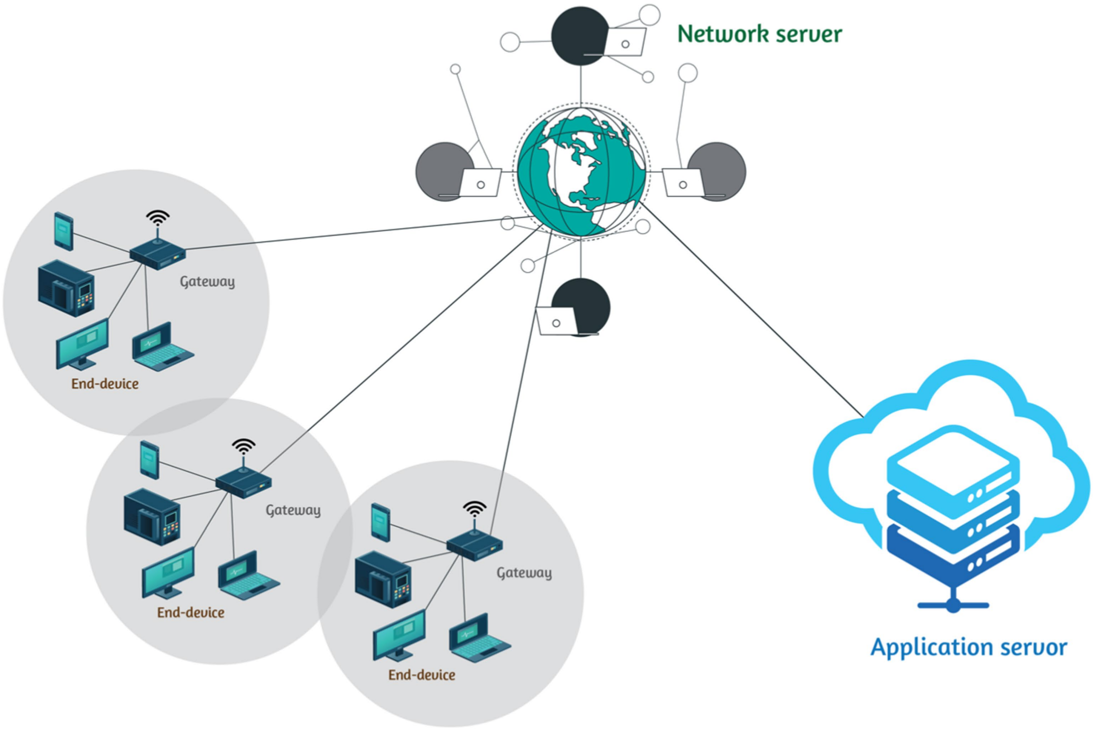


FIGURE 1
LoRaWAN network architecture.

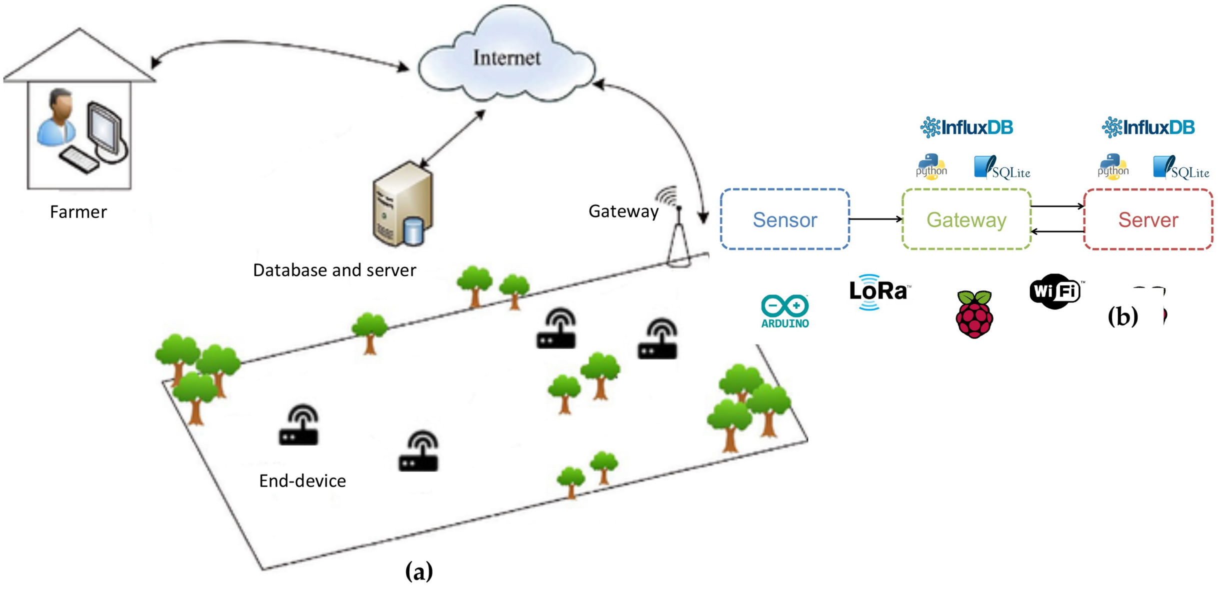


FIGURE 2
(A) AgriLink architecture and **(B)** hardware and software of our system.

the network hardware is explained in the next section. The AgriLink platform's general architecture is presented in Figure 2A, and the hardware and software utilized in this work are shown in Figure 2B.

The AgriLink platform operates through three scenarios, where the collector node collects temperature and humidity measurements from sensors for both air and soil and then sends the data to the gateway via the LoRa device. The system is designed to ensure reliable and efficient data transmission. The gateway then confirms the reception of the packet. The procedure is repeated once more, with new measurements taken after 10 min. If the procedure fails, sensors

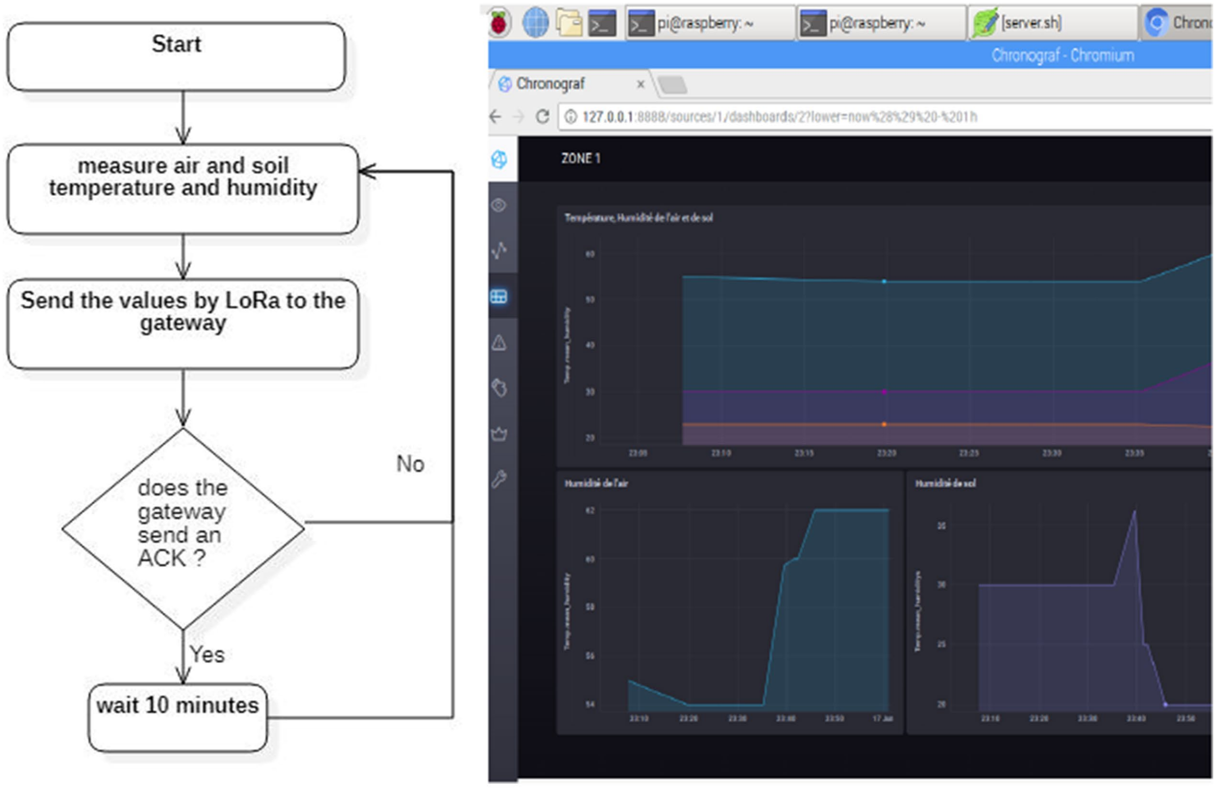


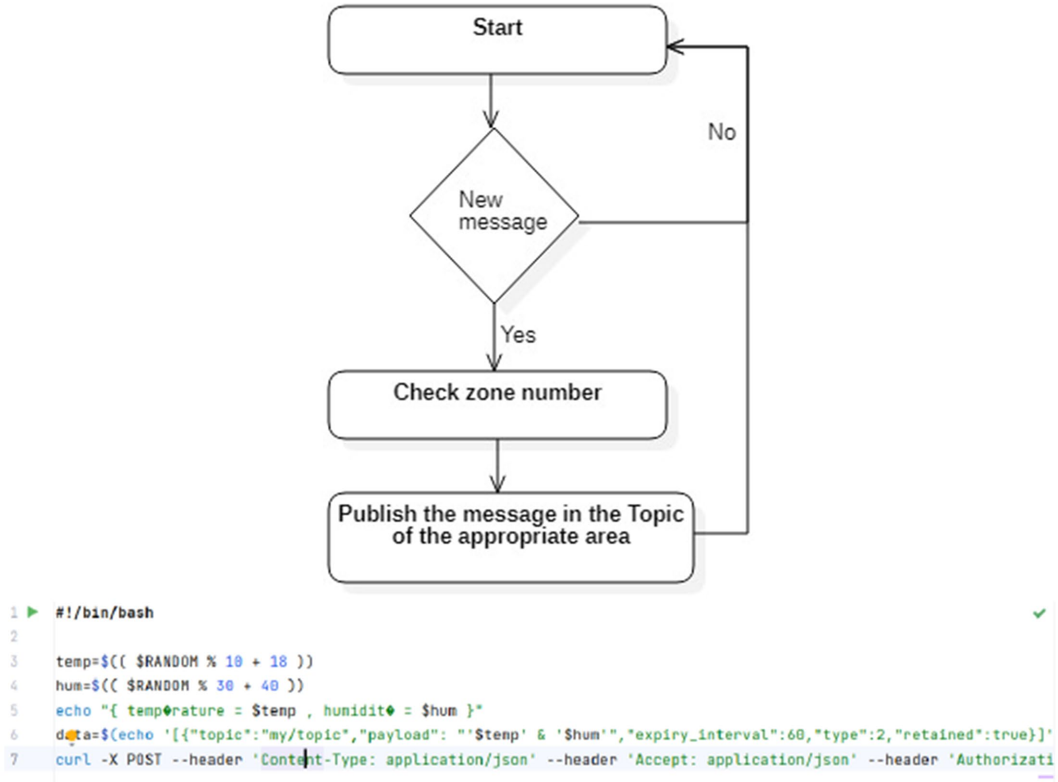
FIGURE 3
Flowchart and Arduino code of the communication between the collector node and the gateway.

will collect new measurements and send them to the collector node (Figure 3). The second scenario outlines the progress of the actuator node, which controls the opening and closing valve. The actuator node communicates with the gateway every time it receives a new message. When a message is received, the actuator node verifies the zone number to confirm that it is the intended recipient. If the zone number is correct, the node executes the command to publish the message in the appropriate area's topic, including the zone number and collected measurements (Figure 4). The third scenario describes the data recording process at the server level. The zone topic is consulted to check for new messages containing measurements, which are then promptly saved in the Influxdb database. Updates are attempted every minute to ensure that any new messages are received (Figure 5).

The Arduino code to execute the instructions of this flowchart (Figure 3) is quite long. A portion of this code is provided below, while the full code can be found in Supplementary material. This Arduino program (SM) is designed to work with a DHT11 sensor and a LoRa module, creating a simple system for monitoring temperature and humidity and sending this data wirelessly over long distances. The sensor collects the temperature and humidity readings from its connected pin (in this case, A0) every 1.5 s. These readings are then formatted into a message that includes a unique sequence number and, optionally, a secure key for added privacy. The message is sent through the LoRa module, which operates on the 433 MHz frequency band-common for IoT applications in many regions. The system is set up to be efficient, with energy-saving features built in. The LoRa module and sensor can go into sleep mode when not in use, which helps conserve power, making this setup ideal for battery-powered or remote installations. Debugging information is also available through the serial port, so you can monitor the system's performance and see what's happening at each stage, like setting up the LoRa module or sending the data. This code is perfect for anyone building a DIY IoT project for long-range environmental monitoring. Whether you are keeping an eye on conditions in a greenhouse or gathering weather data in a remote area, it's a great starting point for creating a reliable, low-power system.

The script for sending the message to Flespi is a Bash script that performs the tasks described in the flowchart (Figure 4). This Bash script simulates the generation and transmission of temperature and humidity data via an HTTP POST request. It generates random values, with the temperature ranging from 18 to 27°C and humidity from 40 to 69%, which are displayed for manual verification. A JSON payload is created to include these values along with metadata such as message topic, expiry interval, message type, and a retention flag. The script uses curl to send the POST request, specifying content type, accepting JSON format, and including an authorization token for secure access. While the token is hard-coded, posing a security risk, it should be securely stored for production use. Designed primarily for testing or demonstrations, the script needs adjustments for real-world deployment.

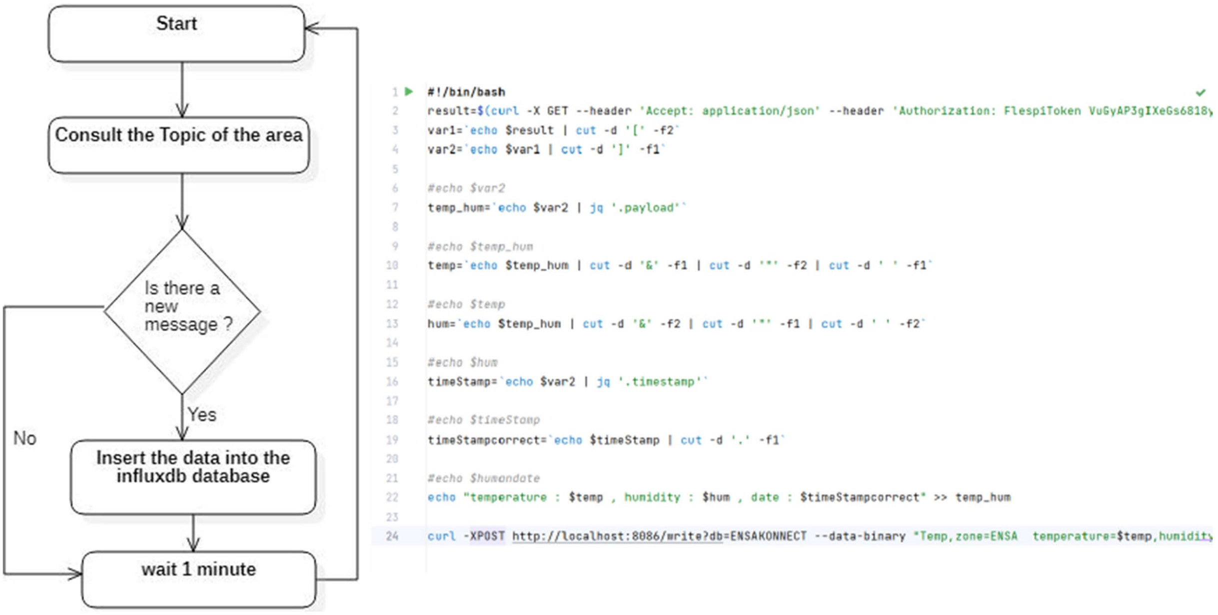
To retrieve data from the Flespi MQTT Broker, we need to develop four scripts (one script for each zone) according to the flowchart (Figure 5). This Bash script is designed to collect temperature and humidity data from an MQTT topic and store it in a local InfluxDB database. It starts by sending an HTTP GET request to a specific MQTT endpoint using 'curl', with the necessary headers for



```bash
#!/bin/bash

temp=$(( $RANDOM % 10 + 18 ))
hum=$(( $RANDOM % 30 + 40 ))
echo "{ temp�rature = $temp , humidit� = $hum }"
data=$(echo '[{"topic":"my/topic","payload": "'$temp' & '$hum'","expiry_interval":60,"type":2,"retained":true}]'
curl -X POST --header 'Content-Type: application/json' --header 'Accept: application/json' --header 'Authorizati
```

FIGURE 4
Flowchart and Arduino code of the communication between the actuator node and the gateway.



```bash
#!/bin/bash
result=$(curl -X GET --header 'Accept: application/json' --header 'Authorization: FlespiToken VuGyAP3gIXeGs6818y
var1=`echo $result | cut -d '[' -f2`
var2=`echo $var1 | cut -d ']' -f1`

#echo $var2
temp_hum=`echo $var2 | jq '.payload'`

#echo $temp_hum
temp=`echo $temp_hum | cut -d '&' -f1 | cut -d '"' -f2 | cut -d ' ' -f1`

#echo $temp
hum=`echo $temp_hum | cut -d '&' -f2 | cut -d '"' -f1 | cut -d ' ' -f2`

#echo $hum
timeStamp=`echo $var2 | jq '.timestamp'`

#echo $timeStamp
timeStampcorrect=`echo $timeStamp | cut -d '.' -f1`

#echo $humandate
echo "temperature : $temp , humidity : $hum , date : $timeStampcorrect" >> temp_hum

curl -XPOST http://localhost:8086/write?db=ENSAKONNECT --data-binary "Temp,zone=ENSA  temperature=$temp,humidity
```

FIGURE 5
Flowchart and Arduino code of the recording data at the server.

authorization and data formatting. Once the data is received, the script uses commands like ‘cut’ and ‘jq’ to parse the response and extract the temperature, humidity, and timestamp from the payload. The temperature and humidity values are isolated and formatted for easy reading, while the timestamp is adjusted to remove any milliseconds, making it more human-friendly.

The script then logs the temperature, humidity, and timestamp to a file named ‘temp_hum’, which can be useful for tracking and reviewing data over time. Finally, it sends this information to a local InfluxDB database using a ‘curl’ POST request formatted in InfluxDB’s line protocol. This approach enables efficient data collection and real-time monitoring for analysis and visualization. However, it’s important to note that hard-coding authorization tokens in scripts poses a security risk, so it’s best to use more secure methods for storing sensitive information.

4 Experimental and hardware setup

The AgriLink platform was successfully deployed in 2020 on a small experimental orange field located at the National School of Applied Sciences (ENSA) site in the city of Safi, Morocco (Figure 6). The platform reliably monitored three key parameters: soil moisture, air temperature, and relative humidity. For that purpose, two low-cost sensors with measurement frequency of 1 Hz were employed: (1) DHT11 Sensor, which measures air temperature within a range of 0 to +50°C, with an accuracy of ±2°C, and relative humidity from 20 to 80%, with an accuracy of ±5%; (2) Soil moisture sensor designed to provide consistent measurements of soil moisture content, enabling real-time monitoring and data-driven agricultural decision-making. The battery-powered sensors collect data and visualize it regularly on the AgriLink platform.

To improve the node’s reliability and decrease its size, a PCB with a slot specifically designed for work was used. The sensor node circuit, depicted in Figure 7, comprises temperature and humidity sensors for the air, soil moisture and soil temperature sensors, the Arduino Mini-Pro, LoRa RF96 module, and LoRa module antenna. The gateway consists of two modules, where the first module is the Raspberry Pi 3 support, which works as a microcomputer with a Linux-based operating system dedicated to the processing of the collected data. The data is then collected in a database temporally installed on the system. The second module is the LoRa RF96 receiving module, which interconnects with the other LoRa module installed on the Arduino.

FIGURE 6
Experimental setup and sensor nodes deployed in the field.

5 Testing the AgriLink platform

The AgriLink testing showcases the pioneering initiative of using the LoRaWAN technique in conjunction with low-cost sensors to control irrigation water in Morocco. This section presents conclusive results that demonstrate the reliability of the AgriLink platform. Once the collected data is saved in the Influxdb database, a new dashboard can be created for the study site (Figure 8) according to the flowchart shown in Figure 5, where we can add all the parameters measured in each zone for subsequent visualization. This dashboard provides a clear and concise graphic interface to visualize the instantaneous time series of the collected data using the high-performance chronograph software, with a time interval that can be set by the user. To display this data, the user can access the platform either locally or remotely using a computer or smartphone. The user, to visualize such a parameter locally, must, for example, access a specific address on the Internet (e.g., “127.0.0.1:8888”) and select the corresponding zone by simply clicking on its name. Finally, the user can click on the dashboard icon, marked by the red arrow in Figure 8, with ease to visualize the measured parameters of the selected zone.

This platform offers users a range of options for visualizing data by selecting desired parameters based on SQL instructions, as demonstrated in Figure 9. For instance, users can select the temperature of the air in the ENSA zone. Furthermore, users can upload data in CSV format for later processing, such as controlling farmers or modeling purposes (Figure 9). The user can easily visualize the time series of all measured parameters at the same time. Figure 10 provides a clear and concise overview of the main visualization interface for the measured parameters: air and soil moisture humidity and temperature. This interface consists of two blocks: the top one displays the evolution of all three parameters together, while the bottom one shows the graphs of each parameter separately. The temperature and humidity values obtained are reasonable for the region’s climate on the date of collection. Users can easily access the data from another computer or smartphone by searching for the server’s IP address on the web using the port number. To remotely access our server, simply enter the following address: 192.168.8.116:8888. Our platform utilizes the LoRaWAN protocol and low-cost instruments to measure meteorological parameters and soil moisture in real-time, providing farmers with the necessary data to achieve optimal crop yields while conserving water. Our technology is proven to be effective and reliable, making it the optimal tool for farmers to achieve optimal crop yields while saving water. In future work, we will enhance the proposed scheme by incorporating additional functionalities based on the farmers’ requests and studying other parameters that affect the performance of LoRa.

To ensure the accuracy and reliability of data collected from low-cost sensors over extended periods, the system employs a

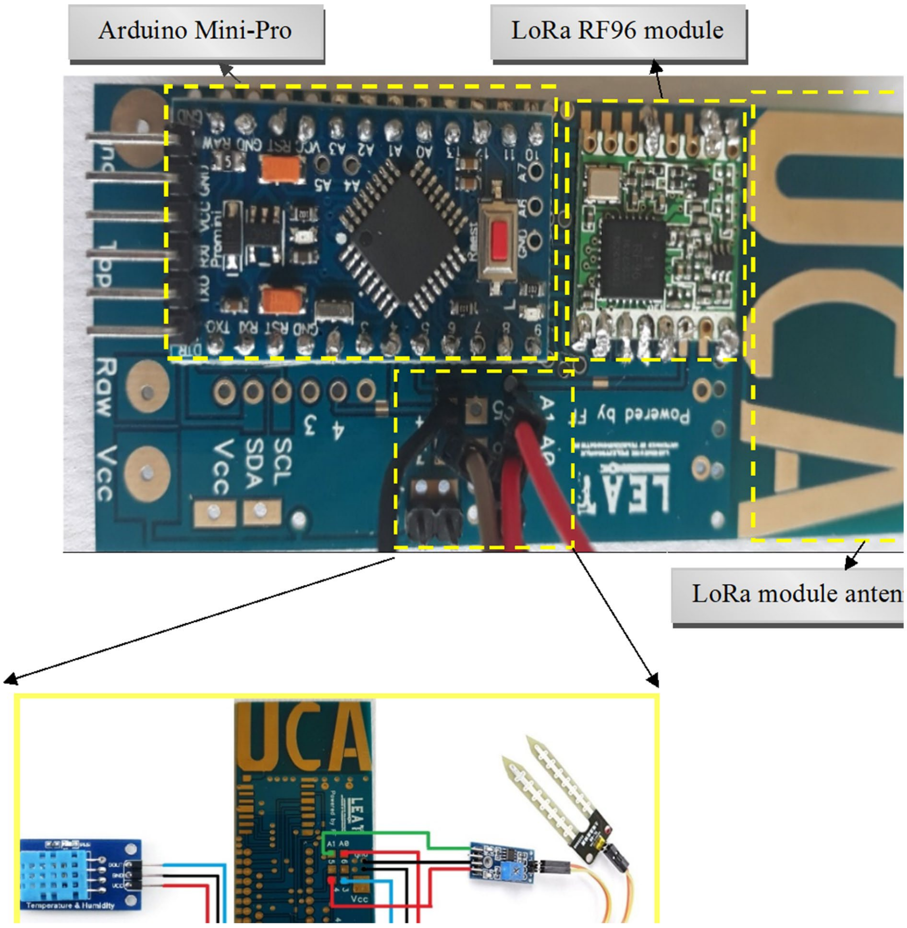
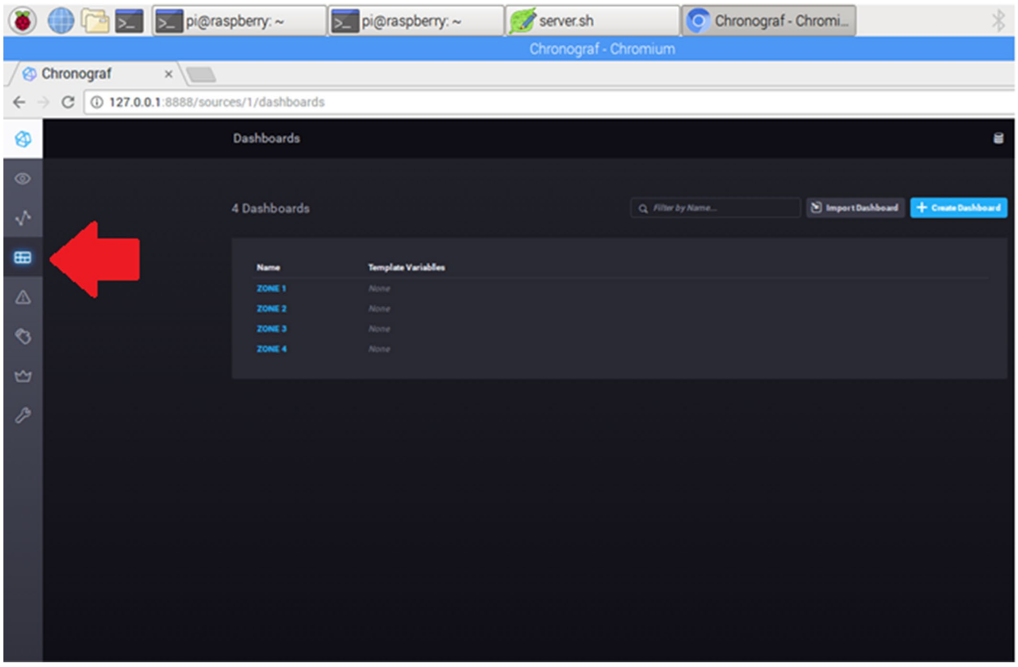


FIGURE 7
Overview of the different sensors used in our platform.



Name	Template Variables
ZONE 1	None
ZONE 2	None
ZONE 3	None
ZONE 4	None

FIGURE 8
Creation of the dashboard on the AgriLink platform.

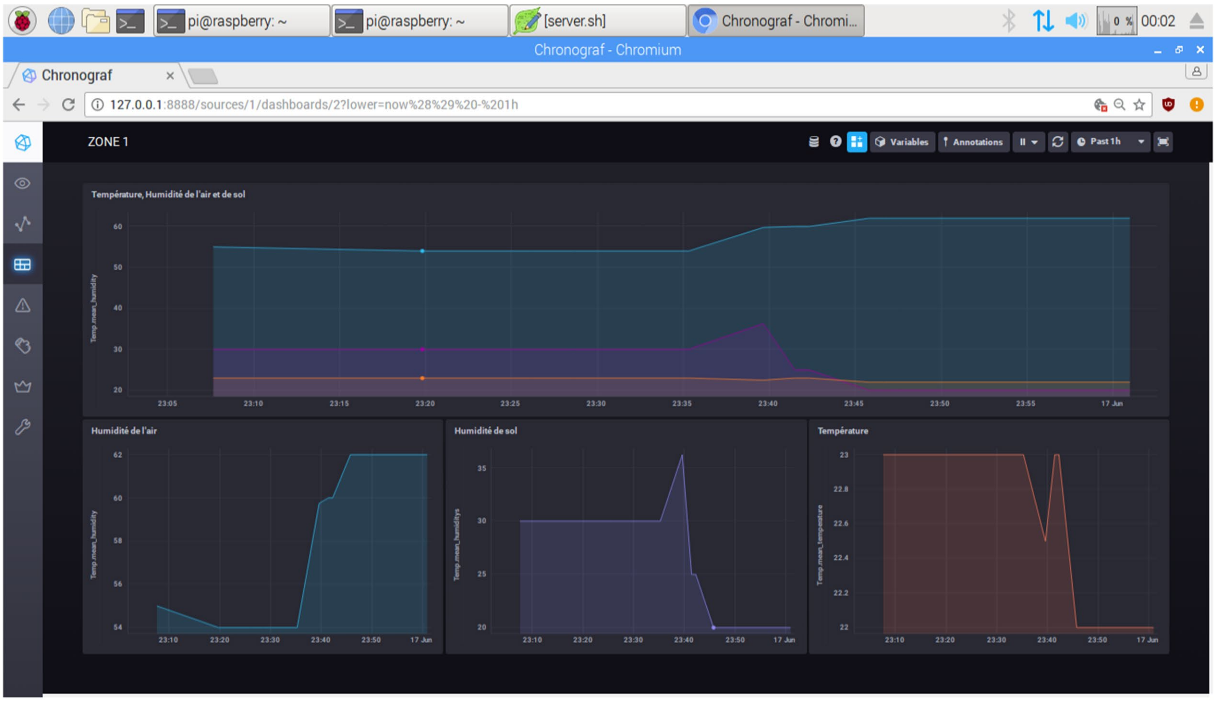


FIGURE 9
An example of selecting the temperature for visualization using SQL instructions.

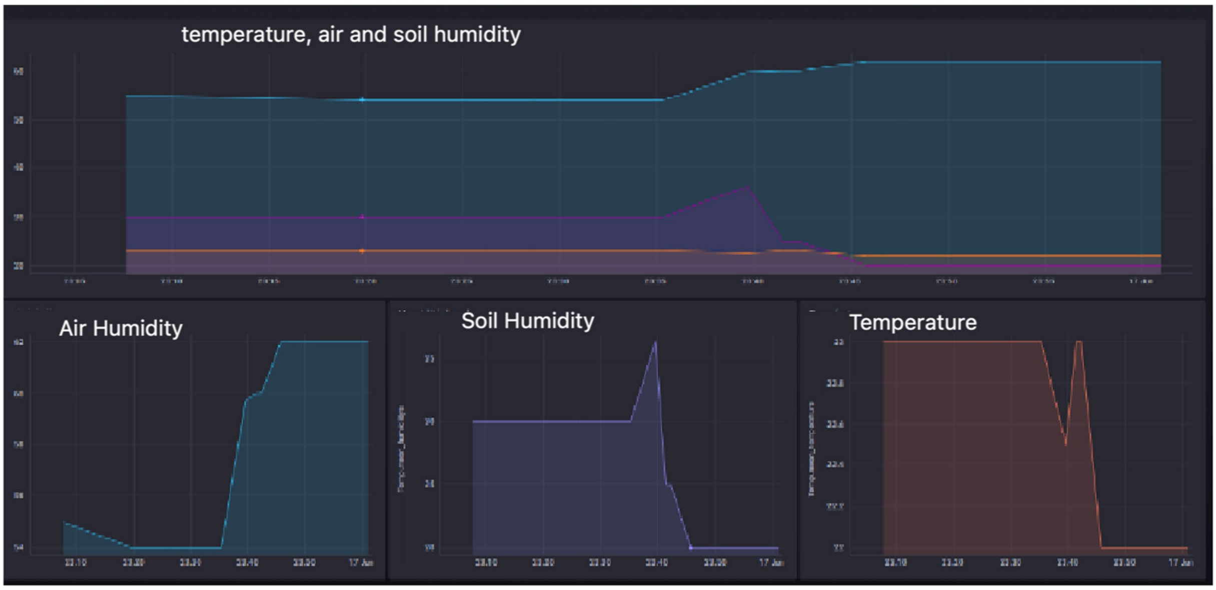


FIGURE 10
Visualization of the three parameters: soil moisture and temperature and humidity of the air.

combination of strategies. Initially, sensors are calibrated using high-precision instruments to establish a baseline, followed by periodic recalibration to correct for drift due to environmental factors or sensor wear. Environmental adjustments are made in real time to account for temperature, humidity, and other variables. Cross-sensor comparisons provide redundancy, with multiple sensors measuring the same parameters, and data fusion algorithms combine their readings to enhance accuracy. Error detection algorithms identify outliers or anomalies, while statistical models monitor long-term sensor performance to detect malfunctions. Some systems also feature self-calibration, where sensors automatically adjust based on external reference data. Regular maintenance, along with automated alerts for performance issues, ensures continuous reliability. Calibration with known standards, such as reference stations or controlled inputs, further improves accuracy. By integrating these methods, the system maintains high-quality data collection, even from low-cost sensors, ensuring long-term performance and reliability.

To handle network failures or data transmission errors, the platform employs several strategies to ensure reliability and data integrity. The system includes error detection mechanisms, such as checksums and error-correcting codes, to identify and correct transmission errors. In case of network failure, data is temporarily buffered locally by sensors or edge devices until the connection is restored, with timestamps applied to maintain chronological order. Automatic retransmission of lost packets occurs, and redundant communication paths, such as multiple network channels or mesh networks, ensure data can be rerouted if one path fails. The platform also uses time synchronization and data compression to recover and align data once the network is restored. Failover mechanisms enable the use of alternative, lower-bandwidth networks, such as SMS or satellite, in case of prolonged primary network outages. Continuous real-time monitoring, along with automated alerts and diagnostic logs, helps detect issues early and allows for quick recovery. These combined features ensure the system's robustness in maintaining data integrity and continuous operation despite network interruptions.

6 Conclusion

In conclusion, the ArgiLink platform, leveraging the LoRaWAN protocol and cost-effective sensors, represents a significant advancement in real-time agricultural monitoring. By providing accurate and timely data on meteorological parameters and soil moisture, the platform equips farmers with actionable insights to optimize crop yields while minimizing water use. This dual focus on productivity and sustainability positions ArgiLink as a valuable tool for modern precision agriculture, addressing the critical challenges of resource management and climate resilience. The platform's proven reliability and efficiency demonstrate its potential to transform traditional agricultural practices into more data-driven and sustainable systems. Its low-cost design ensures accessibility for smallholder farmers, thereby democratizing access to advanced agricultural technology. Looking ahead, future development of ArgiLink will focus on expanding its functionalities to meet evolving farmer needs. This includes integrating additional features based on user feedback and studying the impact of other environmental and technical parameters on LoRaWAN performance. Furthermore, collaboration with different involved stakeholders could enhance knowledge exchange and improve decision-making processes among farmers. To further solidify the role of ArgiLink as an innovative solution for sustainable agricultural management, it is recommended that:

- **Integration with national water management initiatives**: Aligning ArgiLink with Morocco's national program of water savings in Irrigation can enhance its utility in promoting efficient water use across various agricultural sectors, especially within the Moroccan context that suffers from water scarcity.
- **Educational activities**: Implementing training programs for farmers on effectively using the ArgiLink platform can maximize its impact on crop management and water-saving practices.
- **Research and interdisciplinary collaborations**: Partnering with international and national research institutions to explore innovative irrigation techniques, such as remote sensing, satellite imaging and new technologies, could provide additional insights into optimizing water use while maintaining crop productivity.
- **Involvement of different stakeholders**: Reducing the gap between the different actors in the field will result in more effectiveness in terms of sustainable agriculture.

By adopting these recommendations, ArgiLink can play a pivotal role in transforming Morocco's agricultural system to be resilient to climate change while ensuring food security for its growing population. As Morocco continues to face significant challenges related to water scarcity, integrating digital agriculture will be crucial in fostering a sustainable future.

To further enhance the capabilities of the AgriLink platform, several improvements will be considered in future work, such as incorporating advanced analytics powered by AI or machine learning which could help predict water requirements, monitor crop health and optimize resource usage. Other sensors can be used to detect critical parameters such as soil salinity, pH and nutrient levels which would provide deeper insights into soil conditions and enabling precise irrigation and fertilization strategies. Integrating local real-time data with regional weather forecasts would refine irrigation schedules and help farmers prepare for extreme weather conditions. Finally, to ensure data security, replacing hard-coded tokens with dynamically generated ones or encrypted communication protocols would mitigate risks and improve system reliability. Expanding connectivity options can be done by supporting alternative protocols such as NB-IoT which would enhance the platform's versatility, making it adaptable to diverse agricultural settings, including remote or specific regions like rural areas of Morocco.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KB: Funding acquisition, Software, Supervision, Writing – original draft, Writing – review & editing. JE: Methodology, Software, Supervision, Writing – review & editing. MM: Data curation, Funding acquisition, Methodology, Writing – review & editing. HE: Resources, Software, Supervision, Writing – review & editing. GV: Resources, Supervision, Validation, Writing – review & editing. AT: Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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