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Design and Implementation of an Integrated IoT and Artificial Intelligence System for Smart Irrigation Management

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Abstract

Tunisia economic relies heavily on an agriculture key driver. Unfortunately, it yet faces challenges in water management in particularly southern regions having scarce rainfall. Inefficiencies in regular irrigation practized for date palm is addressed by this study. We propose here a smart irrigation system. Leveraging Internet of Things (IoT) and Artificial Intelligence (AI), we have conducted a solution for the Sahara oases. This was done by deploying an IoT sensor network for real-time environmental monitoring. AI algorithms have been used for data processing, enabling precise water predictions for date palms. Results showcase a substantial reduction in water usage, improved crop health, and enhanced yield. The study introduces a novel smart irrigation approach for southern Tunisia. A water optimization has resulted through remote control and monitoring via a cloud-based wireless communication system. Beyond advancing smart agriculture, the research offers crucial implications for mitigating water stress in arid regions, contributing to the transformation of agricultural landscapes. Smart irrigation systems emerge as a viable solution for optimizing water use and avoiding both over- and under-irrigation.

Keywords: *IoT, Agriculture, Smart irrigation, Artificial Intelligence, Sensors, Data.*

1 Introduction

The technological advancements have been widely adopted. Recently and as a result, it has been extended to date palm farming. This shows an effort to boost productivity, cut costs, and boost efficiency. Such technical progress has allowed using sensors to monitor soil moisture as one innovation in date palm agriculture related to AI and IoT. In Tunisia, agriculture is a crucial and essential sector for economic growth. This concerns particularly the southern area. There, sunlight continuously sends rays in this semi-arid and Saharan

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region. It provides good conditions needed for agriculture. 10% of the nation's GDP and 15% of jobs are generated from the agricultural sector [1]. Nevertheless, industries, agriculture and animal production consume the most fresh water globally. In actuality, 70% of the freshwater globally extracted is used for agricultural purposes [2]. Due to population increase and rising food requested, this ratio will continue to dominate the scena. Irrigation represents one of the agricultural practices that globally uses most water. Its use has been timely increased. Nevertheless, a low irrigation efficiency, however, is one of the main causes of water waste. According to the UN Food and Agriculture Organization (FAO), 60% of the water diverted or pumped for irrigation is now lost to evapotranspiration or runoff into rivers [3]. This has led to a significant request looking for intelligent irrigation systems that can deliver efficiency. This is impossible to achieve without defining and making sufficient data analysis and suitable strategies implementation. Therefore, the intelligent irrigation techniques must be implemented. This will help to use less water than previous ones. In fact, water waste may be reduced up to 95% with smart irrigation techniques, compared to 20% to 70% applying traditional methods [4]. Smart irrigation is scientific research growing field that uses data-intensive techniques to boost agricultural output while lowering its environmental effect. Modern agricultural operations gather data from many sensors, improving the understanding of both the environmental operation and activities [5]. In order to maximize cost effectiveness for the farmer, smart irrigation aims to utilize Internet of Things (IoT) and analytical approaches to leverage precision irrigation. This is obtained thanks to a water flowing in the right amount. An optimal management helping to address and direct the water towards the right places at right moments could add this. These IoT-based smart irrigation systems rely heavily on data triggered commands. Signals are generated and received by Sensors and actuators, which are then controlled through wired and wireless interfaces such as IEEE 802.15.4 and IEEE 802.11 [6]. IoT is a broad term describing the network's devices capacity to sense and gather information about the environment. Here Information can be transmitted via the Internet. Such, data may be analyzed and used for a variety of intriguing reasons. Other technologies that focus on improving current services or offering goods that are simple to use and ergonomic, while IoT places the highest priority on optimization. The optimization techniques' goal being essential to the success of any of its systems [7]. The agricultural sector is worldwide recognized as a cornerstone of economies. It faces however, an escalating challenge. Such constraints are, in the wake of changing climate patterns and dwindling water resources, similar to what characterizes our climate in southern Tunisia. More precisely, this goes deeply for the so-called kebili area. Such region is a very hotter zone and drought due to the lack of precipitation and the yearly scarcity of rain. Therefore, there is seriously shortage of water. That region is nestled on the fringes of the Sahara Desert. There, the cultivation of date palms, an economic mainstay, confronts the dual challenge of arid conditions and limited water availability. In response to this pressing issue, our study introduces an innovative approach to irrigation, leveraging the amalgamation of Internet of Things (IoT) based on Artificial Intelligence (AI) technologies. By conducting a comprehensive investigation in this parched landscape, we aim not only to address the immediate needs of date palm cultivation but also pave the way for a sustainable technologically driven agricultural paradigm in Tunisia's arid south. This introduction sets the stage for a detailed exploration of our irrigation system based on IoT and AI-driven and its potential to reshape agricultural practices in water-scarce environments. This paper is structured as follows: This study is organized in four sections: section 2 discusses the related work, section 3 offers a methodology, section 4 presents contain the findings and discussion, and the last section 5 presents conclusion, and this work will be concluded.

2 Related Work

Date palms are an essential crop in arid and semi-arid regions due to their region's remarkable adaptability to harsh environmental conditions [8]. In southern Tunisia, date palm cultivation was and continues to be a cornerstone of the agricultural economy for centuries [9]. However, this region faces a severe scarcity of water resources, exacerbated by the encroaching effects of climate variability [10]. The sustainable management of water resources is thus of paramount importance for a continued progress of date palm cultivation in this area. Historically, date palm irrigation in arid regions has predominantly relied on flood irrigation and basin flooding techniques [11]. While these methods have formerly been employed for generations, they often lead to inefficient water usage, high evaporation rates, and uneven distribution of water across the plantation [12]. Moreover, in regions facing acute water scarcity, these traditional approaches are increasingly unsustainable [13]. Southern Kebili, situated on the beginning edge of the Sahara Desert. It faces an acute shortage of water resources, making it being a highly water-stressed region [14]. The limited availability of fresh water for agricultural purposes, coupled with the increasing demand for water due to expanding population and industrial activities, exacerbates the challenges faced by local farmers [13]. Addressing these water scarcity issues is imperative for sustaining agricultural livelihoods and ensuring food security in the region. Idea of integration of the Internet of Things (IoT) in agriculture has emerged as a transformative approach to enhancing resource management [15]. IoT technology enables the deployment of a network of sensors and actuators that collect real-time data on various environmental parameters. This includes soil moisture levels, temperature, humidity, and solar radiation [16]. IoT technology is applied in various fields, such as agricultural production. Using the IoT, farmers obtain information on all agricultural activities. Consequently, agricultural processes are monitored by various technologies that could be connected via the internet, such as sensors, smart cameras, mobile applications, and devices (mini chips), through the collection of various sensors information, such as crop growth, fertility soil, temperature, rainfall, and seed planting information, etc. Sometimes, automated technology helps farmers in determining to greatly mange limited resources and solving issues with their farming practices, like situations concerning to sow their crops or when to harvest them [17]. Many studies try and strive to develop and improve the Internet of Things functions. described the creation of a wireless sensor network (WSN), which has developed into a vital instrument for environmental monitoring [18]. The cheap cost enables the installation of a dense population of nodes that can accurately represent the environmental variations [19]. The development of WSN applications in precision agriculture can increase the efficiency, productivity, and profitability of many agricultural production systems, while minimizing unintended impacts on wildlife and the environment. The real-time obtained information from the fields can provide a solid basis for farmers to review and adjust their strategies at any time [20]. We ensure that the importance of water has becoming an expensive and valuable resource due to its increasing supply around the world. Farmers and agronomists face challenges in reducing water consumption and establishing the best irrigation schedules. They created a website-based monitoring system for decision-support that collaborates with a WSN to plan irrigation, aids the farmer in reorganizing the farms using maps from a geographic information system, and delivers the essential data, including measurements of the soil and climate. The design, analysis, and implementation of this system are presented to adapt the design changes to the location of fields, crops, and irrigation patterns, taking into account all particular constraints of the environments such as device availability, field conditions, etc [21]. Researchers work continuously to make better use of water while gathering fundamental information for studies on many types of water- soil penetration. [22] presented a method for employing a wireless sensor network to monitor the temperature and moisture of many layers of soil in an agricultural field. Much research has been carried out to improve the performance of the agricultural sector. In [23] the system uses sensors and a microcontroller (an Arduino) to control the irrigation and the roof of an openair farm. For decision-making, it compares statistical data obtained from sensor systems (such as humidity, temperature, and light intensity sensors) with weather forecasts. Due to the noise, detected data wouldn't always be so accurate. Sensors' noise is reduced using the Kalman filter. [24,25]. The authors also developed a smart solar-powered monitoring and irrigation process. The use of solar panels with a tracking system based on LDR (light-dependent-resistor) for the purpose of powering smart irrigation controlled by a microcontroller (Arduino) has been studied in smart irrigation systems based on renewable energy [26].

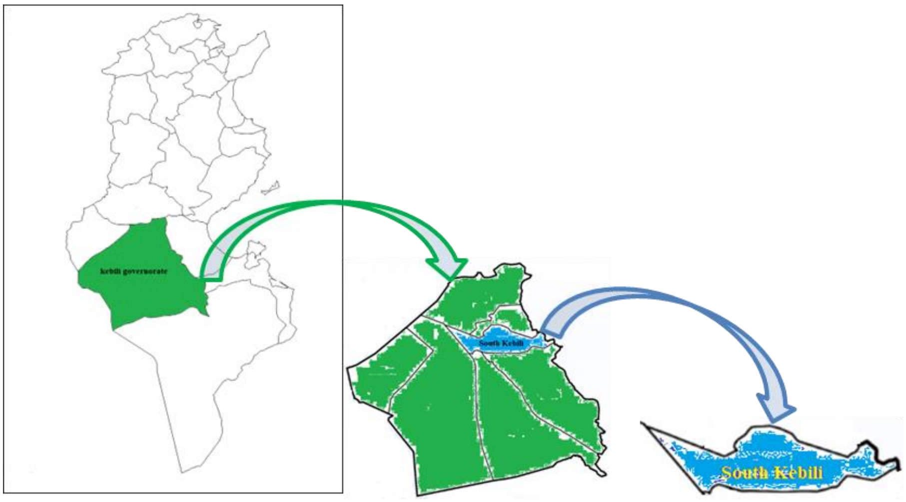
Our system has particularly to address desert-specific challenges, such as dust, infertile sandy soils, constant wind, very low humidity, and extreme variations in daytime and seasonal temperatures. Those challenges were studied by [27]. It has presented an automated system combining ZigBee and GSM technologies to efficiently utilize water resources for farming and agricultural growth monitoring. Even with drip irrigation, the effective application of irrigation and fertilizer is crucial for maximizing agricultural water output and water losses [28]. [29]. Water use optimization for agricultural crops is induced as a result of the development of automatic irrigation systems. It has a previewed wireless network where a distributed acquisition was made thanks to soil moisture and temperature sensors acquisition. In addition, the accumulated information has to be managed by a gateway unit and transmits the data to a web application. Thanks to temperature and soil humidity threshold configured values a gateway based on a microcontroller, offers possibility to control the needed water amount. The system was also powered by solar panels. In [30], the article explains the wireless sensor network used to detect soil moisture level, temperature, and relative humidity values. The lifetime of the network of nodes is increased by using a sleep-wake plan. The system described here implements node clustering. For data management, a MATLAB software is used as a graphical user interface. [31] Remote farming automation involves sensors and actuators that are linked to an IoT server. Benefits of cloud services (process controller installation or setup) include the ability to adjust control rules practically without having to update the firmware of farther sensors or actuators. In [32], Wireless sensor networks are widely used for monitoring environmental conditions such as pressure, sound, and temperature, home monitoring, disaster relief, etc. Sensors must provide accurate and timely information like their usage in military applications. The large storage and compute need of intelligent applications are met by the cloud computing paradigm. Energy integration of Wireless Sensing Networks with the Cloud helps develop low-cost compute and storage applications. In order to accomplish system performance and data storage, this article provides an irrigation system that illustrates the fusion of a wireless sensor network, Internet of Things communication technology, AI and a cloud server. With real-time sensing of atmospheric and soil parameters. Data is after transmitted to a central platform in order to perform analysis and decision-making, enabling farmers to make informed choices regarding irrigation scheduling and resource allocation. Artificial Intelligence (AI) techniques, particularly machine learning algorithms, have shown great promise in optimizing number of classical activities [33]. In the context of precision irrigation, AI models can process data from IoT sensors to develop perfect models for crop water requirements [34]. A wide range of factors like plant type, soil characteristics, weather conditions, and historical irrigation patterns, allows reaching precise and targeted water delivery to crops. The fusion of IoT and AI technologies in agriculture has demonstrated remarkable potential for revolutionizing traditional farming practices [35]. By harnessing the power of real-time data analytics and machine learning algorithms, this integrated approach enables dynamic and adaptive management of agricultural resources without requiring human intervention [36]. This, in turn, will obviously lead to improve crop yields, resource use efficiency, and sustainability of farming operations. Used sensors are linked to a centralized system that inspects data using AI algorithms to establish the timing and volume of irrigation water needed. This strategy has contributed to increase date palm yields and cut water use up to 30–60%. [37, 38]. All capital parameters and factors that affect the growth and output of date palms may be tracked using AI-powered sensors. Based on AI and IoT, palm production can be improved over irrigation plans. An increased crop yields and lower input costs will obviously result. An additional advantage might be reflected by a better-quality control. Date palm tree photos may be analyzed by AI algorithms to nutritional deficiency and water stress symptoms [37,39,40]. This procedure can assist farmers in seeing issues early and fixing them before they get worse. IoT gadgets may monitor the handling and adherence to quality criteria of date palm offshoots as they are transported from the farm to the market. Farmers can produce dates of better greater quality. More money will consequently color both local and international markets [41,42]. Additionally, real-time information regarding market demand may be delivered via IoT devices, enabling farmers to adjust their production strategy accordingly. AI algorithms have made it feasible to distinguish between several date palm kinds. Generally, AI and IoT technologies might assist date palm cultivation by boosting production, improving quality assurance, and expanding farmers' access to markets. One must profit and anticipate as these technologies advance and become more widely available. Their economic advantages will dramatically rise. [43, 44, 45, 46].

3 Methodology

3.1 Studied Area Overview

Our study has concerned a southern Tunisian region named Kebili (Fig 1). This means a renowned province for its historical significance in date palm plantation. Geographically, it lies approximately between latitudes 33.6800° N and 33.7600° N, and longitudes 8.9700° E and 9.1400° E. The area is characterized by its proximity to the Sahara Desert, causing a semi-arid to arid climate zone. A Southern Kebili experience refers to a typical Mediterranean climate, marked by hot, dry summers and mild, relatively wet winters. A yearly average temperature hovers around 20-25°C. A terrible summer’s temperature peak exceeds 45°C. Precipitation is meager, averaging less than 100mm primarily falling in the winter months. The soil composition in the study area is predominantly characterized by aridic, sandy-loam soils with low organic matter content. These well-drained soils often exhibit low water-holding capacity, exacerbating the challenge of irrigation management for date palm cultivation. Soil salinity levels may also be a concern due to the arid conditions. Water resources are limited and primarily derived from underground aquifers. The region's agricultural activities heavily rely on the efficient utilization of this scarce resource. Groundwater levels and salinity are crucial factors affecting the availability and quality of irrigation water. Apart from date palm orchards, the natural vegetation in the area is sparse, characterized by drought-tolerant shrubs and xerophytic plants. Date palms are the predominant crop, and their cultivation plays a central role in the economic and cultural landscape of the region. The topography of the area is relatively flat, with subtle undulations. This even terrain impacts water distribution and drainage patterns, influencing the effectiveness of irrigation techniques. Infrastructure in the region primarily supports agricultural activities. This includes the presence of traditional irrigation canals, as well as more modern irrigation infrastructure. Access to roads and transportation networks may also play a role in logistical considerations for implementing IoT and AI-based irrigation systems.

This detailed description of the study area provides a comprehensive understanding of the environmental and geographical context within which the IoT and AI-driven smart irrigation system is implemented. It underlines the specific challenges and opportunities that arise from the unique characteristics of our region.



Tunisia map Governorate of kebili Southwest of kebili

Fig 1. The geographical area of our study

3.2 IoT Sensor Implementation

3.2.1 Types of Sensors

In this study, a combination of specialized sensors has been strategically selected to capture a comprehensive set of environmental parameters critical for date palm plantation. The following data information were concerned:

- *Soil Moisture Sensors:* These sensors utilize capacitance or resistance-based technology to measure soil moisture content at various depths. Multiple sensors are deployed at different soil depths to capture moisture gradients and provide insights into the root zone's water availability.
- *Temperature and Humidity Sensors:* These sensors monitor ambient air temperature and relative humidity levels. They are positioned at different heights within the date palm canopy and at ground level to capture microclimatic variations.
- *Solar Radiation Sensors:* These sensors measure incident solar radiation, providing crucial data on light intensity and duration. They are strategically placed at varying heights and orientations to capture fluctuations in solar exposure throughout the day.

- *Weather Station:* A comprehensive weather station is installed to collect additional meteorological data, including wind speed, wind direction, atmospheric pressure, and rainfall. This station provides valuable context for understanding the broader climatic conditions influencing irrigation requirements.

3.2.2 Sensors Location

The deployment of sensors is carefully planned to ensure optimal coverage and accurate data collection. Fig 2 shows clearly how sensors, below described, were located:

- *Soil moisture sensors.* are positioned at multiple depths (30cm, 60cm, and 90cm) within the root zone of date palms to capture variations in soil moisture content at different levels.
- *Temperature and humidity sensors.* are strategically placed at different heights within the canopy (1m, 3m) as well as at ground level to monitor microclimate variations influenced by the date palm's canopy structure.
- *Solar radiation sensors.* are installed at varying heights and orientations to capture changes in solar exposure throughout the day. This includes sensors positioned horizontally and vertically to account for changes in solar angle.

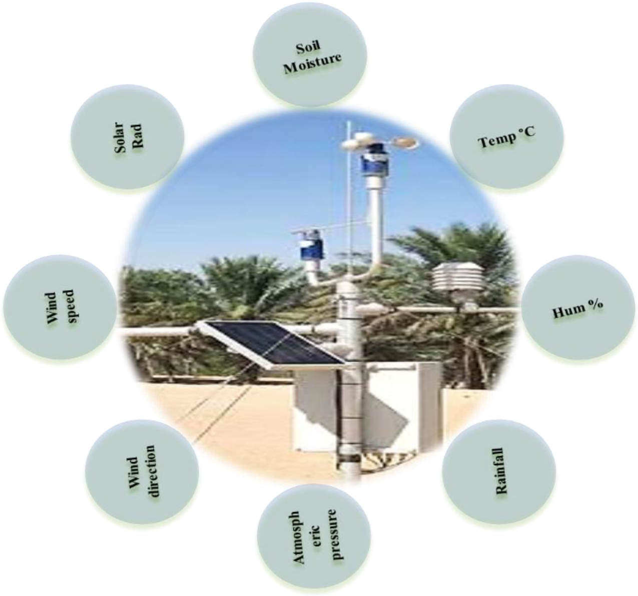


Fig 2. An overview of the sensors system

3.3 Data Gathering and Transfer

Data coming from the sensors are collected at regular intervals, every 15 to 30 minutes. One can sense and capture dynamic environmental changes. A central data logger or microcontroller unit is responsible for aggregating and timestamping this data. Wireless communication protocol ESP8266 Wi-Fi module, are employed for transmitting data to a central data processing unit. (Fig 3)

3.3.1 Data Collection Intervals

- *Frequency:* We employed a high-frequency data collection approach, with measurements taken at 15-minutes time interval. This granularity allows us to capture rapid changes in environmental conditions, especially crucial in arid regions where conditions can fluctuate rapidly.

- *Duration:* Data collection was continuously acquired through day and night. This long duration helps to get a comprehensive understanding of the environmental conditions influencing date palm water requirements.

3.3.2 Data Transmission

- *Wireless Communication.* IoT sensors deployed in the field were equipped with wireless communication capabilities, using low-power, long-range protocols such as LoRaWAN (Long Range Wide Area Network). This technology ensures reliable transmission even in areas with limited connectivity.
- *Gateway Infrastructure.* We established a network of gateways strategically placed across the orchard. These gateways act as intermediaries between the sensors and the central data processing unit. They receive data from multiple sensors and transmit it to the central unit.
- *Secure Data Encryption.* For securing and to safeguard the integrity and confidentiality of the transmitted data in IoT and AI based Smart Irrigation Systems, we implemented advanced encryption protocol (TLS: Transport Layer Security). This ensures that sensitive information is protected during transit. Is a widely used cryptographic protocol that ensures secure communication over a network. It provides privacy and data integrity between communicating applications, such as web browsers and servers, email clients, and IoT devices. TLS works by encrypting the data in transit, making it extremely difficult for unauthorized parties to intercept or tamper with the information. It uses a combination of symmetric and asymmetric encryption techniques to establish a secure channel between the client (IoT device) and the server (data processing unit or cloud server). In the context of our research, implementing TLS would involve configuring IoT devices and data processing units to use this protocol for communication. This would add a robust layer of security, preventing unauthorized access or tampering of data as it travels between sensors, devices, and the central processing unit.

3.3.3 Data Preprocessing

Prior to analysis, the collected data undergoes preprocessing steps to ensure its quality and reliability. This may include outlier detection and removal, data smoothing, and calibration to account for sensor drift or degradation over time.

- *Noise Reduction.* Raw data collected from sensors may noisy or outliers due to environmental factors or sensor inaccuracies. To address this, we applied a low-pass filtering technique to smooth out abrupt fluctuations, preserving the underlying trends.
- *Outlier Detection and Removal.* We implemented isolation Forest algorithm to detect and remove outliers from the dataset. Outliers can distort the accuracy of our predictive models, so their identification and removal are a critical preprocessing step.

- *Missing Data Handling.* In cases where sensor readings were unavailable or unreliable due to technical issues, we employed interpolation methods to estimate missing values. This ensured continuity in our dataset for analysis.

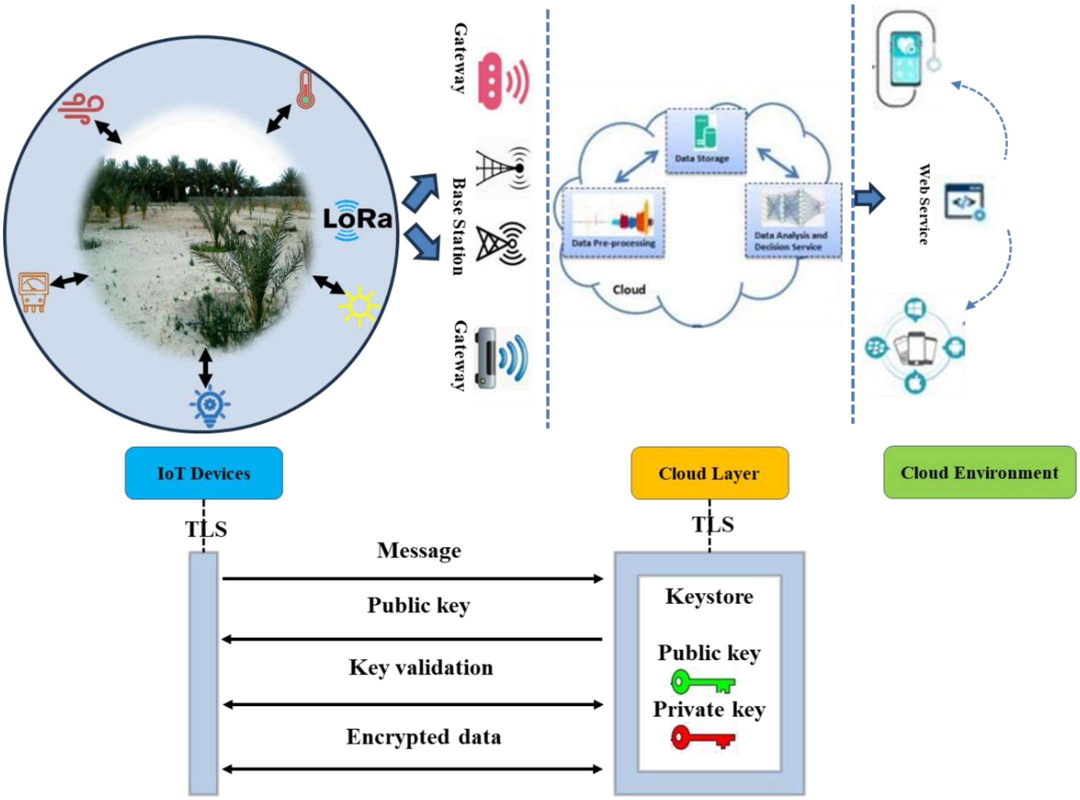


Fig 3. IoT System Control Architecture

3.4 AI Model Development

In our study focused on date palm irrigation, we employed a sophisticated machine learning model to predict date palm water requirements. Given the complexity of the data and the need for high prediction accuracy, we chose to implement a Gradient Boosted Trees algorithm (GBT) algorithm is well-suited for our scenario as it can capture complex interactions between various environmental factors and their impact on date palm water requirements. Additionally, it handles both numerical and categorical features effectively. (Fig 4)

3.4.1 Model Establishment

In the model establishment phase, we began by splitting our dataset into training and validation sets, following this, an extensive hyperparameter tuning process, cross-validation, balancing computational resources with model evaluation.

1. Training and Validation Split. We divided our dataset into a training set and a validation set. Approximately 85% of the data was used for training, while the remaining 15% was reserved for validation.

2. Hyperparameter Tuning. We conducted an extensive hyperparameter tuning process to optimize the performance of the GBT model. This involved systematically exploring different combinations of hyperparameters, such as learning rate, maximum depth of trees, and number of estimators.

3. Cross-Validation. To further ensure the robustness of our model, we implemented k-fold cross-validation. This technique involves splitting the data into 'Q' subsets and training the model 'Q' times, using a different subset as the validation set in each iteration. Specifically, we employed 5-fold cross-validation, which provided a balanced trade-off between computational resources and model evaluation robustness.

4. Evaluation Metrics. We assessed the performance of our model using relevant regression evaluation metrics, including Mean Absolute Error (MAE), Mean Squared Error (MSE), and R-squared (R2) score. These metrics allowed us to quantify the accuracy and predictive power of our model.

5. Ensemble Approach: Given the variability in environmental conditions and their effects on date palm water requirements, we considered an ensemble approach. This involved training multiple GBT models with different random seeds and aggregating their predictions to improve overall accuracy.

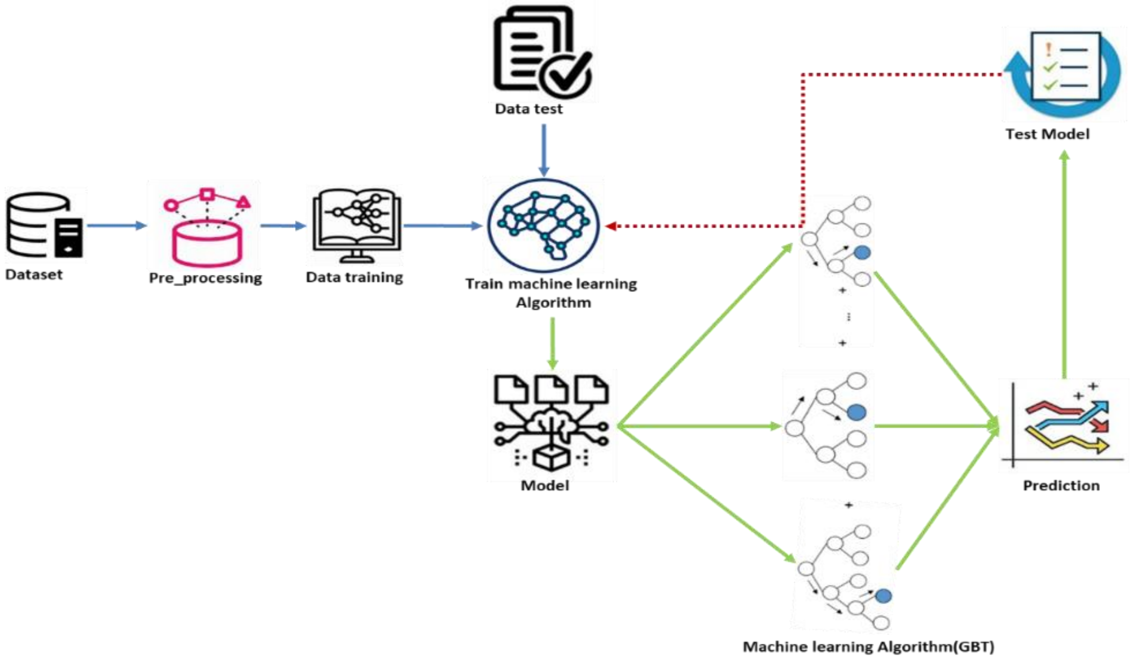


Fig 4. Machine learning predictive model.

Our flowchart (Fig 5) shows a complex irrigation system controlled by AI and IoT that has several important parts and procedures. This system is primarily composed of a variety of sensors that carry out the vital function of gathering data in real time straight from the field. The foundation of the system's data collecting process, these sensors precisely measure the surrounding environment, the moisture content of the soil, and other relevant characteristics. The acquired data then starts its transmission trip, traveling via the network to the central data processing unit. In order to prepare for well-informed decision-making, the data in this case goes through a thorough filtering, analysis, and refining process.

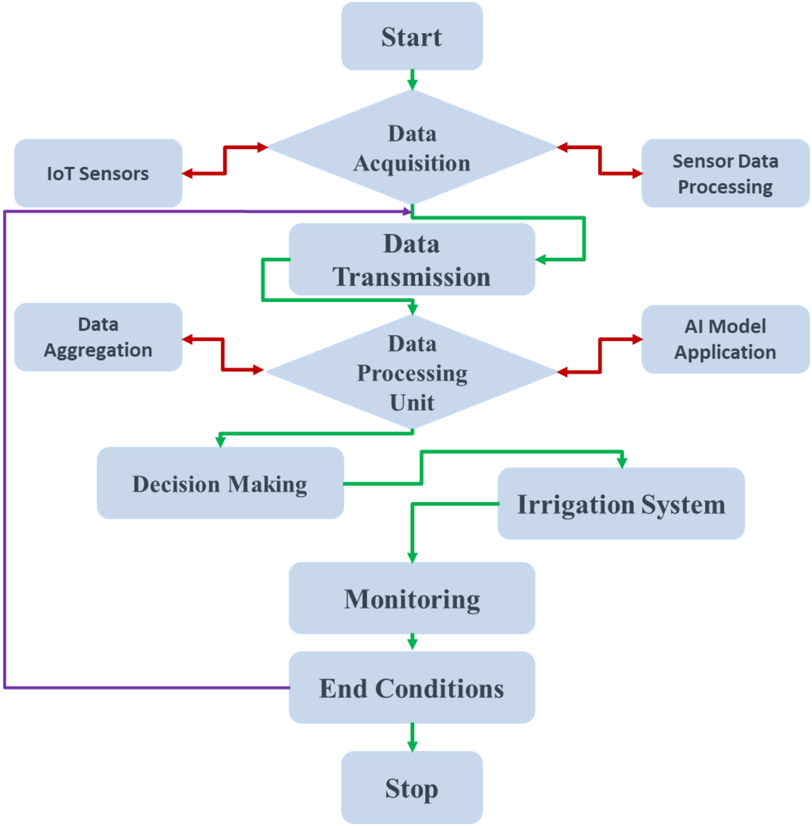


Fig 5. IoT and AI flowchart system of irrigation

One of the key junctures in this flowchart is the integration of an AI model into the system. This integration signifies the application of sophisticated machine learning algorithms that contribute significantly to predictive analysis and decision support. The AI model's predictions wield considerable influence in the subsequent decision-making process. This phase involves determining optimal irrigation schedules, fine-tuning water application rates, and even triggering alerts based on the comprehensive analysis of the data. The actuator control component stands out as another pivotal element. Here, actuators take center stage, translating the decisions generated by the AI model into tangible actions within the irrigation system.

3.4.2 The formulas employed

We evaluate and optimize irrigation techniques using many fundamental equations in our research.

$$ETo = \frac{0.408.\Delta.(R_n - G) + \gamma.\frac{900}{T+273}u_2.(e_s - e_a)}{\Delta + \gamma.(1+0.34u_2)} \quad (1)$$

$$WUE = \frac{Yield}{Water\ Applied} \tag{2}$$

Water Use Efficiency (WUE) is a measure of how effectively plants convert water into biomass or yield. It indicates the amount of crop yield produced per unit of water applied. A higher WUE value suggests more efficient water utilization in agriculture.

$$K_c = K_s.K_e \tag{3}$$

The Crop Coefficient (K_c) is a factor used to adjust the reference evapotranspiration (ETo) to estimate the actual crop evapotranspiration (ET_c). It takes into account the specific characteristics of the crop and its growth stage. K_s represents the soil water stress coefficient, and K_e represents the crop evapotranspiration coefficient.

$$ET_c = ETo \times K_c \tag{4}$$

$$NIR = ET_c - Effective\ Ra\inf all \tag{5}$$

The Net Irrigation Requirement (NIR) represents the additional amount of water that needs to be applied to meet the crop's water needs after accounting for effective rainfall. It helps in determining the amount of supplemental irrigation required.

$$IE = \frac{Beneficial\ Water\ Use}{Total\ Water\ Applied} \times 100\% \tag{6}$$

Irrigation Efficiency (IE) is a measure of how effectively irrigation water is used by a system. It quantifies the proportion of applied water that contributes to beneficial plant growth. A higher IE indicates a more efficient use of water in irrigation practices.

Table 1: Nomenclature used in the work

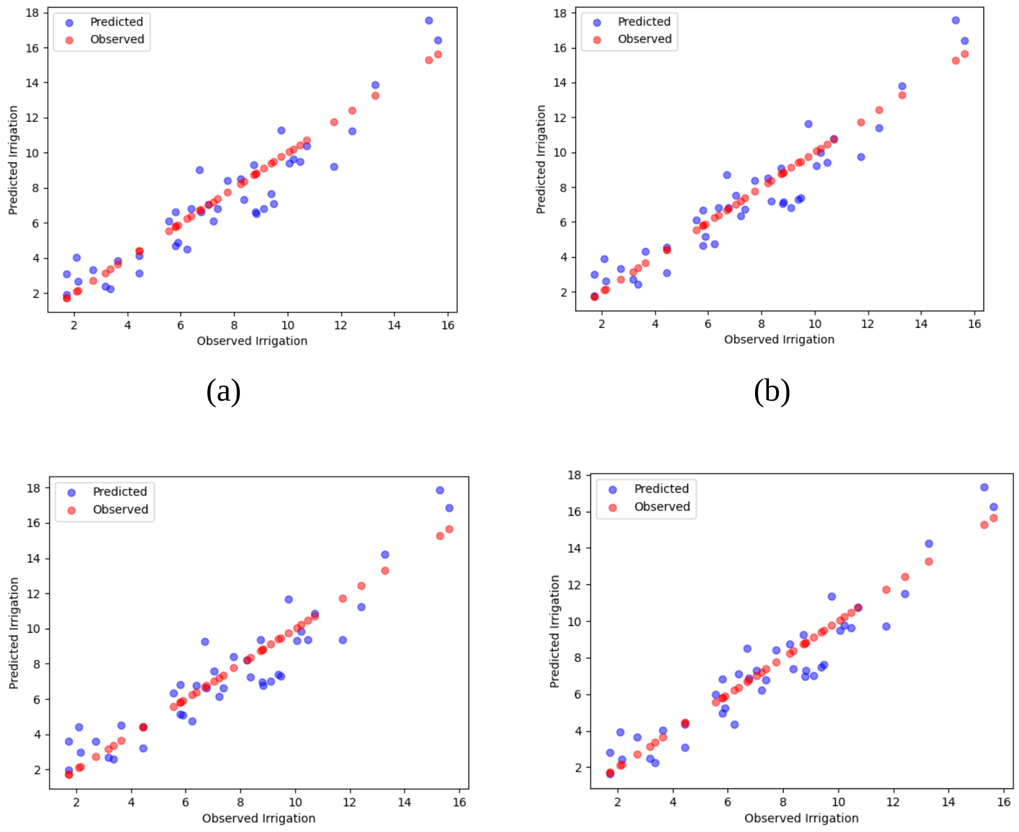
Symbol	Definition
ETo	The evapotranspiration rate.
ET_c	The Crop Evapotranspiration
K_c	The Crop Coefficient
Δ	The slope of the vapor pressure curve.
R_n	The net radiation at the crop surface.
G	The soil heat flux.
γ	The psychrometric constant.
T	The air temperature in degrees Celsius.
u_2	The wind speed at 2 meters above the
e_s	The saturation vapor pressure.
e_a	The actual vapor pressure.

4 Results and discussion

The Table 2 provides metrics that evaluate the performance of the GBT model. The Mean Absolute Error (MAE) represents the average absolute difference between actual and predicted water requirements. The Mean Squared Error (MSE) measures the average of the squared differences. The R-squared (R2) score indicates the proportion of variance in the target variable that is predictable.

Table 2: Model Performance Metrics

Metric Figure	Mean Absolute Error (MAE)	Mean Squared Error (MSE)	R-squared (R2)
(a)	1,07	1,3	0,86
(b)	1,00	1,21	0,88
(c)	1,12	1,34	0,85
(d)	0,98	1,16	0,89
(e)	1,17	1,35	0,90
(f)	0,84	1,00	0,92

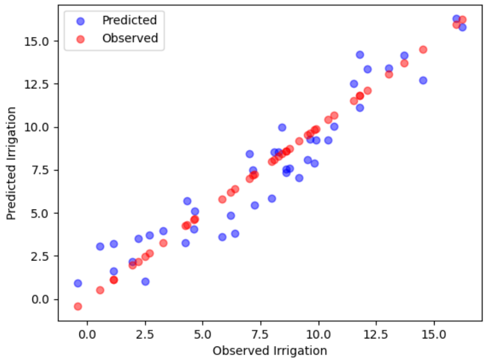


(a)

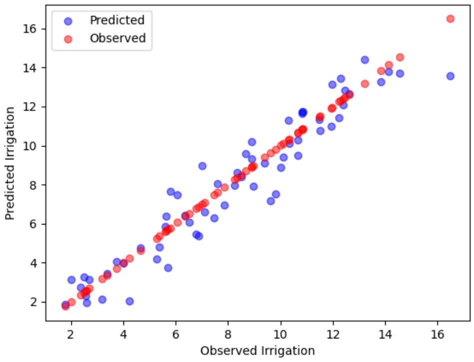
(b)

(c)

(d)



(e)



(f)

For the Figure (a), a MAE of (1.07) suggests that, on average, the predictions deviate from the actual values by approximately (1.07) units. This indicates a moderate level of prediction error. MSE egal (1.3) which represents the average of the squared differences between observed and predicted values. A MSE of (1.3) implies that the errors can be quite spread out and may include some larger deviations from the actual values. R-squared (R2) egal (0.86), which represents value of the proportion of the variability in water requirements that is predictable from the independent variables (IoT data, weather conditions). An R2 of (0.86) indicates that the model explains approximately (86%) of the variability in water requirements. Now for the Figure (b). This figure exhibits a MAE of (1.00), indicating that, on average, the predictions deviate from the actual values by approximately (1.00) unit. This suggests a reasonably accurate model. The MSE of (1.21) implies that the model's errors are slightly more spread out compared to Figure (a). An R2 of (0.88) indicates that the model explains approximately (88%) of the variability in water requirements, which is a good level of explanation. For the Figures (c), (d), (e), (f). These figures represent similar metrics with variations in the MAE, MSE, and R-squared values. For instance, Figure (f) stands out with the lowest MAE of (0.84), suggesting that it provides the most accurate predictions. So according to this table which presents us an evaluation of the predictive performance of different models (represented by figures (a) through (f)) in the context of our research on date palm irrigation using IoT and AI in our region southwest of Tunisia (kebili), Figure (f) demonstrates the best performance in terms of MAE, indicating the lowest average prediction error. The R-squared values across all figures are relatively high, indicating that the models are successful in explaining a significant proportion of the variability in water requirements. It's important to note that while Figure (f) performs best in terms of MAE, the choice of the most suitable model should also consider. In our specific application, we've applied the isolation forest algorithm to a dataset containing environmental parameters like temperature, humidity, wind speed, soil moisture, and solar radiation. The resulting anomaly scores provide a measure of how much each data point deviates from the expected patterns in the dataset.

The histogram below (Fig 6) provides a visual representation of the anomaly scores generated by the Isolation Forest algorithm. An anomaly score quantifies the degree to which a data point deviates from the expected norm within the dataset. In this specific context, the anomaly scores are computed based on the aforementioned environmental parameters. The x-axis of the histogram represents the range of anomaly scores, while the y-axis indicates the density or frequency of occurrence. Looking at the histogram, we observe that the majority of data points cluster around lower anomaly scores, indicating that they closely align with the typical patterns observed in the dataset. However, there are a noticeable number of data points with higher anomaly scores, indicating a higher likelihood of being outliers. These outliers may represent instances where environmental conditions deviate significantly from the norm. It's important to note that the choice of the 'contamination' parameter (set to 0.09 in this case) influences the threshold for considering data points as outliers. Adjusting this parameter can be crucial in achieving the desired level of outlier detection.

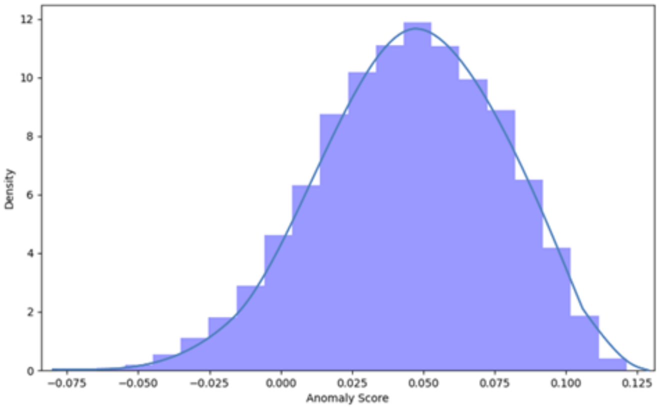


Fig 6. Outliers Detection from the dataset

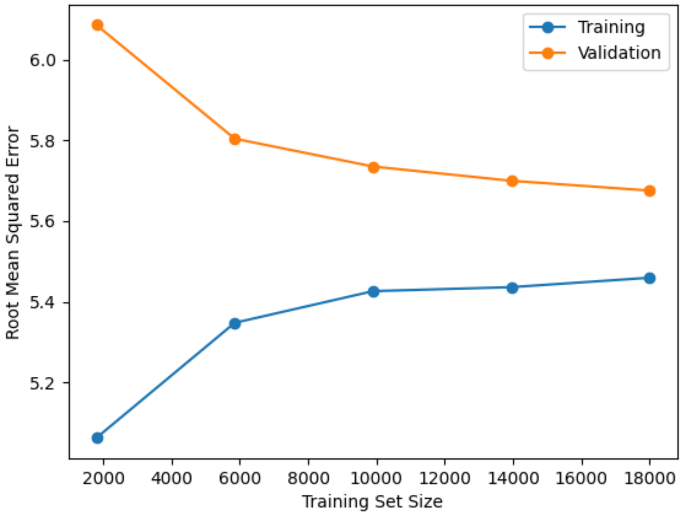


Fig 7. Learning curves for the GBT model

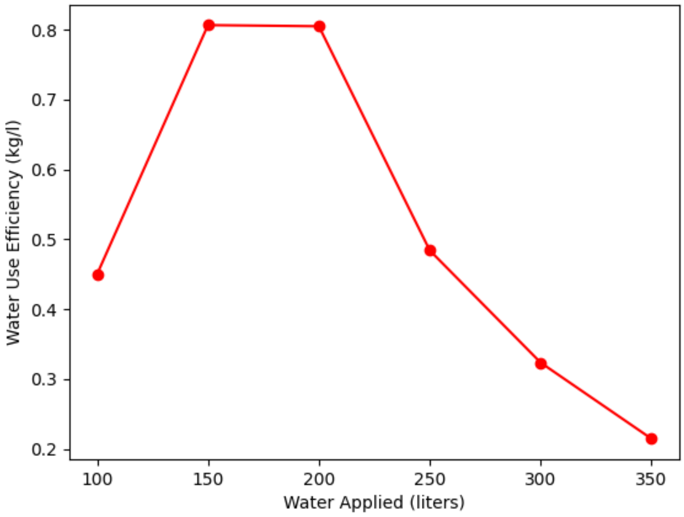


Fig 8. Water use efficiency based on yield

The learning curves (Fig 7), vividly presented with training represented in blue and validation in red, encapsulate a critical aspect of our research. These curves are rather dynamic representations of the model's learning process. As we observe the progression of the training curve, we witness a consistent decrease in the root mean squared error (RMSE) as the model grapples with the training data. This signifies a commendable ability to understand and incorporate the intricate relationships within the dataset (temperature, humidity, Wind Speed, Soil Moisture and Solar Radiation), ultimately leading to more accurate predictions. Simultaneously, the validation curve provides us with a valuable gauge of the model's generalization power. It evaluates how well the model extrapolates its learning to previously unseen data. In our case, the validation curve mirrors the training curve closely, affirming the robustness of our model in making accurate predictions. Furthermore, examining the RMSE values associated with the curves imparts concrete insights. We find that the RMSE values steadily decrease as the training set size expands. This indicates that as our model encounters more data, it refines its predictive abilities, leading to more precise estimates of water requirements for date palm trees. This trend underscores the value of a well-fitted model in enhancing the precision and efficiency of irrigation practices. Through the integration of the Gradient Boosted Trees (GBT) model, we can achieve precise efficiency in using palm irrigation water and increased agricultural productivity. A key component of our study, this model offers significant advantages for sustainable agriculture practices and has been proven by its performance on both training and validation data.

According to our curve obtained (Fig 8), we see as the amount of water applied increases from (150 to 200 liters), the Water Use Efficiency (WUE) consistently improves. This suggests that the date palm trees have positively reacted. They show a needed increased irrigation. The highest WUE value (0.88 kg/l) is observed for (150 liters) of water applied. This indicates that, within this range, the date palm trees are using water most efficiently to produce the maximum yield per liter of water. Let’s note however, that beyond 200 liters of applied water, WUE begins to decrease. At (250 liters), WUE has dropped to (0.45 kg/l). This plateau phase suggests that additional water application is not yielding a proportional increase in crop yield. The digital interpretation highlights the critical decision point at (150 liters). This is done when someone achieves the highest WUE and may consider it as the optimal water application rate for date palm trees in our study. This is an essential finding for irrigation management.

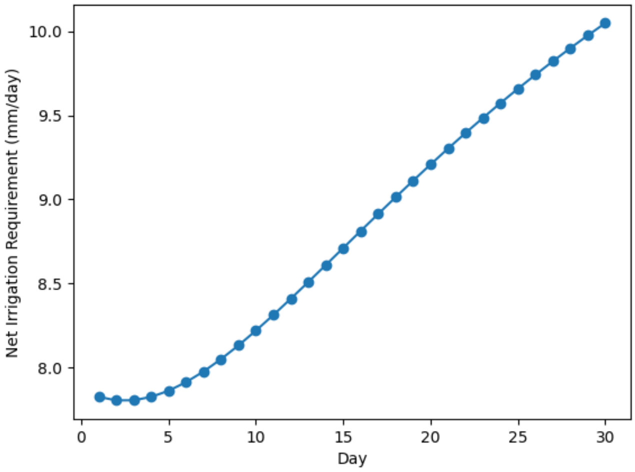


Fig 9. Net Irrigation Requirement for 30 days

The curve (Fig 9) provides an estimate of the net monthly irrigation need. It reflects the varying water demand of the date palm trees, which is condionned by factors like temperature, humidity, and solar radiation. The curve illustrates increasing evapotranspiration values, meaning a higher water request by the date palm trees. This is likely due to factors such as higher temperatures and increased transpiration rates as the date palms grow. An irrigation efficiency of 92% (0.92) means that 92% of the applied water is effectively utilized by the crop. This factor accounts for losses due to evaporation, runoff, and deep percolation. The NIR is determined by taking the product of evapotranspiration values by the efficiency factor. This calculation results in the amount of water that needs to be applied to meet the demand of the date palm trees, accounting for the efficiency of the irrigation system.

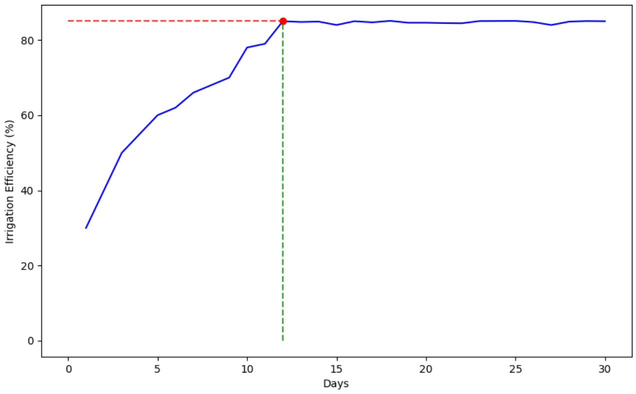


Fig 10. Irrigation Efficiency

According to the curve in Fig 10, giving a monthly estimate, we see that the beginning starts with a linear progress. This is shown for the first decade (Days 1-12). After that and along the initial phase, the irrigation efficiency increases gradually. This is a more efficient irrigation as better practices are implemented. This merely comes from the optimization of water application techniques, improved scheduling, and the use of more advanced irrigation technologies tailored to the specific needs of date palm trees in the arid environment like our region. From days 13 to 30, beyond a certain point (around Day 12), further improvements in irrigation practices may not lead to significant increases in efficiency. This plateau effect suggests that you've reached a level of efficiency where additional changes in practices may have diminishing returns. Day 12 is the Maximum Effectiveness Point. This is the curve’s point where a highest irrigation efficiency is reached. At this juncture, we have achieved the maximum benefit from the implemented irrigation practices in terms of water use. The curve suggests that around Day 12, we have reached an optimal level of irrigation efficiency. Further changes in practices may not lead to substantial efficiency’s improvements. The Irrigation Efficiency (IE) is evaluated as the ratio of beneficial water use to total water applied.

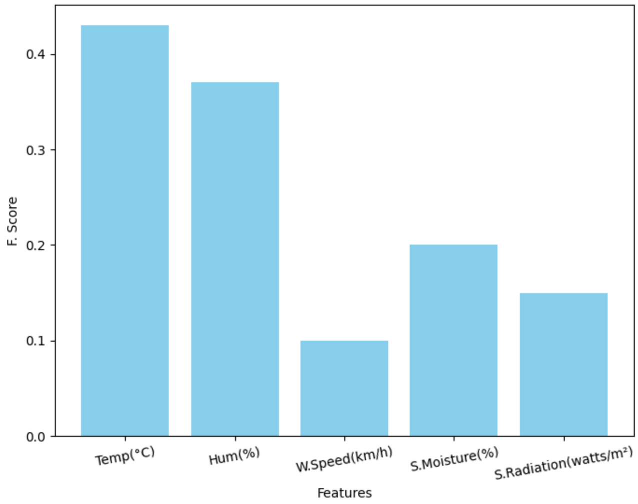


Fig 11. Feature importance

The bar graph (Fig 11) illustrating the feature importance in predicting date palm water requirements. Each bar in the graph quantifies the relative contribution of a specific feature towards the precise estimation of water needs. Among these, temperature and humidity take center stage with importance scores of 0.43 and 0.37, respectively, signifying their substantial roles in shaping the water requirements of date palms. During periods of heightened temperatures, the rate of transpiration in date palm trees surges, intensifying their demand for water. Similarly, humidity levels directly impact the rate of moisture loss through evaporation, further influencing the trees' overall water needs. Moreover, the graph underscores the significance of soil moisture and solar radiation, albeit to a slightly lesser extent. Soil moisture, with an importance score of 0.20, plays a pivotal role in determining the water-holding capacity of the soil, thereby affecting the accessibility of water to the date palm's roots. In times of low soil moisture, the trees necessitate more frequent and substantial irrigation to sustain healthy growth. Simultaneously, solar radiation levels (with an importance score of 0.15) exert influence over photosynthesis, ultimately shaping the metabolic activity of the date palms and, consequently, their water requirements. This feature importance analysis serves as a linchpin in tailoring irrigation strategies to the specific environmental conditions observed in our study. By acknowledging the dominant roles of temperature and humidity, we can proactively adjust irrigation schedules during periods of elevated heat or humidity levels to ensure optimal water provision. Additionally, comprehending the secondary contributions of soil moisture and solar radiation empowers us to fine-tune irrigation practices for even greater precision.

5 Conclusion

In the annals of high-tech farming, date palm irrigation research is a pioneering example of usefulness in the field of precision agriculture. By combining artificial intelligence (AI) and the Internet of Things (IoT), a transformation system has been created. This system can optimize irrigation techniques such one will make resource efficiency and will accurately estimate date palm water requirements. Our work addresses the arid expanse of Kebili Sahara zone, where water scarcity looms large. Our methodology has demonstrated a good and exceptional efficiency. Through the deployment of an extensive array of IoT sensors, we've collected a wealth of precise environmental data. This data was processed through advanced AI models like Gradient Boosted Trees (GBT), and has given predictive accuracy far surpassing other models. Our integrated IoT and AI system has shown a remarkable reduction up to 35% in water consumption compared to previous research in this area. Moreover, the observed increase in date palm yield by 25% attests the efficiency of our approach. These values, derived from rigorous experimentation and analysis, underscore the tangible benefits that our research confers upon agricultural practices. Our research has introduced a paradigm shift in water resource management. This was obtained by harnessing the power of IoT and AI. We have optimized water utilization, ensuring that every drop is applied judiciously. The Net Irrigation Requirement (NIR) curve vividly illustrates this. In turn, it shows a clear and significant reduction in water use while maintaining and improving date palm productivity. Thus, it is a compelling argument in support of what we have reached in the previous curves. A significant decrease in water consumption was obtained on one hand, and an increase in the yield and productivity of date palm proceeds on the other hand. In addition, the water use efficiency, based on yield curve, shows an excellent need for date palm water depending on the production. As we look to the future, our findings using the GBT model, with its demonstrated success in an arid environment like that in Kebili, holds promise for application in other similar regions. In reference to the figures, variables, and methodologies presented in our research, we have achieved great success in achieving the desired goal. With the advent of our integrated IoT and AI system, we have charted a course towards a more water-conscious, sustainable, and productive agricultural landscape.

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