

Efficient IoT-based smart irrigation system using LoRaWAN for resource optimization in agriculture

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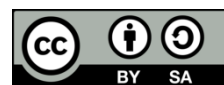
ThingPark server

Water optimization

ABSTRACT

The global agricultural sector faces critical challenges such as climate change, water scarcity, and inefficient irrigation practices. This paper presents an internet of things (IoT)-based smart irrigation system designed to optimize water usage and enhance agricultural productivity in Tunisia's semi-arid regions. The proposed system integrates sensors (YL-69 soil moisture, DHT22 temperature-humidity, FC-37 rain), a STM32L072Z-LRWAN1 board, and long-range wide area network (LoRaWAN) communication to transmit real-time data to a ThingPark server and MongoDB database. A mobile application developed in Flutter enables monitoring and control through manual, automated, and event-driven modes. Experimental validation demonstrates water savings and improved irrigation efficiency compared to conventional systems. Quantitative results, benchmarking, and cost-benefit analysis confirm the system's affordability, energy sustainability, and scalability. This solution contributes to sustainable agriculture in resource-constrained environments.

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1. INTRODUCTION

Agriculture is central to food security and economic stability, particularly in developing regions. Yet, it is increasingly constrained by water scarcity, climate variability, and inefficient irrigation, challenges that are especially acute in semi-arid countries such as Tunisia. By 2050, global food production must increase substantially to meet demand [1], even as rainfall becomes more erratic and temperatures rise due to climate change [2]. In the Near East and North Africa (NENA), where average annual rainfall is often below 200 mm, Tunisia exemplifies a country under acute water stress [3]. Between 1962 and 2018, Tunisia's per capita water availability fell by more than 60%, underscoring the urgency of improving irrigation efficiency. Advances in the internet of things (IoT) have enabled precision agriculture solutions, providing real-time monitoring and automation of irrigation processes [4]. However, most existing IoT-based systems rely on wireless fidelity (Wi-Fi), which is limited by short communication range and high energy consumption [5], making them unsuitable for deployment in large or remote fields.

Several recent studies have proposed IoT-based irrigation architectures with different levels of integration and performance. Aisyah *et al.* [6] implemented a Wi-Fi-based multi-sensor rice field monitoring system, but its short-range constrained scalability. Campos *et al.* [7] introduced the smart and green predictive framework, yet it lacked a robust long-range backbone. Kiv *et al.* [8] demonstrated long-range

(LoRa) for soil moisture sensing in the smart monitoring of land (SMOL) system, showing potential for low-power monitoring, but their implementation required manual calibration and lacked actuator integration. Sabah *et al.* [9] and Chavanne *et al.* [10] developed automatic sensing platforms but without mobile integration or scalability. More recently, Zhang *et al.* [11] validated a long-range wide area network (LoRaWAN) precision irrigation system for tomato cultivation, and Liopa-Tsakalidi *et al.* [12] deployed a LoRaWAN-based IoT platform in olive groves, proving scalability in perennial crops. Despite these advances, current solutions either target specific crops or require significant infrastructure investment. Furthermore, issues of data security and efficient resource management remain unresolved, as highlighted by Shaikh *et al.* [13] and Aldrees *et al.* [14].

As systematically compared in Table 1, while progress has been made, existing systems still provide only partial functionality. A validated, holistic architecture that combines long-range, low-power communication with affordability, usability, and energy autonomy at low cost remains lacking. The present study contributes to addressing this gap by designing and integrating a fully functional, low-cost hardware and software architecture for smart irrigation, conducting a field evaluation that quantifies water savings and communication reliability compared to conventional methods, and providing an engineering rationale for component selection to facilitate replication in resource-constrained environments. Unlike prior works, the proposed system delivers a validated, end-to-end LoRaWAN-based irrigation solution that is affordable, scalable, energy-efficient, and specifically tailored to the semi-arid farming context of Tunisia.

Table 1. Comparative analysis of some related IoT-based smart irrigation systems

Study / system	Communication	Key features	Limitations
Aisyah <i>et al.</i> [6], 2024	Wi-Fi	Multi-sensor monitoring for rice fields	Short-range, high-energy consumption
Campos <i>et al.</i> [7], 2020	Wi-Fi + predictive framework	Smart and green IoT framework	No long-range IoT backbone
Kiv <i>et al.</i> [8], 2021	LoRa	SMOL soil moisture sensing	Manual calibration, no actuator control
Sabah <i>et al.</i> [9], 2024	Custom	Automatic sensing and control	No mobile integration, limited scalability
Zhang <i>et al.</i> [11], 2022	LoRaWAN	Precision irrigation in tomato plasticulture, validated field trials	Higher node cost; no mobile interface or ROI analysis
Liopa-Tsakalidi <i>et al.</i> [12], 2024	LoRaWAN	Large-scale olive grove deployment, real-world validation	Requires significant infrastructure investment
Proposed system	LoRaWAN	End-to-end integration with mobile app, solar-compatible, cost-effective (< €70/node)	Requires internet for app control

2. METHOD

This study proposes an IoT-based irrigation management system designed to address water scarcity and inefficiency in semi-arid regions such as Tunisia. The system leverages the LoRaWAN communication protocol to provide long-range, low-power connectivity, overcoming the limitations of Wi-Fi-based and custom IoT solutions [6], [7], [9]. The architecture integrates environmental sensors, a LoRaWAN-enabled microcontroller, a cloud-based data-management platform, and a mobile application for monitoring and control. The design emphasizes affordability, scalability, and energy efficiency through optimized hardware selection and cost reduction.

2.1. System architecture

The proposed system integrates four core components as shown by Figure 1:

- IoT sensor-actuator nodes: each node employs a YL-69 soil-moisture sensor, a DHT22 temperature-and-humidity sensor, and an FC-37 rain sensor. A relay module drives a mini water pump. The STM32L072Z-LRWAN1 microcontroller, embedding an SX1276 LoRa transceiver, was chosen for its ultra-low-power operation (< 20 nA in standby mode) and high level of integration, which simplifies hardware design and enhances field reliability. While lower-cost alternatives exist (e.g., ESP32 with external LoRa module), this integrated solution was selected to minimize development complexity, ensure robust performance in harsh environments, and provide a solid foundation for future solar-powered deployment, justifying the initial investment.
- LoRaWAN communication protocol: LoRaWAN offers up to 15 km range in rural zones with very low power demand. It was selected instead of NB-IoT to avoid recurring telecom subscription fees and allow fully independent rural deployment.

- ThingPark server and MongoDB database: the Activity ThingPark server manages LoRaWAN connectivity. Sensor data are transferred to a MongoDB Atlas database through Kafka middleware, ensuring reliable, scalable, and secure data exchange [15], [16].
- Mobile application: a Flutter-based app enables farmers to operate in manual, automated, or event-driven modes. It displays real-time sensor data and executed irrigation actions, improving decision-making and usability.

The collected data are transmitted via the LoRaWAN protocol to the Activity ThingPark wireless server, which decodes and forwards the payloads to a MongoDB Atlas database through Kafka middleware. This architecture ensures reliable, secure, and scalable data flow between field nodes and the mobile interface.

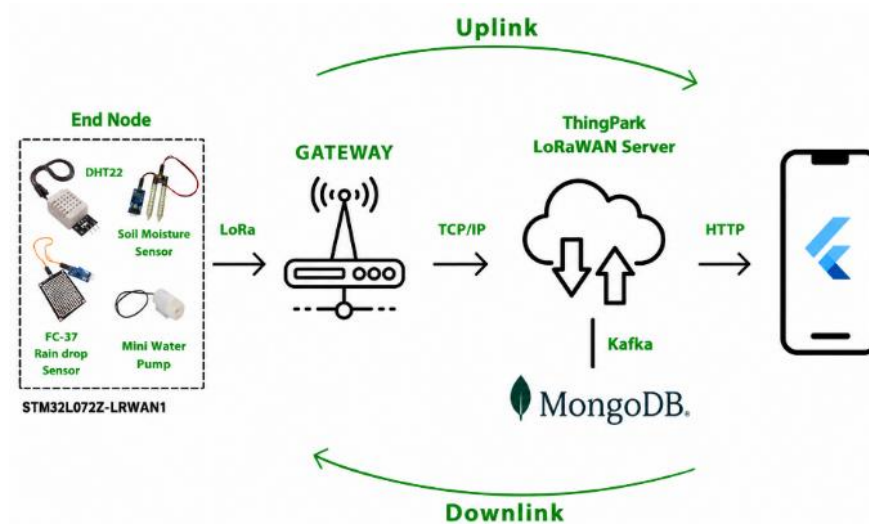


Figure 1. Overall architecture of the proposed irrigation system

2.2. Sensor-actuator node

The sensor-actuator node (Figure 2) integrates the selected sensors and the pump into a single unit connected to the STM32L072Z-LRWAN1 board. The DHT22 measures air temperature and relative humidity, the YL-69 measures soil moisture at root-zone depth (10–20 cm), and the FC-37 detects rainfall events. These components were selected for their wide adoption, low cost, and compatibility with low-power microcontrollers. Table 2 lists the component costs. The total cost of \approx €66 per node demonstrates affordability compared with commercial nodes costing $>$ €150.

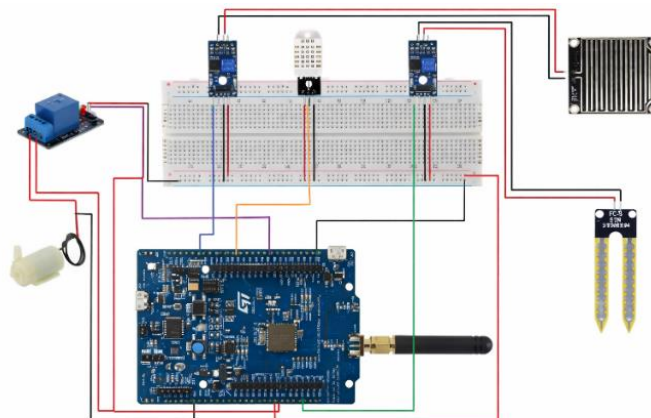


Figure 2. Wiring diagram of the sensor-actuator node

Table 2. Unit price of each component

Component	Unit Price (€)	Rationale
STM32L072Z-LRWAN1 board	45	Ultra-low-power, LoRa-enabled board
DHT22 sensor	6	Accurate temperature and humidity sensing
YL-69 sensor	4	Simple, low-cost soil moisture probe
FC-37 rain sensor	3	Rain detection for irrigation scheduling
Relay module	1	Low-cost pump control
Mini water pump	7	Affordable actuator for small-scale irrigation
Total	66	Affordable prototype (< €70/node)

2.3. Sensor calibration and experimental setup

The YL-69 soil moisture sensor was calibrated using the gravimetric method to ensure accurate readings. The analog-to-digital converter (ADC) outputs were correlated with measured volumetric water content, resulting in a linear calibration curve. This procedure addresses accuracy limitations identified in prior LoRa-based sensing studies [8]. The experimental setup consisted of a single sensor–actuator node deployed in a 0.5-hectare tomato field. The tomato was selected as the test crop due to its economic importance in Tunisian agriculture, high water requirements making it ideal for irrigation optimization studies, and its sensitivity to water stress allowing clear evaluation of system performance. A LoRa gateway was positioned 3 km from the test plot to assess long-range communication performance under real-world conditions. Data were collected continuously over a one-month period.

For benchmarking, an adjacent plot of equal size was irrigated using a conventional timer-based system operating twice daily, serving as the control. This configuration enabled quantitative evaluation of water savings, communication reliability, and irrigation scheduling efficiency.

2.3.1. System implementation and configuration

The implementation prioritized practical deployment reliability over theoretical optimization, focusing on maintainability and scalability for agricultural environments. Several key engineering decisions were made to balance performance, cost, and operational simplicity. LoRaWAN network configuration utilized the EU868 band with unicast communication, selected for its regulatory compliance in Tunisia and reliable data transmission in rural areas. Device authentication employed standard LoRaWAN security identifiers (device extended unique identifier/DevEUI, join extended unique identifier/JoinEUI, and device address/DevAddr) to ensure network integrity while maintaining interoperability with commercial LoRaWAN infrastructure. Cloud data pipeline integrated Actility ThingPark for LoRaWAN network management, leveraging its built-in codec drivers for automatic payload conversion to JavaScript object notation (JSON) format. This approach eliminated the need for custom decoding logic, reducing development complexity. Kafka middleware ensured reliable message queuing between ThingPark and MongoDB Atlas, providing fault tolerance during network interruptions common in rural agricultural settings. Database and application architecture employed MongoDB Atlas for its flexible document-based storage, accommodating heterogeneous sensor data without schema modifications. The Flutter mobile application accessed data through representational state transfer application programming interface (REST API) endpoints, supporting three irrigation modes: manual control for immediate intervention, automated scheduling based on time intervals, and event-driven operation triggered by soil moisture thresholds or rain sensor detection. This integrated architecture demonstrates a practical balance between technical sophistication and operational simplicity, specifically designed for the connectivity challenges and maintenance constraints of agricultural deployment in semi-arid regions.

2.3.2. Power management

Power optimization was a critical design consideration for reliable field deployment in areas with limited energy infrastructure. Each sensor–actuator node consumed approximately 120 mAh per day during normal operation, with transient peaks up to 180 mAh during pump activation. During testing, all nodes were powered from the mains supply to ensure continuous operation and uninterrupted data collection. However, the hardware design remains solar-ready, allowing future integration of a 5 W photovoltaic panel and a 2000 mAh Li-ion battery, which, based on the measured energy profile, could provide up to 16 days of autonomy without sunlight. The system's power budget was optimized by exploiting the STM32L072's ultra-low-power modes (< 20 nA standby) between sensing cycles, implementing duty-cycled LoRa transmissions to minimize radio energy consumption, and applying pulse width modulation (PWM)-based pump control to limit inrush current during motor startup. This energy-aware architecture ensures reliable operation, low maintenance, and affordability, making it suitable for smallholder farmers in energy-constrained regions.

3. RESULTS AND DISCUSSION

3.1. System performance and communication reliability

The LoRaWAN network demonstrated robust performance during the 30-day field deployment. The system achieved a packet delivery ratio (PDR) of 96.2% at the 3 km gateway distance, with an average latency of 2.1 seconds from sensor acquisition to database storage. Of 8 640 expected data frames (30 days \times 288 transmissions/day), the 8,308 were successfully received and logged without corruption. Key performance indicators confirmed operational suitability. Reliable LoRaWAN transmission was maintained at 3 km in open-field conditions, with occasional packet loss (3.8%) during peak daytime interference. Post-calibration soil moisture readings showed a mean absolute error of 4.7% compared with gravimetric measurements. The end-to-end delay from sensor reading to mobile-app display averaged 3.4 seconds. The smart irrigation mode resulted in an approximate 28% reduction in total water consumption compared to the timer-based control system, corresponding to an estimated saving of about 154,000 liters over the 30-day trial period on the 0.5-hectare tomato plot. These results are consistent with LoRaWAN performance reported in agricultural field studies [17], [18] and represent a marked improvement over short-range Wi-Fi systems that typically achieve below 80% reliability under similar rural conditions [6]. The observed performance confirms the system's capability for reliable precision-irrigation management, with packet-loss rates well within acceptable limits for agricultural monitoring applications.

3.2. Water usage efficiency and irrigation performance

Over the 30-day trial period, total water consumption decreased from approximately 550,000 L in the conventional irrigation setup to 396,000 L with the proposed smart system representing a 28% reduction. The water allocation reflected the constrained resource availability typical of smallholder farms in the region, representing approximately 50–70% of theoretical crop water requirements. The event-driven irrigation mode triggered an average of 1.3 irrigation events per day, compared to two fixed daily cycles in the control system. This adaptive control strategy effectively prevented both waterlogging and moisture stress, ensuring more stable soil conditions and improved water use efficiency. These findings are consistent with recent precision-agriculture research highlighting the effectiveness of adaptive, data-driven irrigation approaches in semi-arid regions [11], [18].

3.3. Mobile application usability and data presentation

The Flutter-based mobile application successfully provided real-time monitoring and control capabilities, with sensor data frames reliably decoded and displayed to users. As shown in Table 3, the system accurately interpreted hexadecimal transmissions into actionable agricultural parameters and successfully transmitted them to the cloud platform for visualization.

Preliminary usability testing indicated that the interface was intuitive and responsive, with clear visualization of environmental parameters and straightforward control of irrigation modes. The three available modes: manual, automated, and event-driven along with the rain-sensor override function, provided flexibility and ease of use during field operation.

Table 3. Example of sensor data transmission and interpretation

Hexadecimal frame	American standard code for information interchange (ASCII) frame	Temperature	Air humidity	Soil moisture	Precipitation	Sending date	Sending time
32323734363930	2274690	22 °C	74%	69%	NO	29/05/2024	17:20:01.776
32303739363830	2079680	20 °C	79%	68%	NO	29/05/2024	17:28:28.996

3.4. Irrigation control functions

The water pump actuator (direct current/DC motor) can be controlled either manually or automatically through the mobile application. In manual mode (Figure 3), the user selects the irrigation duration in minutes and activates the pump; a countdown timer indicates the remaining operation time. Once the pump starts, a confirmation page (Figure 4) displays the active irrigation status in real time, allowing the user to monitor system behavior and manually stop irrigation if needed. In automatic mode (Figure 5), the irrigation frequency and duration are predefined according to user preferences and stored in the database. The system then executes irrigation cycles autonomously based on these parameters, ensuring consistent soil moisture without requiring user intervention. In event-driven mode, irrigation automatically pauses when rainfall is detected by the FC-37 sensor, preventing overwatering and improving water-use efficiency. The settings interface allows users to define threshold values for temperature, humidity, and soil moisture that trigger or stop irrigation depending on environmental conditions.

As shown in Table 4, the proposed LoRaWAN-based system significantly reduces water consumption while maintaining stable soil moisture and reliable long-range communication. The cost reduction and energy efficient design confirm its suitability for small-scale agricultural applications in semi-arid regions such as Tunisia.

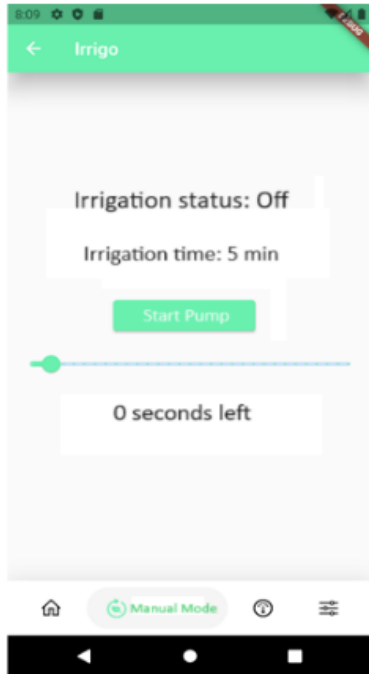


Figure 3. Manual irrigation page

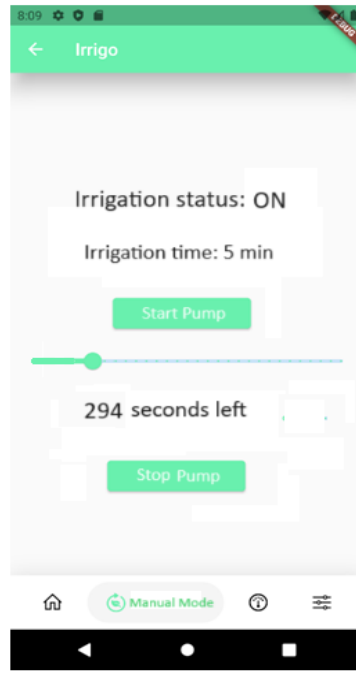


Figure 4. Pump start page



Figure 5. Automatic irrigation page

Table 4. Quantitative performance comparison

Parameter	Conventional	Proposed	Improvement
Total water used (30 days)	550,000 L	396,000 L	28% ↓
Daily irrigation events	2 (fixed)	1.3 (avg)	35% ↓
Average soil moisture	62 ± 12%	70 ± 4%	More stable
Communication success rate	—	96.2%	—
Energy source	Grid	Grid (solar-ready)	Flexible
Cost per node	> €150	€66	56 ↓

3.5. Cost-benefit analysis and scalability

The total hardware cost of approximately €66 per node represents a 56% reduction compared with commercial LoRa-based irrigation systems that typically exceed €150 per unit. With an observed 28% reduction in water consumption over the 30-day trial, the system demonstrates strong economic potential, offering a projected return on investment within two agricultural seasons for smallholder farms in Tunisia. The modular design allowed seamless integration of additional environmental sensors during testing, confirming the system’s scalability and adaptability to diverse crop types. Similar modular and LoRaWAN-based architectures, such as LoRaFarM [19] and other edge-enabled smart-farming systems [20], have demonstrated that scalability depends not only on hardware modularity but also on efficient edge–cloud coordination and lightweight communication management. Nevertheless, as emphasized in recent studies on edge-IoT resource management [14], [21], [22], large-scale deployments involving more than ten nodes would benefit from optimized data aggregation, dynamic scheduling, and fog-computing gateways to maintain energy efficiency and network reliability. These design considerations align with current trends in scalable IoT architectures for smart agriculture, aiming to ensure both cost-effectiveness and sustainable data throughput in rural environments.

3.6. Limitations and practical considerations

Although the proposed system exhibited reliable field performance, several practical limitations were identified. First, the mobile application's real-time control relies on stable Internet connectivity, which may restrict functionality in remote agricultural zones with limited coverage. Second, gateway placement was found to strongly influence communication reliability, particularly in slightly hilly terrain where line-of-sight conditions are variable. Finally, sensor calibration drift remains a concern during extended operation, requiring periodic recalibration to preserve accuracy. These findings highlight opportunities for improvement through the integration of edge-computing capabilities for offline operation, predictive maintenance algorithms based on sensor history, and potential incorporation of machine learning models to enhance autonomous irrigation decision-making [20], [22]–[25].

4. CONCLUSION

This study presented a practical and cost-effective IoT-based smart irrigation system designed for water resource optimization in agriculture. By integrating LoRaWAN communication, the Actility ThingPark server, a MongoDB database, and a Flutter-based mobile application, the system enables real-time environmental monitoring, adaptive irrigation control, and significant water savings. The open and modular architecture ensures scalability and affordability, making it particularly suitable for small and medium-sized farms in semi-arid regions such as Tunisia.

Future developments will focus on intelligent data-driven irrigation, leveraging historical and real-time data stored in MongoDB to develop predictive models for irrigation needs and schedule optimization. Additional work will explore artificial intelligence (AI)-driven coordination between sensors and actuators within an integrated artificial intelligence of things (AIoT) framework, incorporating edge computing, blockchain-based data security, and nanosensor networks to enhance precision and autonomy.

To further improve sustainability, solar-powered operation will be implemented in future prototypes, extending system autonomy and reducing environmental impact. The research team also plans to collaborate with academic institutions, governmental agencies, and agricultural cooperatives in Tunisia to scale system deployment, promoting sustainable agriculture, improved food security, and inclusive rural development.

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AUTHOR CONTRIBUTIONS STATEMENT

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

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Imen Ayachi		✓	✓			✓		✓	✓	✓	✓			

C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nvestigation

R : **R**esources

D : **D**ata Curation

O : Writing - **O**riginal Draft

E : Writing - Review & **E**ditting

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.




DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.




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