

DEVELOPMENT AND FIELD EVALUATION OF AN IOT-BASED SMART IRRIGATION SYSTEM FOR VEGETABLE PRODUCTION IN SEMI-ARID SENEGAL

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ABSTRACT

Agriculture plays a central role in Senegal's economy, contributing about 8% to GDP and providing nearly 70% of economic activity. However, it relies heavily on seasonal crops and is increasingly affected by rainfall deficits linked to climate change. Irrigated agriculture offers an alternative but faces challenges such as limited water availability, labor-intensive manual watering, and low adoption of modern techniques. To address these issues, this study presents the design and implementation of a smart irrigation system that automatically determines crop water requirements based on field parameters (temperature, air humidity, and soil moisture) and local climate conditions. The system was tested on onions, tomatoes, and potatoes, three major crops in Senegalese market gardening. By automating irrigation and enabling remote control through ICT tools, the system reduces manual labor, optimizes water use, and minimizes environmental impact. Over a one-month experimental period, the system achieved an average 21% reduction in water use compared to manual irrigation, with mean monthly requirements of 4.2 m³ for onions, 4.6 m³ for tomatoes, and 4.1 m³ for potatoes. These results confirm the efficiency and adaptability of the proposed IoT-based approach for smallholder farmers under semi-arid conditions.



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I. INTRODUCTION

Traditionally, Senegal's economy has relied on rain-fed agriculture, livestock farming, fishing, and crafts, contributing around 8% to GDP and accounting for nearly 70% of socio-economic activity [1]. In recent decades, however, significant migration flows and recurring droughts have disrupted the country's socio-economic and agro-ecological balance. As a result, irrigation has become a key solution to address population growth and climate-related constraints [2]. Irrigation involves the artificial supply of water to agricultural land, compensating for insufficient rainfall, particularly in market gardening. Optimal production in terms of both quality and quantity requires a consistent water supply throughout the crop's growth stages. Efficient water management relies on an integrated approach that considers soil, water, plants, and nutrients.

Smart, demand-based irrigation programs, which account for crop-specific water requirements, growth stages, and environmental conditions, can enhance water use efficiency by reducing soil evaporation and optimizing plant transpiration. Determining the levels of soil water evaporation and plant transpiration allows for precise irrigation planning, which is crucial for water conservation. In this study, we designed and implemented a smart irrigation system for monitoring and controlling plant water supply. Considering the high water demand of vegetable crops in Senegal, we tested the system on onions, tomatoes, and potatoes—three crops with strong domestic and international demand. Irrigation and environmental data collected from these crops were analyzed against their respective water balances to develop an application for managing and monitoring irrigation requirements. The results demonstrate that our system effectively reduces water consumption while alleviating the labor-intensive tasks associated with manual watering.

The paper is organized as follows: Section II provides an overview of traditional irrigation techniques, modern ICT-based irrigation methods, and crop water requirements. Section III describes the design and implementation of the smart irrigation system. Section IV presents the collection and analysis of results, and Section V concludes with key findings and future research directions.

II. THEORETICAL REFERENCE

II.1 OVERVIEW OF TRADITIONAL IRRIGATION

In Senegal, traditional market gardening irrigation relies on water availability and simple techniques, such as retention basins where water seeps from rivers, or micro-irrigation using porous pipes laid in shallow trenches, particularly suitable for sandy soils (FAO). Commonly, surface irrigation is applied manually with buckets, while drip and sprinkler systems are increasingly adopted for their efficiency and water savings. Typically, water is pumped through channels into fields at regular intervals based on farmers' routines, without precise measurement or feedback on soil moisture.

This uncontrolled approach can hinder crop growth, particularly for plants sensitive to soil water content, and often results in low yields. Moreover, traditional irrigation involves repetitive and labor-intensive manual tasks. To enhance water resource management, irrigation should adopt an integrated approach considering soil, water, plants, and nutrients. Modern watering techniques, which account for crop-specific water requirements and environmental conditions, improve irrigation efficiency. Figure 1 illustrates manual irrigation (a), sprinkler (b), drip (c), and ICT-enabled irrigation techniques (d).

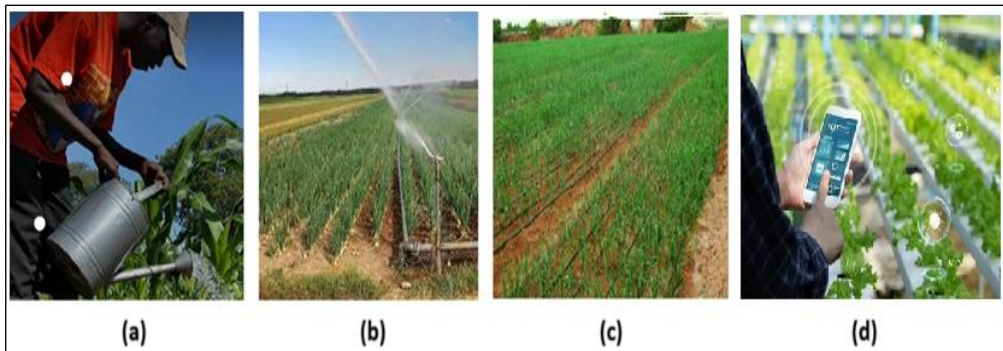


Figure 1: Illustration of traditional and modern irrigation techniques.
Source: Authors, (2026).

II.2 STATE OF THE ART IN IRRIGATION: MODERN ICT-BASED IRRIGATION TECHNIQUES

Recent research has focused on the development of smart irrigation systems using ICT tools. For instance, drip irrigation controlled by soil moisture sensors and wireless sensor networks has been widely explored [3]. Other studies implemented automated systems managed via Android applications, allowing farmers to make irrigation decisions based on real-time sensor data [4], [5]. Several works combined multiple environmental parameters including soil moisture, temperature, solar radiation, and humidity with sensor networks to optimize irrigation scheduling [5], [6]. Innovative solutions also include solar-powered drip irrigation to reduce water and energy consumption [7], and systems integrating GSM modules for remote monitoring and seasonal adjustments [8].

Other approaches focused on automated water management with temperature control and IoT-based cloud storage for data collection, enabling precise irrigation [9-12]. Microcontroller-based solutions, such as Arduino Nano, have been proposed to regulate humidity levels according to crop-specific requirements, minimizing water wastage and protecting plants [13], [14]. These studies highlight the potential of ICT-enabled irrigation to improve water use efficiency, reduce labor, and support precision agriculture. However, designing and implementing such systems requires a thorough understanding of the parameters influencing crop water requirements. Recent studies [15-17] highlight the rapid evolution of LoRa-based smart irrigation architectures in resource-limited environments.

By [15] demonstrated a LoRaWAN-enabled platform applied in olive groves, achieving over 40% water savings through long-range low-power monitoring. In turn [16] introduced a hybrid CNN-SVM classifier to enhance irrigation decision accuracy in LoRa-based IoT networks. By [17] proposed a dual-control LoRa IoT irrigation system combining local sensor feedback with cloud-based scheduling for scalability and resilience in arid environments. However, most of these systems were validated under controlled or short-term conditions. The present study distinguishes itself by providing a 30-day real-field validation in Senegal's semi-arid context, combining FAO Penman-Monteith evapotranspiration modeling with LoRa communication for low-cost, sustainable irrigation management.

II.3 STUDY OF CROP WATER REQUIREMENTS

To achieve optimal crop yields, plants must be grown under appropriate water conditions. These conditions can be ensured by accurately understanding each crop's water requirements, considering parameters such as evapotranspiration, soil water reserves, and external water inputs (rainfall or irrigation). Evapotranspiration is the biophysical process by which water is transferred to the atmosphere through both soil evaporation and plant transpiration. It is typically expressed in millimeters of water, similar to rainfall measurements. As a critical component of the crop hydrological cycle, evapotranspiration, along with soil water reserves, plays a key role in determining irrigation needs and is illustrated in Figure 2. Figure 2 shows the main components of plant water requirements.

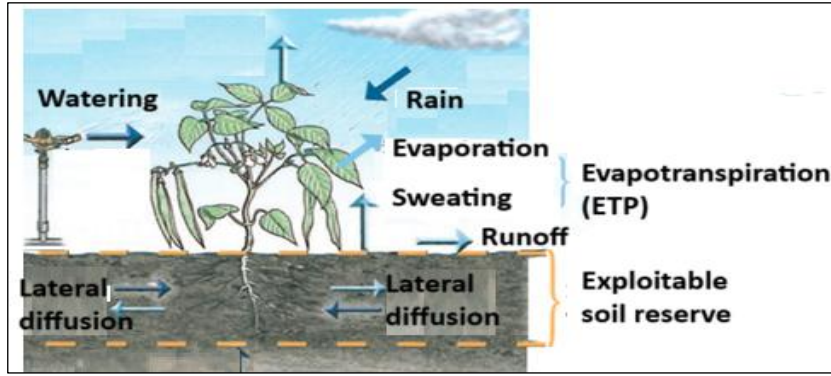


Figure 2: Elements of a plant's water requirements.
Source: [18].

To better understand plant water requirements, we conducted field visits to the National Centre for Agricultural Research in Bambey, Senegal, near the university campus. Discussions with agricultural researchers provided insights into irrigation practices and helped identify the key parameters influencing water management. Irrigation, the artificial supply of water to crops, is widely used in Senegal and other African countries, particularly for market gardening and rice cultivation. For optimal yield and quality, crops require appropriate water at different growth stages, as water needs vary by species and development phase. Thus, ensuring proper irrigation requires considering both the crop's water balance and relevant biological parameters, which are detailed in Sections II.3.1, II.3.2 and II.3.3.

II.3.1 Water Balance

The water balance at a given location and period is determined by comparing water inflows and outflows, while accounting for the formation of soil water reserves and their subsequent use. It provides essential information for calculating irrigation requirements and is primarily based on evapotranspiration. Due to its central role in water resource planning and management, several methods have been developed to estimate evapotranspiration. In this study, we use the Penman-Monteith formula [19], [20], recommended by the FAO as a reference model for its reliability under diverse climatic conditions [21]. In this formula, ET_0 represents the reference evapotranspiration, expressed in mm/day (or mm/hour).

$$ET_0 = \frac{0,408 \times \Delta (R_n - G) + \gamma \times \frac{C_{ste}}{T + 273} \times u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0,34u_2)}$$

$$\Delta = \frac{4098 e_{sat}(T)}{(T + 237,3)^2}$$

$$\gamma = 0,665 * 10^{-3} P$$

$$P = 101,3 \left(\frac{293 - 0,0065 z}{293} \right)^{5,26}$$

$$e_{sat}(T) = 0,6108 e^{\frac{17,27 T}{T+237,3}}$$

R_n = global radiation in MJ/m²/day or MJ/m²/hour, G = heat flux in the soil by conduction in MJ/m²/day or MJ/m²/hour, Δ and γ are constants in kPa/°C, C_{ste} = 900 for a daily time step and 37 for an hourly time step, T and P represent the temperature in °C and atmospheric pressure in kPa, respectively, and z = altitude above sea level (m), $e_s(T) = e_{sat}(T)$, saturated vapour pressure in kPa, $e_a(T)$ = current vapour pressure in kPa.
 u_2 = wind speed 2 meters above ground level in m/s. Finally, $e_a(T) = \frac{\text{Humidité relative} * e_s(T)}{100}$.

ETP is therefore a climatic parameter that depends on the location. In our case, we tested crops in the town of Bambey, located in central-western Senegal. In this area, (Bambey, Senegal) ETP is set at 7.3mm/day.

II.3.2 Soil Water Reserves

Soil functions as a natural water reservoir, absorbing and releasing water like a sponge. The available water reserve (AWR) represents the portion of soil water accessible to crops and depends on soil texture, expressed in mm of water per meter of soil depth. For sandy soils, the total usable reserve (RU) is 180 mm/m. Within this reserve, the readily available water (RFU) corresponds to approximately two-thirds of the RU [2], while the remaining water is tightly bound to soil particles and difficult for roots to access.

II.3.3 Biological Parameters

Biological parameters describe crop-specific characteristics, some of which are constant, while others vary with the plant's development stage. For example, water consumption changes throughout growth, highlighting the need for regular monitoring of soil moisture, air humidity, and temperature. These parameters are integrated into our smart irrigation system. Other key biological factors considered include:

- **Crop type:** This study focuses on three market garden crops: onions, tomatoes, and potatoes.
- **Crop coefficient (Kc):** Defined as the ratio between crop evapotranspiration (ETc) and reference evapotranspiration (ETo), Kc varies by crop type and growth stage (young plant, flowering, ripening, etc.). For the crops studied, Kc values are 1.1 (onion), 1.25 (tomato), and 1.15 (potato). Kc values were defined as 1.1 for onion, 1.25 for tomato, and 1.15 for potato.
- **Loss coefficient (Kp):** This factor depends on the irrigation method; in this study, drip irrigation was used (Kp = 1.05 for drip irrigation).

All these parameters are applied in the design and operation of the smart irrigation system described in Section III.

III. MATERIALS AND METHODS

III.1 DESIGN AND IMPLEMENTATION OF THE SMART IRRIGATION SYSTEM

III.1.1 Architecture and Operation of the Irrigation System

The architecture of the irrigation system is shown in Figure 3 below:

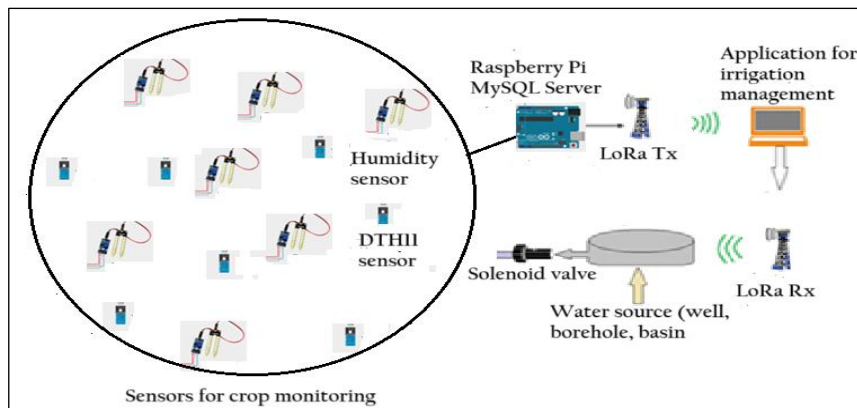


Figure 3: Architecture of the smart irrigation system.

Source: Authors, (2026).

As illustrated in Figure 3, the irrigation system consists of three (3) basic parts:

- **The data collection network** captures field data (soil moisture, ambient air humidity, air temperature) which is transmitted to a Raspberry Pi3 computer running a MySQL database server. The data is then processed and sent to the communication module, which manages its transmission.
- **The transmission part** is implemented using LoRa (Long Range) technology. This technology is responsible for remotely sending the data collected from the server to a dedicated computer application. The transmission part consists of a transmitter for sending data to the computer and a receiver for collecting data.
- **The decision support application** allows users (farmers, agricultural technicians, etc.) to manage and monitor irrigation via a computer (or smartphone). Among other things, the application allows users to view hydrological parameters and crop requirements. It also allows users to activate and/or deactivate watering automatically. The decision to water is made by activating a pump connected to a water source, which may be a mini-borehole or a well. The pump is connected to mechanical solenoid valves that regulate the pump's water flow according to the quantities of water required as determined by the application. Once the flow rate has been determined by the application, the pump is activated for the required watering time. In the following section, we will describe the implementation of our irrigation system.

III.1.2 Implementation of the Smart Irrigation System

Our irrigation system is implemented using DTH11 sensors, which measure air humidity and temperature, and LY-69 soil sensors (or hygrometers) to measure soil moisture. The LY-69 sensor is configured in two parts: the electronic board (bottom) and the two-electrode probe that detects water content (top). As for the deployment of sensors in the irrigation field, we worked on a sample field with an area of $4 \times 5 = 20 \text{ m}^2$. In the field, we deployed three LY-69 soil moisture sensors and three DTH11 sensors (ambient temperature and air humidity), making a total of six sensors. The sensors are connected to an Arduino microcontroller linked to a Raspberry Pi3 (which acts as a computer). We planted crops in each field, namely onions, tomatoes and potatoes. In addition, we monitored the development phases of these crops under the same weather conditions over a period of one month. Images (a), (b), (c) and (d) in Figure 4 show the DTH11 sensors, the soil moisture sensor, the LoRa antennas and the Arduino microcontroller, respectively.

The LoRa antennas are RYLR998 types and are wireless communication modules based on long-range technology, unlike wireless LAN transmission. This technology allows data to be transmitted over long distances (up to approximately 5 km in direct line of sight) with low energy consumption. In our study, LoRa is used as a data transmitter and receiver between the devices in the field (sensors) and the collection unit, the Raspberry Pi. The main features of the LoRa module are :

- Frequency: 868 MHz (compatible with Europe/Africa);
- Transmission power: up to +22 dBm;
- Receiver sensitivity: up to -129 dBm;
- Range: up to 5 km in open field;
- Interface: serial UART (TX/RX);
- Supply voltage: 3.3 V;
- Protocol: LoRaWAN (in point-to-point mode in our system).

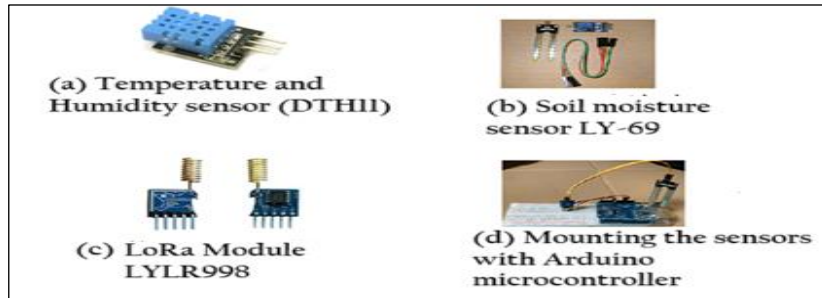


Figure 4: Illustration of the various IoT components used for the system.
Source: Authors, (2026).

Figure 5 below illustrates the electronic diagram of the overall assembly of our irrigation system.

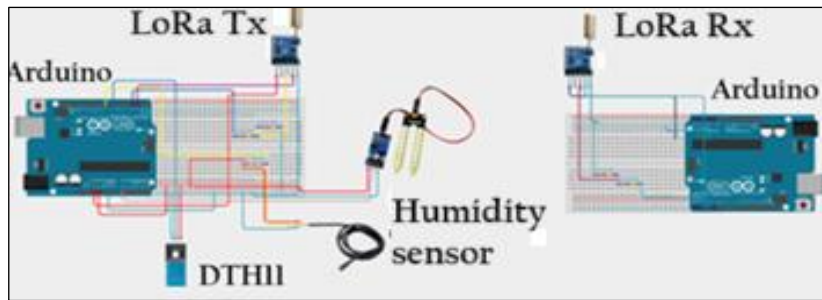


Figure 5: System assembly diagram.
Source: Authors, (2026).

After designing the assembly and configuring the various components, we implemented the intelligent part of the irrigation system. In this part, we implemented the algorithm that controls the entire system. The role of this algorithm is to calculate the water requirements of the crop type in real time, based on the water balance depending on the area and soil type and the irrigation data collected in the fields (ambient temperature, relative humidity and soil moisture). These parameters are then stored, processed and sent from the LoRa [22] transmission module to the computer program, which will decide whether or not to water by activating the pump connected to the water source and the drip system. The pseudo-code for the watering system algorithm is presented below.

III.1.3 Algorithm for Calculating Water Requirements

$$\text{Water_requirements_for_Day} = \text{Etp} * \text{Kc} * \text{Fied_Size} * \text{Kp}$$

Etp: this is the potential evapotranspiration, i.e. a climatic parameter that depends on the location of Bambej, $\text{Etp} = 7.3$

Kc: crop coefficient specific to each type of crop

Onion: $\text{Kc} = 1.1$

Tomato: $\text{Kc} = 1.25$

Potato: $\text{kc} = 1.15$

Kp: loss coefficient, which is specific to the watering method used

Our smart system is connected to a drip irrigation system

Drip irrigation system $\text{Kp} = 1.05$

Area: the area where the crop is grown = $4 * 5 = 20 \text{ m}^2$

The watering time is given by the formula:

$$\text{Daily_Water_Requirements} = \frac{\text{Water_requirements_in_Day}}{\text{Watering flow rate}}$$

We have a drip system with 8 drippers, each with a flow rate of 2L/min.

The flow rate of the system is therefore:

$$\text{Watering flow rate} = 8 * 2 = 16 \text{ liters per minute}$$

Note: the flow rate of the system is either the flow rate of the pump or that of the watering system used. If you are using a drip irrigation system, you must adjust the pump so that it has the same flow rate as the drip system. The total flow rate of a drip system is equal to the sum of the flow rates of each dripper. For example, we are using a drip system with 8 drippers, each with a flow rate of 2liters/min. Therefore, the flow rate of this system is $8 \times 2 = 16\text{L}/\text{min}$.

The experimental setup was extended and refined to include both a smart irrigation plot and a reference manual plot of the same size (20 m²). The manual plot was watered following conventional practices to provide a baseline for comparison, while the smart system applied data-driven irrigation decisions based on the computed water balance. The prototype was evaluated continuously over a 30-day field period, recording daily water consumption for onions, tomatoes, and potatoes. These measurements allowed a more representative validation of the system’s stability and long-term efficiency.

In addition, a detailed wiring schematic was designed to enhance reproducibility. The circuit connects an Arduino Uno, DHT11 temperature/humidity sensor, YL-69 soil moisture sensor, LoRa transceiver, and Raspberry Pi controller that manages computation and data logging. The system automatically computes daily irrigation needs using the FAO Penman–Monteith equation and crop-specific coefficients (Kc), ensuring that irrigation is activated only when necessary.

IV. RESULTS AND DISCUSSIONS

IV.1 TESTS, COLLECTION OF RESULTS AND ANALYSES

The smart irrigation system was deployed on a 20 m² sandy-soil plot in Bambey, Senegal, and tested on three vegetable crops: onion, tomato, and potato. After system calibration (soil type, crop type, irrigation method, and pump flow rate), environmental parameters (temperature, relative humidity, and soil moisture) were collected using sensors and transmitted via LoRa. Environmental parameters were collected via LoRa for 30 days. Daily water requirements were calculated using the Penman–Monteith evapotranspiration (ET₀), crop coefficient (Kc), and pump flow rate. Results in Table 1 show that onions, tomatoes, and potatoes required 160 L, 182.9 L, and 167.9 L per day during the initial growth stage, corresponding to irrigation times of 10.25, 11.69, and 10.76 minutes, respectively.

Table 1: Water requirements and irrigation times for onion, tomato and potato crops.

	Daily water requirements (in m ³)	Daily water requirements (in L)	Watering time (in minutes)
Onion	0.1600	160	10.25
Tomato	0.18285	182.85	11.69
Potato	0.1679	167.9	10.76

Source: Authors, (2026).

Cumulative water requirements over the first ten days are summarized below in table 2.

Table 2: Calculation of cumulative water requirements for the first 10 days of irrigation for onion, tomato and potato crops.

Day	Water requirements (in m ³) for onions	Water requirements (in m ³) for tomatoes	Water requirements (in m ³) for potatoes
1 ^e	0.16	0.182	0.167
2 ^e	0.32	0.364	0.334
3 ^e	0.48	0.546	0.501
4 ^e	0.64	0.728	0.668
5 ^e	0.8	0.91	0.835
6 ^e	0.96	1.092	1.002
7 ^e	1.12	1.274	1,169
8 ^e	1.76	1.456	1,336
9 ^e	1.92	1.638	1,503
10 ^e	2.08	1.82	1.67

Source: Authors, (2026).

Sensor measurements confirmed that the system maintained stable conditions throughout the monitoring period. Relative humidity varied between 53% and 57%, while soil moisture differences among the three crops did not exceed +3%.

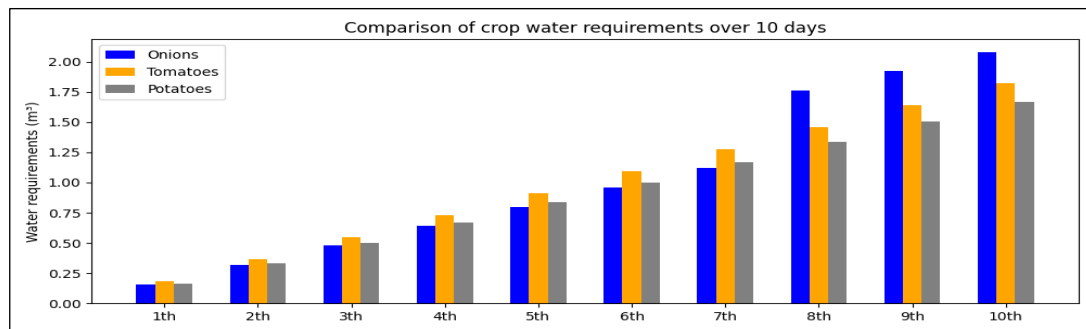


Figure 6: Variation in cumulative water requirements.

Source: Authors, (2026).

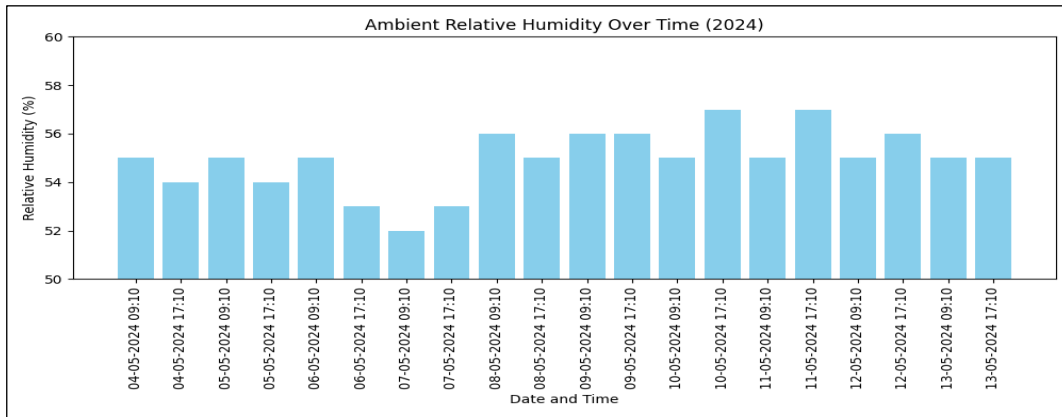


Figure 7: Relative humidity levels during the 10-day test period.
Source: Authors, (2026).

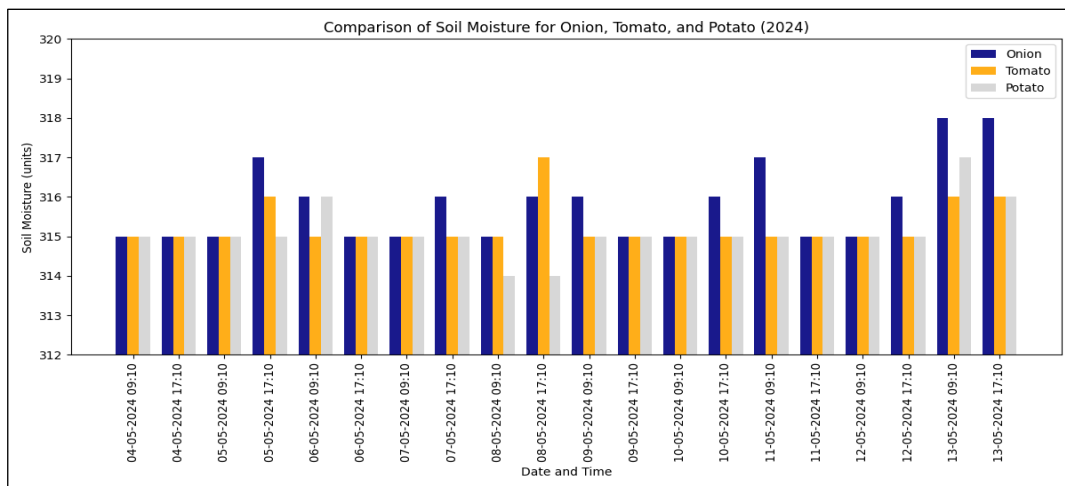


Figure 8: Soil moisture levels for onion, tomato, and potato crops.
Source: Authors, (2026).

Sensor data confirmed that soil moisture remained within acceptable ranges, with minimal variation between crops (Figures 6, 7, and 8). Figure 6 shows that the cumulative water requirement increased steadily with crop growth. Figures 7 and 8 confirm that relative humidity and soil moisture were maintained within optimal bounds, validating the consistency of the control algorithm across all test conditions. This stability reflects both the accuracy of irrigation scheduling and the reliability of the IoT-based control system. These results indicate that the system effectively supplies water according to crop-specific requirements while avoiding water stress during early developmental stages.

IV.2 COMPARATIVE ANALYSIS: IOT-BASED VS MANUAL IRRIGATION SYSTEMS

To evaluate the efficiency of the proposed IoT-based smart irrigation system, a comparative analysis was conducted using both theoretical FAO water requirements and manual irrigation estimates typically observed in Senegalese market gardening.

a. Comparison with Theoretical (FAO) Water Requirements

Table 3: Comparison between FAO Reference and Smart System Water Requirements.

Crop	FAO Reference (m ³ /month)	Measured (Smart System, m ³ /month)	Difference (%)
Onion	5.0	4.2	-16%
Tomato	5.5	4.6	-16%
Potato	5.2	4.1	-21%

Source: Authors, (2026).

Compared to FAO-based natural water requirements, Table 3, the smart irrigation system achieved an **average reduction of 16–21%** in water use while maintaining optimal soil moisture levels. This indicates that the IoT-based regulation prevented the over-irrigation commonly observed in manual practices relying on fixed time intervals rather than soil and climate feedback. The cumulative sensor data recorded during the first ten days (Table 2) exhibited a nearly linear increase in water requirements across all three crops. When these early-stage values are linearly extrapolated to a 30-day period, they result in higher projected totals (6.24 m³ for onion, 5.46 m³ for tomato, and 5.01 m³ for potato) than those reported in Table 3 (4.2–4.6 m³ per month). This apparent discrepancy reflects the adaptive behavior of the IoT-based irrigation control system rather than a measurement error. After approximately ten days of operation, soil moisture levels stabilized, leading to fewer irrigation events and a gradual reduction in daily water application.

Consequently, the measured monthly averages represent the **regulated water use** over the entire growth period rather than a simple linear accumulation of initial daily rates. These findings confirm the system’s ability to **self-adjust irrigation frequency** based on real-time soil moisture feedback, thereby preventing over-irrigation and ensuring sustainable water management efficiency over time.

b. Comparison with Manual Irrigation (Traditional Practices)

Table 4: Comparison with manual irrigation.

Crop	Manual (m ³ /month)	IoT-Based (m ³ /month)	Water Saving (%)
Onion	5.4	4.2	22.2%
Tomato	5.8	4.6	20.7%
Potato	5.2	4.1	21.2%

Source: Authors, (2026).

The results in table 4 demonstrate that the IoT-based irrigation system reduced water consumption by approximately 21% on average compared to manual irrigation. This improvement results from the real-time computation of evapotranspiration (ET_o) and dynamic adjustment of irrigation time based on local environmental variables. Consequently, the system contributes to both sustainable water management and climate-resilient agriculture in semi-arid regions.

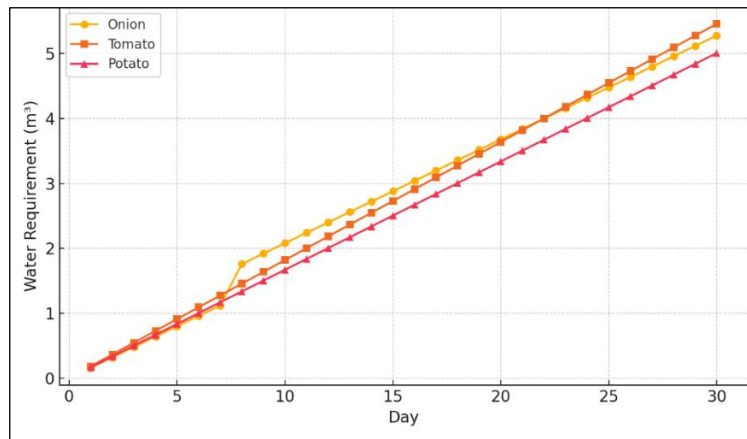


Figure 9: Daily water requirements for onions, tomatoes, and potatoes over a 30-day period under the smart irrigation system.

Source: Authors, (2026).

The results show a steady linear increase in cumulative water demand corresponding to crop growth stages. The IoT-based control maintained consistent irrigation across all crops, with tomato plots exhibiting the highest water demand due to greater canopy coverage. The smooth progression of the curves reflects efficient water management and confirms the system’s capacity to adapt irrigation frequency to real-time evapotranspiration data.

c. Energy Efficiency

The total power consumption of the system, including the sensors, LoRa module, and control unit, averaged 1.8 W in active mode and 0.25 W in standby mode. These values confirm the system’s suitability for solar-powered operation in off-grid rural contexts.

IV.3 DISCUSSION

The results demonstrate that the proposed smart irrigation system can effectively optimize water distribution in vegetable crops. By integrating environmental data (temperature, relative humidity, and soil moisture) with evapotranspiration-based calculations, irrigation was precisely adjusted to crop-specific needs. Compared to conventional methods (manual watering, surface irrigation), this approach offers several key advantages:

- **Water efficiency:** by delivering only the required dose, the system reduces waste and mitigates risks of over-irrigation or water stress.
- **Crop adaptability:** by incorporating biological parameters (crop type, K_c, growth stage), the system ensures better alignment with plant development.
- **Context relevance:** unlike many ICT-based irrigation systems designed in controlled environments, this prototype was tested under real agroecological conditions in Senegal, on sandy soil and with locally important vegetable crops. This strengthens its applicability and transferability to similar contexts.
- **Low-cost and frugal design:** the system leverages LoRa communication and simple sensors, making it affordable and energy-efficient an important feature for smallholders with limited resources.

Sensor data confirmed that soil moisture remained within acceptable ranges, with minimal variation between crops. This stability reflects both the accuracy of irrigation scheduling and the reliability of the IoT-based control system. The combination of Penman–Monteith evapotranspiration with crop-specific coefficients provided a robust basis for irrigation planning, ensuring that the system aligned closely with actual plant water demand.

These findings are consistent with recent studies on ICT-based irrigation, which highlight the potential of IoT and sensor networks to address water scarcity challenges in agriculture. However, the contribution of this work lies in bridging the gap between conceptual models and field validation in African agroecological conditions. Nonetheless, further experiments over longer growth cycles, across different soil types, and with more crop varieties are required to fully evaluate scalability and robustness.

V. CONCLUSIONS

This paper presented the design, deployment, and evaluation of an IoT-based smart irrigation system for vegetable crops in Senegal. By combining environmental sensing, evapotranspiration-based water balance, and automated control, the system was tested on onion, tomato, and potato crops during their early growth phase. The collected data confirmed that the prototype ensures reliable monitoring, reduces water consumption, and alleviates the burden of manual irrigation practices commonly used in Senegalese market gardening.

Beyond technical performance, the system demonstrates the feasibility of frugal and modular IoT solutions tailored to African smallholder contexts. Its reliance on affordable sensors, LoRa-based communication, and simple control algorithms makes it particularly suitable for rural areas with limited connectivity and infrastructure. This strengthens its potential as a scalable and sustainable tool for resource-efficient agriculture. Looking ahead, future work will focus on:

- Extending the tests to a wider range of crops and longer growth cycles.
- Integrating renewable energy sources, such as solar panels, to enhance autonomy in rural areas with limited access to electricity.
- Adapting the system to large-scale crops like rice, where water management remains a critical issue.
- Exploring advanced data analytics and predictive algorithms to further optimize irrigation scheduling.
- Investigating participatory approaches with farmers to ensure usability, adoption, and local ownership of the system.

In sum, the proposed system constitutes a promising step toward sustainable, resource-efficient, and context-adapted agriculture in Senegal and other regions facing similar constraints. The findings confirm that the smart irrigation system effectively reduces water consumption while maintaining crop adaptability under real field conditions. Future work will extend the monitoring to a full crop growth cycle (≈ 90 days) and explore the integration of solar energy and predictive irrigation models using weather forecast data and soil moisture prediction algorithms. By demonstrating both technical feasibility and contextual relevance, this work contributes to narrowing the gap between IoT innovation and its real-world application in agroecology.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Pape El Hadji Abdoulaye Gueye, Diery Ngom.

Methodology: Pape El Hadji Abdoulaye Gueye.

Investigation: Diery Ngom.

Discussion of results: Pape El Hadji Abdoulaye Gueye.

Writing – Original Draft: Pape El Hadji Abdoulaye Gueye.

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