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Fuzzy logic-based IoT system for optimizing irrigation with cloud computing: Enhancing water sustainability in smart agriculture

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ABSTRACT

Faced with the growing challenges of water scarcity and the effects of climate change, intelligent irrigation management is essential to guarantee food security and promote sustainable agriculture. Traditional irrigation methods are often inefficient, waste water and expose crops to water stress. This paper proposes an innovative irrigation system integrating the Internet of Things (IoT), embedded systems, fuzzy logic and cloud computing for optimized water management. The system is based on three layers: IoT devices in the field comprising ESP32 microcontrollers, temperature and humidity sensors and actuators; a cloud layer using ThingSpeak for real-time data collection and analysis via HTTP protocol; and an interactive dashboard for irrigation monitoring and control. Mathematical modeling plays a key role, integrating fuzzy logic to dynamically adjust irrigation according to environmental conditions. MATLAB is used to simulate and visualize fuzzy membership functions, enabling optimized decision-making. Results show that the system reduces water losses by adjusting watering periods according to soil temperature and humidity. Thanks to ThingSpeak, it effectively maintains soil humidity close to the target threshold of 62 %, ensuring more precise, weather-responsive irrigation. Evaluation over an extended period shows a significant reduction in water wastage thanks to strategic management based on well-defined rules. What's more, with a cost of just 32 USD, this IoT system proves more affordable than conventional methods requiring significant investment in infrastructure and maintenance. This intelligent irrigation system represents a promising solution for sustainable water management in agriculture. By integrating real-time soil and climate data, it improves water efficiency, optimizes yields and minimizes the risk of water stress, thus contributing to the resilience of agricultural practices in the face of current and future environmental challenges.

1. Introduction

Agriculture is central to economic and social development, providing much-needed supplies of food for an ever-increasing world population [1]. However, farming nowadays faces unprecedented challenges in its path since it will be grossly affected by the impacts of climate change, inefficient management of water resources, and the need to sustain long-term operability. Smart agriculture emerges as a promising solution for these problems of food security while still preserving the environment [2]. Smart agriculture involves the introduction of advanced technologies like IoT, AI, and sensors into novel agricultural practices [3–5]. These developments enable better and more efficient management of process inputs such as water, one of the key variables in crops. Smart agriculture brings automated irrigation with soil moisture sensors, which worsens due to water scarcity and climate change, which may optimize water use by reducing its waste. Other important challenges to global agriculture include changes in climate, which have impacts on crop productivity, water availability, and soil health [6].

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Smart agriculture provides tools for mitigating the effects of such challenges by adapting agricultural practices to changing climatic conditions and promoting greener methods of production. For example, predictive models can be used to gauge the risks posed by climate change and adjust planting schedules accordingly to make crops more resilient against climatic hazards. Besides, sustainability in agriculture is described as a reduction of environmental impacts while sustaining adequate food production to meet the needs of the present and future [7]. Smart agriculture executes this process by paving the way for environmentally appropriate agricultural practices that include precision farming, diminishing the use of pesticides and fertilizers, and regenerative agriculture for restoring health to soils. The present paper will be dedicated to the design of an intelligent irrigation system based on some of the newest technologies, namely IoT, embedded systems, fuzzy logic, and cloud computing. The high vision is to devise a solution that can optimize crop irrigation in line with changing climate conditions and soil requirements. This three-layer architecture—comprising IoT field devices, the ThingSpeak cloud platform, and an interactive dashboard—is designed to enhance water-use efficiency, effectiveness, and accuracy in responding to the management of water resources.

Fig. 1 highlight traditional farming practices in Fez region of Morocco (North Africa). This rural territory carries representative methods of farming passed down through generations and showcases attachment to its farming culture within the community. The following images highlight traditional techniques shaped by the region's topography and unique climate. It also symbolizes the tool, crop, and method of work peculiarities that characterize this region. These images express all the resistance of the locals and their important role in the maintenance of agricultural biodiversity in this part of North Africa.

This article [8] introduced an innovative solution combining embedded systems and environmental sensors for a real-time intelligent irrigation system. The system automatically adjusts irrigation according to environmental conditions, improving water use efficiency. Using an Arduino Mega 2560 microcontroller and various sensors (temperature, DHT22 humidity, soil moisture, water level), it optimizes irrigation and reduces water waste while increasing agricultural productivity. The developed algorithm allows continuous monitoring and adaptive control of pumps with data recording for real-time feedback. In addition, article [9] presents a real-time fire detection system for smart agriculture, using IoT, embedded systems, and cybersecurity measures. It quickly detects smoke or flames thanks to sensors and a Raspberry Pi 3 B+, with real-time visualization via a Flask interface. Results confirm its effectiveness. Further, article [10] proposes an intelligent irrigation system, based on IoT, embedded systems, and cloud, which monitors humidity, temperature, and water levels in real-time, and automatically controls water pumps via ThingSpeak and ThingView. This article [11] presents an intelligent IoT-based precision irrigation system integrated with the platform. It details the architecture and operation of the IoT node used. In addition, a radio-frequency energy harvesting technique is applied to power the IoT node. A rectenna is manufactured and validated, demonstrating satisfactory performance in an outdoor environment. Article [12] proposes a similar solution by integrating the IoT for fully automated pump management. Further, the article [13] describes a real-time precision irrigation system, combining a fuzzy logic controller with LoRa protocol, allowing advanced optimization of irrigation times and efficient management of agricultural resources via an IoT platform. On the other hand, this research [14] proposed a fuzzy computational analysis for IoT-based intelligent irrigation systems, integrating fuzzy logic for decision analysis and secure data collection via the Blockchain. Various sensors were deployed to measure temperature and humidity, while the position of the valves was determined by a fuzzy Mamdani model. Another study [15] proposed smart monitoring of agriculture with fixed and mobile sensors, providing detailed maps of crop conditions. A zoning irrigation system [16] was also developed, optimizing plant growth and reducing water and energy consumption through a fuzzy logic controller and Node-RED interface. Finally, an innovative solution [17] was presented to address the challenges of food production, using a fuzzy controller in a small greenhouse to adjust environmental conditions in real-time, improving agricultural efficiency and sustainability. Article [18] presents a smart agriculture framework that integrates renewable energy, the IoT for precise irrigation, and an Android-controlled robotic system. A case study in Sharjah shows the effectiveness of these technologies via the Blynk platform. Article [19] describes a system using smart sensors and fuzzy logic to optimize irrigation and environmental control in mushroom crops. Article [20] proposes a fuzzy irrigation system for cotton fields, improving water efficiency and reducing infestations. The study [21] develops a cloud-based irrigation system to centralize and optimize water use, while the article [22] proposes a tool to improve infrastructure sustainability by reducing CO_2 emissions.

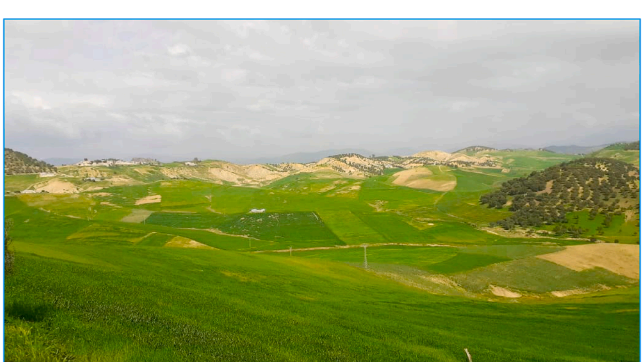

Fig. 1. Traditional agricultural practices Fez, Morocco (North Africa).

This article [23] has studied farmers in most regions of India; the majority of those did not have any viable irrigation system. In finding the solution, a solar irrigation system was designed and deployed; an innovative system integrated with IoT-based automated systems. The IoT system works on the logic of soil moisture and ensures at the right time the crops get the right amount of water. It is also an advanced photovoltaic pumping system with all the required capabilities to overcome irrigation challenges throughout various Indian climatic zones, namely composite, hot and humid, cold, and moderate, in addition to hot and dry climates. This paper [24] also presents a model for sustainable, smart greenhouse photovoltaic solar energy sources efficiently utilized by intelligent control systems for irrigation, temperature, and humidity optimization of a closed agricultural atmosphere. This system provides autonomous management due to IoT and microcontrollers. Moreover, compared with the traditional greenhouse, there will be an increase in the efficiency of water consumption by 40 %. This is supplied with condensate from air-conditioning systems that provide 65 % of the water required to irrigate the vegetables for added profitability, more so in the Gulf Countries Council. Article [25] discussed the smart grid to include IoT and cloud for better sustainability and reliability. It depicts an IoT strategy reducing solar panel fouling and saving costs of cleaning; thereby, enhancing sustainable energy production. This system also introduces new IoT-enabled sensors for solar installations that will extend the life of your equipment while achieving energy efficiency and accurate information on system operations. Additionally, CloudIoT uses progressive networks through predictive analytics, energy optimization, and smart design. It will finally propose a system based on fog computing in order to reach optimum demand with advantageous pricing while intelligently managing the grid with respect to energy sustainability. This paper [26] proposes an "Open Edge IoT System for Energy Monitoring in Buildings." As deployed within the Faculty of Electromechanical Engineering of the University of Colima, it optimizes this already existing network infrastructure by taking advantage of edge-fog computing, and securely processes sensitive electrical data. It is also compatible with various IoT technologies, ensuring the accuracy of power, voltage, and current measurements. This describes how the effectiveness of edge computing stands compared to other cloud architectures. This article [27] discusses the precision farming technology adapted to home gardening. It gives economic, health, physiological, and psychological benefits. It presents an integrated sensor system for smart irrigation by using wireless sensor networks for the analysis of soil and water, including accurate pH and humidity measurements. In [28], it presents an enhanced method for fault detection in a wireless irrigation network. Sensor failure is one of the main issues to guarantee real reliability and performance within the systems. This approach will provide improvements in maintenance by facilitating the identification of faulty sensors in a faster and more effective manner. Article [29] contributes to this review of intelligent manufacturing systems in depth, within the context of advanced technologies. It goes deep in exploring the analysis of associated technologies, AI, and robotics together with challenges related to their implementation, which indeed is an important pre-requisite when considering the integration barriers of such systems within existing production environments. Article [30] also deals with the shift toward sustainable and circular practices, providing nineteen facilitating factors in the technology adoption of the circular economy. These technological, economic, and regulatory factors are essential for the correct application of circular economy principles in industries. Still, on the topic of the circular economy, article [31] proposes a possible role Logistics 4.0 could play in supporting the agri-food sector. It highlights best practices in sustainability and how resource management is connected with the adoption and diffusion of Logistic 4.0 tools and technologies, enabling the spread of the Circular Economy concept through advanced information systems and traceability. Meanwhile, article [32] is about how to contribute to reducing emissions in the agricultural sector of the countries of South Africa. The existing strategies, such as sustainable agriculture and clean technologies, were assessed, taking into consideration their actual contribution to carbon footprint reduction in this sector. Article [33] reviews the contribution of rural cooperatives from the point of view of this question, while Article [34] makes a comparison between digital and green technologies for decarbonization but shows precisely in what aspects each of these approaches contributes to reduced carbon emissions and therefore to the general sustainability of the agricultural sector. The use of real-time monitoring to boost the efficacy of nature-based flood management techniques is suggested in this research [35]. This methodology outperforms standard methods in reducing water levels and optimizing storage, according to a study conducted in the Rangsit district of Thailand. However, this contribution [36] offers a framework for the implementation of IoT in agriculture and compares several applications. Four research topics were addressed by a systematic review of 82 recent articles. The findings demonstrate that research has shifted toward real-world application and is increasingly utilizing machine learning methods. Additionally, an examination of IoT integration for sustainable water management is provided in this work [37]. It finds 25 elements, uses principal component analysis to group them into 7 enablers, and uses a fuzzy theory-based multi-criteria technique to rank them. The IoT ecosystem, its setup, and data mobility are the primary enablers. An automated IoT system for calculating environmental river flows using publicly available hydrological data is proposed in this contribution [38]. Being reusable and expandable, it improves the value of already-existing data, lowers costs, and makes environmental compliance easier. Furthermore, by lowering greenhouse gas emissions, innovation and technology support sustainable agriculture, as this research [39] highlights. It shows how the adoption of technology affects productivity and emissions, and how the uneven adoption of technology in Asian nations has an impact on environmental sustainability. Applications of machine learning also provide opportunities to advance sustainable farming methods. However, small-scale production and outdated technology hinder Southeast Asia's main industry, agriculture [40]. Farmers' adoption of new technology is influenced by several characteristics, which may be used as a guide to evaluate their intentions [40]. This paper [41] presents the awareness of skin diseases and their impact on the implementation of IoT-based intelligent skin monitoring systems. It also explores the awareness of IoT systems and their influence on the implementation of these technologies, while highlighting the benefits of using an IoT system to improve the management and monitoring of skin conditions. In addition, this article [42] demonstrates the positive effects of performance expectancy, effort expectancy, social influence, and facilitating conditions on the intention to adopt IoT technology. However, among older farmers, acceptance of changes in working methods (including the use of IoT) becomes more difficult with age. In addition, individuals with higher incomes are generally risk-averse and reluctant to accept the costs of installing modern smart technologies. Further, this study [43] provides a review of smart technologies and their impacts on rural communities, highlighting the need for empirical research and consideration of socio-cultural contexts. It also explores the contribution of a socio-technical perspective in this field. On the other hand, this article [44] examines the adoption of digital technologies in agriculture, a gradual process influenced by performance expectations and social pressure. Farmers' intentions and the characteristics of their farms play a key role in the decision to adopt these technologies. Well-structured and organized farms are more inclined to incorporate these innovations. The motivation comes from the increasing challenges imposed upon agriculture by both the scarcity of water resources and the impact of climate change. Traditional irrigation methods were quite incapable under those conditions of dealing with such changes in the environment, and even furthering water waste and stress to crops. In the presence of such scenarios, the present work offers a new efficient perspective toward the optimization of irrigation, making use of modern technologies that will bring better sustainability in water and food resources toward resilient and sustainable agricultural development. Fig. 2 presents a graphical abstract of this study.

Although numerous irrigation systems leveraging the IoT have been conceived, a significant proportion of these pertains to reliance upon static thresholds or elementary sensor feedback mechanisms, which may incite either an excess or deficiency in irrigation, particularly amid varying environmental circumstances. This paper delineates a unique methodology that propels existing paradigms forward by amalgamating IoT with fuzzy logic control frameworks, which proffer a more sophisticated and flexible modality for the administration of irrigation grounded in real-time atmospheric data. In contrast to systems predicated upon fixed thresholds, Fuzzy logic enables more flexible decision-making by interpreting input variables, such as temperature and soil moisture, in colloquial classifications (e.g., 'low,' 'medium,' and 'high') and formulating irrigation determinations that are responsive to real-time adjustments for the preservation of optimal soil moisture metrics. The distinctive contributions engendered by this research can be enumerated as follows:

- Adaptability enhancement: The added flexibility through the use of fuzzy logic further increases; hence, the proposed framework can adapt to a wide range of environmental conditions and contemporaneously recasting irrigation schedules in order not to over- or underapply water resources.
- Improved water efficiency, since it automatically changes the irrigation time by conducting an in-depth analysis of the temperature and soil moisture conditions to depict an appropriate time for releasing water.
- Fostering cloud computing integration: Improvement in cloud computing integration: Because the Thingspeak cloud continuously stores real-time data in a single repository, there is true continuous monitoring and improvement; hence, the system will be more responsive and accurate than any other manual method.
- Empirical validation in realistic environments: This system was taken further into the field within the real agricultural environment, hence corroborating its efficiency to keep soil moisture closer to the

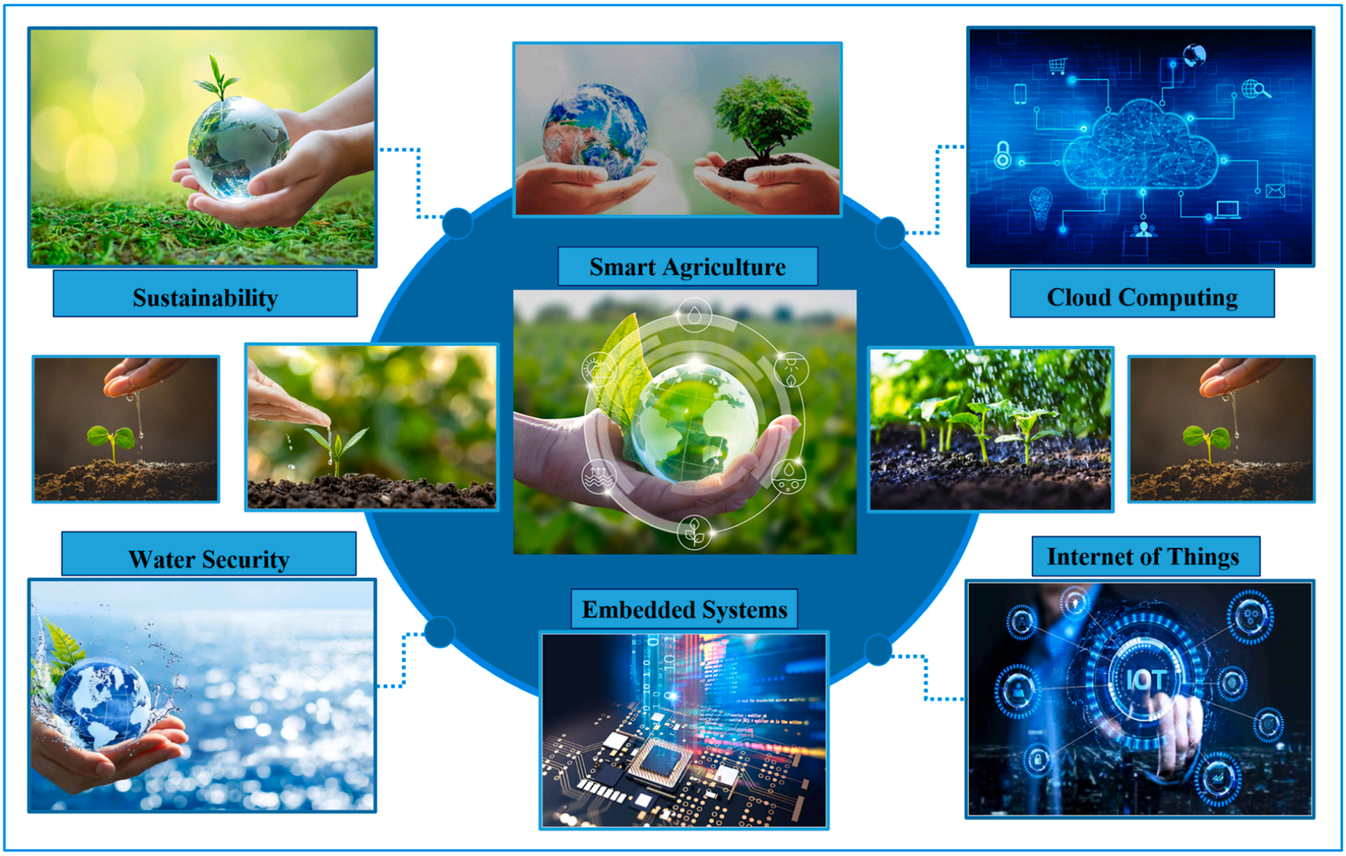

Fig. 2. Graphical abstract of the proposed system.

optimal thresholds irrespective of the variations in the environmental conditions.

This demonstrates that a key contribution of this paper is to present the advantages of fuzzy logic over conventional control systems implemented in a real-world environment.

The paper is organized as follows: Section 2 presents Materials and Methods, Section 3 discusses Results and Discussion, and Section 4 is devoted to Conclusion and Future Work.

2. Materials and methods

This section presents a rigorous methodological approach for the development and implementation of an intelligent irrigation management system, integrating IoT technologies, cloud computing, and fuzzy logic. The main objective of this research is to design an architecture capable of meeting the growing needs for sustainable water management in agriculture while improving crop resilience in the face of environmental challenges. The three tiers in the proposed architecture are out-of-the-field deployed devices, computations on the cloud through the ThingSpeak platform, and visualization in real-time through a dashboard. IoT devices include ESP32 microcontrollers, temperature, humidity, and soil moisture sensors, and motors like pumps. They shall handle the responsibility of gathering environmental data and transmitting the same over HTTP to the cloud in near real-time. In turn, this will be elaborated, stored, and analyzed in real-time through ThingSpeak, delivering critical information to support decisions. Finally, displaying the possibility of a real-time dashboard allows for the visualization and optimization of irrigation strategies. The application of fuzzy logic for decision-making is at the core of this research. In relation to the subject, fuzzy logic plays its part in modeling all these complex and uncertain environmental conditions, thus allowing more flexible and efficient management of irrigation. Membership functions are defined in measured values, giving the specific operating levels for the irrigation system at certain critical parameters: temperature, humidity, and soil moisture. Finally, this section provides an in-depth description of the proposed scheme algorithm, explaining each key step of the process in detail to clarify the underlying mechanisms and logic involved. This approach ensures that irrigation is adapted to actual crop needs, contributing to more sustainable management of water resources.

2.1. *Framework of the system*

IoT technologies, cloud computing, and real-time dashboards contribute something new to intelligent irrigation management to optimize water resource use for agriculture. The system is made up of three well-organized yet interdependent layers that authorize correct monitoring and effective managing of the environmental conditions of crops. The collection, analysis, and interpretation of data in real time strengthen not only the process of decision-making but also contribute to sustainability by way of resource wastage reduction. This system also contributes to sustainable development and protection of water resources by managing water resources in a more balanced and responsible way. Fig. 3 depicts the architecture of the system here proposed, whose description is given below, considering peculiar functionalities of each layer composing it-namely, IoT devices deployed in the field, cloud computing via ThingSpeak, and a real-time dashboard. Each device will play its role in developing automation and optimization irrigation processes in general for achieving more efficient and resilient agriculture.

2.1.1. *IoT devices (field layer)*

The main heart of the IoT system is the integration of intelligent components with field condition sensing and real-time actuation. The ESP32 microcontrollers are the center of the field layer, as they will be

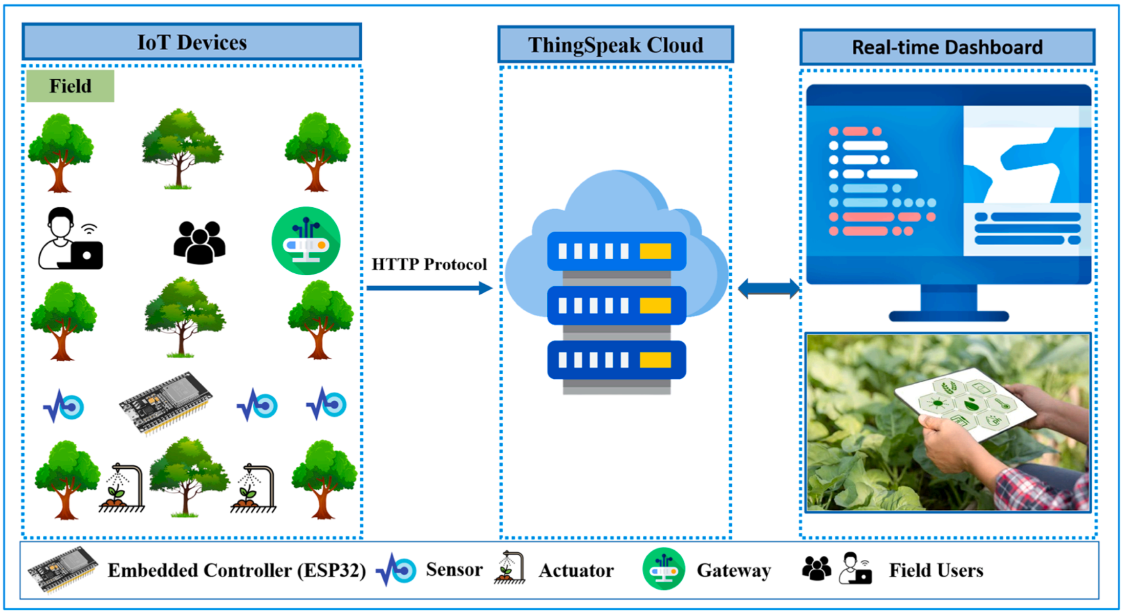

Fig. 3. Framework of the proposed scheme.

the orchestrator in the entire process based on the data gathered from the sensors installed within the field. Sensors operating due to ventilation measure all the indispensable parameters, such as temperature, air humidity, and soil moisture for an effective overall picture of the environmental condition. Information gathered, therefore, acts as input to actuators, which could be irrigation pumps. They water the land automatically and precisely, should the need be in that particular area. All this is powerfully effective through a communication gateway that enables flawless data transfer between the field devices and the cloud. Communication using HTTP protocol allows for secure and efficient data transmission to the ThingSpeak cloud platform. In real practice, this system - implemented by the field users, the majority of whom are farmers through the friendly user interfaces - returns highly accurate recommendations on irrigation management for decision-making to sustain farming.

2.1.2. Cloud computing (ThingSpeak)

The ThingSpeak cloud computing platform occupies a strategic position within this architecture, ensuring not only the storage of data collected in the field but also its real-time analysis. Data sent from ESP32 microcontrollers via the HTTP protocol is aggregated and processed on this platform. ThingSpeak uses advanced algorithms to analyze environmental conditions, enabling trends and the proactive identification of irrigation needs. In addition, the platform offers robust visualization capabilities, enabling raw data to be transformed into actionable information. These analyses are essential to maintain optimal irrigation, thus reducing water waste and ensuring that crops receive adequate water. With ThingSpeak, users can also store large amounts of historical data, making it easier to make informed decisions based on past and present patterns.

2.1.3. Real time dashboard

The real-time dashboard is the system's user interface, providing a dynamic overview of field operations. The dashboard shall be enabled with ThingSpeak, showing continuous data and analytics on the critical operational parameters related to farmers like soil moisture, ambient humidity, and temperature, among others. Intuitive visualization of complex information in simple ways will enable users to reach quick decisions. Moreover, the dashboard should be interactive where the user will be able to change the system settings in light of the received recommendations for better precision and timeliness of irrigation management. The interface will be of assistance to the end-users because it will transform technical data into understandable, directly applicable information, hence will contribute to increasing the general efficiency of the irrigation management system.

2.2. Mathematical modeling and fuzzy logic rules

When developing an intelligent irrigation system based on fuzzy logic, rigorous mathematical modeling is essential to ensure efficient and optimized water management. This modeling is based on a fuzzy approach that considers uncertainties and variations in environmental parameters, such as temperature and soil moisture, to adapt the irrigation duration dynamically. This process comprises several key steps: input fuzzification, which converts numerical values into fuzzy sets using membership functions; fuzzy inference, based on a set of logical rules formulated from the analysis of environmental conditions and their impact on irrigation; and finally, defuzzification, which transforms the fuzzy output into a concrete value representing the optimal irrigation duration. The aim is to detail the various stages in the mathematical modeling of the system, highlighting the formulas used and their role in real-time decision-making for intelligent, sustainable irrigation. Input fuzzification is the process of converting precise input values into fuzzy values using membership functions. This process is used to represent the uncertainty and variability of environmental conditions in smart irrigation. The system's input variables are defined as follows:

- Input Variables: Temperature T (°C): *Low* (L_T), *Midium* (M_T), *High* (H_T)
- Soil Moisture S (%): *Low* (L_S), *Desired* (D_S), *High* (H_S)

Each input value x_i is associated with a fuzzy set A_i via a membership function $\mu_{A_i}(x_i)$ which expresses the degree to which this value belongs to a given set, as shown in Eq. (1) :

$$\mu_{A_i}(x_i) \in [0, 1] \tag{1}$$

For example, soil moisture fuzzification is represented by the following membership functions, as illustrated in Eq. (2):

$$\mu_{L_s}(S), \ \mu_{D_s}(S), \ \mu_{H_s}(S) \tag{2}$$

where $\mu_{L_s}(S)$ represents the degree to which soil moisture belongs to the

Low category.

Defining membership functions, the membership functions used to represent fuzzy variables are generally triangular and trapezoidal. These functions ensure a smooth transition between the different fuzzy categories of input variables. Triangular function: defined by three parameters (a, b, c), it is given by Eq. (3) :

$$\mu_A(x) = \begin{cases} 0, \ x \le a \ or \ x \ge c \\ \frac{x-a}{b-a}, \ a \le x \le b \\ \frac{c-x}{c-b}, \ b \le x \le c \end{cases} \tag{3}$$

Trapezoidal function: defined by four parameters (a, b, c, d), it is given by Eq. (4) :

$$\mu_A(x) = \begin{cases} 0, \ x \le a \ or \ x \ge d \\ \frac{x-a}{b-a}, \ a \le x \le b \\ 1, \ b \le x \le c \\ \frac{d-x}{d-c}, \ c \le x \le d \end{cases} \tag{4}$$

A rule-based inference system, fuzzy inference relies on a set of logical rules that describe the relationship between inputs (soil temperature and moisture) and output (irrigation duration). The fuzzy rules are formulated based on the provided rule Table 2. The general structure of a fuzzy rule is given by Eq. (5):

$$R_i : \text{IFTis } \ A_T \, \text{ANDSis } \ A_S \, \text{THENIis} \, A_I \tag{5}$$

Where:

A_i: Temperature fuzzy set ($L_T, \ M_T, \ H_T$)

A_s: Soil Moisture fuzzy set ($L_S, \ M_S, \ H_S$)

A_I: Irrigation fuzzy set (Long, Medium, Short)

Each rule is applied using the minimum operator to represent logical conjunction (AND). The degree of activation of each rule is given by Eq. (6) :

$$\omega_i = \min\left(\mu_{A_T}(T), \ \mu_{A_S}(S)\right) \tag{6}$$

Where ω_i represents the weight of the rule as a function of the degrees to which the inputs belong to the corresponding fuzzy sets.

Defuzzification is the reverse process of fuzzification. It converts the fuzzy values obtained at the output of the inference system into a precise numerical value representing the irrigation time. A classic defuzzification method is the center of gravity, where the output value I is calculated according to Eq. (7):

$$I = \frac{\sum_i \omega_i \ c_i}{\sum_i \omega_i \ c_i} \tag{7}$$

Where ω_i is the rule active weight. On the thar hand, ω_i is crisp irrigation value (e.g., Long = 10 min, Medium = 5 min, Short = 2 min). In this way, defuzzification makes it possible to determine an irrigation time suited to the environmental conditions measured, guaranteeing optimized management of water resources.

This part presents the fuzzy logic rules and membership functions used in our intelligent irrigation management system. Fuzzy Logic Rules: Fuzzy logic rules have been very important in determining, concerning temperature variation and soil moisture, the ideal duration of irrigation. The membership functions model such parameters as linguistic variables that enable automatic decision-making. It becomes critical for the realization of better sustainability and efficiency in agricultural practices, as it gives an exact regulation of crop water requirements, considering fluctuating environmental conditions. This is represented by the figures below, showing the input and output variables membership functions. The table of rules gives an insight into the decisions taken by the system. Some of the fuzzy rules that can be used to control this intelligent irrigation system are listed below. Some of these are shown in Table 1. These will ensure that this system makes optimized decisions on the duration of the irrigation from the prevailing ambient temperature and soil moisture content. This table tabulates nine rules with respect to all the possible variations that might arise from two main inputs: temperature and soil moisture. Each of these inputs is categorized into three levels: low, medium, or high-desired in the case of soil moisture. According to the combination of these levels, the corresponding rule determines for how long-that is, short, medium, or long-the irrigation should be effected. It proposes a long irrigation time with high temperatures, adding the factor of low soil moisture to compensate for high evaporation and maintain adequate soil moisture for crops. In cases of high humidity in the soil at high temperatures, the duration of irrigation is reduced to avoid the excess water that would hurt plant growth, not to mention waste of such a valuable resource. Fuzzy logic allows the system to change dynamically with field conditions, hence improving water usage efficiency and sustainable agriculture. This intelligent model reduces overdependence on continuous human interference and assures that irrigation is precisely and optimally done for the attainment of food security and environmental sustainability. The use of fuzzy logic in this study provides a robust approach to intelligent irrigation management, contributing to optimized and adaptive decision-making in the face of environmental variations. Precise adjustment of membership functions improves system reliability and ensures better water security by regulating water supply efficiently.

Fig. 4 illustrates the membership functions associated with the “temperature” input variable in the context of the intelligent irrigation system. The temperature interval considered ranges from 15 °C to 45 °C, covering three linguistic categories: Low, Medium, and High. The Low membership function has a trapezoidal shape, reaching a maximum value between 15 °C and 25 °C, then decreasing linearly until it reaches zero at 25 °C. Above average, the triangular membership function peaks at 30 °C. the ideal temperature. From this optimum, the membership value decreases linearly with deviation in either direction from this optimum. The High membership function, which is trapezoidal, starts an increase at 35 °C and reaches full membership at 45 °C. These functions provide a basis for assessment for the temperature condition under which irrigation decisions are made.

Fig. 5 presents the membership functions of the input variable "soil moisture," which becomes necessary for the determination of the irrigation needs of the system. The considered classes are Low, Desired, and High. The variations in soil moisture range from 55 % to 70 %. For the Low class, it was adopted with a trapezoidal curve, signaling low levels of soil moisture. Its membership becomes complete within the interval from 55 % to 59 %, then declines. The conventional triangular membership function for class Desired, with its peak at 62 %, can be interpreted as an optimum soil moisture condition. The maximum membership will be attained only at 62 %, and it represents the ideal state where no further irrigation is needed for the crop. In the same way, the High membership function has its peak above 63 % in the same way as in the Low category, designating excessive levels of the soil moisture where irrigation should be minimized or stopped. Fig. 6 Membership functions corresponding to the output variable "irrigation duration" sets

Table 1
Fuzzy logic rules.

Rules.No	Temperature	Soil Moisture	Irrigation Duration
1	Low	Low	Long
2	Low	Desired	Medium
3	Low	High	Short
4	Medium	Low	Long
5	Medium	Desired	Medium
6	Medium	High	Short
7	High	Low	Long
8	High	Desired	Medium
9	High	High	Short

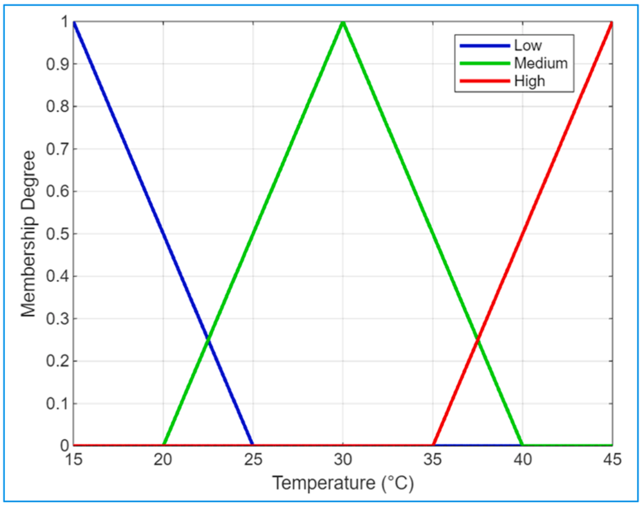

Fig. 4. Temperature membership functions.

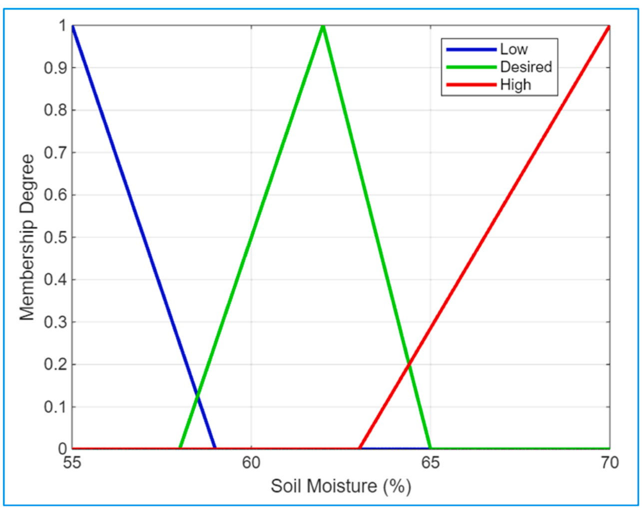

Fig. 5. Soil moisture membership functions.

the time period over which irrigation has to be applied. Irrigation duration, varying between 0 to 10 min, is divided into three linguistic terms or categories: Short, Medium, and Long. The trapezoidal shape of the Short membership function reflects minimal irrigation with its peak lying between 0 and 2 min, then it starts to decline. The triangular membership function of Average irrigation duration peaks at a value of 3 min, reflecting an irrigation requirement at the level of medium. In the same way, the increasing function Long ranges from 5 to 10 min. This denotes that the conditions may be such that long irrigation is called for. With these, the system will be able to fine-tune the irrigation duration in response to the environmental parameters assessed. In this intelligent irrigation system, the specific needs of crops are calculated to optimize water use. By customizing humidity and sun temperature, the system adjusts irrigation to the specific requirements of tea crops, such as rice or tomatoes. The use of fuzzy logic enables dynamic adaptation of irrigation duration and frequency, taking into account environmental conditions and the characteristics of the tea crop. In addition, by exploiting historical and temporal data, the system optimizes irrigation using climatic and local conditions, which also guarantees efficient water management. The user interface enables farmers to customize irrigation parameters for tea cultivation, guaranteeing a fluid and robust approach.

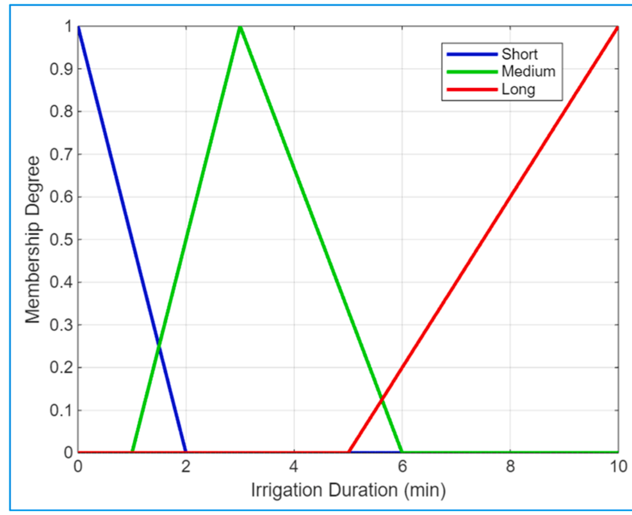

Fig. 6. Irrigation duration membership functions.

2.3. *Algorithm of the proposed scheme*

Table 2: The pseudo-code of the suggested intelligent irrigation using fuzzy logic explains the way real-time intelligence is involved in an irrigation system to optimally manage water based on with prevailing environmental conditions, taking into consideration soil moisture, ambient temperature, and air humidity. It shall be constituted of a simple ESP32 platform, sensors, a water pump, and a fuzzy logic-based controller. It initializes the soil moisture sensors, temperature, and air humidity, beside the water pump. Then, the ESP32 connects to the Wi-Fi network to enable communication with the ThingSpeak cloud, which is a platform used for data monitoring and recording in real-time. Input variables will be defined from sensor measures: soil moisture, temperature, and air humidity, and only one output variable will be defined, namely irrigation duration. In this way, a membership function is generated using MATLAB that can classify data into classes such as High, Low, Short, Medium, Long, and Desired such that the sensor data is qualitatively interpretable. The fuzzy logic rules are now imposed on the system to obtain the optimal time of irrigation. For example, in the case of low soil moisture coupled with high temperature, the irrigation time is increased. These rules can also be moved depending on what a certain crop needs, and allow flexibility within the process. The sensors will be interrogated regularly for new measures that will be translated into fuzzy values (fuzzification). Later on, this decision process will apply fuzzy rules and will perform defuzzification with the purpose of estimating a concrete irrigation duration. If the irrigation is computed, then the pump is turned on for the computed time, and data about this operation -time and length- is sent to ThingSpeak; in case irrigation is not needed, the pump stays off but again the status of the system is transmitted to the cloud. The acquired data from all sensors is periodically sent to ThingSpeak, using HTTP POST requests. This, in turn, enhances the possibility for real-time environmental condition analysis and, thus, makes decisions based on irrigation. The system constantly monitors for any type of failure; for example, sensor failures or failures on the cloud connection. Any problem detected gets logged, and an automatic attempt to reset or reconnect to Wi-Fi gets launched. If it is doomed with continuous failure, then notification would be provided to the user through ThingSpeak itself. MATLAB has been used in the design for simulation and fine-tuning of membership functions and fuzzy rules for optimization of the onboard controller to perform efficient irrigation in terms of the right need at any instance. Lastly, shutdown can be done either manually or automatically based on preset conditions. It will switch off the pump at the time of shutdown and disconnect the Wi-Fi connection while saving data for further analysis.

Table 2
Algorithm 1: Pseudo-code of the proposed smart irrigation-based fuzzy logic.

```
// Initialization of sensors and devices
  Initialize soil moisture sensor
  Initialize temperature sensor
  Initialize air humidity sensor
  Initialize water pump
  Initialize ESP32 microcontroller
  // Network connection configuration
  Configure Wi-Fi connection
  Configure ThingSpeak connection using API keys for data transmission (via HTTP)
  // Initialization of fuzzy logic controller
  // Define input fuzzy variables (temperature, soil moisture)
  // Define output fuzzy variable (irrigation duration)
  Define fuzzy sets for temperature: [Low, Medium, High]
  Define fuzzy sets for soil moisture: [Low, Desired, High]
  Define fuzzy sets for irrigation duration: [Short, Medium, Long]
  // Use MATLAB to create membership functions for classifying sensor data into fuzzy levels:
  For temperature: Low, Medium, High
  For soil moisture: Low, Desired, High
  For irrigation duration: Short, Medium, Long
  // Define fuzzy logic rules based on the following table:
  Rule 1: If temperature is Low AND soil moisture is Low, THEN irrigation duration is Long
  Rule 2: If temperature is Low AND soil moisture is Desired, THEN irrigation duration is Medium
  Rule 3: If temperature is Low AND soil moisture is High, THEN irrigation duration is Short
  Rule 4: If temperature is Medium AND soil moisture is Low, THEN irrigation duration is Long
  Rule 5: If temperature is Medium AND soil moisture is Desired, THEN irrigation duration is Medium
  Rule 6: If temperature is Medium AND soil moisture is High, THEN irrigation duration is Short
  Rule 7: If temperature is High AND soil moisture is Low, THEN irrigation duration is Long
  Rule 8: If temperature is High AND soil moisture is Desired, THEN irrigation duration is Medium
  Rule 9: If temperature is High AND soil moisture is High, THEN irrigation duration is Short
  // Main loop
  Infinite loop:
  // Read sensor data
  soilMoisture = Read soil moisture sensor
  temperature = Read temperature sensor
  // Fuzzification: Convert sensor values into fuzzy sets (Low, Desired, High for soil moisture; Low, Medium, High for temperature)
  fuzzyMoisture = Fuzzify(soilMoisture)
  fuzzyTemperature = Fuzzify(temperature)
  // Apply fuzzy logic rules to determine irrigation duration
  irrigationDuration = ApplyFuzzyRules(fuzzyTemperature, fuzzyMoisture)
  // Defuzzification: Convert fuzzy output (irrigation duration) to a concrete value
  concreteDuration = Defuzzify(irrigationDuration)
  // If irrigation is needed, activate pump for a calculated duration
  If concreteDuration > 0:
  Activate pump for concreteDuration seconds
  Send data to ThingSpeak (soil moisture, temperature, irrigation duration)
  Else:
  Send data to ThingSpeak (soil moisture, temperature, no irrigation)
  // Transmit all system data to ThingSpeak cloud for remote monitoring
  Send soilMoisture, temperature, system status to ThingSpeak via HTTP POST request
  // Monitor for potential errors
  If sensor failure or Wi-Fi disconnection is detected:
  Log the error and send to ThingSpeak
  Attempt to reconnect Wi-Fi or reset sensors
  // Wait 2 seconds before the next sensor reading
  Wait(2000 ms)
  // Shutdown sequence
  If the system is manually or automatically stopped:
  Deactivate pump
  Disconnect from Wi-Fi
  Save data and logs for future analysis
```

3. Results and discussion

It gives a detailed analysis of the obtained results and presents a deep discussion on the developed intelligent irrigation management system. The design of the system was performed by combining modeling and analysis using a simulation tool represented by MATLAB. The execution of the algorithm, together with its control of hardware peripherals, has been accomplished using C programming, also called Arduino IDE. This ESP32 module integrates several sensors for data gathering, while the management and visualization are done through the ThingSpeak platform. To ensure effective and timely communication between sensors and the ThingSpeak platform, communication is implemented using HTTP protocol. It is in this section of the paper where the results of how effective fuzzy logic algorithms are when applied to irrigation management in relation to variations in temperature and humidity are simulated and experimentally dealt with. Hence, this analysis is done on the basis of the accuracy of the data collected, its impact on irrigation decisions, and how the system works efficiently in an agricultural setting. This discussion will cover the performance evaluation of the system, focusing on the positive points and making some recommendations for future improvements to achieve maximum efficiency and reliability from the system. To guarantee long-term operational reliability, our system has been subjected to several rigorous tests under various environmental conditions, including extreme situations. These tests evaluated system stability, sensor accuracy and the consistency of fuzzy logic-based irrigation decisions. Particular attention was paid to sensor maintenance, essential to ensure system durability. The algorithm developed includes self-diagnostic mechanisms to detect any sensor drift or failure in real time. This approach enables the system to dynamically adjust its parameters or signal the need for intervention, thus guaranteeing optimal long-term performance. The tests carried out and the maintenance strategies implemented reinforce the system's robustness, guaranteeing efficient, reliable irrigation, even under demanding agricultural conditions.

In this study, we paid particular attention to the implementation of robust security measures to guarantee the confidentiality and integrity of the data collected and transmitted by the system. The ThingSpeak cloud platform used for data management offers advanced security features that protect sensitive information throughout its lifecycle. The system uses a login authentication mechanism to secure access to data stored on the ThingSpeak platform. This restricts access to authorized users only, ensuring strict control over data operations. This measure protects the integrity of information by preventing unauthorized access that could compromise system reliability. In addition, to guarantee the confidentiality of data exchanged between IoT sensors in the field and the cloud platform, we have integrated the use of the HTTP protocol. This protocol encrypts transmitted information, offering protection against attempts to intercept or alter data. Encryption enhances communication security, ensuring that sensitive information, such as environmental parameters and irrigation decisions, is protected throughout the transmission process.

Fig. 7 shows in detail a geospatial mapping of the location of the LISAC-Laboratory of Informatics, Signals, Automation, and Cognitivism, being part of Faculté des Sciences Dhar El Mahraz - FSDM of the Université Sidi Mohamed Ben Abdellah - USMBA, in Fez, Morocco. It is by this Google Earth picture that the scene will be set for the current paper, which is going to introduce a new intelligent irrigation system. Advanced technologies of fuzzy logic, IoT, and embedded systems were integrated in the laboratory to allow the realization of the solution for irrigation management with high performance. In fact, the proposed system shall contribute to achieving sustainable agriculture that ensures food security by introducing new agricultural practices that make optimum use of available water resources. This figure highlights the expected global impact of this research. In the same fashion, this collocates the work in the particular geographical and academic context of the USMBA, a benchmark institution in the field of agricultural technologies.

Over the specified observation period, the fuzzy logic-based irrigation system demonstrated its ability to adjust irrigation periods according to slight variations in weather conditions, as illustrated in the following figures and rules. Fig. 8 illustrates the variations in soil moisture levels throughout the day, compared with the desired moisture level of 62 %. The line graph shows that soil moisture averages varied between 57.5 % and 65 %. Soil moisture was below 62 % at several points, including 12:00 (59.5 %), 13:00 (58.5 %) and 17:15 (60 %). However, humidity levels exceeded 62 % at certain times, such as 12:15 pm (62.5 %), 2:30 pm (64 %) and 3:15 pm (61 %). The dotted line at 62 % is the target moisture; it is convenient to compare with the actual soil moisture values throughout the day. Such variability in this case is controlled by fuzzy logic rules that measure how much irrigation is deemed necessary by prevailing humidity levels as well as temperature conditions. Fig. 10 represents temperature variation throughout the day. The temperature data varies from 15.25 °C at 01:45 to 40 °C at 11:00. Notable temperature points include 39.1 °C at 13:00 and 26 °C at 15:30. The figure captures temperature fluctuations and their extremities, which are of essence for the analysis that this serves in showing how temperature controls soil moisture and irrigation need. In the daily performance evaluation, it was observed that the fuzzy logic controller effectively prevents system operation during periods of high heat, as shown in Fig. 9. In addition, it favors short irrigation times when the input parameters are moderate. This method significantly reduces the losses due to evapotranspiration throughout the day. In addition, the controller determines precisely the optimal times and durations for system activation through carefully defined fuzzy logic rules. Further, Fig. 10 illustrates the correlation between temperature and irrigation duration throughout the day, i.e. irrigation duration as a function of temperature evolution. The scatter plot reveals significant variation in irrigation times in response to temperature changes. For example, when the temperature reached 40 °C at 11:00, the irrigation time was 6 min. Conversely, at a lower temperature of 15.25 °C at 01:45, irrigation time was minimal. The rules of fuzzy logic play a decisive role in extending irrigation periods when temperatures are high, to ensure that the soil retains a target humidity of 62 %. This pedoclimatic irrigation method was validated during the summer season. The fuzzy logic controller avoids watering during times of significant weather fluctuations, as shown in Fig. 10, which minimizes water losses by evaporation while maintaining plants in optimal condition, that is, without water stress. In addition, the duration of irrigation is adjusted according to data provided by sensors such as soil moisture, temperature, and ambient humidity.

Fig. 7. Geospatial mapping of research Laboratory at FSDM, USMBA - Fez on Google Earth.

Fig. 11 depicts instantaneous values of measured temperature presented in the ThingSpeak platform. This graph shows the continuous evolution of the measured temperatures; such a graph provides a clearer snapshot about the current climatic situation. In such a graph, one can study real-time temperature variations and thus study the climatic tendencies that might come out to be of great relevance regarding anticipating when irrigation should be done. Fig. 12 shows, in turn, the real-time values of air humidity as captured and visualized on ThingSpeak. This graph provides an accurate real-time view of the outdoor humidity condition that is highly important for the reactive adjustment of irrigation management practices based on data acquired. Indeed, to monitor such humidity variations in real time will be an advantage in optimizing the effectiveness of irrigation interventions. In addition, Fig. 13 illustrates soil moisture levels in real-time, as monitored on ThingSpeak. This graph shows soil saturation at different times, enabling continuous and accurate monitoring of soil moisture status. Real-time access to this data is crucial for assessing irrigation requirements with a high degree of accuracy, guaranteeing optimal management of water resources, and contributing to the sustainability of agricultural practices.

In order to assess the affordability of the proposed system compared with traditional irrigation methods, we present a detailed cost analysis of the main components used in this study. Table 3 below summarizes the prices of essential components, including the on-board microcontroller (ESP32), sensors (soil moisture sensor, DHT22 sensor), irrigation water pump, as well as other necessary components (test plate, resistors, connection cables, etc.). In addition, we take into account data management solutions via the cloud (ThingSpeak) and the software tools used for data processing (MATLAB in trial version). The total cost for

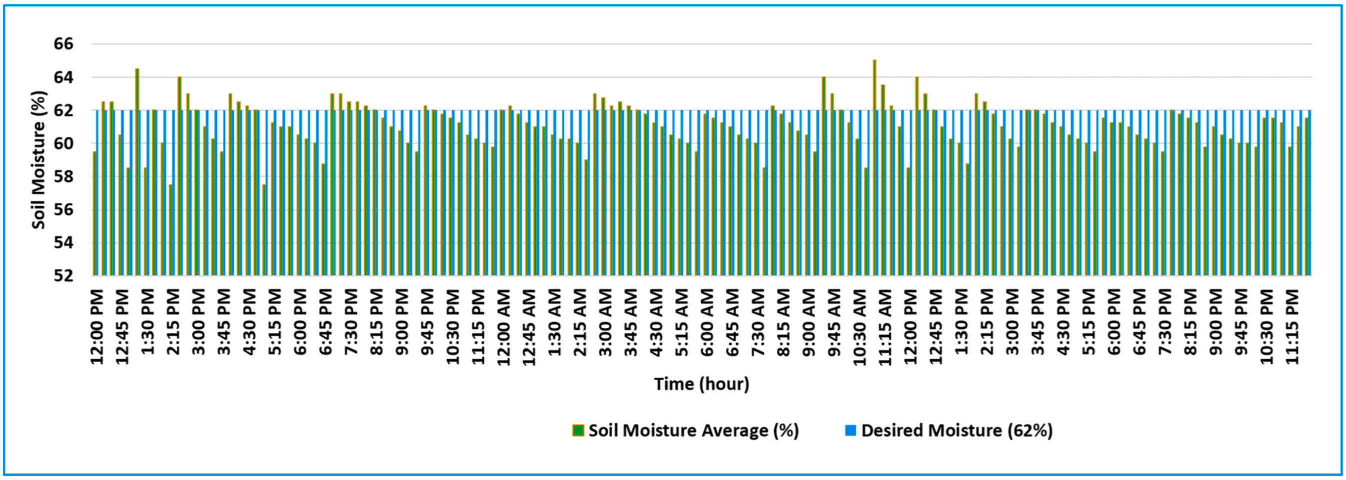

Fig. 8. Soil moisture evolution and desired moisture.

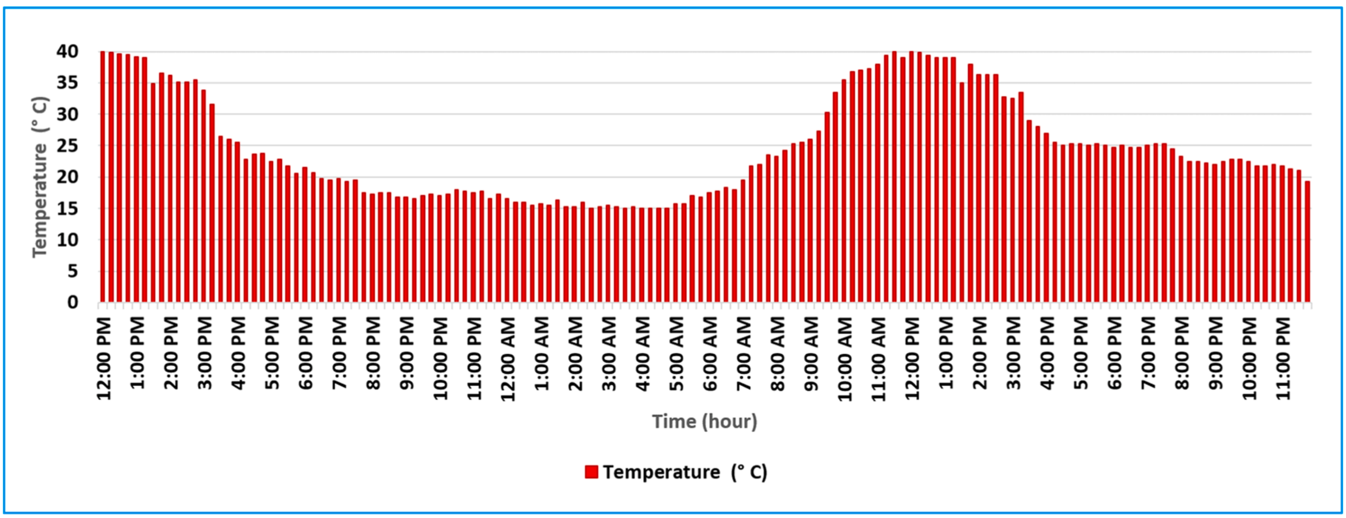

Fig. 9. Temperature value.

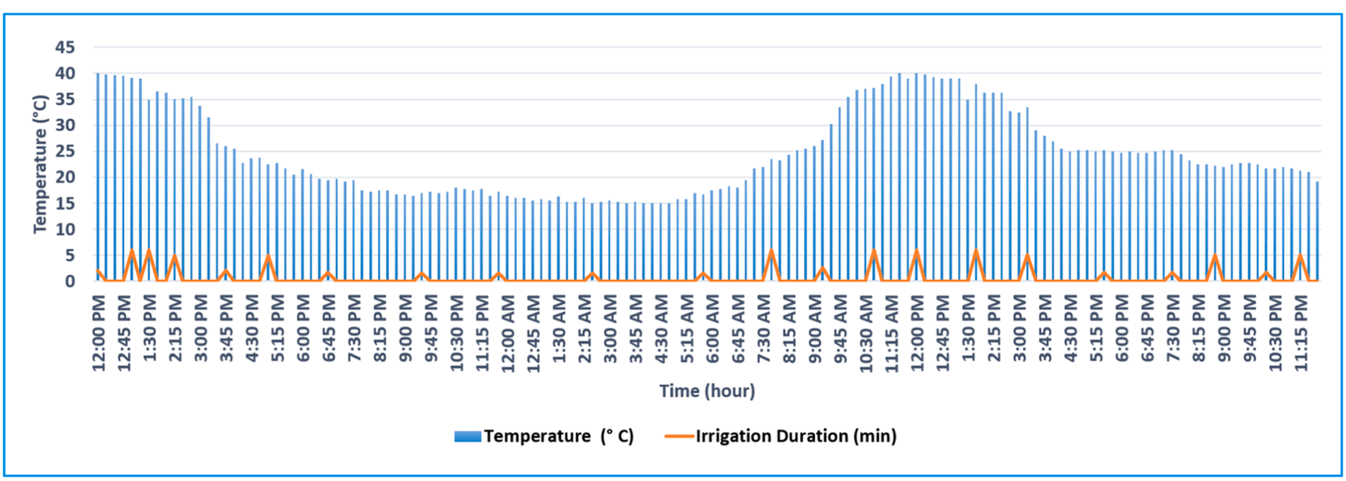

Fig. 10. Irrigation duration in the function of temperature evolution.

implementing the IoT-based smart irrigation system, integrating all the components mentioned, comes to 32.00 USD. This is significantly lower than the costs associated with traditional irrigation methods, which typically require high investments in infrastructure installation and maintenance (pumps, pipe networks) as well as manual monitoring of soil moisture levels. While traditional methods involve high initial

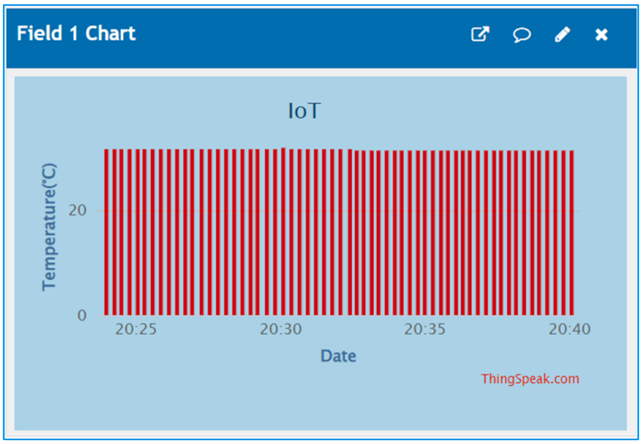

Fig. 11. Temperature value in real time on ThongSpeak cloud.

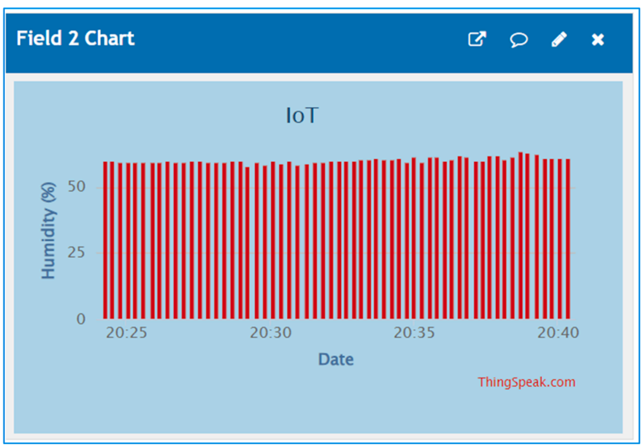

Fig. 12. Humidity value in real time on ThongSpeak cloud.

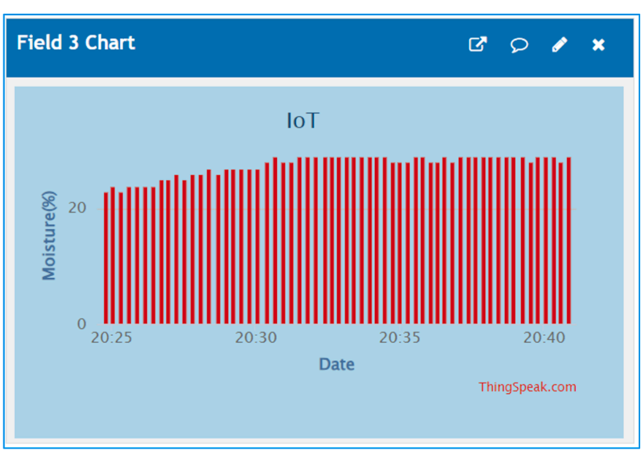

Fig. 13. Moisture value in real time on ThongSpeak cloud.

outlay, the proposed system is based on low-cost, on-board technologies that improve irrigation efficiency, optimize water resource management and reduce manual workload. In the long term, this approach offers a more economical and sustainable solution for farms.

In addition to the advancements in precision agriculture, the present paper proposes an intelligent irrigation system based on fuzzy logic with novelty in integrating IoT devices, cloud computing, and real-time monitoring. It highly contributes to enhancing water management

Table 3
Detailed cost analysis.

Component	Description	Price (USD)
ESP32 Microcontroller	Embedded development board ensuring communication and management of sensors and actuators.	6.00
Moisture Sensor	Measures soil moisture to optimize irrigation decisions.	3.00
DHT22 Sensor	Detects ambient temperature and humidity to adapt irrigation to climatic conditions.	4.00
Water Pump	Ensures irrigation of the soil based on data collected by sensors.	10.00
Other components	Allows the prototyping and secure connection of different electronic components. Stabilize electrical signals and ensure proper circuit operation	9.00
ThingSpeak (Cloud Platform)	Provides real-time collection, storage and visualization of sensor data.	0.00 (Free)
MATLAB (Trial Version)	Utilisé pour l'analyse et la visualisation avancée des données du système.	0.00 (Free-Trial)
Total Cost		32

practices of vital importance for those regions that have big problems with water scarcity and totally unpredictable weather conditions. The system will be based on a fuzzy logic controller that will dynamically adjust the irrigation schedule by taking real-time data input from a network of sensors deployed in the area. These sensors are interfaced using ESP32 microcontrollers that monitor critical environmental parameters: ambient temperature, soil moisture, and humidity in the air. Contrary to most irrigation systems, which water on rigid schedules or are activated by fixed threshold triggers, our system interprets sensor data in real-time using fuzzy logic to make informed decisions on plant water needs. It, in turn, enables more precise and appropriate management, hence assuring that water is only made available when it is needed, reducing the risk of under or over-irrigation. The system comprises three interoperable layers: IoT devices-ESP32 controllers, sensors, pumps, and gateways-cloud services, ThingSpeak; stores and processes data, and there is a real-time dashboard used for the control and monitoring of the device. The collected data is sent over the HTTP protocol to the ThingSpeak platform for analysis and visualization. On the other side, performance requirements made it essential to simulate and visualize, by using MATLAB, membership functions of fuzzy logic in order to tune them with precision in the development of control algorithms. In this way, fuzzy logic rules would best correspond to specific environmental conditions of the study area, thus optimizing the system's efficiency. Real-life test results demonstrated clear advantages compared to conventional irrigation methods. A fuzzy logic controller that could adjust irrigation time with the systematic maintenance of soil moisture close to the target of 62 % was able to optimize water use.

Our system was performed by saving 70 % water compared to conventional irrigation methods while optimum soil moisture was maintained. This level of savings confirms the system's effectiveness in optimizing of its water resources, particularly in those short periods of supply. That way, this approach enables farmers to act in a more considerate manner when modifying irrigation, thus contributing to resource conservation. Another value addition is that the adaptive nature of fuzzy logic in irrigation management has been highly effective, as against the threshold-based conventional systems. This permits flexibility in decision-making during variable weather conditions. In fact, during temperature peaks, the system delays irrigation during peak hours to minimize losses due to evaporation. Similarly, when temperatures fell, irrigation was trimmed to prevent over-irrigation, a factor that underlined the effectiveness of fuzzy logic in a complex scenario where decisions were to be made based on many factors. The benefits derived from this system are not confined to water savings alone. This also ensures proper and timely irrigation of crops, increasing their yield and improving their quality. Real-time and long-term analysis enables farmers to make better decisions, which are enabled through the ThingSpeak cloud platform. Meanwhile, two other important milestones in applying IoT in agriculture have been the use of ESP32 microcontrollers for IoT applications and the further development of advanced sensing technologies. The case presented in the paper can show the possible transformation of fuzzy logic in irrigation management function that requires intelligent and adaptive solutions from contemporary agriculture. This cropping system regulates soil moisture efficiently and resists climatic oscillations; hence, it will play a greater role in the promotion of sustainable agriculture by judicious use of available water resources in most water-stressed regions.

(1) The proposed architecture has been designed to guarantee modularity and scalability to meet the varied needs of farming operations. The field layer is based on ESP32 microcontrollers, which orchestrate the collection and analysis of data from environmental sensors (temperature, air and soil humidity). Thanks to an efficient communication gateway and the use of HTTP protocol, this data is transmitted securely to the ThingSpeak cloud platform. This architecture ensures optimized resource management, reducing network overload and maintaining operational efficiency even in complex, extended environments. In addition, the ThingSpeak platform provides real-time analysis of collected data, facilitating dynamic adaptation of irrigation cycles to environmental conditions. It can also store historical data to optimize long-term decision-making. The real-time dashboard is an essential interface for farmers, offering them a clear and intuitive visualization of critical system parameters. Its interactivity enables them to adjust settings according to recommendations, guaranteeing precise and efficient irrigation management. To enhance the system's scalability, we plan to integrate advanced strategies such as segmenting the network into intelligent sub-systems, using IoT gateways and optimizing data processing algorithms. These improvements will enable the system to be adapted to large-scale farming operations, while guaranteeing sustainable management of water resources. Using MATLAB to adjust membership functions can be tedious for some users. To make this task more accessible, user-friendly alternatives can be considered, such as web interfaces or mobile applications offering intuitive adjustment, as well as No-Code/Low-Code dashboards enabling simplified adjustments. The use of Excel with VBA or Python is an accessible solution without the need for MATLAB. In addition, the integration of artificial intelligence-based tools, such as genetic algorithms or particle swarm optimization, enables dynamic adjustment of membership functions according to the data collected. These approaches aim to improve the accessibility and efficiency of fuzzy models without requiring advanced programming expertise.

The development of the smart irrigation system with the use of fuzzy logic and IoT comes with its own advantages in handling agricultural water management. Besides, there are also certain challenges and limitations on its scalability, cost, and connectivity among other issues. Thus, this should be taken as a wider diffusion perspective in developing regions.

1. Scalable System: One of the main challenges facing large farms is scalability. The perfect implementation of our system in small and medium-scale farming makes integration over larger areas very complicated with sensors and more IoT devices. This would require an extended sensor network with considerable communication infrastructure to manage a large volume of data in real-time. Moreover, the technological change would have to be implemented on many control points and actuators so they could keep up with high response and elaboration speed. The use of LoRaWAN or mesh technologies would prolong their coverage in large environments and give added value to data management.
2. Cost: The initial implementation cost of such a system is rather high since it relies so much on technological infrastructure. Buying ESP32 microcontrollers, sensors, and communication devices alone subscriptions to cloud platforms such as ThingSpeak is an initial investment that can turn out quite unaffordable for certain farms, at least in developing regions. Further added is the cost of maintenance and powering IoT devices. While long-term savings in water and increases in yield may therefore be seen as reasonable rationalization for the adoption of such technologies, specific profit-making assessments about the short term are indispensable, particularly in low-income areas. Consideration of subsidies or even public-private partnerships encouraging the same in regions where water management is urgent should, therefore, be underlined.
3. Internet connectivity: The major bottleneck in rural areas pertains to internet connectivity. Therefore, the proposed system relies heavily on a stable connection with the cloud for data transmission and real-time monitoring. However, internet access in most remote agricultural areas is thin or negative, making it a possible hindrance to the efficiency of the proposed system. This is further limited by the constant presence an internet connection requires. This could be overcome using long-range, low-power communication networks, such as LoRaWAN, which does not need an internet connection constantly but also allows for transmission over longer distances with energy consumption. Hybrid approaches could therefore be introduced that would implement local communications and edge computing in order to make the full functionality of the system possible even without a stable connection to the Internet.
4. Computational complexity: Although fuzzy logic may be powerful, the implementation involves high computational costs. Processes such as fuzzification, inference, and defuzzification are hugely computation-intensive, especially in the cases of complex systems or large datasets. The heavy computational burden may reduce performance in these kinds of systems when operating in resource-constrained environments or real-time applications. Whereas increased computing power has softened some of these constraints, the challenge remains very real for systems deployed to rural areas lacking ready access to large computing resources.
5. Membership functions: Membership functions are subjective, and their selection is one of the most fundamental issues in fuzzy logic systems; this still remains very subjective. These functions, to a great degree, depend on human expertise or intuition for their definition. These points become causes for variance in systems design due to different interpretations by different experts. This may result in biased or inconsistent behavior of the system and hence will affect accuracy and reliability in the irrigation decision-making process. This may be optimized by strict membership function validation and periodic calibration of the system to reduce such errors and give reliable results.
6. Socio-economic factors in the adoption of agricultural technologies: Limited attention to socio-economic factors, such as farmers' willingness to adopt new technologies, can hamper the practical implementation of these innovations. To remedy this, it is essential to implement awareness-raising and training strategies tailored to farmers. Targeted educational programs, practical field demonstrations and awareness campaigns can play a key role in promoting understanding of the benefits of agricultural technologies. In addition, it is important to consider the economic aspects, offering incentives and business models adapted to local realities, in order to facilitate adoption and ensure successful integration of technologies into farming practices.

4. Conclusion and future work

This study presented an innovative smart irrigation system, combining the Internet of Things (IoT), fuzzy logic, cloud computing and real-time sensors to address the challenges of water management in agriculture. Thanks to mathematical modeling, the system dynamically adjusts irrigation needs according to soil temperature and humidity, enabling more precise management of water resources and a significant reduction in wastage. The integration of fuzzy logic in irrigation decision-making guarantees fine-tuned adaptation to changing conditions, such as climatic variations and fluctuating soil moisture. The use of MATLAB to simulate and model fuzzy membership functions enables clear visualization of decision mechanisms and dynamic adjustment of irrigation parameters. The results show that, thanks to intelligent irrigation management, the system is able to maintain optimum soil moisture around the target threshold of 62 %, while avoiding over-irrigation, in particular by reducing watering time during moderate temperatures and increasing it during periods of intense heat. This not only reduces water loss through evaporation, but also water stress in crops, ensuring optimal plant growth. In terms of performance, analysis over an extended period showed a marked improvement in irrigation efficiency. The system achieved a substantial reduction in water losses, using strictly defined fuzzy rules to adjust irrigation to actual crop needs. These dynamic adjustments also enabled a reduction in water consumption, thus contributing to a more sustainable management of water resources. The results show a significant reduction in water consumption, and the system is more affordable (USD 32.00) than traditional methods. The use of the ThingSpeak cloud platform enables continuous monitoring and rapid decision-making. This offers greater responsiveness and faster, more accurate decision-making, which is essential in the context of climate change and increasingly variable weather conditions. The integration of climate data and soil parameters also enables better prediction of crop water requirements, ensuring optimal irrigation management.

In addition to the prospects already mentioned, the integration of renewable energy sources, such as solar panels, is a key avenue for enhancing the system's energy sustainability. Although this approach has been discussed, its actual implementation remains to be explored in future work. The use of solar energy would enable sensors and IoT devices to be powered autonomously, reducing dependence on traditional energy sources and improving system viability in isolated agricultural environments. In addition, advanced data analysis using artificial intelligence and machine learning technologies will be further developed to optimize irrigation scheduling. The application of artificial intelligence algorithms will make it possible to refine the assessment of crop water requirements based on the environmental parameters collected, thus ensuring more precise and adaptive irrigation. In addition, the system will be extended to other types of crops, soils, and climates. This adaptation enables the system to meet the specific water requirements of different crops and optimize irrigation based on local conditions, thereby improving overall efficiency. Finally, particular attention will be paid to data security in the IoT. Future research will focus on strengthening secure transmission protocols and implementing advanced encryption mechanisms to ensure the protection of sensitive information and the integrity of communications between the various system components. Additionaly, plan to focus our future work on developing a stand-alone website for monitoring farm system data. These lines of research will not only improve the efficiency and security of water resource management, but also increase the system's resilience in the face of future environmental and technological challenges.

CRediT authorship contribution statement

Abdennabi Morchid: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zafar Said:** Writing – review & editing, Visualization, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation. **Almoataz Y. Abdelaziz:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis, Data curation. **Pierluigi Siano:** Visualization, Validation, Resources, Investigation, Formal analysis, Data curation. **Hassan Qjidaa:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Formal analysis, Data curation.

Declaration of competing interest

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

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The authors used generative AI tools to assist in grammar correction, clarity improvement, and refinement of language throughout this manuscript. All content was reviewed and validated by the authors to ensure accuracy, originality, and adherence to ethical standards.

Data Availability Statement

All the data is presented in this paper.

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