



The applications of IoT network to enhance farming at Al-Aziziah palm trees farm in Saudi Arabia

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ABSTRACT

This paper explores the use of Internet of Things (IoT) technologies to reduce high water consumption and attached operational costs in date palm farming at Al-Aziziah Palm Trees Farm in Hail, Saudi Arabia. Conventional irrigation practices often lead to inefficient water use and elevated expenses, particularly from the diesel-powered water pumps. To overcome this, an on-farm living lab was deployed using Internet of Things (IoT) network for real-time sensor monitoring, where collected data is analysed using cloud analytics to enable data-driven decision-making with enhanced water efficiency. Findings demonstrate that this IoT-based system can significantly enhance irrigation accuracy for 45 % reduction in water pump usage, and consequently, a notable decrease in diesel fuel consumption. The cost model developed in this study estimates significant potential savings per year. This paper presents a replicable framework for deploying IoT technologies in large-scale date palm farms, promoting economic and environmental benefits of sustainable farming practices in Saudi Arabia and similar arid regions.

1. Introduction

The agriculture sector is undergoing transformation driven by digital technologies aimed at enhancing productivity and sustainability, where Internet of Things (IoT) emerged as a crucial component, enabling real-time, data-driven decision-making that allows farmers to optimise resource use, particularly water and fertilisers. These advancements are essential for addressing global challenges such as climate change, water scarcity, and food security [1]. Numerous studies have demonstrated IoT technologies in agriculture can save up to 35 % water and improve yield, especially when combined with machine learning and predictive analytics [2,3].

Saudi Arabia, the world's second-largest date fruit producer, illustrates the potential and difficulties of this digital shift. In 2021, it produced over 1.5 million metric tonnes of dates, yet it still depends on traditional, labour-intensive farming methods [4]. Al-Aziziah Farm in Hail, part of Al-Aziziah Group, faces operational challenges with management of its 100,000 date palm trees, which receive 100–150 litres of water every two days. Their traditional outdated practices result in excessive water use, high operational costs due to diesel-powered pumps, frequent equipment failures, and inconsistent fruit yield and

quality [5]. Al-Aziziah Farm own 50 pumps and incur about £10,000 monthly for operating one diesel powered pump, along with maintenance issues and environmental concerns. To address this, Al-Aziziah Group launched a digital transformation initiative focused on modernising operations and enhancing sustainability and profitability. Central to this strategy is the implementation of an IoT-enabled smart farming system, which optimises irrigation and fertilisation processes through continuous, real-time monitoring of soil conditions [2,6]. However, most research focuses on large-scale technologically advanced operations, leaving a notable gap in literature about cost-effective, scalable IoT systems for traditionally managed farms in arid regions. By focusing on this under-researched segment, this project addresses a key industry gap [7].

This paper addresses the identified research gap by presenting a novel and replicable framework for deploying a low-cost, scalable IoT network to optimise irrigation in a real-world setting. The primary contribution is a comprehensive demonstration of how a data-driven approach, supported by a custom-designed IoT system, leads to tangible economic and environmental benefits. Specifically, we quantify the exact water requirement for significant reduction in water pump usage that induces diesel fuel cost savings, providing a practical case

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study for the digital transformation of traditional date palm farms. The three main objectives are first, to design a low-cost, scalable IoT network for Al-Aziziah Palm Trees Farm. Second, to create a living lab for real-time soil moisture monitoring and adaptive irrigation control. Third, to integrate this sensor system with a cost calculation model to evaluate the financial viability of various irrigation strategies. Together, these objectives provide a structured framework to evaluate both the technical feasibility and economic impact of digital transformation in traditional farming systems [8].

1.1. Research methodology

The research methodology has been conducted following 5 different phases, where key tasks are described below:

Phase 1 – Problem definition and scoping: A literature review coupled with on-site contextual analysis of current farming and irrigation processes at Al-Aziziah Farm to identify inefficiencies and establish research gaps.

Phase 2 - Development of IoT network architecture: A customised IoT network architecture based on the ISO/IEC 30,141:2024 standard was developed, prioritising homogeneity, cost-effectiveness, and scalability.

Phase 3 - Implementation of IoT network: IoT components were purchased and evaluated for basic intended functionality. A living lab consisting of three palm trees was established at Al-Aziziah Farm with moisture sensors, a micro controller (Raspberry Pi), an automated pump, and cloud uploads to demonstrate a closed loop system.

Phase 4 – Mathematical cost model development: Field data on generator diesel consumption, and water pump usage, were collected to analyse and establish operational baselines. The mathematical cost model quantified potential savings against baseline operational costs.

Phase 5 - Case study validation: Confirmation of established IoT network reliability through real time data collection, cloud transmission, alert generation, demonstrating the smart farming system's benefits and scalability potential.

2. Review of the related literature

To understand the IoT architecture design, it is essential to introduce the broader concept of IoT. IoT refers to a network of physical devices embedded with sensors, software, and connectivity that collect and exchange data over the internet. This structure allows for autonomous sensing, processing, communication, and actionable feedback as shown in Fig. 3 [9]. These devices interact through four primary components: hardware interfaces, embedded software, communication modules, and service platforms. The rapidly evolving IoT model extends connectivity from human-human to human-thing and thing-thing interactions. Despite these new growing deployments, architectural heterogeneity persists. Among proposed frameworks, the five-layer model comprising Perception, Network, Processing, Application, and Business layers has emerged as a practical blueprint for balancing conceptual clarity and implementation of Internet of Things Networks [10–12]. This paper adopts the ISO/IEC 30,141:2024 standard as our architectural reference as it codifies modular, scalable, and resilient IoT frameworks that directly address critical agricultural challenges such as intermittent power supply and equipment interoperability [13,14].

In Saudi Arabia, agriculture uses about 85 % of the country's water resources, making efficient water use essential for food and water security. Date palm cultivation, which represents over 70 % of the fruit-cultivated area, is a focus for sustainable irrigation innovations [15]. Techniques such as drip irrigation, subsurface drip systems, and fertigation have proven effective in reducing water and fertiliser use while enhancing yields [15–17]. Fertigation, which combines irrigation with nutrient delivery, has resulted in an increase in date palm yield and a reduction in fertiliser use over three years [16,17]. However, challenges such as high labour demands for installation and maintenance, along with operational costs, hinder widespread adoption. Additionally, many

farming decisions rely on experience and intuition rather than real-time data, limiting the effectiveness of these technologies [18].

Smart farming technologies have been investigated to tackle inefficiencies in water and nutrient management. A study demonstrated the potential to reduce water use while maintaining crop health through a Controlled Subsurface Irrigation System integrated with cloud-based IoT sensors, enabling precise, real-time soil-moisture monitoring, and targeted water delivery [8]. Similarly, machine-learning models calibrated with meteorological and soil parameters have been shown in simulation studies to optimise both irrigation and fertilisation schedules, reportedly yielding a 7.5 % increase in productivity alongside a 10 % reduction in water consumption [3,19]. However, both approaches remain limited by their reliance on simulated data rather than validation under field conditions.

Beyond date palms, IoT-enabled irrigation platforms across Saudi Arabia have delivered measurable gains in water-use efficiency and operational cost savings. Concurrently, deep-learning frameworks, most notably convolutional neural networks, have achieved over 93 % accuracy in detecting fruit ripeness and early pest infestations, underscoring their suitability for large-scale orchard monitoring [20,21]. Field trials in Moroccan oases have further extended IoT's reach where a fog-computing robotic system deployed via mobile units automated red-palm-weevil detection, though without an accompanying economic feasibility assessment [22]. As these systems become more complex and generate vast amounts of data, processing data offline reduces latency and bandwidth usage, making IoT systems more efficient and scalable for the vast, often remote, areas typical of large-scale farms. Despite these technological advancements, practical challenges related to cost, maintenance, and a reliance on traditional farming intuition over real-time data continue to hinder widespread adoption [10–12].

2.1. Research gaps

A critical analysis of the existing literature reveals several key research gaps relevant to this project:

1. Limited field validation of IoT technologies for large-scale date palm farms in arid environments such as Saudi Arabia.
2. Insufficient development of scalable and cost-effective IoT infrastructure tailored for agricultural contexts.
3. Inadequate integration of real-time data collection with automated and adaptive decision-making processes.
4. Comprehensive analyses that evaluate technical performance, economic viability, and practical implementation challenges

2.2. Overview of Al-Aziziah palm tree farm

Traditional date palm farming in Saudi Arabia, including practices observed at Al-Aziziah Farm, is heavily reliant on manual labour and intuitive decision-making rather than data-driven approaches. Key agronomic variables such as soil moisture, nutrient levels, and temperature are rarely measured with precision, resulting in inefficient water usage, suboptimal fertilisation, and delayed pest management responses [16].

As shown in Fig. 1, a detailed process mapping of traditional farming at Al-Aziziah Palm Trees Farm highlights a labour-intensive workflow where plantation, cleaning, fertilisation, irrigation, pest control, pollination, thinning, and harvesting are all manually executed [17].

Irrigation infrastructure consists of a basic network of pipes branching out from high-capacity diesel-powered pumps, delivering water through progressively smaller pipes down to individual palm tree basins, as shown in Fig. 2. However, without real-time data collection, farmers cannot verify flow rates, detect leaks, or optimise water use.

Without precise monitoring, irrigation is often excessive or poorly timed, leading to inefficiencies, water loss, and reduced yield potential. Depending on the date palm variety, optimal yield of 80–120 kg per tree

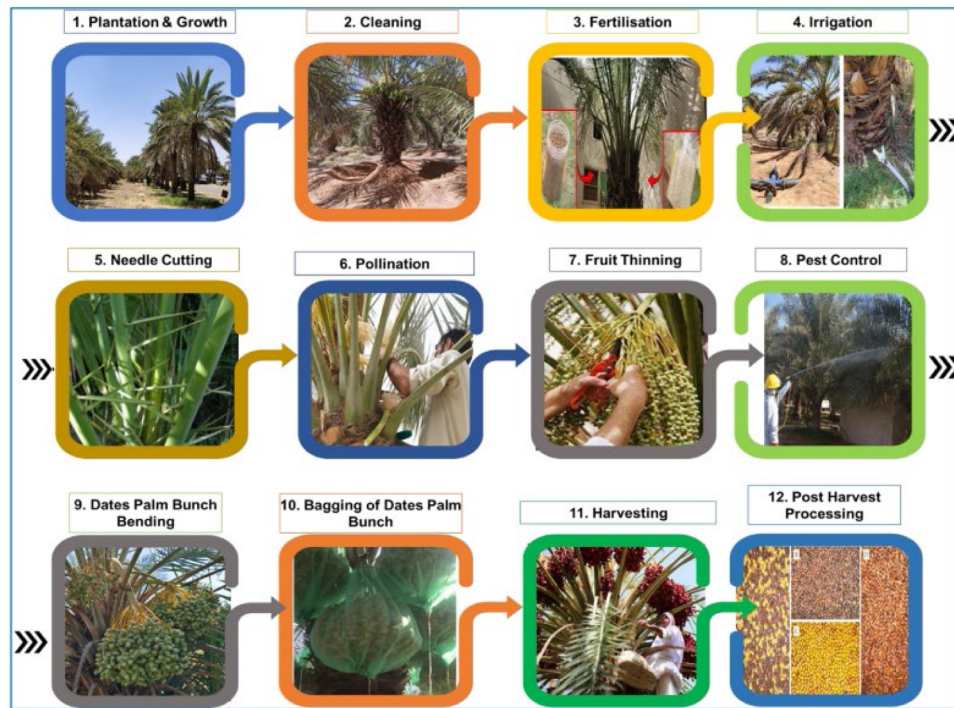


Fig. 1. Traditional date palm cultivation at Al-Aziziah farm.

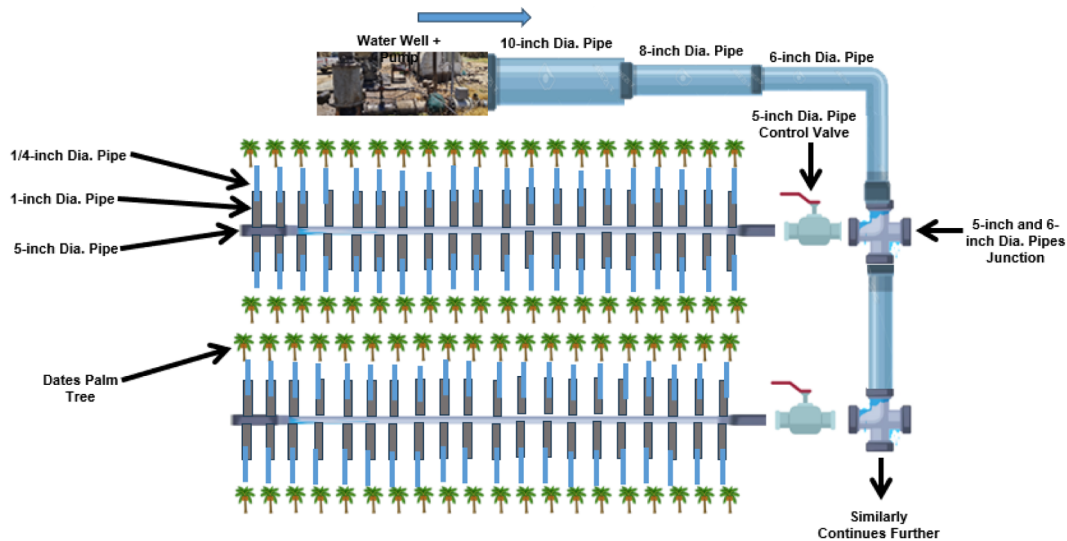


Fig. 2. Irrigation pipework and water distribution network at Al-Aziziah farm.

is achievable. Maximum yield can be attained through controlled conditions that are not consistently maintained in traditional settings [16]. The absence of advanced monitoring also limits timely responses to soil nutrient deficiencies, pest pressure, and salinity. These issues could be better addressed with support from agronomic expertise and digital diagnostics. Furthermore, traditional systems provide no visibility into the distribution network of pipes, pumps, and valves, making leak detection, flow rate regulation, and dosing adjustments difficult to manage. Integrating IoT-based technologies addresses these limitations by introducing sensors, smart pumps, and real-time dashboards that visualise system health and environmental data. Thus, traditional systems not only limit yield potential but also hinder the ability to make timely, data-driven agronomic decisions, a barrier that modern IoT architectures are designed to overcome [17].

3. Implementation of IoT in Al-Aziziah Palm Trees Farm

3.1. Definition of IoT architecture

Fig. 3 presents the proposed IoT Network Framework developed by the authors to be the foundation for the physical implementation of the IoT Network in the Palm Tree Farm. Table 1 present the explanation of each of the element of IoT Framework. The formation and the explanation of the framework is based on the understanding of the reviewed literature. Column called "Example" in Table 1 represent the proposed implementation in Al-Aziziah Palm Tree Farm.

Building on this foundation, agricultural IoT systems typically follow a multi-layered architecture. At Al-Aziziah Farm, the project's IoT network is structured according to the layers shown in Table 1.

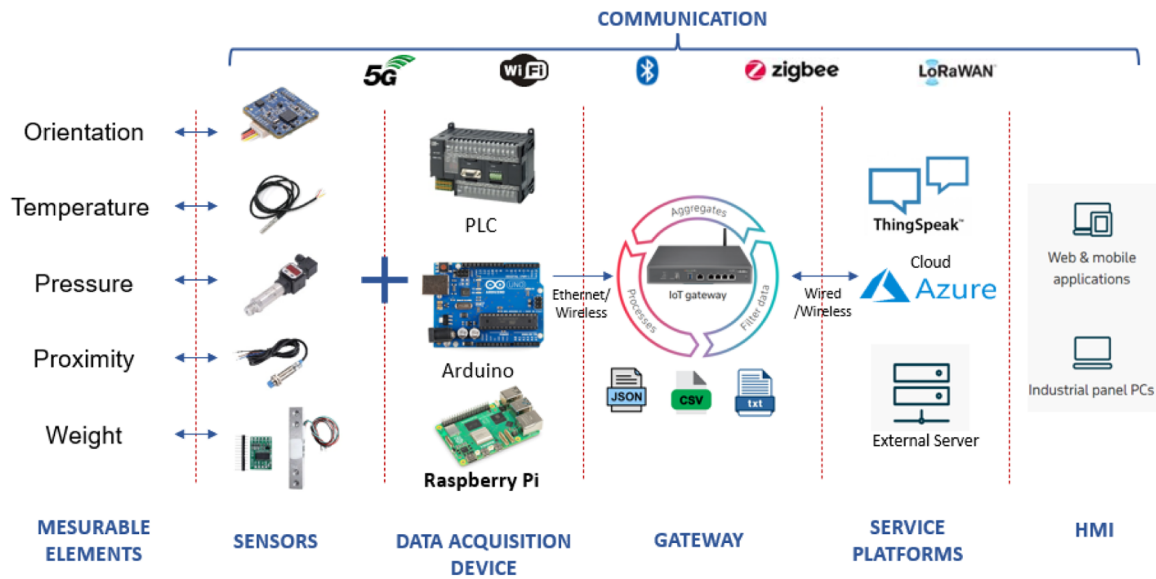


Fig. 3. Generic IoT network framework (author).

Table 1
Design layers to structure the IoT network.

Layer	Description	Example
Measurable Elements	Physical soil properties measured	Moisture of soil
Sensors	Devices that detect environmental variables	Soil moisture sensors
Data Acquisition Device	Collects and processes raw sensor data	Raspberry Pi
Communication	Transfers data from field to cloud	Wi-Fi
Gateway	Aggregates and formats data for the cloud	Integrated into Raspberry Pi
Service Platform	Visualises and stores data for decision-making	ThingSpeak Cloud
Human-Machine Interface (HMI)	User interface for monitoring and control	ThingSpeak Dashboard

These layers represent the practical IoT framework applied at Al-Aziziah Farm, following which the IoT architecture has been designed as shown in Fig. 4.

The IoT Architecture shown in Fig. 4 has five components: 1.) Moisture soil sensors 2.) Hardware 3.) Software 4a.) Control option for water delivery - message alerts for farmers 4b) Control option for water delivery - automated water delivery. The soil moisture sensors are installed at the base of each palm tree, three sensors per tree for overall monitoring. Wired sensors ensure stability and reduce signal loss in the open field. Their main purpose is to sense whether soil is "wet" or "dry" relative to predetermined thresholds, delivering valuable information for irrigation management.

Sensor information is communicated to a Raspberry Pi (Shown in Fig. 4), which is the master controller. It was chosen due to its low cost, open-source architecture, and built-in Wi-Fi for connection to the cloud. Initially, it is hooked up with a monitor, keyboard, and mouse, but in the field, it can operate independently. The Raspberry Pi reads sensor data and reacts to it using programmed logic. Use of a Raspberry Pi compared to Programmable Logic Controllers (PLC) as the master controller reduced cost and power consumption, and affords modular expansion for bigger sections of the farm with wireless functionality built in. Raspberry Pi is programmed using Python coding language to read sensor values and compare them to a soil moisture threshold value. If the soil is "dry," it turns on one of two modes of operation. Meanwhile, it posts all sensor values to ThingSpeak Cloud Storage for real-time

viewing and historical monitoring. ThingSpeak was used because it is free, MATLAB-friendly for analytics, and ideal for lightweight IoT applications.

In the first operational scenario (Option 4a in Fig. 4), when the soil is detected as "dry", a message (mobile alert) is sent to the farmer via the cloud interface. The farmer can then manually open the valve and start irrigation. This semi-automated approach maintains human oversight and is more appropriate during early deployment phases or in areas where automated pump integration is not yet in place. In the second scenario (Option 4b in Fig. 4), the system is configured to trigger an automated pump, which starts immediately when the soil is dry. This fully autonomous irrigation reduces labour demands and increases precision. It is particularly effective for large-scale farming operations or remote zones where manual intervention would be delayed or inefficient.

The deployment aligns with ISO/IEC 30,141:2024 standards for IoT architecture, particularly under the construction and functional view-points. The modular setup, comprising sensing devices, local gateways and cloud services, ensures scalability and system interoperability. Moreover, the project's reliance on open protocols such as MQTT and ThingSpeak reflects best practices outlined in the ETSI IoT Global Standardisation Report, emphasising decentralised analytics and modular design for agricultural IoT applications [13,14].

3.2. Implementation of IoT architecture at Al-Aziziah farm

The IoT architecture was realised by three experiments that progressively built up a completely automated irrigation system. Experiment one established a lab proof of concept of sensors, communication protocols, and data-acquisition software. Results of this stage guided the second experiment, in which the improved hardware and firmware were implemented in real conditions at Al-Aziziah Palm Trees Farm in Saudi Arabia. The third experiment added an automated pump within the laboratory, completing the feedback loop and illustrating a total autonomous IoT framework. Cumulatively, these trials provided a step-by-step evolution from theoretical verification to field-deployment readiness. Every step was directly informed by problems observed during earlier experiments, whether hardware durability, software logic, or environmental interference, so that later steps could eradicate those issues.

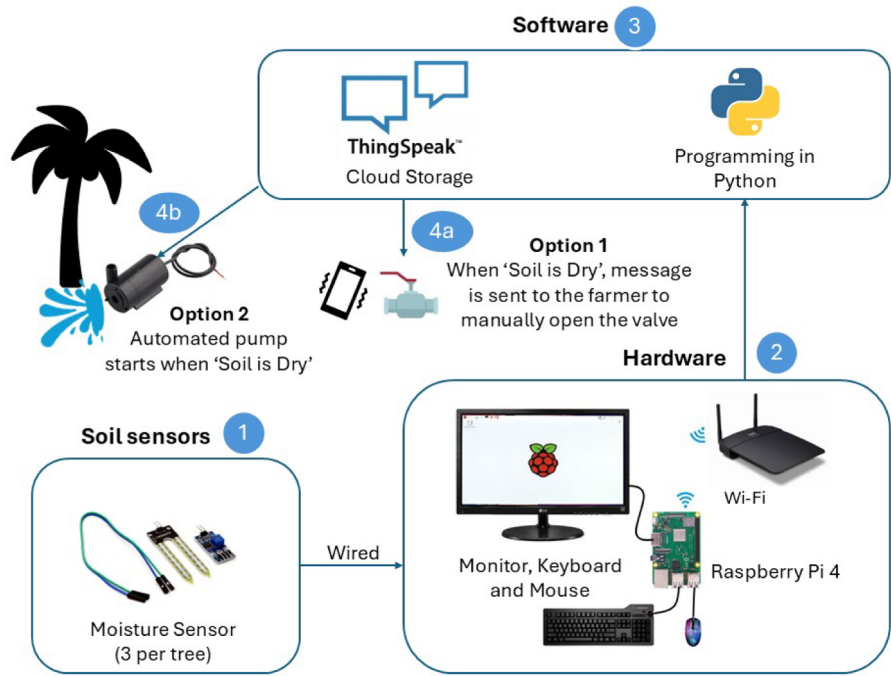


Fig. 4. IoT Architecture designed for Al-Aziziah farm.

3.2.1. Experiment 1: purchase and test the IoT technologies in the lab

The initial experiment was a pre-deployment preparation. All necessary hardware, including Raspberry Pi units, soil moisture sensors, jumper wires, microSD cards, and power supplies, were procured as seen in (Fig. 5 and Fig. 6).

All components were evaluated in a laboratory at Cranfield University to confirm correct operation and wiring. Soil-moisture sensors were connected to a Raspberry Pi 4 through their GPIO pins as described below:

- 1) Sensor VCC Pin is connected to the 5 V Pin of the Raspberry Pi 4
- 2) Sensor GND Pin is connected to the GND Pin of the Raspberry Pi 4

- 3) Sensor DO Pin is connected to one of the GPIO Pins of the Raspberry Pi 4

The sensors and the Raspberry Pi 4 were then wired to the monitor, the keyboard and the mouse as shown in Fig. 7-A. The soil moisture sensors were then tested to verify the electrical continuity and basic sensor responsiveness via the power LED as shown in Fig. 8-A, to calibrate the moisture-detection threshold by fine-tuning the on-board potentiometer until a consistent transition point between “dry” and “wet” was achieved and to validate the status LEDs by inserting the probes into “dry” and moistened soil samples to ensure the visual indicator corresponded to the actual condition as shown in Fig. 8-B and in Fig. 8-C.



Item n°	Description
1	Raspberry Pi Monitor
2	Soil Moisture Sensor Kit
3	Raspberry Pi Cases
4	Raspberry Pi
5	Resistor Kit
6	Power Supply
7	Breadboard
8	Soldering Iron
9	Solder Wire
10	Female/Male Jumper Wires
11	Micro-HDMI to HDMI Cables
12	Wire Strippers
13	Prototyping Wire Spool Set
14	Electrical/Insulation Tape
15	Soldering Iron Stand
16	MicroSD Card
17	Keyboard and Mouse
18	Ethernet LAN Cable

Fig. 5. Complete set of IoT technologies.

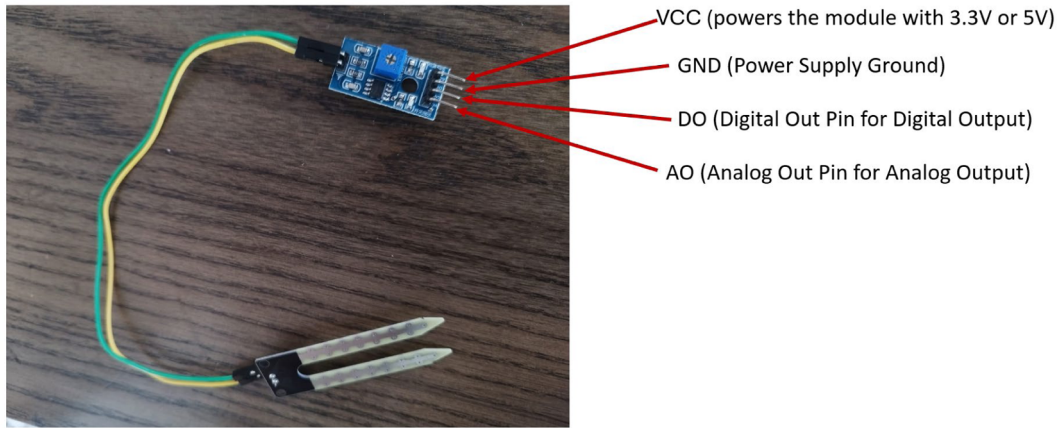


Fig. 6. Soil moisture Sensor Pin's description.

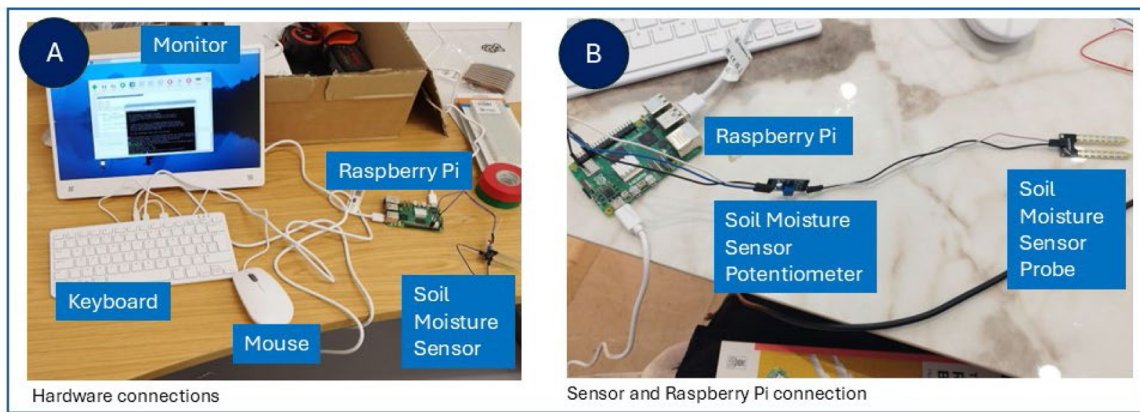


Fig. 7. Test of hardware connection in the lab.

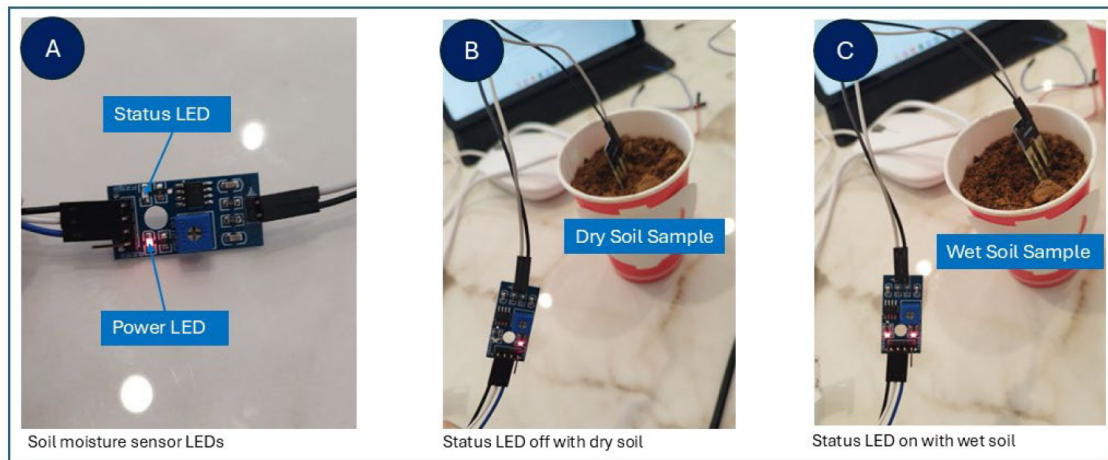


Fig. 8. Soil moisture sensor LED functionality.

Before the IoT Network was deployed in the field, a Python code was adapted and modified from an online guide [23] to read the soil moisture sensor data as shown in Fig. 9. The written Python code makes use of the gpiozero library, thereby permitting the Raspberry Pi 4 to interrogate the sensor's digital-output (DO) pin directly and to generate an alert whenever the specified moisture level is detected.

Once the Python code in Fig. 9 successfully reads sensor data, it was modified to transmit readings to the ThingSpeak cloud platform every

15 min, creating a 24-hour live feed of soil moisture. The modified Python code in Fig. 10 uses the gpiozero library to read the digital state of each sensor connected to the Raspberry Pi 4. Based on whether the soil is "wet" or "dry", values of "1" or "0" are assigned. These values are sent via an HTTP GET request to the ThingSpeak API to update the data feed. The loop pauses for 900 s before repeating, ensuring continuous data updates for monitoring.

After transmitting and storing sensor data in the ThingSpeak cloud

```

BEGIN
  //--- Setup ---
  INITIALIZE Sensor1 as a digital input on Pin 4
  INITIALIZE Sensor2 as a digital input on Pin 17
  INITIALIZE Sensor3 as a digital input on Pin 9

  //--- Main Loop ---
  LOOP FOREVER
    //--- Check Sensor 1 ---
    READ the value from Sensor1
    IF the value is LOW (0) THEN
      DISPLAY "Sensor 1: Soil is wet"
    ELSE
      DISPLAY "Sensor 1: Soil is dry"
    END IF

    //--- Check Sensor 2 ---
    READ the value from Sensor2
    IF the value is LOW (0) THEN
      DISPLAY "Sensor 2: Soil is wet"
    ELSE
      DISPLAY "Sensor 2: Soil is dry"
    END IF

    //--- Check Sensor 3 ---
    READ the value from Sensor3
    IF the value is LOW (0) THEN
      DISPLAY "Sensor 3: Soil is wet"
    ELSE
      DISPLAY "Sensor 3: Soil is dry"
    END IF

    //--- Pause ---
    WAIT for 900 seconds (15 minutes)
  END LOOP
END

```

Fig. 9. Pseudocode code to read soil moisture sensor data.

platform, the IoT Network employed the Twilio API to support timely manual intervention. Specifically, when any sensor registers a “dry” condition (indicated by a binary “0”), the Python code sends a pre-defined alert via WhatsApp to a designated farm worker, notifying the need to irrigate as shown in Fig. 11. The Python code in Fig. 10 has been modified with the requisite Twilio credentials and incorporates a one-hour delay between successive alerts for each sensor to prevent spamming as shown in Fig. 12 and Fig. 13. This approach effectively combines real-time monitoring with manual notifications, ensuring quick responses to moisture deficits and improving soil moisture management in agriculture.

3.2.2. Experiment 2: installation of IoT technologies at Al-Aziziah farm

3.2.2.1. Establishment of the IoT living lab in the farm. To investigate the effects of water-saving irrigation approaches, a living-lab experiment has been established on the farm, consisting of three mature date-palm trees that are being monitored over a year. Present agronomic practice supplies each palm with approximately 100 litres of water every two days. To monitor the effects of evapotranspiration and deliver the exact amount of water required by the palm trees at a given point, irrigation volume has been set for Tree 1 to receive 75 litres per two-day cycle, Tree 2 receives 50 litres, and Tree 3 receives 30 litres. Fig. 14-B shows a weather-resistant utility box has been installed amidst the three experimental trees; this enclosure provides protected power and data ports for connecting all monitoring and control hardware required by the study. The effects on soil moisture, growth of the trees and dates, and the effects of this reduction on the operational cost will be monitored for one year.

3.2.2.2. Implementation of the IoT network in the living lab at Al-Aziziah farm. Sensors for each tree have been connected to a Raspberry Pi 4, with each tree having an independent Raspberry Pi 4. Sensor cables were extended using copper wire which were soldered and covered with electrical tape for weather resilience. At three equidistant points within the root zone of every palm, pits 20–30 cm deep were excavated to accommodate the probes of the moisture sensors as shown in Fig. 15. The depth was selected to promote intimate soil contact and minimise temperature fluctuations, thereby enhancing signal fidelity.

```

BEGIN
  //--- Configuration and Setup ---
  SET API_KEY to "LZKT4PFUPZBK8NWU"
  SET API_URL to "https://api.thingspeak.com/update"

  INITIALIZE Sensor1 as a digital input on Pin 4
  INITIALIZE Sensor2 as a digital input on Pin 17
  INITIALIZE Sensor3 as a digital input on Pin 9

  DECLARE Sensor1_Value, Sensor2_Value, Sensor3_Value as integers

  //--- Main Program Loop ---
  LOOP FOREVER
    //--- Read Sensor 1 Status ---
    READ the state from Sensor1
    IF the state is LOW THEN
      DISPLAY "Sensor 1: Soil is wet"
      SET Sensor1_Value to 1
    ELSE
      DISPLAY "Sensor 1: Soil is dry"
      SET Sensor1_Value to 0
    END IF

    //--- Read Sensor 2 Status ---
    READ the state from Sensor2
    IF the state is LOW THEN
      DISPLAY "Sensor 2: Soil is wet"
      SET Sensor2_Value to 1
    ELSE
      DISPLAY "Sensor 2: Soil is dry"
      SET Sensor2_Value to 0
    END IF

    //--- Read Sensor 3 Status ---
    READ the state from Sensor3
    IF the state is LOW THEN
      DISPLAY "Sensor 3: Soil is wet"
      SET Sensor3_Value to 1
    ELSE
      DISPLAY "Sensor 3: Soil is dry"
      SET Sensor3_Value to 0
    END IF

    //--- Send Data to ThingSpeak ---
    TRY
      // Create the data payload to be sent
      CREATE a data payload containing:
        - "api_key": API_KEY
        - "field1": Sensor1_Value
        - "field2": Sensor2_Value
        - "field3": Sensor3_Value

      // Send the data via an HTTP GET request
      SEND GET request to API_URL with the data payload
      CATCH an Exception (e.g., network error)
      DISPLAY "Error sending data to ThingSpeak:", followed by the error details
    END TRY

    //--- Pause before next cycle ---
    WAIT for 900 seconds (15 minutes)
  END LOOP
END

```

Fig. 10. Pseudocode to read moisture sensor and send data to cloud platform.

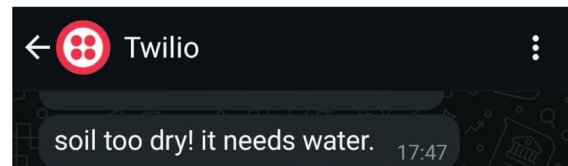


Fig. 11. WhatsApp message from Twilio sent when the soil is “dry”.

The probes were carefully seated in the prepared pits and the soil compacted around them to eliminate voids. Installing three sensors per tree, arranged triangularly as shown in Fig. 16, increased spatial coverage and enabled subsequent data-quality checks through cross-validation and data triangulation. Together, these steps produced a stable, high-quality monitoring array suitable for long-term agro-environmental research.

3.2.2.3. Execution of the installed IoT network in the living lab. After installation of the sensors, the three Raspberry Pi 4 placed in the weather


```

BEGIN
//--- Configuration and Initialisation ---
// ThingSpeak API settings
SET THINGSPEAK_API_KEY to "LZKT4PFUPZBK8NWU"
SET THINGSPEAK_URL to "https://api.thingspeak.com/update"

// Twilio WhatsApp API credentials
SET TWILIO_SID to "ACb99cec6b4f867..."
SET TWILIO_TOKEN to "a245254c07887..."
SET WHATSAPP_FROM_NUMBER to "+14155238886"
SET WHATSAPP_TO_NUMBER to "whatsapp:+966500382142"

// Alert timing variables
SET Last_Alert_Time to 0 // Stores the timestamp of the last alert sent
SET Alert_Interval to 900 // Minimum time in seconds between alerts (15 minutes)

// Hardware setup
INITIALIZE Sensor1 as a digital input on Pin 4
INITIALIZE Sensor2 as a digital input on Pin 17
INITIALIZE Sensor3 as a digital input on Pin 9

DECLARE Sensor1_Value, Sensor2_Value, Sensor3_Value as integers

//--- Function Definition for Sending Alerts ---
FUNCTION Send_WhatsApp_Alert()
TRY
  INITIALIZE Twilio API Client with TWILIO_SID and TWILIO_TOKEN
  SEND WhatsApp message with body "Soil too dry! It needs water."
  FROM: WHATSAPP_FROM_NUMBER
  TO: WHATSAPP_TO_NUMBER
  DISPLAY "WhatsApp alert sent."
CATCH any Exception
  DISPLAY "Error sending WhatsApp alert.", followed by the error details
END TRY
END FUNCTION

//--- Main Program Loop ---
LOOP FOREVER
//--- Read Sensor Status (1 for wet, 0 for dry) ---
READ state from Sensor1
IF state is LOW THEN
  DISPLAY "Sensor 1: Soil is wet"
  SET Sensor1_Value to 1
ELSE
  DISPLAY "Sensor 1: Soil is dry"
  SET Sensor1_Value to 0
END IF

READ state from Sensor2
IF state is LOW THEN

```

Fig. 12. Pseudocode to send a message when the soil is “dry” (1).

```

DISPLAY "Sensor 3: Soil is wet"
SET Sensor3_Value to 1
ELSE
  DISPLAY "Sensor 3: Soil is dry"
  SET Sensor3_Value to 0
END IF

//--- Send Data to ThingSpeak ---
TRY
  CREATE a data payload containing:
  - "api_key": THINGSPEAK_API_KEY
  - "field1": Sensor1_Value
  - "field2": Sensor2_Value
  - "field3": Sensor3_Value
  SEND GET request to THINGSPEAK_URL with the data payload
CATCH any Exception
  DISPLAY "Error sending data to ThingSpeak.", followed by the error details
END TRY

//--- Check if an Alert is Needed ---
SET Current_Time to the current system timestamp

// Condition: Is any sensor dry AND has enough time passed since the last alert?
IF (Sensor1_Value is 0 OR Sensor2_Value is 0 OR Sensor3_Value is 0) AND
(Current_Time - Last_Alert_Time >= Alert_Interval) THEN
  CALL Send_WhatsApp_Alert()
  SET Last_Alert_Time to Current_Time // Update the timestamp to reset the timer
END IF

//--- Pause Before Next Cycle ---
WAIT for Alert_Interval seconds (15 minutes)
END LOOP
END

```

Fig. 13. Pseudocode to send a message when the soil is “dry” (2).

proof box were connected once at a time to the monitor, the keyboard and the mouse and turned on to run the Python code in Fig. 12 and Fig. 13. The same Python code was executed on each Raspberry Pi 4, as each unit managed data collection from the three sensors installed per tree. The only variation across the Python codes was the unique ThingSpeak channel API key, since each tree was assigned an individual channel for data storage as shown in Fig. 17.

The system operated effectively with the message sent to the farmer when the soil was “dry”, demonstrating the feasibility of using a low-cost, modular IoT solution for soil moisture monitoring in real-world agricultural conditions.

3.2.3. Experiment 3: automated pump integration in the lab

To demonstrate a complete automatic irrigation system, a lab-based experiment was conducted. Due to time constraints this experiment was not implemented in the living lab at Al-Aziziah Palm Tree Farm but it demonstrated the possibilities of the automated irrigation of the palm trees using a simple cost-effective submersible pump as shown in Fig. 18 and Fig. 19-A.

The submersible pump, rated at 80 L/h, was connected to a Raspberry Pi 4 as shown in Fig. 19-B to enable an automated, closed-loop irrigation system. A PVC tube was connected to the pump outlet, with its other end placed directly into a soil-filled container, as illustrated in Fig. 19 for water delivery. The experiment simulated realistic field conditions by embedding a soil moisture sensor within a cup full of soil, continuously monitored by the Raspberry Pi 4. A Python code, adapted from available online sources [24] and shown in Fig. 20, was executed on the Raspberry Pi 4 to continuously evaluate soil moisture levels at 15-minute intervals. Whenever the Python code detected soil moisture values below a predefined threshold, the relay interfaced with the Raspberry Pi 4 was activated, energising the pump and delivering water directly to the root zone without human intervention. Conversely, once the soil moisture returned to the target range, the relay automatically disengaged, switching the pump off and thereby preventing excessive irrigation. This autonomous control mechanism ensured irrigation occurred only as required, optimising water usage and closely replicating efficient, automated agricultural practices.

3.3. IoT network implementation outcomes

The IoT network outputs consist of soil moisture data streamed to ThingSpeak Cloud where three separate channels have been configured, one for each experimental palm as shown in Fig. 20. Within every channel, three fields are defined as shown in Fig. 21, each corresponding to one of the sensors installed around that tree: each field records either “0” or “1”, respectively for a “dry” or “wet” soil moisture detected state. This structure of the ThingSpeak channels provides a clear, real-time visualisation of moisture conditions for all sensors and trees under observation.

Based on the transmitted data, two operational outcomes have been established:

1. **Manual Pump Activation via SMS Notification:** an SMS notification is sent to alert a designated farm worker when dry soil condition is detected (value = “0”). Upon receiving the alert, the worker initiates the pump manually. This approach ensures that the irrigation is both timely and appropriate.
2. **Automatic Pump Activation:** when the sensor data indicates a dry condition (value = “0”), the system is configured to automatically trigger the submersible irrigation pump. This automated response ensures that soil moisture deficits are promptly addressed as soon as they are detected, without human intervention.

Together these outcomes demonstrate the efficacy of integrating real-time sensor data with cloud-based visualisation and control strategies, thereby supporting the overall goal of optimising irrigation

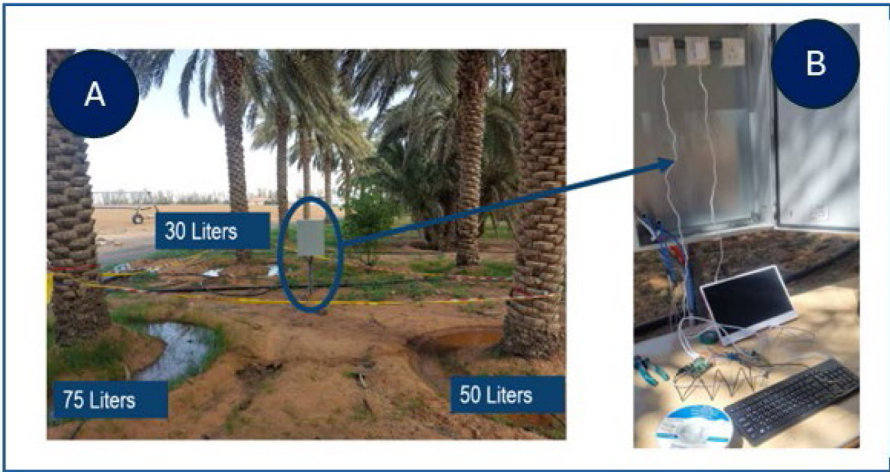


Fig. 14. Established living lab in Al-Aziziah Palm Trees Farm.



Fig. 15. Field hole digging.

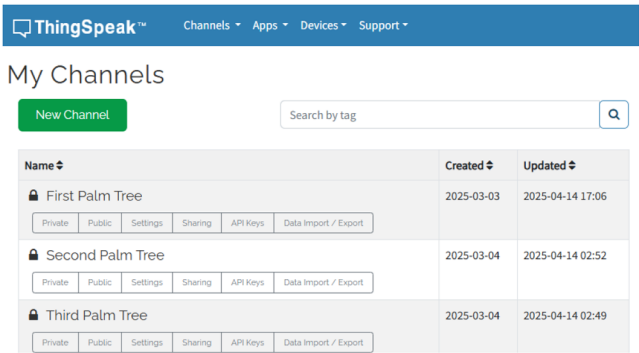


Fig. 17. Created Channels in ThingSpeak Cloud.



Fig. 16. Sensor Setting around the Palm Tree.

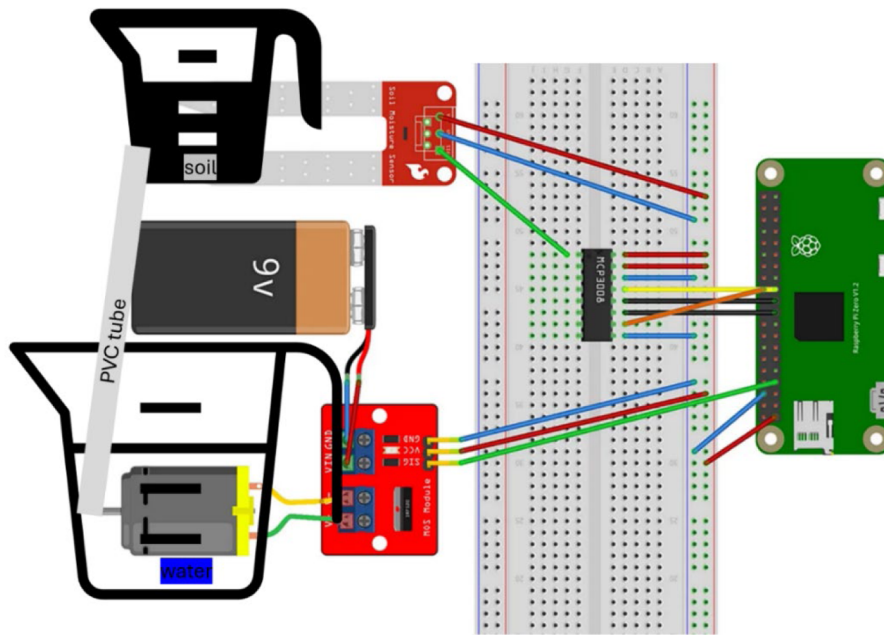


Fig. 18. Set of the experiment with the submersible pump (adapted and modified from Kunz, 2023).

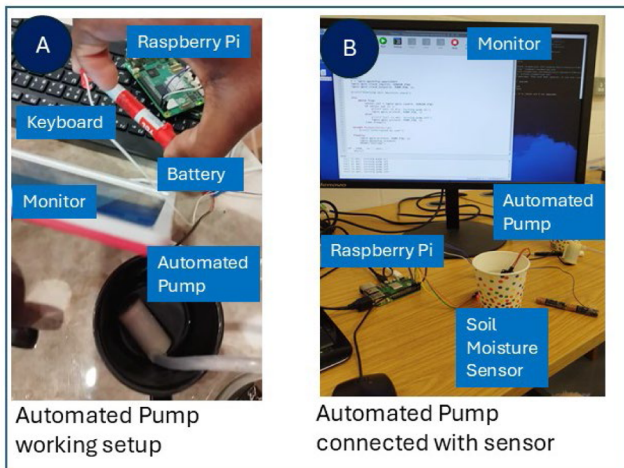


Fig. 19. Connection between submersible pump, sensors and Raspberry Pi.

management through digital transformation.

4. The mathematical calculations of the operational cost reduction

4.1. Development and definition of mathematical equations of pump cost

Currently, all the irrigation in Al-Aziziah Farm is based on pumping water from water well that spread across 26 farms. Each water well uses a pump as shown in Fig. 22.

There are a total of 50 water pumps in all the Al-Aziziah Group farms. The operational cost of each pump relies on the cost of diesel, which has increased by 200 % in the last few years. This makes the operational cost of each pump around £10,000. Therefore, it is particularly important to leverage the use of IoT network and other digital enabling technologies to significantly reduce the operational cost of those water pumps. This section discusses the derivation of formulas to compute the current costs, and it depicts how the IoT network can significantly lower operating costs by managing water usage for palm date tree irrigation.

```
BEGIN
//--- Configuration ---
SET GPIO_Chip to 0
SET Sensor_Pin to 4
SET Pump_Pin to 17

//--- Main Program Procedure ---
PROCEDURE Main()
//--- Initialisation ---
HANDLEh = OPEN connection to GPIO_Chip

CONFIGURE Pin Sensor_Pin as INPUT using handle h
CONFIGURE Pin Pump_Pin as OUTPUT using handle h, set initial state to LOW (off)

DISPLAY "Starting soil moisture check. Press Ctrl+C to stop."

//--- Main Loop with Error Handling ---
BEGIN TRY
LOOP FOREVER
// Read the sensor value (1 = wet, 0 = dry)
READ value from Sensor_Pin into Sensor_Value

IF Sensor_Value is 1 THEN // Soil is wet
DISPLAY "Soil is wet, turning pump off"
SET Pump_Pin to LOW(0)
ELSE // Soil is dry
DISPLAY "Soil is dry, turning pump on"
SET Pump_Pin to HIGH(1)
END IF

// Wait before the next check
WAIT for 900 seconds
END LOOP

CATCH KeyboardInterrupt // If user presses Ctrl+C
DISPLAY "Interrupted by user."

FINALLY // This block runs no matter how the loop exits
DISPLAY "Turning off pump before exiting..."
SET Pump_Pin to LOW(0)

DISPLAY "Releasing GPIO resources..."
CLOSE connection to GPIO_Chip using handle h

DISPLAY "GPIO resources released. Exiting."
END TRY
END PROCEDURE

//--- Program Execution Start ---
CALL Main()
```

Fig. 20. Pseudocode for automatic pump activation when the sensor reveals "dry" soil moisture.



Fig. 21. Example of Visualisation of Data Sent to ThingSpeak Cloud.



Fig. 22. Water pump at Al-Aziziah Farm [17].

To estimate the financial impact of optimised irrigation, a set of mathematical equations were developed to model the operational cost of water pumping at Al-Aziziah Farm. These equations are adapted and modified from engineering guidelines and generator fuel charts commonly used in agricultural and industrial energy modelling [25–27].

The operational cost of the water pump is calculated as:

Eq. (1)

$$\text{Operational Cost} = \text{Average Diesel used per hour} \times \text{Duration} \times \text{Cost of Diesel} \quad (1)$$

Where:

- **Average Diesel:** it represents the rate of diesel consumption.

- **Duration:** it reflects the time needed to pump a specified volume of water.
- **Cost of Diesel:** it is the market cost per litre in GBP.

The Average Diesel used per hour is derived as:

Eq. (2)

$$\text{Average Diesel used per hour} = \frac{\text{Volume of Diesel (l)}}{\text{Total Operating Hours (hr)}} \quad (2)$$

The Duration for pump operation is calculated from:

Eq. (3)

$$\text{Duration} = \frac{\text{Volume of Water to Pump (l)}}{\text{Pump Flow Rate} \left(\frac{\text{l}}{\text{hr}} \right)} \quad (3)$$

These relationships allow real-time soil moisture data to drive intelligent irrigation scheduling, optimising both resource usage and operational costs.

4.2. Capturing current water pump operational parameters

Applying the defined mathematical equations to Al-Aziziah Farm requires capturing the real operational data of the water pump, obtained from site monitoring and farm management reports. The pump operational parameters for Al-Aziziah Farm are listed in Table 2.

First, the volume of water to pump is determined for each irrigation scenario based on the number of trees irrigated in all the Al-Aziziah Farms (80,000 trees):

- For 100 litres/tree: $Volume = 100 \frac{\text{litres}}{\text{tree}} \times 80,000 \text{ trees} = 8,000,000 \text{ litres}$
- For 75 litres/tree: $Volume = 75 \frac{\text{litres}}{\text{tree}} \times 80,000 \text{ trees} = 6,000,000 \text{ litres}$
- For 50 litres/tree: $Volume = 50 \frac{\text{litres}}{\text{tree}} \times 80,000 \text{ trees} = 4,000,000 \text{ litres}$
- For 30 litres/tree: $Volume = 30 \frac{\text{litres}}{\text{tree}} \times 80,000 \text{ trees} = 2,400,000 \text{ litres}$

Then Eq. (3) is applied for each scenario to calculate the duration of the pump operation:

- Duration (100 L/tree): $\frac{8,000,000 \text{ litres}}{363,360 \text{ litres/hour}} \approx 22.02 \text{ hours}$
- Duration (75 L/tree): $\frac{6,000,000 \text{ litres}}{363,360 \text{ litres/hour}} \approx 16.51 \text{ hours}$
- Duration (50 L/tree): $\frac{4,000,000 \text{ litres}}{363,360 \text{ litres/hour}} \approx 11.01 \text{ hours}$
- Duration (30 L/tree): $\frac{2,400,000 \text{ litres}}{363,360 \text{ litres/hour}} \approx 6.61 \text{ hours}$

Then, the Average Diesel used per hour is computed using Eq. (2):

$$\text{Average Diesel used per hour} = \frac{32,000 \text{ litres}}{400 \text{ hour}} = 80 \text{ litres/hour}$$

Finally, Eq. (1) is applied to compute the operational costs of the water pump every 2 days for each irrigation scenario:

- 100 litres/tree: $80 \frac{\text{litres}}{\text{hour}} \times 22.02 \text{ hours} \times 0.35 \frac{\text{£}}{\text{litre}} = \text{£ } 616.56$
- 75 litres/tree: $80 \frac{\text{litres}}{\text{hour}} \times 16.51 \text{ hours} \times 0.35 \frac{\text{£}}{\text{litre}} = \text{£ } 462.28$
- 50 litres/tree: $80 \frac{\text{litres}}{\text{hour}} \times 11.01 \text{ hours} \times 0.35 \frac{\text{£}}{\text{litre}} = \text{£ } 308.28$
- 30 litres/tree: $80 \frac{\text{litres}}{\text{hour}} \times 6.61 \text{ hours} \times 0.35 \frac{\text{£}}{\text{litre}} = \text{£ } 185.08$

These calculations highlight the clear relationship between irrigation volume, runtime, and diesel costs.

4.3. The total operational cost of all the pumps and the possible savings

The application of the operational cost equations to different irrigation quantity levels revealed significant potential savings. Using the obtained results of the operational costs every 2 days, it was calculated the monthly and yearly water pump operational costs associated with different volumes of water delivered per tree every two days, including

Table 2
Pump operation parameters of Al-Aziziah Farm.

Parameter	Value
Total diesel used per 40 days	32,000 litres
Diesel cost per litre	£0.35
Generator run time per day	10 h
Total operating hours per 40 days	400 h
Pump flow rate	363,360 litres/hour
Number of trees irrigated	80,000

Table 3

Actual operational costs of the water pumps.

ACTUAL COST	Per month		Per year	
	1 pump	50 pumps	1 pump	50 pumps
100 litres every 2 days	£9248	£462,420	£112,522	£5626,110

Table 4

Comparison of cost savings for the operational cost of the water pumps.

COST SAVINGS	Per month		Per year	
	1 pump	50 pumps	1 pump	50 pumps
75 litres every 2 days	£2314	£115,700	£28,156	£1407,795
50 litres every 2 days	£4624	£231,190	£56,261	£2813,045
30 litres every 2 days	£6472	£323,590	£78,745	£3937,245

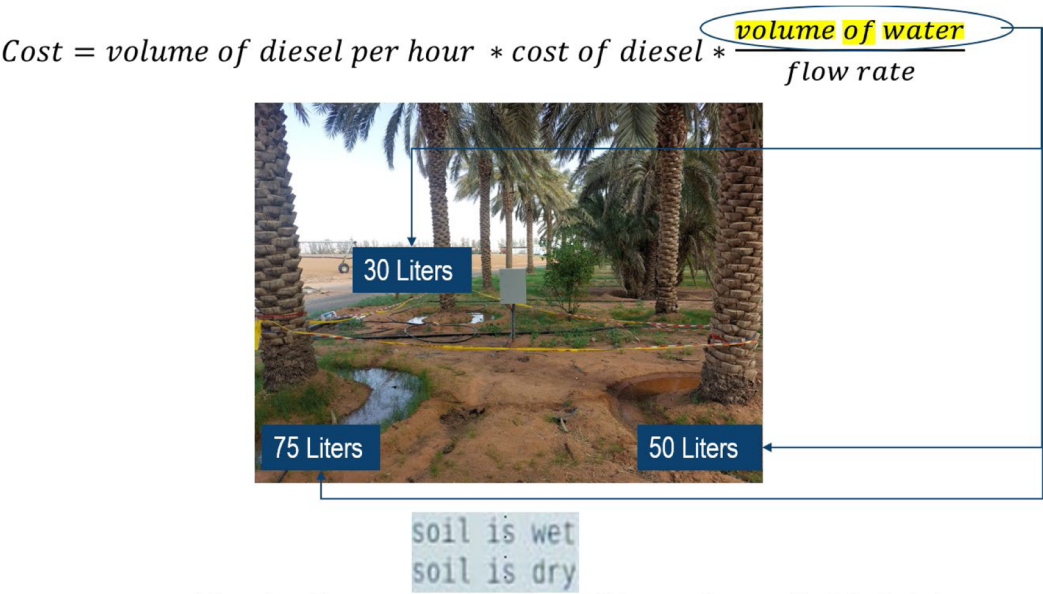
the current baseline scenario of 100 litres to have a clear comparison between them, as shown in Table 3 and Table 4.

The cost analysis clearly illustrates the financial impact of over-irrigation and the substantial benefits of optimising water use. Currently, irrigating with 100 litres every two days incurs a significant operational cost: £9248 per month or £112,522 per year for a single pump, and £462,420 per month or £5626,110 per year when scaled across 50 pumps. These figures highlight the unsustainable nature of the current irrigation strategy, particularly as diesel prices continue to rise. However, by reducing the irrigation volume to 75 litres, annual savings of £28,156 for one pump and £1407,795 for 50 pumps become immediately attainable, with no reported adverse effects on soil moisture or crop health. More aggressive reductions to 50 litres and 30 litres increase annual savings even further, up to £56,261 and £78,745 for one pump, and £2813,045 and £3937,245 for 50 pumps respectively. These results underscore the transformative potential of precision agriculture enabled by IoT. Rather than following fixed irrigation schedules, the farm can now base decisions on real-time soil data. Not only does this reduce unnecessary diesel consumption, but it also ensures that water is applied only when and where it is needed.

4.4. Integration of the equations with the IoT architecture

The integration of the operational water pump cost calculations with the IoT-based irrigation network provides a dual-pathway framework to validate the system's effectiveness. This combined approach integrates real-time operational data from the IoT network with an economic cost model to quantify the financial and resource efficiency of different irrigation strategies. The system leverages the following two complementary approaches:

- 1) **Fixed volume irrigation assessment:** the IoT network monitors how quickly the soil moisture level drops to a dry state following application of predefined water volumes (30 L, 50 L, and 75 L). IoT soil moisture sensors continuously monitor the rate of moisture depletion. This determines how long each fixed volume could sustain adequate soil moisture before conditions become too dry, factoring in real-world evapotranspiration. The total water volume consumed during these fixed trials is used as a direct input for the pump's operational cost equation "Eq. (1)". As illustrated in Fig. 23, this workflow allows for a direct calculation of the expenditure associated with common, non-adaptive watering schedules.
- 2) **Sensor-Driven adaptive irrigation:** predefined thresholds for "dry" state of the soil moisture trigger either automated pump activation or SMS alerts prompting manual irrigation, thereby aligning water usage directly with actual field conditions rather than relying on estimated averages. Crucially, the cumulative water volumes applied under this adaptive irrigation approach are recorded in the same observation window of the previous approach and used in the same



sensors reveal the duration required for the soil to reach specific “dry” states

Fig. 23. Visual explanation of IoT is integrated with the mathematical equations by testing different fixed irrigation volumes.

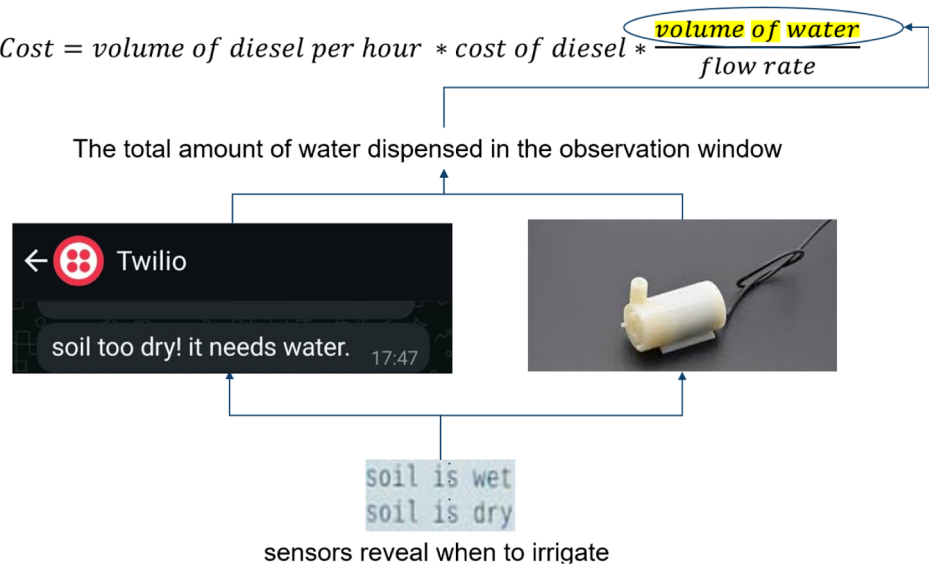


Fig. 24. Visual explanation of IoT is integrated with the mathematical equations by calculating the needed amount of water.

cost equation “Eq. (1)” employed for the fixed-volume method as shown in Fig. 24, ensuring analytical consistency across both strategies. What distinguishes this integration is not only the automation or precision, but the alignment between physical data, operational behaviour, and financial output. It transforms the IoT sensor system from a passive monitoring tool into a closed loop decision-support mechanism grounded in quantitative validation.

By contrasting the costs and water usage from the fixed-volume trials (Approach 1) against those from the sensor-driven method (Approach 2) over the same period, we can quantitatively demonstrate the efficiency gains. This transforms the IoT network from a passive monitoring tool into a validated decision-support platform, providing clear data on the financial and environmental return on investment (ROI) of smart irrigation.

5. Results and discussion

5.1. Effectiveness of IoT implementation

Fig. 21 shows successful collection and transmission of real-time soil moisture data from the living lab at Al-Aziziah Farm to the ThingSpeak cloud platform. The real-time dashboard displaying the status of each sensor confirms:

1. Precalibrated binary threshold values ‘1’ for “wet” and ‘0’ for “dry” are an unambiguous and immediate reading of soil moisture depletion under different irrigation volumes. The system reliably triggers WhatsApp alerts via the Twilio API whenever a ‘0’ value was detected, with a high-resolution dataset transmitted every 15 min to ThingSpeak cloud
2. Actionable intelligence eliminates guesswork and reduces the risk of both over- and under-watering. The dashboard serves as a powerful

human-machine interface (HMI) that transforms a traditional intuition-based approach to a data-driven, on-demand approach

5.2. Economic, environmental and sustainability benefits

Current practice (100 litres/tree) incurs an annual operational cost of £112,522 for a single pump and £5626,110 for all 50 pumps. By using IoT data to irrigate only when the soil is "dry," significant savings will be made. A data-justified reduction to 50 litres/tree unlocks potential annual savings of £2813,045, while a 30-litre strategy could save up to £3937,245. This represents a potential 25 % to 70 % reduction in diesel-related operational expenses, yielding an exceptionally high return on investment (ROI) for the low-cost IoT hardware.

Environmentally, the implications of reducing water and diesel usage are particularly relevant in the context of Saudi Arabia's acute water scarcity. Water resource stress is a primary concern in the region, and IoT application offers a scalable, low-cost way to manage inputs while maintaining or even improving productivity [28]. The use of open-source technologies like Raspberry Pi 4 and ThingSpeak further enhances the economic viability of the system, especially for small and medium-sized farms. While the current setup lacks advanced features such as automated valves and nutrient feedback, its modular design provides a platform for incremental upgrades, such as machine learning-based irrigation forecasting.

6. Recommendations and conclusions

6.1. Conclusions

This project created clear, mutual value for both the academic team and the industrial partner. The researcher's immersive, on-site work at the Saudi Arabian date-palm farm provided essential, hands-on insight that desk-based studies alone could not capture.

The principal take-aways are:

- 1) Al-Aziah Farm in general could enhance their productivity and reduce operational costs by leveraging the digital enabling technologies (Industry 4.0)
- 2) Performing the work in a living lab in the farm is the ideal condition to get the best of the experimental work.
- 3) Defining the right IoT network architecture that represents the reality of the farm is important to lead effective IoT applications.
- 4) There are always challenges of integrating different hardware and software of the digital technologies that could not be addressed without having direct experiments.
- 5) The project demonstrated that the real-life data of the IoT application could help to significantly reduce the operational cost of a farm.
- 6) The real transformation into smart farms will not be achieved without having real hands-on knowledge of the applications of the enabling digital technologies.

6.2. Recommendations for future work

This work on defining and implementing the IoT architecture for the Al-Aziah Palm Trees Farm has achieved its stated objectives, demonstrated the effectiveness of the proposed solution and layered a robust foundation for an operational digital ecosystem. Nevertheless, numerous opportunities for further development remain, which can broaden the system's functionality and overall value. A long-term field deployment of the proposed IoT network should be conducted to capture continuous, real-world data on soil conditions and microclimate parameters, thereby enabling a rigorous analysis of how varied irrigation volumes influence both vegetative growth and fruit quality over multiple seasons. Hands on experimentation highlighted the need to investigate use of wireless technology in the perception layer. Wireless sensors will stress test the Raspberry Pi for its suitability at scale, reduce

implementation costs, spotlight responsiveness of the IoT system, and enable remote power supply considerations [29].

Incorporation of digital potentiometers as a perception layer device, together with precision pressure regulators in the irrigation lines and programmable digital timers to automate valve actuation, will refine water delivery and ensure consistent, reproducible irrigation cycles [30]. The laboratory-tested automated pump system, so far evaluated only under controlled conditions at Cranfield University, must now be validated in the field to assess its hydraulic performance, durability, and integration with the sensor system under the farm's environmental and operational stresses; once proven, it would enable fully automated irrigation, eliminating the current semi-automated setup that relies on sending a message to the farmer to manually open the valve when the soil becomes "dry". Moreover, to ensure uninterrupted operation of the monitoring-and-control system, a dependable power-backup architecture is indispensable. The Raspberry Pi lacks native power-management circuitry; therefore, any voltage sag or complete loss of the DC supply triggers an abrupt shutdown, exposing data to loss and the SD card to corruption. This vulnerability can be mitigated with dedicated power-management HATs, such as PiJuice, Sleepy Pi, and WittyPi, which incorporate uninterruptible power-supply (UPS) functionality and automatically transfer the load to a battery whenever the primary power source fails [31].

Ethics statement

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

Abdulaziz Aljumaiah: Conceptualization. **Olusolabomi Temowo:** Investigation. **Gabriella Marseglia:** Investigation. **Giulia Sciannimanico:** Investigation. **Freda Naa Ayorkor Otoo:** Investigation. **Ravi Parihar:** Investigation. **Ahmed Al-Ashaab:** Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.

Data availability

Data will be made available on request.

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The applications of IoT network to enhance farming at Al-Aziziah Palm Trees Farm in Saudi Arabia

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