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PROPOSTA DE ARQUITETURA IOT DE BAIXO CUSTO PARA MONITORAMENTO E AUTOMAÇÃO DA IRRIGAÇÃO NO SEMIÁRIDO PARAIBANO: ANÁLISE PRELIMINAR DE VIABILIDADE TÉCNICO-ECONÔMICA E DE SUSTENTABILIDADE HÍDRICA

LOW-COST IOT ARCHITECTURE PROPOSAL FOR IRRIGATION MONITORING AND AUTOMATION IN THE SEMIARID REGION OF PARAÍBA: PRELIMINARY TECHNICAL-ECONOMIC AND WATER SUSTAINABILITY ANALYSIS

PROPUESTA DE ARQUITECTURA IOT DE BAJO COSTO PARA EL MONITOREO Y LA AUTOMATIZACIÓN DEL RIEGO EN LA REGIÓN SEMIÁRIDA DE PARAÍBA: ANÁLISIS PRELIMINAR DE VIABILIDAD TÉCNICO-ECONÓMICA Y DE SOSTENIBILIDAD HÍDRICA

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Resumo
Este artigo apresenta uma proposta técnica de baixo custo para o monitoramento e a automação da irrigação, orientada por sensores, em área agrícola experimental no semiárido paraibano. O estudo

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teve como objetivo propor uma arquitetura baseada em internet das coisas – sensores de umidade do solo, microcontroladores, comunicação sem fio, válvulas solenoides e supervisão remota – e realizar uma análise preliminar de sua viabilidade técnico-econômica, sem validação experimental em campo. As estimativas indicam investimento inicial de R$ 2.310,00, *payback* simples projetado em 2,29 anos e Taxa Interna de Retorno projetada de 33,3%. Projeta-se ainda redução de até 30% no consumo de água e incremento de até 10% na produtividade anual, valores que dependem de confirmação experimental. Conclui-se que a proposta apresenta potencial técnico e de replicação, a ser confirmado por meio de implantação e validação em campo.
Palavras-chave: internet das coisas; irrigação inteligente; automação rural; agricultura familiar; sustentabilidade hídrica.

Abstract

This article presents a low-cost technical proposal for sensor-based monitoring and automation of irrigation in an experimental agricultural area located in the semiarid region of Paraíba, Brazil. The study aimed to propose an architecture based on the Internet of Things – soil moisture sensors, microcontrollers, wireless communication, solenoid valves, and remote supervision – and to carry out a preliminary technical-economic feasibility analysis, without field validation. Estimates indicate an initial investment of BRL 2,310.00, a projected simple payback of 2.29 years, and a projected Internal Rate of Return of 33.3%. A reduction of up to 30% in water consumption and an increase of up to 10% in annual productivity are also projected, values that depend on experimental confirmation. It is concluded that the proposed solution has technical and replication potential, to be confirmed through implementation and field validation.
Keywords: internet of things; smart irrigation; rural automation; family farming; water sustainability.

Resumen

Este artículo presenta una propuesta técnica de bajo costo para el monitoreo y la automatización del riego, orientada por sensores, en un área agrícola experimental ubicada en la región semiárida de Paraíba, Brasil. El estudio tuvo como objetivo proponer una arquitectura basada en internet de las cosas – sensores de humedad del suelo, microcontroladores, comunicación inalámbrica, válvulas solenoides y supervisión remota – y realizar un análisis preliminar de su viabilidad técnico-económica, sin validación experimental en campo. Las estimaciones indican una inversión inicial de R$ 2.310,00, un *payback* simple proyectado de 2,29 años y una Tasa Interna de Retorno proyectada de 33,3%. También se proyecta una reducción de hasta el 30% en el consumo de agua y un incremento de hasta el 10% en la productividad anual, valores que dependen de confirmación experimental. Se concluye que la propuesta presenta potencial técnico y de replicación, a confirmarse mediante implementación y validación en campo.
Palabras clave: internet de las cosas; riego inteligente; automatización rural; agricultura familiar; sostenibilidad hídrica.

1. Introduction

The Brazilian Northeastern semiarid region faces structural challenges of water scarcity and irregularity, which compromise the efficiency of family farming. Automation technologies based on the Internet of Things (IoT) have proven to be viable alternatives for more rational water use, especially when adapted to low-cost solutions compatible with the reality of small rural properties (Bolfe *et al.*, 2020; Gupta *et al.*, 2025). Public policies such as the National Research and Innovation Program for Family Farming and Agroecology (PNPIAF) reinforce the relevance of accessible

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technological solutions adapted to different territorial contexts (Brasil, 2024).

Given this context, this work aims to propose a low-cost, sensor-oriented architecture for monitoring and automating irrigation in an experimental agricultural area in the semiarid region of Paraíba, and to preliminarily estimate its technical-economic feasibility. The proposal integrates soil moisture sensors, microcontrollers, wireless communication, solenoid valves, and remote supervision, seeking a replicable model for family farming and the rational use of water in semiarid regions.

2. Literature Review

2.1. Digital agriculture and Smart Farm

Digital agriculture has transformed agricultural systems by incorporating information, communication, automation, and data analysis technologies into the production process. This advance makes it possible to replace practices based solely on empirical observation with more precise, connected, and data-driven strategies, supported by sensors, microcontrollers, communication networks, and digital platforms for monitoring soil, irrigation, and crops (Bolfe *et al.*, 2020; Cherubin *et al.*, 2022; Soussi *et al.*, 2024).

The Smart Farm concept is related to the integration of physical devices, computational systems, and digital platforms to monitor, control, and automate agricultural activities. Based on field-collected data, it becomes possible to support decisions on irrigation, energy, operational management, input application, and production planning (Rejeb *et al.*, 2022; Soussi *et al.*, 2024).

In semiarid regions, this approach is especially relevant, as water constraints demand greater efficiency in water and energy use. Digital agriculture can reduce waste, improve control of growing conditions, and expand the producer's ability to respond to climatic and operational variations (Bolfe *et al.*, 2020; Brasil, 2024).

Mishra (2025) reports productivity gains of up to 30% associated with the use of artificial intelligence-driven data analysis, while Onike (2025), based on international case studies including Brazil, associates the adoption of agricultural IoT

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with productivity increases of around 25% and water consumption reductions close to 30% (Assis; Piantoni; Azevedo, 2024).

2.2. IoT, sensors, and irrigation automation

The Internet of Things (IoT) consists of the integration of connected physical devices capable of collecting, transmitting, and processing data through communication networks. In agriculture, it enables the connection of sensors, microcontrollers, actuators, and supervisory platforms, converting soil, water, climate, and equipment data into information useful for agricultural management (Obaideen *et al.*, 2022; Soussi *et al.*, 2024).

Sensors are central components of IoT systems, as they capture physical, chemical, or environmental variables and convert them into processable signals. In agricultural applications, soil moisture, temperature, air humidity, luminosity, reservoir level, soil pH, and electrical conductivity sensors stand out, used to monitor growing conditions in real time (Obaideen *et al.*, 2022; Soussi *et al.*, 2024).

In smart irrigation, soil moisture sensors allow the identification of water availability in the root zone. With this data, the system can activate or interrupt irrigation according to defined thresholds, avoiding water waste, water deficit, and unnecessary pump activation. Automation occurs through the integration of sensors, microcontrollers, and actuators. Microcontrollers receive data, process the information, and send commands to relays, solenoid valves, contactors, or pumps, allowing irrigation to operate in a data-driven manner with less dependence on manual intervention (Gupta *et al.*, 2025; Jiang *et al.*, 2025; Uberti *et al.*, 2023).

In addition to local control, IoT systems enable remote monitoring through dashboards, applications, or supervisory platforms. These interfaces enable real-time data visualization, device tracking, alerts, and manual commands, especially when irrigation or water capture points are far from the operator (Obaideen *et al.*, 2022; Soussi *et al.*, 2024).

The choice of communication network depends on the distance between devices, data volume, energy consumption, and available infrastructure. In nearby

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areas, Wi-Fi may be sufficient; over greater distances, long-range, low-power technologies such as Long Range (LoRa) and Low-Power Wide-Area Network (LPWAN) become suitable for rural agricultural applications (Obaideen *et al.*, 2022; Soussi *et al.*, 2024).

2.3. Low-cost technologies for family farming

Family farming plays a relevant role in food production, rural income, and the maintenance of diversified production systems. However, it still faces limitations in credit, connectivity, technical assistance, infrastructure, and access to higher value-added technologies. Thus, the adoption of digital solutions depends on equipment availability and its suitability to the economic, social, and operational conditions of producers (Mizik, 2023; Trendov; Varas; Zeng, 2019).

In this context, low-cost technologies are alternatives for expanding digital inclusion in rural areas. Affordable microcontrollers, simple sensors, wireless communication modules, open platforms, and automation devices can enable smart systems on small properties, reducing initial investment and facilitating replication across different production areas (Junaid; Sukhi; Anita, 2024; Puig; Diaz; Soriano, 2022).

In the Brazilian context, recent initiatives already demonstrate the feasibility of low-cost IoT architectures applied to family farming. Caetano *et al.* (2025) developed an embedded automated irrigation system with LoRa communication for family horticulture in Arapiraca (AL), dispensing with Wi-Fi in the cultivation area and demonstrating technical feasibility even in regions with limited connectivity. Similarly, Silva (2024) proposed an IoT-based automated irrigation system for a family farming property in the interior of São Paulo, adopting the Design Science Research method for developing the technological artifact.

Tools such as TensorFlow Lite, Edge Impulse, and TinyML enable the execution of Machine Learning (ML) models on low-cost embedded devices, allowing local data processing even in environments with connectivity limitations (David *et al.*, 2021; Donskoy; Gvindjiliya; Ivliev, 2025).

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These works reinforce the relevance of low-cost IoT solutions for Brazilian family farming, although, in both cases, data processing and storage depend on cloud services, unlike the proposal presented here, which uses a local supervisory platform.

Open source platforms also reduce dependence on proprietary solutions and recurring costs. Integrated with low-cost devices, they allow greater configuration flexibility, local data control, customization, and adaptation to the needs of each rural property (Puig; Diaz; Soriano, 2022; Quy *et al.*, 2022).

Beyond cost, usability is decisive for technology adoption. Systems aimed at small producers must be simple, intuitive, and easy to maintain, avoiding excessive complexity and permanent dependence on specialized support. User training must accompany the deployment of digital solutions. The efficient use of sensors, supervisory platforms, and automated devices requires producers to understand the system's logic, the indicators presented, and the decisions possible from the collected data (Mizik, 2023; Trendov; Varas; Zeng, 2019).

Thus, a low-cost Smart Farm should be understood as an incremental innovation model. Rather than starting with complex technologies such as drones, artificial intelligence, or advanced Big Data systems, deployment can begin with basic monitoring and automation modules, such as soil moisture sensors and irrigation control. New modules can be incorporated as production needs, financial availability, and the property's technological maturity evolve.

2.4. Water sustainability and economic feasibility in the semiarid region

Water sustainability is a central challenge for agriculture in semiarid regions, due to rainfall irregularity, high evapotranspiration, reservoir limitations, and competition for water use. Therefore, irrigation must consider the actual needs of crops, soil conditions, and water availability throughout the production cycle (Coelho *et al.*, 2017).

Studies conducted in the Paraíba semiarid region itself corroborate this relationship between hydraulic efficiency and productive sustainability: Dantas Neto *et al.* (2013), when evaluating drip irrigation systems in small properties in the region,

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found relevant variations in flow rate and pressure between units, reinforcing the importance of adequate hydraulic sizing and continuous monitoring to ensure the efficiency of localized irrigation in contexts similar to the present research.

Smart irrigation systems contribute to this objective by applying water only when necessary and in more appropriate amounts. Soil moisture sensors, controllers, and automated valves reduce dependence on fixed schedules, avoid waste, decrease energy consumption, and improve water use efficiency (Gupta *et al.*, 2025; Obaideen *et al.*, 2022).

In this context, economic feasibility must be analyzed together with environmental sustainability and operational efficiency, through indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and simple payback, especially relevant in family farming, where investment resources are more limited (Gupta *et al.*, 2025; Junaid; Sukhi; Anita, 2024; Coelho *et al.*, 2017; Puig; Diaz; Soriano, 2022).

2.5. Original contribution relative to similar solutions

Table 1 presents a comparative synthesis between the proposal presented and the closest related works identified in the literature.

Table 1 – Comparison between the proposal and related works

Criterion	This work	Caetano *et al.* (2025)	Puig, Diaz and Soriano (2022)
No. of zones/sectors	6 zones + capture point	Not zoned (2 modules: field + residence)	2 sectors (22.7 ha and 19.3 ha)
Sensors	Soil moisture (capacitive V2.0) + level (float)	Soil moisture (capacitive V2.0) + air temperature/humidity (DHT11)	3 probes per node (moisture, EC, and temperature, 15-45 cm) + water potential sensor
Communication	Wi-Fi (local) + LoRa (capture, ~1 km)	LoRa (no Wi-Fi in the field)	Configurable (LoRaWAN, SigFox, NB-IoT, GSM, Wi-fi or Bluetooth)
Local control	Yes (Home Assistant, existing PC)	No (paid cloud, DigitalOcean)	Yes (local Raspberry Pi, via Docker)
Power supply	Solar + battery	5V power supply or rechargeable lithium battery	18650 battery + solar panel + TP4056 charger
Approximate cost	R$ 2,310.00 (detailed total investment)	Only unit price range (US$ 4-10/sensor); no complete or total materials list	Detailed component list; no monetary value reported
Field validation	No (preliminary study)	No (limitation acknowledged by the authors)	Yes (one complete irrigation season)

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Application	Fruit growing (mango), Paraíba semiarid region	Horticulture (lettuce, chives, cilantro), Arapiraca-AL	Olive growing (22.7+19.3 ha), Córdoba-Spain
Limitations	No experimental validation; sensor calibration pending	No field validation; depends on paid cloud	Higher complexity and deployment cost; much larger scale

Source: Authors.

Although the literature already presents low-cost IoT architectures for irrigation – such as the open-source platform based on the FIWARE framework by Puig, Diaz and Soriano (2022), validated on an olive grove in Spain, and the LoRa-based system by Caetano *et al.* (2025), applied to family horticulture in Arapiraca (AL) –, the present proposal differs mainly in its context-specific diagnosis of the Paraíba semiarid region, which guided design choices such as zone-based sectorization, remote water capture approximately 1 km from the reservoir, and the combination of Wi-Fi (local supervision) with LoRa (long-range link).

The use of a local supervisory platform (Home Assistant), although already documented in residential automation applications and open-source projects aimed at domestic irrigation, had not yet been associated, in the consulted literature, with a technical-economic feasibility study of irrigation for family farming in the Brazilian semiarid region.

Thus, the contribution of the present study lies less in the isolated originality of each technological component – already documented individually in the national and international literature – and more in the integration of these elements based on a real field diagnosis and a preliminary feasibility analysis specific to the context addressed.

3. Methodology

3.1. Research design

The research is characterized as applied, descriptive, and exploratory, of a predominantly quantitative nature, aimed at technological design and preliminary technical-economic feasibility assessment. It is applied because it proposes a technological solution for monitoring and automating irrigation in an agricultural area of the Paraíba semiarid region.

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The quantitative character stems from the measurement of technical and economic variables (such as costs, financial indicators, water consumption, and productivity), although supported by an initial diagnosis of the operational context of the study area, including physical conditions, infrastructure, water availability, and the existing irrigation system.

The descriptive character relates to the characterization of the area, the technological components, the operating logic, and the planning stages of the solution. It is also exploratory in structuring a replicable model, still at the proposal and technical-economic assessment stage, aimed at future applications in small rural properties and experimental agricultural units (Gil, 2022; Silva, 2015).

3.2. Study area characterization

The study was conducted in an experimental agricultural area located in the municipality of São Domingos, Paraíba, within the Northeastern semiarid region. The property covers approximately 30 ha. The region presents typical semiarid conditions, with water restrictions, rainfall irregularity, naturally low-fertility soils, and limited nutrient retention.

Figure 1 presents the cultivated area and the spatial organization of the plants.

Figure 1 – Cultivated area and spatial organization of the plants



Source: Adapted from Google Earth (satellite image from 11/15/2025, scale 20 m), coordinates 6°48'43.63"S, 37°56'13.55"W, elevation 187 m; authors.

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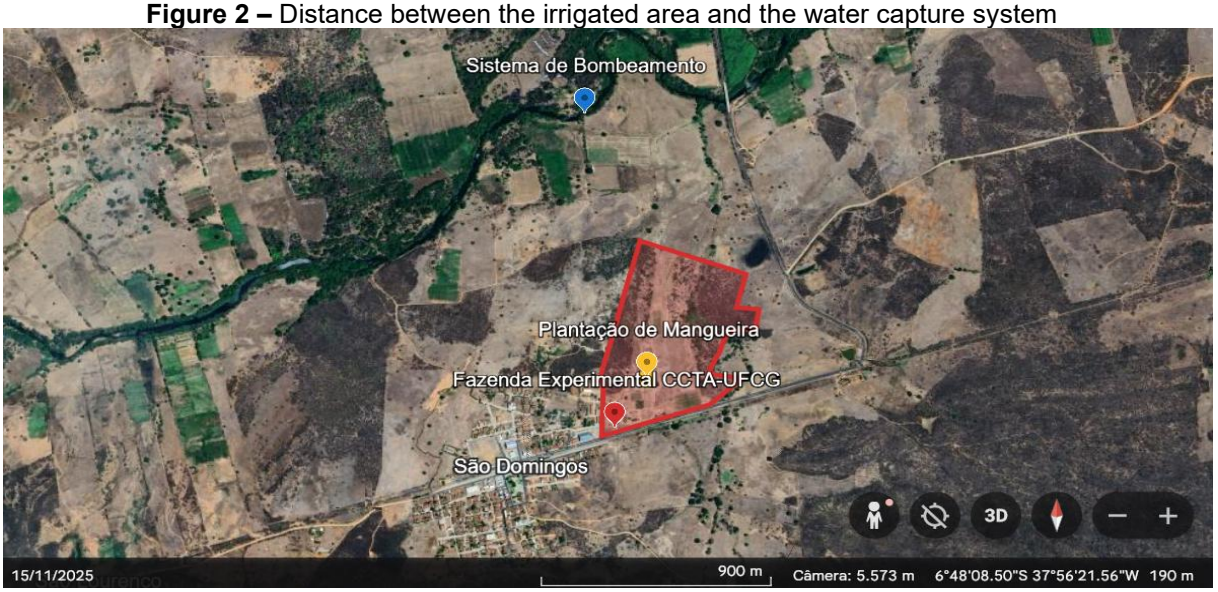
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The region is located in the Alto Sertão region of Paraíba, where Luvisols predominate, with localized occurrences of Lithic Neosols and Vertisols (Francisco *et al.*, 2017). Given the high variability in available water capacity observed in this soil class, resulting from the variable volume of gravel in the surface horizon, detailed physical characterization of the area (field capacity, permanent wilting point, bulk density, and phenological phase) was not carried out at this preliminary stage (Table 14). These characteristics make rational water management essential to local agricultural development.

The research area corresponded to approximately 1,600 m^2, cultivated with 36 mango trees in a 6 x 6 spatial arrangement (6 rows of 6 trees). This configuration allowed the system to be divided into six irrigation zones, each associated with a region of the terrain. The area was selected because it has basic irrigation infrastructure, sectorization feasibility, and potential to evaluate a modular, low-cost, and replicable solution for small production units. The existing system consisted of piping, hoses, and a water capture pump, but with predominantly manual activation.

As shown in Figure 2, the pumping point is located approximately 1 km from the irrigated area, which increases management time, requires physical travel, and exposes workers to risks common in rural environments, such as uneven terrain, intense heat, and the presence of venomous animals.

Figure 2 – Distance between the irrigated area and the water capture system



Source: Adapted from Google Earth (satellite image from 11/15/2025, scale 900 m), coordinates 6°48'08.50"S, 37°56'21.56"W, elevation 190 m; authors.

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This limitation is detailed in the following subsection, dedicated to the technical-operational diagnosis of the system.

The water used for irrigation is captured directly from a surface watercourse, without prior treatment, which exposes hydraulic components and sensors to sediment and suspended organic matter. It is recommended to install a line filter upstream of the solenoid valves, with a periodic cleaning routine, to mitigate the risk of emitter clogging and accelerated component wear (Table 14).

3.3. Technical and operational diagnosis

The technical diagnosis was the first methodological stage of the research and sought to identify the actual conditions of the agricultural area, the available resources, and the limitations of the conventional irrigation system. Aspects such as location, terrain characteristics, crop type, irrigation infrastructure, electricity and internet availability, distance between the reservoir and the capture point, equipment activation method, and automation possibilities were observed.

The analysis indicated that the main operational limitation was the manual activation of irrigation and the capture pump. The absence of automatic soil moisture monitoring favors decisions based on empirical observation or fixed routines, which may result in water excess or deficit. In the semiarid region, this limitation is critical, as inadequate water use compromises water sustainability and productive efficiency. The need for distinct communication solutions for the irrigated area and the capture system was also identified.

While local connectivity can be met by Wi-Fi, communication between the reservoir and the capture point requires longer-range, low-power-consumption technology. This condition justified dividing the architecture into two integrated subsystems: automated irrigation, aimed at sectorized control of water application, and remote capture, dedicated to the automated activation of the supply pump.

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3.4. Technological planning and organization of actions

After the diagnosis, the system's technological planning was carried out, covering hardware component selection, definition of the operating logic, choice of communication technologies, and structuring of the supervisory interface. This stage was guided by the principle of seeking low-cost solutions, easy acquisition, simplified maintenance, and compatibility with the context of family farming and small production areas.

To organize the implementation stages and justify the technical decisions, the 5W2H tool was used, comprising the questions: What, Why, Where, Who, When, How, and How much. The application of this tool made it possible to systematize what would be proposed, why the technology would be necessary, where the system would be applied, which agents would be involved, at which stages the solution could be implemented, how the components would be integrated, and what costs would be associated with the project (Silva; Canola, 2023), as shown in Table 2.

Table 2 – Technological planning structured using the 5W2H tool

Element	Description applied to the proposed system
What	Proposal of a low-cost system for irrigation monitoring and automation
Why	Reduce water waste, improve operational efficiency, and decrease dependence on manual activation
Where	Experimental agricultural area with mango cultivation in the Paraíba semiarid region
Who	Technical team involved in the planning, installation, supervision, and evaluation of the system
When	After the area diagnosis, definition of components, and organization of the automation architecture
How	Integration of moisture sensors, microcontrollers, relays, solenoid valves, wireless communication, and supervisory platform
How Much	Cost estimate based on physical components, installation, maintenance, and training

Source: Prepared by the authors based on Silva and Canola (2023).

The planning structured in Table 2 guided the detailed technical decisions described below, in the selection and sizing of the system's components.

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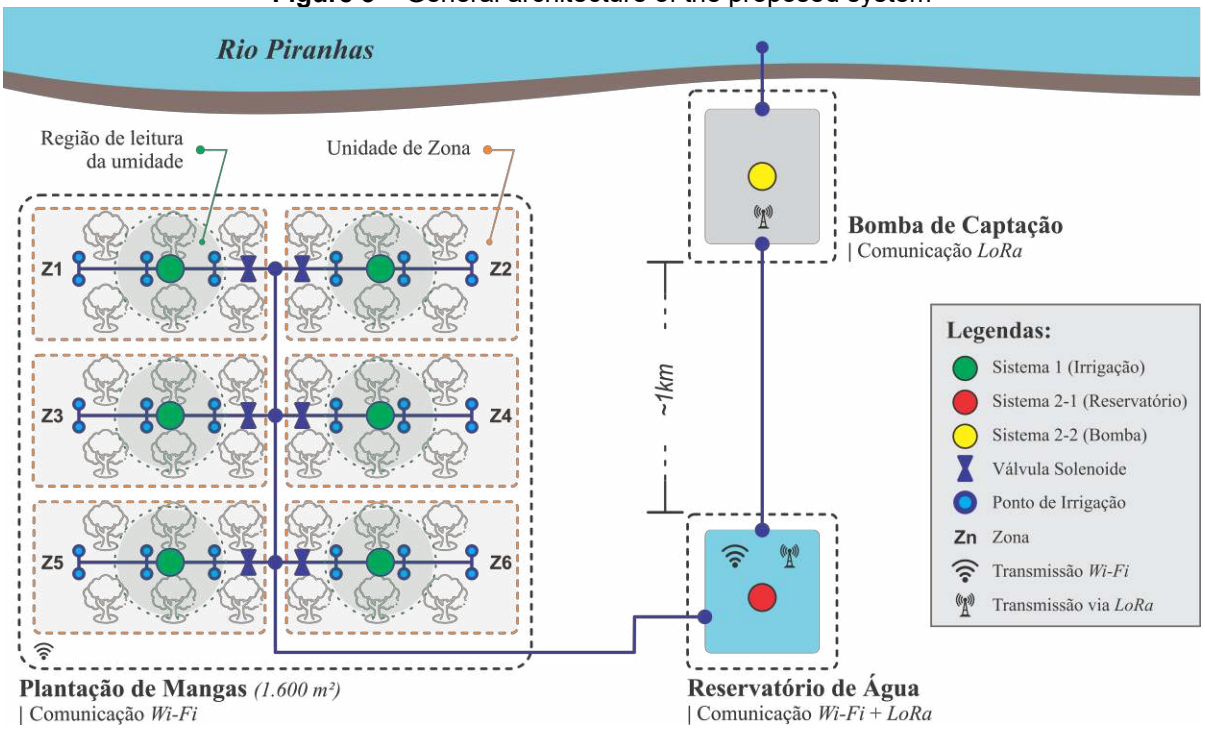
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3.5. General architecture of the proposed system

The system was designed based on a distributed and modular architecture, composed of input, processing, communication, activation, and supervision devices. The input devices correspond to the sensors responsible for data collection, with emphasis on soil moisture sensors and reservoir level sensors. Local processing is performed by ESP8266 NodeMCU microcontrollers, while the output devices include relay modules, solenoid valves, and an electrical contactor, responsible for activating the irrigation and pumping systems.

Figure 3 presents the system's overall organization, highlighting the relationship between sensors, microcontrollers, wireless communication, actuators, reservoir, pump, and supervisory interface.

Figure 3 – General architecture of the proposed system



Source: Authors.

A distributed architecture was chosen, with an independent microcontroller per zone, over a centralized architecture with a single controller and multiple output channels. Although centralization reduces component costs, it introduces a single point of failure: the unavailability of the central controller would interrupt the operation

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of all zones simultaneously, compromising the system's operational robustness. The distributed architecture, although more costly, preserves the independent operation of each zone, so that a failure affects only the affected unit.

The proposed architecture was divided into two integrated subsystems: the irrigation subsystem and the remote capture subsystem. In the irrigation subsystem, the cultivated area was divided into six independent zones. Each zone covers 6 trees in a 2x3 layout, consisting of a soil moisture sensor, microcontroller, relay module, and solenoid valve. The use of a single sensor per zone, positioned near the geometric center of the block, is consistent with the system's cost-reduction objective, even though it compromises reading precision relative to the other trees within the same zone. Table 3 describes the items required for one zone.

Table 3 – Description of the items required for one zone

Item	Function	Type	Qty.	Value
V2.0 capacitive soil moisture sensor	Monitor soil moisture.	Input	1	R$ 20.00
ESP8266 NodeMCU microcontroller	Collect soil moisture sensor data, process and send/receive data remotely (internet), control the relay module (on/off).	Processing	1	R$ 30.00
12V relay module - 1 channel	Activate/deactivate solenoid valve	Output	1	R$ 10.00
12V ¾" NC solenoid valve	Activate/deactivate irrigation line	Output	1	R$ 40.00
			Subtotal per zone	R$ 100.00
			Number of zones	6
			Subtotal - Irrigation	**R$ 600.00**

(Average prices estimated in july/2026 in online electronics stores)
Source: Authors.

This configuration allows irrigation to be activated only in the zone where moisture is below the previously defined threshold, avoiding simultaneous and unnecessary activation of the entire area.

Table 4 describes the control items for the capture pump.

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Table 4 – Description of the control items for the pump that captures river water to the reservoir

Item	Function	Type	Qty.	Unit value	Total value
Electromechanical float-type level sensor	Monitor water reservoir level	Input	1	R$ 40.00	R$ 40.00
ESP8266 NodeMCU microcontroller	Collect level sensor data, process and send/receive data remotely (internet), send/receive data from the LoRa module, control the relay module (on/off)	Processing	2	R$ 30.00	R$ 60.00
LoRa SX1278 module	Send/receive LoRa module signal	Processing	2	R$ 50.00	R$ 100.00
12V relay module - 1 channel	Activate/deactivate contactor	Output	1	R$ 10.00	R$ 10.00
Subtotal - Capture					**R$ 210.00**

(Average prices estimated in july/2026 in online electronics stores)
Source: Authors.

In the remote capture subsystem, long-range radio communication with LoRa modules was adopted, due to the approximate 1 km distance between the reservoir and the pumping point, capable of reaching distances of approximately 1 to 5 km in rural environments with moderate vegetation, and potentially exceeding that range under ideal line-of-sight conditions.

The reservoir is monitored by a level sensor connected to a microcontroller. When the minimum level is reached, the signal is sent to the capture point, where another microcontroller activates a relay and an electrical contactor to turn on the pump. When the maximum level is reached, the system sends a shutdown command, reducing energy waste and the risk of overflow.

Table 5 synthesizes the main functional elements of the architecture.

Table 5 – Synthesis of the proposed architecture's subsystems

Subsystem	Main components	Operational function
Irrigation	Moisture sensor, ESP8266 NodeMCU, relay, and solenoid valve	Monitor soil moisture and activate irrigation in a sectorized manner
Remote capture	Level sensor, ESP8266 NodeMCU, LoRa SX1278 modules, relay, contactor, and pump	Monitor the reservoir and remotely activate the capture pump
Supervision and control	Wi-Fi network, LoRa communication, and supervisory platform	Integrate system data, enable remote monitoring, and provide manual or automatic commands

Source: Authors.

Organizing the system into subsystems makes the solution simpler, modular, and replicable. This division allows the use of Wi-Fi communication in zones close to the access point and LoRa communication for remote capture, adapting the transmission technology to the operational conditions of each part of the system.

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3.6. Component selection criteria

Component selection was guided by four main criteria: low cost, commercial availability, ease of installation, and replication potential. These criteria were adopted to ensure that the proposed solution would be compatible with small production areas, with less dependence on proprietary equipment and greater ease of maintenance.

Each component was selected based on the technical justification summarized in Table 6, prioritizing connectivity, low cost, and compatibility with automated per-zone control.

Table 6 – Selection criteria for the system's components

Component	Selection criterion	Technical justification
ESP8266 NodeMCU	Low cost, Wi-Fi connectivity, and compatibility with IoT applications	Performs local data processing and enables wireless communication in the irrigation zones
Capacitive soil moisture sensor	Low cost and direct reading of the soil's water condition	Enables irrigation activation based on the actual moisture of the cultivated zone
Relay module	Ease of activation and integration with microcontrollers	Acts as an interface between the microcontroller and the electrical activation devices
Solenoid valve	Automatic control of water flow	Allows independent opening and closing of irrigation in each zone
Electrical contactor	Safety in activating higher-power loads	Allows activation of the capture pump without overloading the relay or microcontroller
LoRa SX1278 module	Long-range, low-power communication	Enables communication between the reservoir and the capture point, approximately 1 km apart

Source: Authors.

Converting the capacitive sensor's voltage reading (0 to 3V) into soil moisture content depends on local calibration, since manufacturers do not provide a calibration curve or precision data for the sensor. As a complementary agronomic reference, Pinto, Coelho, and Simões (2020) suggest soil water tension ranges between 15 and 25 kPa for medium-textured soils, a range compatible with the textural variability of the Luvisol characteristic of the study area, as an indicator of the appropriate time for irrigation. This calibration must be performed using a gravimetric method, comparing the sensor reading to soil samples from the area itself with known moisture content (Table 14).

For pump control, the use of an electric contactor is indispensable, since the equipment's power requires an adequate and safe activation device. In this

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arrangement, the relay acts only as a command element, while the contactor performs the activation of the higher-power load, protecting the microcontrollers and reducing electrical risks.

The sizing presented covers the low-voltage power supply of the nodes (sensors and microcontrollers) and does not replace the design of the capture pump's activation circuit, which involves higher voltage and power. In accordance with NBR 5410 (Low-Voltage Electrical Installations – the Brazilian technical standard equivalent to IEC 60364), this circuit must include, at minimum: a circuit breaker and thermal overload relay sized for the motor's rated current; phase-failure protection; grounding and a residual current device (RCD); surge and lightning protection; and an enclosure with a degree of protection suitable for the rural environment. The complete electrical diagram, the sizing of these protection devices, and the installation must be prepared and executed by a qualified professional, and were not included at this preliminary stage, as they depend on a specific survey of the pump's existing electrical installation on the property.

Communication between the devices in the irrigation area was designed to occur via Wi-Fi network, due to the shorter distance between nodes. For communication between the reservoir and the pump, LoRa technology was used, suitable for longer-range, low-power applications in rural areas. Thus, the system combines short- and long-range technologies, adjusted to the operational needs of each subsystem.

To ensure the system's operational reliability, the following design requirements were defined: (i) periodic calibration of moisture sensors, with manual verification of soil conditions at regular intervals; (ii) physical protection of devices against dust, moisture, and direct solar radiation, using IP65 enclosures; (iii) prior testing of the range and delivery rate of the Wi-Fi and LoRa communication modules before continuous operation; (iv) preventive maintenance routine covering emitter cleaning, valve inspection, and pump verification; and (v) user training for alert interpretation, simple fault identification, and manual system activation when necessary.

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3.7. Data supervision and management platform

For system supervision, the Home Assistant platform was adopted, configured on a local server. This choice was motivated by its open-source nature, local data processing, and the possibility of integration with IoT devices, reducing dependence on proprietary services and recurring costs.

Communication between the IoT nodes and the supervisory platform was designed using the Message Queuing Telemetry Transport (MQTT) protocol. MQTT was considered suitable as a lightweight protocol aimed at exchanging small messages between connected devices, especially in applications with connectivity constraints.

The platform allows the creation of monitoring dashboards for real-time visualization of soil moisture, valve status, actuators, and reservoir level. In addition to automatic operation, the interface allows manual commands via computer or mobile device, which expands operational flexibility and enables intervention in emergency situations or system adjustments.

The use of the Home Assistant platform, hosted on a computer already existing on the property, eliminates the need to purchase a dedicated device (such as a Raspberry Pi), and the already installed internet connectivity eliminates the need for additional network infrastructure. Operational information-security aspects – such as routine backup of collected data, historical data retention policy, user authentication, and remote access control to the platform – were not detailed at this preliminary stage (Table 14), in line with the native security features already available on the platform itself (username/password authentication, local and remote access control, and integration with automated backup services).

3.8. System operating logic

The system's operating logic was structured around two main flows: irrigation control and capture control. In the irrigation subsystem, each zone has a soil moisture sensor, responsible for periodically collecting the local water condition. When

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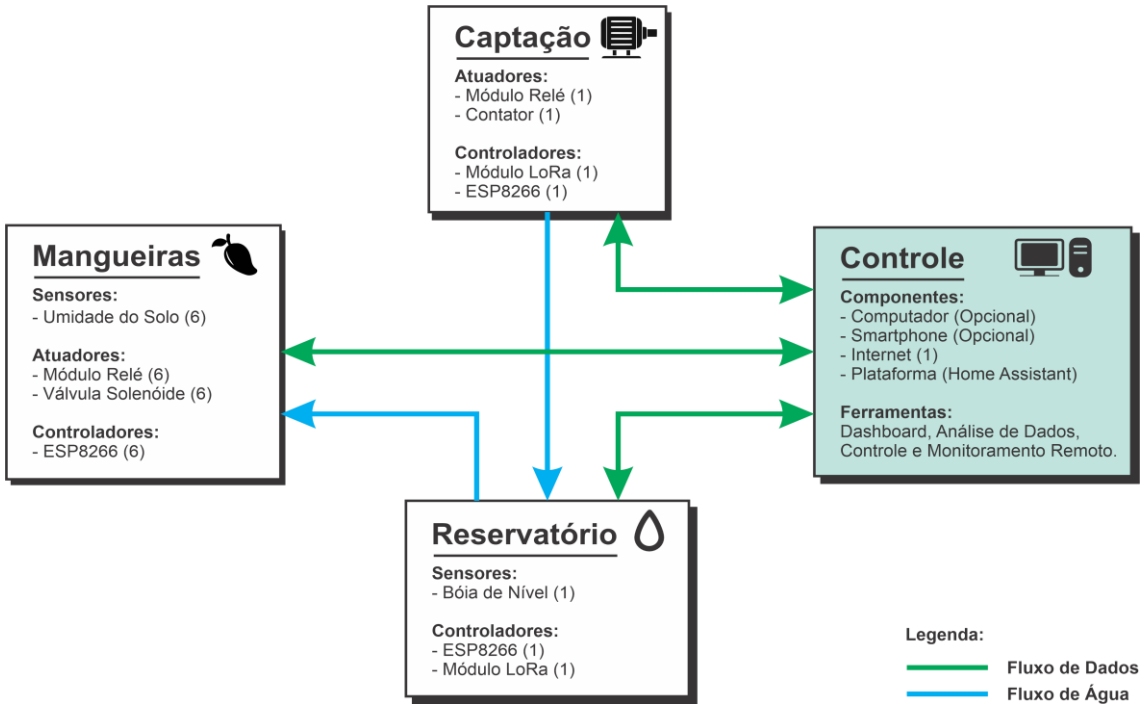
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moisture falls below the configured minimum threshold, the microcontroller activates the relay and opens the corresponding solenoid valve. When moisture reaches the appropriate threshold, the valve is closed, interrupting irrigation.

The solenoid valve adopted operates at 12V DC, with a maximum flow rate of 28 L/min, an operating pressure between 12.9 psi and 116 psi, and a maximum operating temperature of 40°C. Hydraulic supply is provided by a 5 HP pump already existing on the property, shared with the other plantations, from which an average flow rate of 20 L/min per solenoid valve was reserved – equivalent to 71.4% of the valve's maximum flow rate. Figure 4 presents the simplified operational flow.

Figure 4 – Simplified operational flow of the proposed system



Source: Authors.

Irrigation is carried out by micro-sprinkling, a system recommended for mango cultivation because it provides a larger wetted area than drip irrigation in medium- to sandy-textured soils. Considering a reference consumption of 80 L per plant per day (Pinto; Coelho; Simões, 2020) and 6 plants per zone, each zone requires 480 L of water per day, corresponding to 24 minutes of irrigation at the available flow rate. This time is divided into 6 cycles of 4 minutes, instead of a single continuous cycle, reducing the uninterrupted opening time of the solenoid valve and mitigating the risk

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of coil overheating. This strategy also favors water absorption by the root zone in shallow, low-retention-capacity soils, such as the Luvisol characteristic of the region, by reducing deep percolation loss in each application.

In the capture subsystem, control occurs based on the reservoir level. When the sensor identifies the minimum level, the system sends a command to activate the pump. When the maximum level is reached, the shutdown command is sent. This logic uses an operating range between minimum and maximum levels, avoiding repetitive activations and reducing mechanical wear, energy consumption, and overflow risk.

Table 7 synthesizes the main input conditions, control decisions, and actions executed by the system.

Table 7 – Synthesis of the system's operating logic

Subsystem	Monitored condition	Action executed
Irrigation	Soil moisture below the minimum threshold	Activation of the corresponding zone's solenoid valve.
Irrigation	Soil moisture within the appropriate range	Deactivation of the solenoid valve and interruption of irrigation.
Remote capture	Reservoir at minimum level	Command sent to activate the capture pump.
Remote capture	Reservoir at maximum level	Command sent to deactivate the capture pump.
Supervision and control	Need for adjustment or operational emergency	Manual activation of devices via the supervisory interface.

Source: Authors.

The integration between the two subsystems allows water supply and distribution to operate in a coordinated manner. While the capture subsystem keeps the reservoir at adequate levels, the irrigation subsystem distributes water in a sectorized manner, based on soil moisture data. This arrangement replaces exclusively manual management with automated logic, more compatible with the water scarcity conditions of the semiarid region.

To mitigate risks associated with moisture sensor failures, the system incorporates the following safeguards: (i) plausible physical limits, discarding readings outside the sensor's expected output voltage range (0 to 3V); (ii) stuck-sensor detection, by identifying identical readings for a period longer than 6 hours, indicating a possible fault or disconnection; (iii) maximum activation timeout, limiting each

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irrigation cycle to 4 minutes regardless of the sensor reading, avoiding prolonged valve opening in case of failure; (iv) fail-safe default closure, already ensured by the normally closed (NC) valve in the event of power or communication loss; (v) alarm logging on the local supervisory platform when a fault condition is detected.

Cross-validation using a second indicator (e.g., a redundant sensor) and scheduled manual review were not incorporated at this preliminary stage (Table 14).

3.9. Power supply and energy autonomy requirements

Each zone node operates at a nominal voltage of 3.3-5V (ESP8266 and sensor) and 12V DC (solenoid valve), and can be powered by a rechargeable lithium-ion battery, associated with a photovoltaic solar panel (5V~1.25W) and a boost converter for step-up to 12V, with an estimated autonomy of approximately 4 days without solar incidence when operating in low-power (deep sleep) mode, reduced to a few hours under continuous operation. The capture point maintains power from the conventional electrical grid, already available on the property. In the event of a network communication failure (Wi-Fi or LoRa), the solenoid valve remains in its default normally closed (NC) state, interrupting irrigation until communication is restored – a fail-safe behavior that prevents unintended activation in the event of signal loss.

3.10. Financial feasibility and sensitivity analysis

Financial feasibility was assessed using Net Present Value (NPV), Internal Rate of Return (IRR), and simple payback, considering the initial investment, recurring maintenance costs, and estimated economic benefits from water savings, operational reduction, and productivity gains. A Minimum Attractive Rate of Return (MARR) of 10% per year – a reference value for low-risk investments in the family farming context – and a five-year analysis horizon, compatible with the estimated service life of the system's main components, were adopted for this analysis.

NPV was estimated using Equation 1, considering the initial investment (I_0),

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the annual net cash flow (FC_t), the minimum attractive rate of return (i), and the analysis horizon (n).

$$NVP = -I_0 + \sum_{t=1}^{n} \frac{FC_t}{(1+i)^t} \quad (1)$$

IRR corresponds to the rate that makes NPV = 0, as shown in Equation 2.

$$0 = -I_0 + \sum_{t=1}^{n} \frac{FC_t}{(1+IRR)^t} \quad (2)$$

Simple payback was calculated as the ratio between the initial investment and the annual net cash flow, as shown in Equation 3.

$$Payback = \frac{I_0}{FC_{liq}} \quad (3)$$

The discount factor, used to bring each cash flow to present value, was calculated using Equation 4, where FD_t represents the discount factor in period t, and i corresponds to the minimum attractive rate of return already.

$$FD_t = \frac{1}{(1+i)^t} \quad (4)$$

4. Results and Discussion

4.1. Technical-economic assessment

The technical-economic estimate points to a projected initial investment of R$ 2,310.00 for system implementation, as shown in Table 8.

Table 8 – Estimated investment for system implementation

Category	Initial investment (R$)	Recurring annual cost (R$)
Physical components	810.00	–
Installation	1,000.00	–
Training and capacity building	500.00	–
Maintenance	–	500.00
Software and storage	–	0.00
Total	**2,310.00**	**500.00**

Source: Authors.

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Considering the experimental area with 36 mango trees distributed across six irrigation zones, the average cost corresponds to R$ 385.00 per zone and R$ 64.17 per monitored plant. These values indicate compatibility with small production areas, especially since they allow modular implementation and gradual system expansion.

The R$ 500.00 annual maintenance cost covers the anticipated replacement of wear-prone devices (such as moisture sensors and solenoid valves), as well as occasional calibration adjustments and minor repairs throughout the year. The installation cost covers expenses for powering the components (electrical grid or batteries), as well as an IP65 enclosure for protection against water exposure, dirt, and sunlight.

The investment presented does not include infrastructure items already existing on the property, which are reused by the proposal at no additional cost: the piping and capture pump, the electrical contactor responsible for pump activation, the computer used as the Home Assistant platform server, and the already installed internet connection. This criterion was applied consistently to all pre-existing resources, distinguishing them from items actually acquired for the implementation of the proposed system. In properties or replication contexts where these resources are not available, their acquisition and installation costs should be incorporated into the initial investment calculation, which tends to raise the total value estimated in this study.

The largest share of the investment refers to installation, at R$ 1,000.00, equivalent to 43.3% of the total. Physical components represent R$ 810.00, or 35.1%, while training corresponds to R$ 500.00, or 21.6%. This composition shows that the feasibility of the solution does not depend solely on device acquisition, but also on proper installation, calibration, and user training.

The annual maintenance cost was estimated at R$ 500.00, corresponding to R$ 83.33 per irrigation zone and R$ 13.89 per plant per year. The absence of software and storage costs reinforces the low-cost proposal, based on open solutions with easy integration. This result contributes to reducing adoption barriers and brings the proposal closer to the concept of an accessible Smart Farm, in which digitalization must be adjusted to the producer's economic and operational conditions.

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Table 9 presents the synthesis of the projected results for water use and productivity.

Table 9 – Synthesis of projected results for water use and productivity

Indicator	Conventional scenario	Scenario with Smart Farm
Annual water consumption	1,051.2 m^3	735.8 m^3
Water consumption reduction	–	30% (315.4 m^3)
Estimated annual production	2,880 kg	3,168 kg
Productivity increase	–	10% (288 kg)

Source: Authors.

The operational benefits indicate a 30% reduction in annual water consumption, considering an average consumption of 80 liters per plant per day (Pinto; Coelho; Simões, 2020), decreasing from 1,051.2 m^3 to 735.8 m^3, representing savings of 315.4 m^3 per year. This reduction results from the elimination of redundant irrigation events – such as applications on days when soil moisture is already adequate, for example after rainfall – and not from a decrease in the reference amount applied per event, which remains the same (80 L/plant) in both scenarios.

It also shows an estimated 10% increase in annual productivity, considering an average productivity of 80 kg per plant per year (Mouco, 2015), rising from 2,880 kg to 3,168 kg, representing an increase of 288 kg per year.

These results should be interpreted as a preliminary projection, associated with improved water management and reduced irrigation deficit or excess situations.

Table 10 consolidates the financial indicators estimated for the system.

Table 10 – Financial indicators estimated for the system

Indicator	Estimated result
Initial investment	R$ 2,310.00
Annual maintenance cost	R$ 500.00
Annual net benefit	R$ 1,008.40
Simple payback	2.29 years
Internal Rate of Return (IRR)	33.3% p.a.
Net Present Value (NPV)	R$ 1,512.63

Source: Authors.

The estimated annual net benefit of R$ 1,008.40 results from the sum of water

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savings of R$ 788.40 (considering an irrigation cost of R$ 2.50/ m^3) and additional revenue from the productivity gain of R$ 720.00 (considering a sale price of R$ 2.50/kg), less the annual maintenance cost of R$ 500.00. Considering a MARR of 10% p.a. and a five-year analysis horizon, the proposed system presents a projected simple payback of 2.29 years, a projected IRR of 33.3% p.a., and a projected NPV of R$ 1,512.63.

Table 11 presents the projected cash flow of the proposed system, including the discount factor applied to each period and the resulting cumulative flow.

Table 11 – Projected cash flow of the proposed system

Year	Investment	Net benefit	Cash flow	Discount factor	Discounted flow	Cumulative flow
0	- R$ 2,310.00	–	- R$ 2,310.00	1.0000	- R$ 2,310.00	- R$ 2,310.00
1	–	R$ 1,008.40	R$ 1,008.40	0.9091	R$ 916.73	- R$ 1,393.27
2	–	R$ 1,008.40	R$ 1,008.40	0.8264	R$ 833.39	- R$ 559.88
3	–	R$ 1,008.40	R$ 1,008.40	0.7513	R$ 757.63	R$ 197.74
4	–	R$ 1,008.40	R$ 1,008.40	0.6830	R$ 688.75	R$ 886.49
5	–	R$ 1,008.40	R$ 1,008.40	0.6209	R$ 626.14	**R$ 1,512.63**

Source: Authors.

The cash flow shows that the return on investment occurs between the second and third year of operation, as indicated by the cumulative flow crossing from negative to positive.

As highlighted by Junaid, Sukhi and Anita (2024), the economic analysis of agricultural technologies must consider indicators capable of expressing investment return and attractiveness, but also the risks associated with actual usage conditions. The estimates, therefore, indicate that the proposed system presents preliminary feasibility, relatively low cost, and potential to contribute to the rational use of water on small properties in the semiarid region.

The confirmation of all the results presented in this section – water, productive and financial – depends on experimental validation, considering climate variability, crop response, component durability and operational stability of the system.

4.2. Water savings and implications for the semiarid region

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In the semiarid context, the gain presented in Table 9 has technical and productive relevance, as limited water availability, rainfall irregularity, and dependence on pumping make irrigation efficiency a central factor for agricultural sustainability.

The projected savings result not only from the reduction in applied volume, but from a change in management logic. Irrigation no longer depends predominantly on fixed schedules or the operator's empirical perception, and becomes guided by soil moisture conditions. This result is aligned with the discussions of Obaideen *et al.* (2022), Soussi *et al.* (2024), Gupta *et al.* (2025), and Jiang *et al.* (2025), who highlight the use of sensors, microcontrollers, and IoT systems as a strategy to rationalize water application, reduce waste, and improve operational efficiency in agricultural systems.

Beyond direct water savings, automation can reduce unnecessary pump activation, manual management time, and the producer's exposure to repetitive field-verification routines. This rationalization is particularly relevant on small properties, where the availability of labor, energy, and water tends to be limited. Thus, the benefit should be interpreted in an integrated manner: lower applied volume, less dependence on manual operation, and greater regularity in meeting plants' water needs.

The 315.4 m^3 per year savings should be understood as an initial indicator of water efficiency and improved management. Although the estimate depends on field validation, the results suggest that low-cost control systems can contribute to the rational use of water in the semiarid region, especially when associated with modular solutions, simplified operation, and adaptability to family farming.

4.3. System sensitivity

The results indicate preliminary attractiveness of the solution, as the estimated return occurs within a period slightly longer than two years. This performance results from the combination of low initial investment, projected water sustainability, and estimated productivity gains. The interpretation of these indicators, however, must

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consider that digital agricultural technologies are subject to operational uncertainties, such as component durability, maintenance frequency, communication stability, and the crop's actual response to automated management. This caution is consistent with Junaid, Sukhi, and Anita (2024) and Mizik (2023), who highlight the need to associate financial indicators with risk analysis and practical technology-adoption conditions.

To verify the economic robustness of the proposal, a sensitivity analysis was carried out with three scenarios, as presented in Table 12.

Table 12 – Sensitivity analysis of the proposed system's financial indicators

Scenario	Main assumption	NPV (R$)	IRR (%)	Payback (years)
Conservative	Gross benefit 40% lower than the base scenario	-774.58	-4.2	5.70
Base	Results estimated in Table 10	1,512.63	33.3	2.29
Optimistic	Gross benefit 20% higher than the base scenario	2,656.23	49.0	1.76

Source: Authors.

The sensitivity analysis was constructed by varying the annual gross benefit (sum of water savings and productivity gain) by -40% (conservative scenario) and +20% (optimistic scenario) relative to the base scenario, keeping the initial investment, maintenance cost, MARR, and analysis horizon fixed. The financial indicators (NPV, IRR, and payback) were recalculated for each scenario based on the respective annual net benefit.

The asymmetry between scenarios reflects the higher probability of reducing factors (operational failures, below-expected crop response, climate variability) relative to unforeseen additional gains. It should be noted that the joint and proportional variation of the two benefit components constitutes a methodological simplification; a more robust analysis could treat each variable (water savings, productivity gain, water price, and mango price) independently.

The sensitivity analysis indicates that the proposal remains economically attractive in the base and optimistic scenarios, with positive NPV and IRR above the adopted MARR. In the conservative scenario, however, the system ceases to be viable within the five-year horizon considered, with negative NPV and IRR below the MARR. This result shows that the system's financial attractiveness is sensitive to the adopted water savings and productivity gain assumptions, reinforcing the need for

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experimental validation to confirm the parameters used in this preliminary analysis.

Thus, financial feasibility is not associated solely with the low cost of components, but with the system's ability to generate recurring benefits over time, as also discussed by Gupta *et al.* (2025), Jiang *et al.* (2025), and Puig, Diaz, and Soriano (2022) in studies on automation, water efficiency, and agricultural digitalization.

4.4. Replicability, scalability, and adaptation to family farming

The factors presented in Table 13 reinforce this potential for application in small production units. Modularity allows the number of irrigation zones to be adjusted to the cultivated area; low cost reduces the initial adoption barrier; wireless communication facilitates installation in rural areas; the local platform reduces dependence on paid services; and visual operation favors monitoring by the producer. These elements bring the proposal closer to the recommendations of Trendov, Varas, and Zeng (2019), Puig, Diaz, and Soriano (2022), and Mizik (2023), who indicate that agricultural digitalization should be economically accessible, operationally simple, and adaptable to local conditions.

Table 13 – Factors associated with the replicability and scalability of the solution

Factor	Contribution to application in small production units
Modularity	Allows expanding or reducing the number of irrigation zones according to the cultivated area
Low cost	Reduces the initial adoption barrier for small producers
Wireless communication	Reduces the need for cabling and facilitates installation in rural areas
Local platform	Reduces dependence on paid services and expands user control over data
Visual operation	Facilitates system monitoring through dashboards and mobile devices

Source: Authors.

The replicability of the solution stems directly from these factors, which favor its adaptation to different area sizes, crops, and operational conditions. In this sense, the proposal is not limited to irrigation automation, but offers a gradual alternative for production modernization, in which new zones, sensors (air humidity, temperature and soil pH, luminosity, among others), and functionalities (AI and ML) can be incorporated according to the producer's financial availability and needs, thereby validating the term smart.

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It should be noted, however, that the investment estimates presented in the Technical-Economic Assessment section consider the reuse of infrastructure already existing on the studied property – such as piping, capture pump, electrical contactor, server computer, and internet connection. In replication contexts where this infrastructure is not available, the initial investment required will be higher than that estimated in this study, which should be considered when assessing economic feasibility for other properties.

The values presented reflect the average market price for individual component acquisition. Purchasing larger quantities – through multi-unit kits, available for items such as moisture sensors, microcontrollers, LoRa modules, relays, and others – can reduce the system's total investment, without any change to the architecture or functionality of the proposal. This reduction margin varies according to the supplier, the quantity purchased, and market conditions at the time of purchase.

Scalability also stems from the independence between the irrigation, capture, and supervision subsystems. This organization allows the system to be adjusted without fully altering its architecture, which expands its application in areas with different crop arrangements and water availability. Wireless communication and the local platform reduce the need for complex infrastructure, an aspect relevant in rural regions with connectivity and specialized-service limitations, as discussed by Obaideen *et al.* (2022) and Soussi *et al.* (2024).

In the family farming context, visual operation represents a strategic element, as it facilitates system monitoring and preserves the possibility of manual intervention when necessary. This feature prevents technology from fully replacing the producer's experience, functioning instead as support for decision-making and operational control. Thus, the elements presented in Table 13 indicate that the solution has replication potential in small production areas in the semiarid region, provided it is accompanied by training, field validation, and adjustments to local soil, crop, and management conditions.

4.5. Technical robustness, operational limitations, and local maintenance

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The system's technical robustness was guided by the calibration, physical protection, communication testing, and preventive maintenance requirements defined at the design stage (Component Selection Criteria section). Even so, operation in a rural environment remains subject to not fully controllable factors, such as variations in dust, heat, humidity, and power failures.

The points of greatest sensitivity – moisture sensors, Wi-Fi/LoRa communication, and hydraulic and electromechanical components – already guided the requirements defined at the design stage (Component Selection Criteria section), consistent with what Obaideen *et al.* (2022), Soussi *et al.* (2024), Trendov, Varas, and Zeng (2019), and Puig, Diaz, and Soriano (2022) discuss regarding the need for monitoring, calibration, and operational simplicity in agricultural IoT systems.

Thus, the robustness of the proposed system is not related solely to component selection, but to the set of installation, protection, calibration, and maintenance practices. Field validation should assess device durability, communication stability, failure frequency, and the producer's ability to operate the system autonomously. These factors are decisive for confirming the technical feasibility of the solution and its replicability in small production areas in the semiarid region.

4.6. Limitations and future validation

Table 14 summarizes the main technical and agronomic aspects not contemplated in this preliminary stage, indicated for treatment in the experimental validation phase.

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Table 14 – Technical and agronomic aspects not covered in this study

Factor	Situation in this preliminary stage
Physical characterization of the soil	Field capacity, wilting point, apparent density, among others not determined
Moisture thresholds by phenological phase	Single threshold adopted; differentiation by phase not contemplated
Soil moisture sensor calibration	Local calibration curve (gravimetric method) to be performed
Durability of components in the field	Sensors, valves, and other devices not tested under continuous exposure to dust, heat, and moisture
Wi-Fi/LoRa range and reliability	Values declared by specification, not validated in the field
Direct flow measurement	Meter installation (water meter or turbine/pulse sensor) recommended
Treatment of water abstracted	Line filter and cleaning routine recommended, not quantified
Electrical pump safety	Prior need; dimensioning by a qualified professional
Backup and access security	Native features available, not configured in this step
Cross-validation of sensors	Redundant sensor and scheduled manual review not built-in
Operational continuity on server failure	Each zone operates autonomously via local logic; only remote supervision is affected
Comparison with commercial/conventional systems	Recommended as a future benchmark reference
Adoption by the producer	Behavioral factors indicated by Da Silveira *et al*. (2025)

Source: Authors.

The results presented should be interpreted as preliminary estimates, since the system was proposed and evaluated based on technical diagnosis, architecture planning, and performance projections, without validation over a complete production cycle. Thus, the indicators of water efficiency, productivity increase, and financial return depend on confirmation under actual operating conditions, considering climate variations, soil type, crop response, nutritional management, and water availability.

The main limitation of the study relates to the absence of continuous field monitoring. Sensor durability, Wi-Fi and LoRa communication stability, failure frequency, calibration needs, and the system's hydraulic behavior need to be assessed over time. This step is essential, as, according to Obaideen *et al.* (2022), Soussi *et al.* (2024), and Mizik (2023), the efficiency of IoT systems applied to agriculture depends not only on the technological architecture, but also on operational reliability in environments subject to dust, heat, humidity, and infrastructure limitations.

Another limitation relates to the economic assumptions adopted. Although the financial indicators point to preliminary feasibility, NPV, IRR, and payback may vary according to maintenance costs, component service life, energy price, production

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value, and the effectiveness of the productivity gain. Therefore, future studies should include an expanded sensitivity analysis and comparison with commercial systems or conventional irrigation practices, as recommended by Puig, Diaz, and Soriano (2022).

As a future step, it is recommended to implement the system experimentally for at least one complete production cycle, with measurement of water and energy consumption, productivity, operational failures, maintenance costs, and user perception. This validation will allow the technical robustness of the solution to be verified, activation parameters to be adjusted, the estimated water savings to be empirically confirmed, and its suitability for family farming to be assessed.

For the continuous recording of water consumption, it is proposed to install a flow meter (water meter or turbine-/pulse-type flow sensor) at the irrigation point for the mango trees. This instrument was not included in the budget, because it constitutes a scientific measurement and monitoring resource for the experiment, rather than a functional component indispensable to the operation of the automated irrigation system itself.

The actual adoption of the technology by the producer was not investigated in this study. As discussed by Da Silveira *et al.* (2025), based on the behavioral profile of farmers adopting 4.0 technologies, factors such as prior familiarity with digital devices, perceived usefulness, and confidence in the system's autonomous operation directly influence adoption.

Thus, the proposal could progress from an estimated architecture to a validated, low-cost Smart Farm model, replicable in small production areas in the semiarid region.

5. Conclusion

The results indicate that the proposal presents preliminary technical-economic feasibility and potential for application in small production areas in the semiarid region. The combination of low cost, sectorized automation, and remote supervision proved adequate to reduce dependence on manual management and support more rational water use.

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The solution also presents potential for future replication in family farming, mainly due to its modular structure and the possibility of adaptation to different scales, crops, and operational conditions. Thus, the proposed system contributes as an accessible alternative for the gradual modernization of irrigation in regions with water restrictions.

It is concluded, therefore, that the proposal lays the groundwork for a future stage of experimental field implementation, with sensor calibration, wireless-communication assessment, and performance monitoring throughout the production cycles. This stage will be essential to confirm the water, operational, and economic gains estimated in this study.

References

ASSIS, K. C. d. C.; PIANTONI, J.; AZEVEDO, R. F. Tecnologias em agricultura inteligente: eficiência e sustentabilidade. **Research, Society and Development**, v. 13, p.e7013445072, 2024. Disponível em: https://doi.org/10.33448/rsd-v13i4.45072

BOLFE, É. L. *et al.* Precision and digital agriculture: adoption of technologies and perception of Brazilian farmers. **Agriculture**, v. 10, p. 653, 2020. Disponível em: https://doi.org/10.3390/agriculture10120653

BRASIL. **Decreto n° 12.287, de 3 de dezembro de 2024**. Institui o Programa Nacional de Pesquisa e Inovação para a Agricultura Familiar e a Agroecologia. 2024. Diário Oficial da União, Brasília, DF, ed. 230, p. 11, 4 dez. 2024. Acesso em: nov. 2025. Disponível em: https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/decreto/d12287.htm

CAETANO, A. K. *et al.* Low-cost LoRa-based IoT system for automated irrigation and remote monitoring in family horticulture. *In*: WORKSHOP DE COMPUTAÇÃO APLICADA À GESTÃO DO MEIO AMBIENTE E RECURSOS NATURAIS (WCAMA), 16., 2025, Maceió/AL. **Anais** [...]. Porto Alegre: SBC, 2025. p. 21-29. ISSN 2595-6124. Disponível em: https://doi.org/10.5753/wcama.2025.7069

CHERUBIN, M. R. *et al.* Precision agriculture in Brazil: the trajectory of 25 years of scientific research. **Agriculture**, v. 12, p. 1882, 2022. Disponível em: https://doi.org/10.3390/agriculture12111882

COELHO, E. F. *et al.* **Sistemas e manejo de irrigação de baixo custo para agricultura familiar**. 2. ed. Cruz das Almas, BA: Embrapa Mandioca e Fruticultura, 2017. 45 p. Acesso em: ago. 2026. Disponível em:

CC BY

REMUNOM
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Received: 17/07/2026 - **Accepted:** 12/08/2026
Vol: 13.18 - August
DOI: 10.66104/6253bv06
Pages: 1-35

http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1070445

DA SILVEIRA, F. *et al.* Behavioral profile of farmers in the adoption of agriculture 4.0 technologies in the agri-food system: a case study in Brazil. **Frontiers in Sustainable Food Systems**, v. 9, p. 1624753, 2025. Disponível em: https://doi.org/10.3389/fsufs.2025.1624753

DANTAS NETO, J. *et al.* Desempenho de sistema de irrigação por gotejamento em áreas de pequenos produtores do semiárido paraibano. **Enciclopédia Biosfera**, Goiânia, v. 9, n. 16, p. 679-688, 2013. Disponível em: http://www.conhecer.org.br/enciclop/2013a/agrarias/desempenho.pdf

DAVID, R. *et al.* TensorFlow Lite Micro: Embedded Machine Learning on TinyML Systems. *In*: MLSYS CONFERENCE, 4., 2021, San Jose. **Proceedings** [...]. San Jose, CA, USA, 2021. Acesso em: 22 maio 2026. Disponível em: https://proceedings.mlsys.org/paper_files/paper/2021/file/6c44dc73014d66ba49b28d483a8f8b0d-Paper.pdf

DONSKOY, D.; GVINDJILIYA, V.; IVLIEV, E. TinyML Classification for Agriculture Objects with ESP32. **Digital**, v. 5, n. 4, art. 48, 2025. Disponível em: https://doi.org/10.3390/digital5040048

FRANCISCO, P. R. M. *et al.* Potencial pedológico do Estado da Paraíba para o cultivo do algodão herbáceo (*Gossypium hirsutum*). *In*: CONGRESSO TÉCNICO CIENTÍFICO DA ENGENHARIA E DA AGRONOMIA (CONTECC), 2017, Belém. **Anais** [...]. Belém: Confea, 2017. Disponível em: https://www.confea.org.br/sites/default/files/antigos/contecc2017/agronomia/97_ppdedppocdahgh.pdf

GIL, A. C. **Como elaborar projetos de pesquisa**. 7. ed. São Paulo: Atlas, 2022.

GUPTA, S. *et al.* Smart agriculture using IoT for automated irrigation, water and energy efficiency. **Smart Agricultural Technology**, v. 12, p. 101081, 2025. Disponível em: https://doi.org/10.1016/j.atech.2025.101081

JIANG, L. *et al.* Overview of agricultural machinery automation technology for sustainable agriculture. **Agronomy**, v. 15, p. 1471, 2025. Disponível em: https://doi.org/10.3390/agronomy15061471

JUNAID, K. A. M.; SUKHI, Y.; ANITA, S. Low-cost smart irrigation for agricultural land using IoT. **IETE Journal of Research**, v. 70, n. 3, p. 2659-2672, 2024. Disponível em: https://doi.org/10.1080/03772063.2023.2178535

MISHRA, H. A review on artificial intelligence, machine learning and IoT integration in precision agriculture. **Journal of Scientific Agriculture**, v. 9, p. 101-109, 2025. Disponível em: https://doi.org/10.25081/jsa.2025.v9.9497

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REMUNOM
ISSN 2178-6925

Received: 17/07/2026 - **Accepted:** 12/08/2026
Vol: 13.18 - August
DOI: 10.66104/6253bv06
Pages: 1-35

MIZIK, T. How can precision farming work on a small scale? a systematic literature review. **Precision Agriculture**, v. 24, n. 1, p. 384-406, 2023. Disponível em: https://doi.org/10.1007/s11119-022-09934-y

MOUCO, M. A. do C. (ed.). **Cultivo da mangueira**. Autores: Anderson Ramos de Oliveira *et al.* 3. ed. Petrolina: Embrapa Semiárido, 2015. (Embrapa Semiárido. Sistemas de Produção, 2). Disponível em: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1031747

OBAIDEEN, K. *et al.* An overview of smart irrigation systems using IoT. **Energy Nexus**, v. 7, p. 100124, 2022. Disponível em: https://doi.org/10.1016/j.nexus.2022.100124

ONIKE, N. J. The internet of things (IoT) in farming: smart solutions for a sustainable future. **International Journal of Poverty, Investment and Development**, v. 5, p. 31-44, 2025. Disponível em: https://doi.org/10.47941/ijpid.2650

PINTO, J. M.; COELHO, E. F.; SIMÕES, W. L. Irrigação. *In*: BORGES, A. L.; CORDEIRO, Z. J. M. (Ed.). **Sistema orgânico de produção de manga para a Região da Chapada Diamantina, Bahia**. Cruz das Almas, BA: Embrapa Mandioca e Fruticultura, 2020. (Sistema de Produção, 49). ISSN 1678-8796. Disponível em: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1130625

PUIG, F.; DIAZ, J. A. R.; SORIANO, M. A. Development of a low-cost open-source platform for smart irrigation systems. **Agronomy**, v. 12, n. 12, p. 2909, 2022. Disponível em: https://doi.org/10.3390/agronomy12122909

QUY, V. K. *et al.* IoT-enabled smart agriculture: Architecture, applications, and challenges. **Applied Sciences**, v. 12, n. 7, p. 3396, 2022. Disponível em: https://doi.org/10.3390/app12073396

REJEB, A. *et al.* Examining the interplay between artificial intelligence and the agri-food industry. **Artificial Intelligence in Agriculture**, v. 6, p. 111-128, 2022. Disponível em: https://doi.org/10.1016/j.aiia.2022.08.002

SILVA, A. M. d. **Metodologia da pesquisa**. 2. ed. Fortaleza: EDUECE, 2015.

SILVA, E. G. **A eficiência de um sistema de irrigação automatizado de baixo custo baseado na tecnologia de Internet das Coisas (IoT): aplicação em uma agricultura familiar**. 2024. 127 f. Dissertação (Mestrado Profissional em Gestão e Tecnologia em Sistemas Produtivos) – Centro Estadual de Educação Tecnológica Paula Souza, São Paulo, 2024.

SILVA, K. L. d.; CANOLA, G. A. Planejamento estratégico: uma proposta de implementação da matriz 5W2H como ferramenta da qualidade no setor de compras em uma empresa no ramo do agronegócio na cidade de Sorriso-MT.

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Vol: 13.18 - August
DOI: 10.66104/6253bv06
Pages: 1-35

Revista FT, v. 28, n. 128, 2023. Disponível em: https://doi.org/10.5281/zenodo.10198582

SOUSSI, A. *et al.* Smart sensors and smart data for precision agriculture: a review. **Sensors**, v. 24, p. 2647, 2024. Disponível em: https://doi.org/10.3390/s24082647

TRENDOV, N. M.; VARAS, S.; ZENG, M. Digital technologies in agriculture and rural areas: Briefing paper. **Food and Agriculture Organization of the United Nations**, 2019. 26 p. Acesso em: ago. 2026. Disponível em: https://openknowledge.fao.org/handle/20.500.14283/ca4887en

UBERTI, V. A. *et al.* Rice-irrigation automation using a fuzzy controller and weather forecast. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 27, n. 10, p. 779-784, 2023. Disponível em: https://doi.org/10.1590/1807-1929/agriambi.v27n10p779-784

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