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A Self-Powered IoT Platform with Security Mechanisms for Smart Agriculture

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ABSTRACT

In response to escalating global challenges posed by climate change and resource scarcity, an innovative Internet of Things (IoT) framework has been developed which is specifically designed for smart agriculture applications. This work integrates a self-powered system with advanced security mechanisms to manage water resources effectively. System central are sensing node and an (ESP32+WIFI) base station, leveraging NRF24L01 technology for efficient data communication. The architecture of the platform is characterized by its integration of hardware components. which are facilitates seamless data collection from multiple sensing nodes. These nodes transmit information to a base station, where data consolidation occurs before secure transmission to a server via Wi-Fi. A key aspect of the framework is its emphasis on security (incorporating robust encryption, authentication) and access control strategies to mitigate risks, which associated with IoT deployments in agricultural system. Furthermore, the system's power management strategy is meticulously designed to enhancing energy efficiency and to extending the operational lifespan of the platform. This system combination (hardware and software elements) results in a reliable and secure IoT solution. Which it enabling real-time data acquisition, analysis, and decision-making processes for sustainable smart agriculture practices. This all-encompassing strategy not only satisfies present agricultural demands, but also coincides with environmental aims.

1. INTRODUCTION

The rapid technological advancements across various sectors have catalyzed innovation, notably in agriculture. As the global population escalates, the enhancement of agricultural systems becomes imperative to ensure food security, optimize resource utilization, and mitigate environmental impacts. In this context, the integration of IoT technology has been transformative, enabling sophisticated agricultural systems that monitor, analyze, and manage aspects of crop production and livestock management [1].

Previously, the energy sources adopted by the Internet of Agricultural Things systems for the purpose of operating sensors and data transfer units were electricity or batteries. However, access to reliable electrical infrastructure has been restricted, especially in off-grid locations. Furthermore, the question arises whether those sources can be relied upon for sustainability and scalability [2]. As a result of these obstacles, the self-powered mode of IoT devices for IoT applications has emerged as a new way of meeting these challenges. It combined energy aggregators with efficient energy management algorithms. This allowed autonomy and responsibility in the work of Internet of Things devices for agricultural applications. These platforms have been able to adapt, durable and cost-effective by using alternative energy sources such as wind, sun and movement [3].

The aim of this study is to demonstrate that a revolution in agriculture can see the light of day if the transformative potential is relied upon so that IoT systems are self-powered. Where there is no dependence on external sources of energy, these systems can provide farmers with real-time observations, improved resources in terms of allocation, as well as sustainable agricultural practices and improved production crops. By scrutinizing the subject, this study sought to drive research ideas to probe innovation in smart agriculture, to make the future of agriculture more efficient and more durable.

2. RELATED WORKS

This article subdivided the literature into three subparts when analyzing the literature relevant: Smart agriculture, Internet of Things technologies, and self-powered systems.

2.1 IoT systems in agriculture

Presents a kind of IoT based system that takes into account the difficulties of greenhouse rose cultivation. Also, it has being intelligent and environmentally friendly [4]. It has been demonstrated that aerial imagery, machine learning, and Internet of Things-based automation systems all increase agricultural output and soil fertility [5, 6] talks about a cloud-based software solution that uses the Internet of Things to automate irrigation plans based on input from agricultural professionals and environmental data gathered in the field [7]. Lastly, the architecture and subsystems of the ARETHOU5A

IoT platform, including its utilization of RF energy harvesting for power, are explored in the study of Boursianis et al. [8].

2.2 Smart agriculture solutions

Innovations in smart agriculture have seen significant advancements. A study proposed a low-cost, wireless sensor network (WSN)-based intelligent irrigation scheduling system that accounts for crop and soil water variability [9]. Another research developed an intelligent irrigation management system employing IoT technologies and a ZigBee wireless sensor network [10]. The creation of a communication protocol for smart irrigation within a Smart City framework is discussed, highlighting the use of low-cost instruments and minimal packet loss [11]. The monitoring of soil moisture and the automated control of plant irrigation using IoT are investigated in the study of Shobana et al. [12].

2.3 Self-powered systems in agriculture

The evolution of self-powered systems in agriculture reflects a growing emphasis on sustainability. Research has described a solar-powered hydroponics system designed for romaine lettuce cultivation in controlled environments [13]. The study of solar-based irrigation systems, including solar-powered pumping, has demonstrated their durability and long-term economic benefits [14, 15]. The Solarfertigation project, an IoT system for smart agriculture powered by a photovoltaic plant, is an exemplar of energy self-sustainability [16]. Additionally, a long-range, self-powered IoT device prototype suitable for aquaponics and precision agriculture has been developed, capable of harnessing ambient energy [17].

Collectively, these studies contribute significantly to understanding the challenges and advancements in IoT-based solutions for intelligent farming. This work with its focus on energy-efficient processes, intelligent irrigation, and sustainable power sources. They informs the proposed approach of this study to particularly in addressing the issues outlined in the introduction.

3. SUGGESTED SYSTEM DESCRIPTION

The proposed smart agriculture system is structured around a central base station node, interconnected with multiple sensing nodes. Utilizing NRF technology, these nodes efficiently gather agricultural data, which is then communicated to the base station. Equipped with robust power management systems and an effective solar panel, the system is designed to operate continuously, even in remote rural locations. The data collated at the base station is subsequently transmitted to the cloud, leveraging IoT technology, thereby facilitating rapid dissemination to a centralized server and enabling remote user access. This smart agricultural system, as illustrated in Figure 1, is specifically designed to meet these objectives.

The architecture of the proposed system encompasses the following pivotal components:

Sensing and Monitoring: This segment includes sensing devices for monitoring soil conditions. A soil moisture sensor, incorporating two conducting probes, is employed to measure soil moisture levels. These probes function by detecting variations in resistance to determine moisture content. The sensor's design consists of two primary elements: the prob and the signal conditioning circuit, as depicted in Figure 2.

Actuators and Automation: The system integrates actuators, such as irrigation controllers and automated machinery, which can be remotely operated or programmed for irrigation tasks. An electrical water pump, governed by a relay, is utilized for water pumping purposes.

Data Communication: Data gathered from sensors and devices are wirelessly transmitted via two primary communication methods: the NRF24L01 wireless transceiver and Wi-Fi. The NRF24L01 transceiver, illustrated in Figures 2 and 3, is employed for transmitting sensor data to the base station. This transceiver is a single-chip 2.4GHz unit with an integrated baseband protocol engine, designed for ultra-low power consumption in wireless applications within the global ISM frequency range [18]. Wi-Fi connectivity is utilized for uploading data from the base station to the cloud.

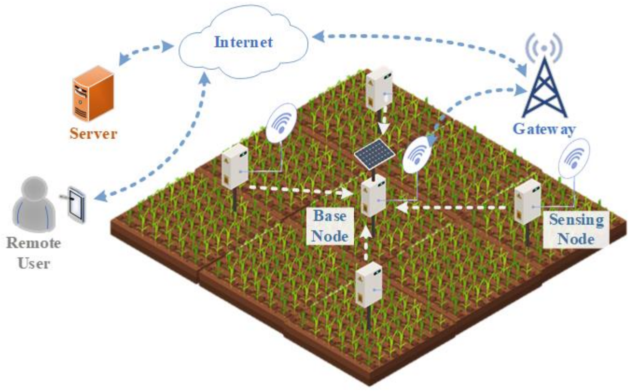

Figure 1. Suggested smart agriculture

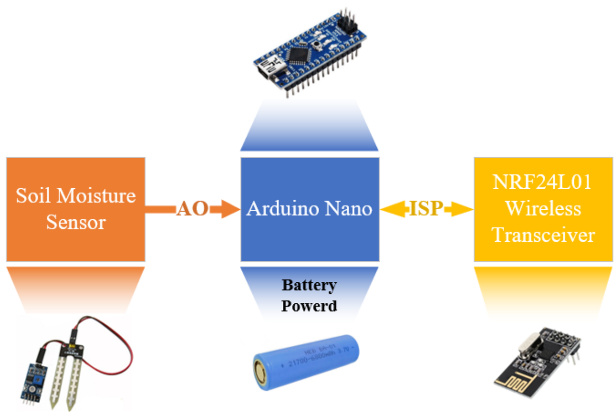

Figure 2. Suggested sensing node

Figure 3. Suggested sensing node

Cloud and Decision Support System: In this system, data collected from various sensors undergoes processing and analysis utilizing computing resources and advanced data analytics techniques. The ESP32 board, a system on chip microcontroller featuring integrated Wi-Fi, plays a pivotal role in executing these algorithms [19]. These algorithmic models are designed to extract valuable insights, identifying optimal irrigation patterns that correlate with crop growth and efficient water usage. The processed data is subsequently made accessible to farmers via user-friendly interfaces. Mobile applications, developed using the Blynk platform, offer real-time information and enable farmers to manage irrigation controls effectively. For the processing of sensing node data, an Arduino Nano board is utilized [20].

A Sustainable Power Source: To ensure continuous operation of the system, a combination of lithium-ion batteries (3.7V, 6800mAh) and solar cells (6V, 132×82 mm) is employed. The system incorporates a T6845-C charging module, characterized by its input voltage range of 3.7V to 5.5V, to facilitate the efficient charging of the lithium-ion battery via the solar cell. This module utilizes integrated MOS technology, capable of delivering a 1A output current, thus simplifying the charging and discharging processes.

4. RESEARCH METHODOLOGY

This paper's research methodology encompasses three integral components: the design of smart nodes, the development of a power management strategy, and the implementation of a proposed security model.

4.1 Smart nodes design

The prototype of the proposed system is bifurcated into two distinct units: the sensing node and the base node. The sensing node's primary function is to collect soil moisture data using a soil moisture sensor. This data is read by an Arduino Nano Board through its analog input port and subsequently mapped. The mapped information is then transmitted to the base node via an NRF24L01 wireless transceiver, which interfaces with the Nano board through the SPI protocol. The corresponding circuit diagram is depicted in Figure 4. Power to the sensing node is supplied by a battery.

Conversely, the base node is responsible for aggregating information from up to six sensing nodes and processing this data. It receives information through an NRF24L01 wireless transceiver. Based on the processed data, the base node manages the operation of irrigation motors. The circuit diagram detailing the base node configuration is illustrated in Figure 5.

The base node's functionality is sustained by renewable power sources. During daylight hours, a solar panel powers the node while simultaneously charging its battery. At night, the node is powered solely by the battery. The T6845 model is utilized for effective power management, and its circuit diagram is shown in Figure 6.

The irrigation system is regulated by specific processing algorithms. This system is activated when sufficient water reserves are available. It operates by monitoring soil moisture based on data received from the sensing nodes. When the soil moisture level falls below a predetermined threshold, indicating dry conditions, the water pump is activated to irrigate the crops. The quantity of irrigation water is pre-determined by the algorithm, ensuring precise and efficient water usage.

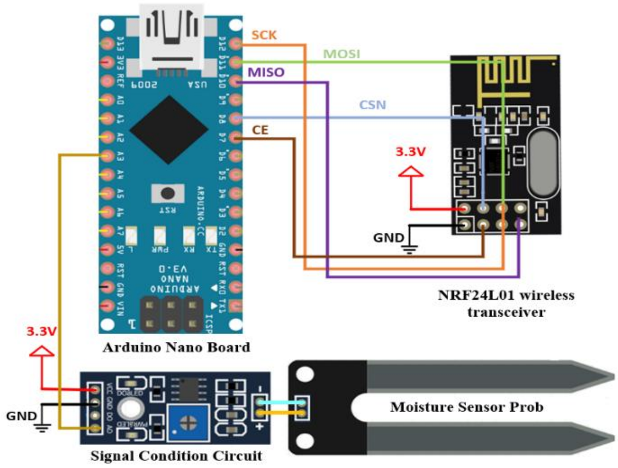

Figure 4. Sensing node circuit diagram

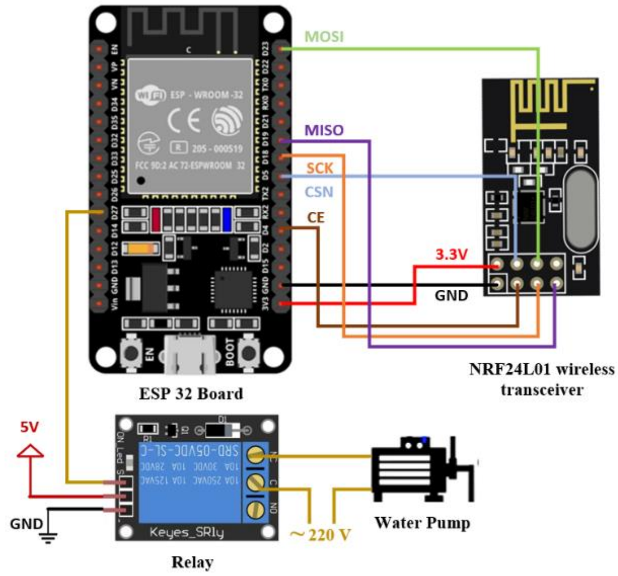

Figure 5. Base node circuit diagram

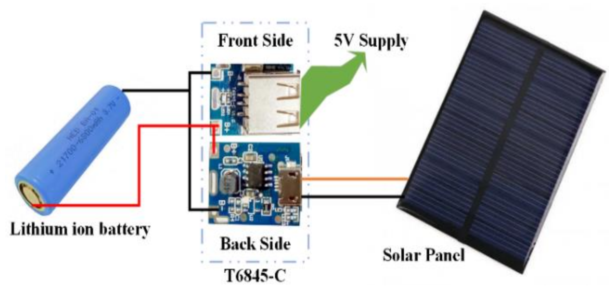

Figure 6. Sustainable power sources circuit diagram

4.2 Power management strategy

The power strategy of the proposed system involves a detailed assessment of node lifespan, taking into account the energy consumption associated with both reception and transmission activities. This evaluation considers the number of Arduino Nano nodes within the system, along with their individual power characteristics. To optimize the energy replenishment, the energy output from the solar panel is calculated and then offset against the total energy consumption.

For the battery lifetime estimation of the IoT platform, two specific equations are utilized. The first equation is dedicated to estimating the battery lifetime of the ESP32 base node, which serves as the system's primary processing unit.

$$Battery\_Capacity = \frac{Battery\_Capacity}{N \times \left(T_{rx_{esp32}} \times \left(I_{rx_{esp32}} + I_{sleep_{esp32}}\right) + T_{tx_{esp32}} \times I_{tx_{esp32}}\right)} - \frac{Battery\_Capacity}{Solar\_Panel\_Current} \quad (1)$$

where,

N: Number of Nano nodes.

$T_{rx_{esp32}}$: Reception time for Nano node packets by ESP32.

$I_{rx_{esp32}}$: Current during the reception for ESP32.

$T_{tx_{esp32}}$: Transmission time for the aggregated packet by ESP32.

$I_{tx_{esp32}}$: Current during transmission for ESP32.

$I_{sleep_{esp32}}$: Current during sleep for ESP32.

Battery_Capacity: Battery capacity of ESP32.

Solar_Panel_Current: Current provided by the solar panel.

Based on these factors, the equation calculates the average power consumed by the ESP32 node and then divides this by the solar panel current to determine the required solar panel output power.

The second equation estimates the battery lifetime of the Arduino Nano sensing nodes.

$$Nano\ Node\ life\ time = \frac{C\_battery}{N\_packets \times E\_packet \times \frac{3600\ seconds}{DC * T}} \quad (2)$$

where,

T: Total cycle time.

DC: Duty cycle (percentage of active time compared to the total cycle time).

E_packet: Energy consumed per packet transmission (Joules).

N_packets: Number of packets transmitted per hour.

I_transmission: Current drained during transmission (mA).

I_sleep: Sleep current (mA).

C_battery: Battery capacity (mAh).

Battery_life: Node lifetime (hours).

The equation determine the battery lifetime in hours by calculating the average Arduino Nano node consumed energy per hour and then divides it by the battery capacity.

4.3 Security threat model

The security threat model for the proposed agriculture IoT system with sensing nodes connected to a base station. It may include the following potential vulnerabilities and risks:

Unauthorized Access: There is a possibility of unauthorized inter-device communication or access to IoT devices. The integrity and confidentiality of the transmitted data between the base station and Arduino Nano sensing nodes could be violated by attackers attempting to intercept or alter it.

Data Tampering: The attacker might try to change the data that the sensing nodes collected. The sensing nodes would send the incorrect data to the base station. This could lead to incorrect decisions based on data, which could have a negative impact on rural activities.

Device Spoofing: Connecting sensing nodes with the base station is performed by employing the NRF24L01 wireless communication where device spoofing attacks are conceivable. Attackers may disguise themselves as trustworthy nodes to gain unauthorized access to the system. Also, he can bypass authentication protections and maybe influence or interfere with the system's functionality.

Denial of Service (DoS): Attackers may use this type of attack to disable or unresponsively affect the base station or the sensing nodes. This may interfere with the proposed system's operations, affecting real-time monitoring and decision-making procedures.

Physical Security: Attackers may tamper to obtain physical access to the system's nodes: base station, sensing nodes, or both. this will allow the attacker to extract sensitive information from them. or change the configuration of the system. which might result in unauthorized access or compromised functioning.

Network Vulnerabilities: Attackers may be able to use the weaknesses in the wireless network being utilized for communication. For example, the weak or default network credentials, unencrypted communication, or inadequate network security measures. the attacker may gain unauthorized access, eavesdropping, or network-based assaults might be made against the system.

5. IMPLEMENTATION AND ANALYSIS

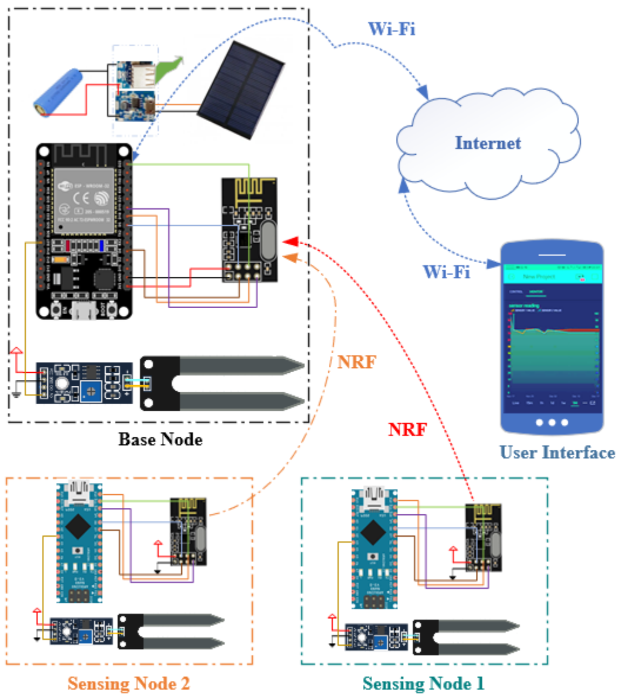

Figure 7. System implementation

In the proposed system, three nodes have been implemented: two sensing nodes and one base node. The sensing nodes are powered by 6800mAh batteries, while the base node is powered by a 6800mAh battery and a solar panel. These nodes are interconnected using NRF technology. The sensing nodes transmit data to the base node, which collects and processes the data based on predefined user configurations set via a mobile phone. The data is then sent to the internet and cloud, serving as the bridge between the user and the system, as illustrated in Figure 7. For detailed network data flow, please refer to Table 1.

A mobile app, utilizing the Blync platform, has been developed for control and monitoring purposes. This app features two tabs: "Monitor" and "Control." The "Monitor" tab displays real-time data received from the sensing nodes, allowing remote monitoring of sensor values and data storage.

In the "Control" tab, users receive notifications regarding critical system parameters, including water tank levels, pump motor status (ON/OFF), server connection status, and the Control terminal. The Control terminal facilitates farm management through order codes, including secure system access (via username and password), a "logout" command for saving and exiting, support for four plant mode types, status inquiries to retrieve mode information, and details about plant dates and remaining time. Figure 8 provides a visual representation of the control tab's interface.

Table 1. Network traffic map

Traffic Type & Description	Source	Destination	Packet Length (Header+Data)	Packet Rate	Communication Medium	Average Latency
Periodic messaging of sensing	Arduino Nano	ESP 32	100 Byte	4 Packets/hour	NRF	400.5 μsec
Periodic messaging of Aggregated data	ESP 32	Server	1000 Byte	1 Packet/hour	Wifi	45.95 μsec
Aperiodic messaging for configuration	Server	ESP 32	74 – 1518 Byte	1 Packet	Wifi	3.86 - 69.5 μsec
Aperiodic messaging for Status	Arduino ESP 32	ESP 32 Server	74 – 1518 Byte	1 Packet	NRF Wifi	Variable

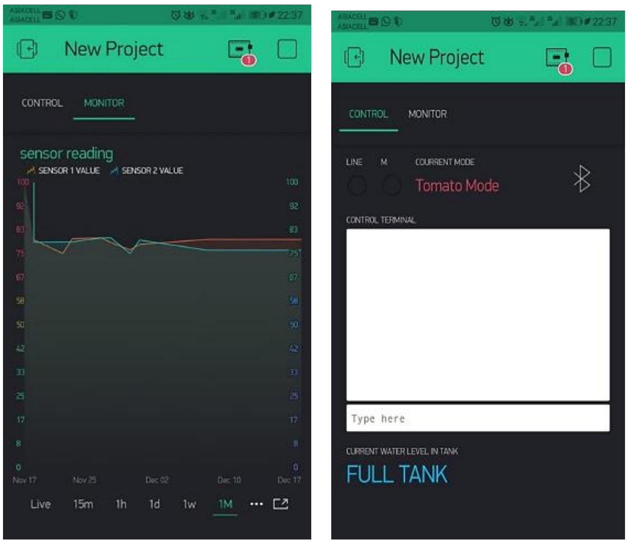

Figure 8. System app tabs

5.1 Power analysis

The power consumption for each operational mode is calculated and summarized in Table 2. The battery capacity for the proposed system is 6800mAh.

Table 2. System power consumption

Name	Operation	Power Consumption
Base Node (ESP 32)	Transmit to the server (WIFI)	240 mA
	Sleep	1 mA
	Receive from sensing node (NRF)	60 mA
Sensing Node (Arduino Nano)	Transmit to Base node (NRF)	34 mA
	Receive from the Base node (NRF)	32 mA
	Sleep	5 mA

To estimate the battery lifetime of the ESP32 base node, the following parameters are considered:

N: six nodes.

$T_{rx_{esp32}}$: 15 minutes = 900 seconds.

$I_{rx_{esp32}}$: 32 mA.

$T_{tx_{esp32}}$: 1 hour = 3600 seconds.

$I_{tx_{esp32}}$: 240 mA.

$I_{sleep_{esp32}}$: 1 mA.

Battery_Capacity: 6800 mAh.

Solar_Panel_Current:Solar_Panel_Current = 160 mA.

The total calculation for the base node is presented in Table 3.

To achieve a neutral energy balance, the solar panel should ideally generate approximately 0.9766 Watts. This estimate assumes perfect conditions and a steady power consumption pattern. However, actual performance may vary due to factors such as ambient temperature, battery efficiency, fluctuating power usage, and other specific system characteristics.

Table 3. Main features and performance of the proposed irrigation system

Type	Calculation	Value
Base node ESP 32	Reception Time	0.0032 seconds
	Energy per Packet Reception	0.1024 Joules
	Transmission Time	0.0364 seconds
	Energy per Packet Transmission	8.736 Joules
	Energy per Hour	14.6496 Joules
	Battery Life	464.681 hours
	Total Energy Consumption	14.6496 Joules
	solar panel output power	58.5984 Joules/minute
	solar panel output power	≈ 0.9766 Watts

Our tests involved single solar cells (6V, 132×82 mm), conducted on a sunny day in September under typical conditions. Hourly measurements of the power output were taken using a voltmeter. These observations indicated that the maximum power output from the panel, around midday, was approximately 0.775 Watts. For days with cloudy or rainy weather, power estimations can be adjusted following [21]. Additionally, the annual variation in sunlight hours [21], necessitates planning for the least favorable conditions. For practical implementation, particularly for powering ESP32 circuits and charging battery cells for uninterrupted night-time operation, a 10 W solar panel is recommended. Consequently, a configuration of 13 solar cells (each 6V, 132×82 mm) is required. The characteristics and performance of this solar panel configuration are detailed in Figure 9.

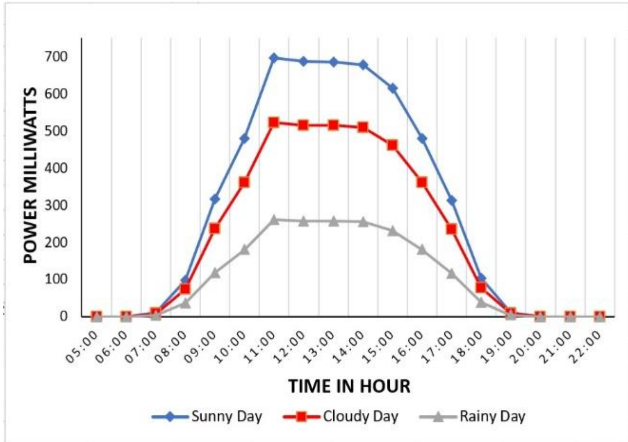

Figure 9. System app tabs

Table 4. Main features and performance of the proposed irrigation system

Type	Calculation	Value
Sensing Node Arduino Nano	Transmission Time	0.0032 seconds
	Energy per Packet	0.1024 Joules
	Energy per Hour	0.4096 Joules
	Battery Life	16604.297 hours

To estimate the battery life of Arduino Nano sensing nodes, we consider nodes operating on a fixed duty cycle. Each node remains active for a predetermined amount of time before entering sleep mode for the remainder. This cycle of active and sleep periods remains constant, unaffected by network conditions or traffic fluctuations. In our scenario, the active time per cycle corresponds to the duration required for both reception and transmission, totalling 15 minutes. The average energy consumption of the Arduino Nano node per hour is calculated based on this duty cycle. This average consumption is then divided by the battery's capacity, as per Eq. (2), to determine the node's battery life in hours. The results of this calculation are presented in Table 4.

Consequently, under the specified conditions of power consumption and duty cycling, the anticipated lifespan of the node is approximately 16,604 hours, or roughly 1.89 years. It's important to note that this estimate is based on ideal circumstances and assumes a consistent pattern of power usage. However, actual battery life may vary due to factors such as ambient temperature, battery efficiency, variations in power consumption, and other system-specific factors.

5.2 Suggested security model and analysis

This work outlines the core concepts, strategies, and principles of the proposed security model, focusing on its conceptualization and design. While the model is theoretical and not yet applied in practice, it is structured to address identified threats effectively. We conduct an extensive security analysis of the model using established methodologies in this domain. This analysis involves assessing the model's strengths and vulnerabilities, as well as its capability to counter theoretical risks. By adhering to these standard procedures, our objective is to enhance the theoretical understanding of security practices, even without their practical implementation in this specific context. Our method aligns with industry norms, allowing us to provide a comprehensive analysis of the design and potential effectiveness of the proposed security framework. Table 5 presents a detailed security analysis of the solutions pertaining to each node within the smart agriculture IoT system.

Table 5. System security analysis

Node	Security Solutions	Detailed Security Analysis
Arduino Nano Sensing Devices	Secure Communication Protocols	Transmission between the sensing nodes and the base node is kept secure. Also, preventing introtuder from being intercepted or altered data by encryption.
	Device-level Authentication Mechanisms	Prohibiting unauthorized devices acess from connecting to the system. the device authentication ensures that only trustworthy modes may participate in data exchange based on secure tokens or digital certificates.
	Tamper Detection Measures	The integrity of the sensing nodes and the gathered data protected by tamper detection which detected any physical tampering efforts.
ESP32+ WIFI Base Station	Limited Privileges for Device Access	Giving sensing nodes restricted rights decreases the possible effect of hacked devices and restricts the unlawful actions they may undertake. Ensure that each nodes has the appropriate rights to carry out its intended activities but is not allowed to access crucial resources.
	Secure Network Configuration	Unauthorized access to the base station is prevented via a secure network setup. which also, defends against network-based threats.
	Strong Authentication Mechanisms	Unauthorized persons are prevented from obtaining access to the management systems or administrative interface of the base station by robust authentication procedures.
	Intrusion Detection and Monitoring	Detecting suspicious activity or abnormalities in the system network is made possible with the aid of intrusion systems (intrusion detection or intrusion prevention systems).
NRF24L01Wireless Commu.	Encryption Protocols (e.g., AES)	Data sent between the sensing nodes and the base station (ESP32+WIFI) is protected from unwanted access and tampering via wireless connection encryption.

6. OBJECTIVES, SCOPE AND LIMITATIONS

Smart Nodes Design: The primary objective of this research stream was to develop a system (cost-effective, energy-efficient smart node) capable of consistently monitoring soil data. This stream included selecting hardware components, developing software (data acquisition and transmission), and evaluating performance of the node. Limitations in this stream were primarily the use of the components and the testing environment.

Power Management Strategy: This research proposed a power strategy that would enhance the smart nodes life time. Its objectives included researching power usage trends, developing power management algorithms, and putting the plan through real-world testing. The limitations include on simplified power consumption models and a limited duration for testing.

Proposed Security Model: This research stream's purpose was to discover possible security vulnerabilities in the smart agricultural IoT system. Also, it provides a security model to address these risks. The scope involved conducting a system threat analysis, identifying security requirements, and designing secure communication protocols. The primary limitations were the limited scope of testing for the security model and the use of qualitative threat analysis techniques.

As demonstrated in Table 6, the proposed system exhibits superior efficiency and capability when compared with other systems.

The main features and performance of the proposed irrigation system are shown in Table 7.

Table 6. Systems comparison

Work	IoT	Power Source	Security	Communication	Water Management	Power Management
[1]	√	N/A	√	6LowPAN , radio	√	√
[7]	√	solar panel and battery	N/A	ZigBee	√	√
[10]	√	solar photovoltaic panels and lead-acid batteries.	N/A	ZigBee	√	N/A
[11]	√	N/A	N/A	LoRa and WiFi	√	N/A
Proposed work	√	Solar and lithium battery	√	Wifi and NRF	√	√

Table 7. Main features and performance of the proposed irrigation system

System Software	**Nano Node: C code under Arduino IDE** **ESP32 Node: C code under Arduino IDE**
System Hardware	Nano Node: Arduino nano, NRF transceiver, soil moisture sensor, and battery ESP32 Node: ESP32, NRF transceiver, relay, solar cell, and battery.
Networking Issues	Networks Types: Wifi, NRF Networks Standards: IEEE 802.11g, IEEE 802.15.4 Networks Data Rate: NRF:250Kbps, Wifi:22Mbps. No. of served Nodes/Base Station:6/1 Network Span: 1 Km^2 Packets Length: Nano 100 Byte, ESP 32 1000Byte Packets Rate: Nano 4 packet/hour, ESP 32 1 packet/hour.
Possible threats detected	Unauthorized Access, Data Tampering, Device Spoofing, Denial of Service (DoS), Physical Security, Network Vulnerabilities
Energy Requirements	Nano Node: Battery Capacity: 6800 mAh Power Management Method: Fixed Duty Cycling (Wake up/Sleep) Period <<<1% Node Life Time: 1.89 Years ESP32 Node: Battery Capacity: 6800 mAh Power Management Method: Fixed Duty Cycling (Wake up/Sleep) Period <1% Solar panel Characteristics: Power (10 W)
Estimated Cost (June 2023)	220$

7. CONCLUSION

Our innovative IoT platform represents a substantial advancement in smart agriculture. It offers robust security measures, real-time data processing, and efficient power management. This system not only promotes increased crop yields and resource optimization but also facilitates informed decision-making and operational efficiency for farmers. Distinguished by its self-sufficiency, advanced security, real-time insights, scalability, and effortless cloud integration, our platform significantly outperforms existing solutions in the field.

Future developments could focus on incorporating predictive analytics and machine learning, alongside partnerships with agricultural organizations to foster broader adoption. This conclusion emphasizes the platform's role in revolutionizing smart agriculture, highlighting its commitment to safety, reliability, and environmental stewardship without redundant introductory content.

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