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Efficient irrigation system using a combined wireless sensor network based on LoRaWAN and IEEE 802.15.4 technologies and photosynthetically active radiation measurements

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ABSTRACT

To address the demands of wireless communication, small amount of transmission, low power consumption, and cost-effectiveness in agricultural Internet of Things (IoT) applications, this paper introduces a hybrid information monitoring approach. It combines a low-data-rate personal area network based on IEEE 802.15.4 with a low-power wide-area network utilizing LoRaWAN. This method employs a communication architecture comprising a central node, multiple subnodes, and end devices to support the needs of large-scale information monitoring. Specifically, the main node is designed using LoRaWAN communication technology and performs in-field measurements of photosynthetically active radiation (PAR) using a device calibrated through intercomparison with reference radiometers. The subnodes or cluster heads incorporate LoRaWAN, sensor technologies, and IEEE 802.15.4. End devices also utilize IEEE 802.15.4 and sensor technologies. A control terminal manages sensor data and transmits the collected information to a web application for further processing. The advantages of this approach are that combining IEEE 802.15.4 and LoRaWAN at the device level enhances the spatial variability of agricultural fields, since tree and star network topologies are integrated to collect detailed information about specific crop areas, while providing low-power, long-distance network services and reducing the operating costs of the wide-area network information monitoring system. Additionally, hardware and firmware strategies were applied to further extend the system autonomy, and it can be self-powered. System testing revealed that, in a challenging environment, the maximum communication range reaches up to 60 m for IEEE 802.15.4 and 2 km for LoRaWAN. The average energy consumption is only 0.55 mAh, supporting real-time monitoring with latency under 100 ms, and the packet loss rate is approximately 2.5 %. Overall, the system operates reliably, and the data collected are accurate. The findings indicate that the proposed method effectively fulfills the needs for data gathering, transmission, storage, and processing across large areas. Furthermore, it proves to be valuable for implementing strategies aimed at improving both irrigation systems and the cultivation process of strawberry crops.

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1. Introduction

In most regions of the world, agriculture accounts for 70 % of all freshwater consumption and the growing population has steadily increased the demand for this resource. Agriculture continues moving toward complete digitalization and the introduction of mature information technology can further promote its growth and economic development. Thus, the evolution of wireless sensor networks (WSNs), Internet of Things (IoT) technologies, and recent advances in sensors have allowed the progress and development of smart irrigation systems [11,15,23,30]. Given the increasing demand for IoT applications, the performance of sensors and their interface circuits is of particular importance [44]. In recent years, data from advanced monitoring systems in agriculture has significantly increased. Substantial water savings can be achieved by monitoring ambient properties such as soil moisture, temperature, and salinity, among others, to provide immediate benefits, as well as creating new strategies based on science and technology. Thus, the water status of the plant has been monitored based on the canopy temperature distribution of its foliage, acquired through thermal imaging [48]. Other systems use crop water stress index (CWSI) [5]. Estimating plant evapotranspiration serves as an alternative parameter for determining crop irrigation needs. This estimation is influenced by climatic factors such as solar irradiation, temperature, relative humidity, wind speed, and crop-specific characteristics [33]. A data acquisition system was deployed to monitor crop conditions by measuring soil moisture, as well as soil, air, and canopy temperatures in cultivated fields. Data was downloaded via a laptop connected through a serial port for analysis and storage [9].

Current monitoring methods in this field can be enhanced by utilizing WSNs that incorporate microcontrollers and communication technologies, enabling real-time responses and improving the spatial scale of measurements. For instance, a system designed to enhance water management efficiency was developed using a WSN and a weather station to monitor drainage water via the Internet, employing capillary wick-type distributed passive lysimeters. The leachate flow beneath the root zone in an irrigated cropping system was measured [19]. Additionally, irrigation systems can be automated using information on volumetric soil water content, with the help of water-saving moisture sensors and WSNs [16]. Hybrid architectures are used, with wireless modules placed inside the greenhouse for greater flexibility, and wired modules used outdoors as actuator controllers [27].

Therefore, most monitoring applications are based on WSNs and provide numerous benefits, such as reduced costs owing to the lack of cabling, system scalability, numerous network topologies, and lower system commissioning and maintenance costs. The widespread adoption of smart sensors and the advancement of communication protocols have enabled WSNs to deliver successful solutions across various fields [10,21,25,28,39,43,45]. For applications where short-to-intermediate distances are required and the latency and reliability requirements are less demanding, such as environmental monitoring and precision agriculture, the most widely used protocols are ZigBee (IEEE 802.15.4), Wi-Fi (based on IEEE 802.11), and Bluetooth (IEEE 802.15.1) [20,31,40]. Various emerging wireless technologies exist, such as Sigfox, LoRa/LoRaWAN, NB-IoT, and LTE-M [1,12,26,41]. In particular, LoRaWAN is a network standard for telecom operators with technology based on the LoRa physical layer (PHY) implementation [8,22,38,47]. It is used to provide network services enabling the long-distance wireless transfer of data between devices and remote gateways. The LoRaWAN standard is based on a star network topology with only one allowed hop in the communication between the gateway and LoRa device. LoRa devices can transmit data up to 15 km in an open area; according to some experiments, this range is sufficient for most current-day-long-range IoT applications.

This study proposes a combined WSN based on IEEE 802.15.4 and LoRa standards in the context of IoT systems with low power requirements. Thus, the system integrates a wireless low data-rate personal area network (LR-WPAN) such as IEEE 802.15.4 with a low-power wide-area network (LPWAN) such as LoRa, which complements IoT requirements. By simultaneously using nodes that connect with only one of the networks as well as nodes with dual connectivity, one can create a joint network that combines the characteristics of low data rates and the hardware requirements of IEEE 802.15.4 with the low power requirements and cost of LPWAN technologies. The wide range of coverage and low power consumption of LPWAN technologies have been achieved mainly because of the optimisation of the modulation and simplification of the network topology (star architecture) compared with the multi-hop configurations of LR-WPANs.

The wireless communications based on the IEEE 802.15.4 standard use the beacon-enabled mode with guaranteed time slot (GTS). This ensures the data transmission and a synchronous acquisition with sleep/wakeup periods for the nodes, achieving an optimized power consumption of the system. The coverage range of several tens of meters of this protocol results suitable to deploy a distributed in-field sensor-based site-specific irrigation system to increase the yield and quality while saving water and also addressing the substantial variations in soil properties across most fields. The developed irrigation system allows adjustments in accordance with specific crop needs and has minimum maintenance requirements. Given its modular configuration, the system can be scaled up to accommodate open fields and large greenhouses. A tailored WSN solution, a self-sustaining strategy, and the calibration of the PAR sensor to ensure data reliability are also included. By virtue of its duplex communication controlled through the Internet, the system offers a powerful decision-making tool that can be adapted to all types of agricultural scenarios. Additionally, the presence of an Internet link enables remote supervision of the system using mobile telecommunication devices such as smartphones. The use of this type of irrigation system is justified not only by monetary savings from improved water use but also because it preserves natural resources.

2. Related work

The application of wireless networks in agriculture has been explored in many studies. Using real-time measurement and control enables farmers to lower their operating costs, and investing in IoT technologies for monitoring crop health and growth is crucial for preventing unnecessary water and financial waste. Artificial intelligence (AI) and machine learning (ML) are becoming more prevalent in precision agriculture. These technologies analyze large volumes of data gathered from IoT sensors to improve decision-making for

Table 1
Summary of the literature on the practical implementation of wireless technology in agriculture.

Reference	Wireless technology	Parameters	Possible future scope
[29]	LoRa	Measuring water pH, soil pH, and soil moisture, crop monitoring, adverse weather conditions in agriculture-IoT	To improve modulation efficiency and optimizing LoRa parameters (BW, SF)
[18]	LoRaWAN along with PLC	Humidity conditions, remote farm monitoring, automated irrigation, adjusting the temperature inside the warehouse	Utilization of ML algorithms for more effective agriculture monitoring
[34]	Wi-Fi	Turbidity, pH, temperature, soil moisture	AI /ML algorithms
[40]	ZigBee	Humidity, carbon dioxide, pH, temperature	Power consumption, human-computer interface, data verification and analysis
[24]	NB-IoT	Soil moisture, temperature	Size of the antennas, range, higher data speeds or higher transmission rates
[42]	SigFox	Temperature, humidity, illuminance, carbon dioxide	Degradation of temporal, frequency, and spatial diversity effects due to multi-frame collisions.
[16]	MODBUS RTU and GSM	Soil moisture-based irrigation decision support system	Nested characteristics of the system will involve communicating and transferring at the regional scale
(This work)	IEEE 802.15.4 and LoRaWAN	Soil-moisture, nitrogen, phosphorous, potassium, temperature and PAR	ML and AI techniques to enhance agricultural productivity

farming machinery, increase the accuracy of environmental sensing, and enhance path planning algorithms, collectively elevating the intelligence of agricultural production [2]. Nonetheless, the progress of smart farming depends not only on sophisticated AI techniques but also on reliable and efficient communication technologies that enable real-time data transfer and coordinated operation of agricultural equipment. As a result, choosing the right communication technology is essential for ensuring the stable and effective functioning of agricultural IoT systems.

A reliable and efficient communication network is crucial for smooth data gathering, remote management, and coordination among multiple machines. Since different application scenarios have unique communication needs, various technologies are currently used in agriculture. The leading communication options include NB-IoT, Bluetooh, LoRa, SigFox, Wi-Fi, and Zigbee, each offering specific benefits and compromises related to coverage area, energy use, bandwidth capacity, and latency [6,46]. Table 1 summarizes some related works that have implemented wireless technology in practical agricultural applications, classified by the wireless technology.

[29] introduced an IoT system that uses LoRa technology for efficient monitoring of irrigated crops in agriculture. The system includes sensors that measure hydrogen water potential (pH), soil pH, and soil moisture, all of which communicate with an Arduino microcontroller via the 915 MHz LoRa frequency. The primary goal of their system was to avoid excessive water usage and mitigate the effects of unpredictable weather, leading to positive outcomes in plant growth. In essence, the IoT-LoRa system improved agricultural practices by ensuring that crops received water at the correct pH level [18]. proposed a sensor node topology utilizing affordable components for effective water management. The system, powered by LoRa LPWAN technology, showed potential for both manual and automated farm management, with the integration of a mobile application for easier control [34]. developed a device named to monitor soil health. This device uses REST API and TCP protocol. The developed sensor node monitors various soil parameters, including pH, turbidity, moisture, and temperature, using Wi-Fi technology, and transmits the sensor data to the end-user [40]. designed a set of agricultural digital greenhouse system based on ZigBee wireless sensor network technology, and uses a controller under the particle filter optimization technology to optimize the error of the corresponding data acquisition system, and eliminate the corresponding noise and interference [24]. developed a prototype NB-IoT based quasi-smart water management platform for irrigation for the rational exploitation of vineyard in correlation with the soil moisture and temperature [42]. derived an experimental approximation formula of battery lifetime considering real Sigfox node behavior for smart agriculture as an IoT use case outdoors [16]. designed, calibrated and validated a soil moisture-based irrigation decision support system using a wireless monitoring network, where the FDR soil moisture uses the MODBUS RTU protocol to interface with a specific data transmission unit and communicates directly with the server via a GSM connection.

The adoption of precision agriculture services faces several challenges, including the integration of heterogeneous IoT devices, ensuring interoperability between various platforms and proprietary systems, and the high costs associated with the necessary technological infrastructure. Additionally, several factors need to be considered when designing farming applications and services, such as coverage, cost, data delivery rate, energy consumption, throughput, and potential collisions. The system proposed in this work features a device-level, combined wireless network based on IEEE 802.15.4 and LoRaWAN standards, taking advantage of the strengths of each. IEEE 802.15.4 technology allows a more comprehensive monitoring of small and medium-sized areas with soil-moisture, nitrogen, phosphorous, potassium, and temperature sensors placed in the root zone of the strawberry plants. Moreover, the IEEE 802.15.4 standard supports the configuration of various network topologies, such as tree or mesh, to expand the monitored crop area. The LoRaWAN network collects data from the IEEE 802.15.4 network, measuring the same parameters in addition to photosynthetically active radiation, and transmits this data remotely over greater distances using a star network topology. Furthermore, both IEEE 802.15.4 and LoRaWAN standards enable private networks with minimal maintenance, ensure coverage across any desired operational area, and allow users to avoid the commercial interests of telecom companies, which may alter rates, services, or coverage levels, potentially impacting the functionality of the proposed solution. The IoT methods for collecting real-time data, storing it in a database, and providing a web user interface for farmers to view crop parameters, empower them to make informed decisions quickly and effectively. Moreover, the use of combined network connectivity enables seamless live monitoring of the entire crop area, which is crucial for crop management, crop selection, and water level forecasting.

3. System architecture

The field of electronics has been significantly influenced in recent years by the emergence of the IoT, with an increasing demand for the development of IoT applications. As commercial sensors for agricultural systems are expensive, a growing interest exists in designing low-cost solutions for irrigation management and agricultural monitoring to implement wireless customised systems that make use of low-cost sensors that can be connected to IoT nodes.

The architecture of the proposed WSN is illustrated in Fig. 1. It consists of wireless sensor nodes, processing units, and a user management interface. The sensing, coordination, and control data are managed using a combined WSN based on LoRaWAN and IEEE 802.15.4 technologies. Autonomous, compact, and low-cost sensor nodes installed in the field gather the measured data and transfer them to the gateway node. Two types of sensor nodes have been designed. One is based on the IEEE 802.15.4 communication standard and collects data on the ground. These nodes are positioned at tens of meters and obtain information about specific areas because local in-field information is essential for the precise management of crop growth. The second type of sensor node gathers data on the ground and coordinates an IEEE 802.15.4 tree network that transfers the data (both from the 802.15.4 network and that which is self-obtained) to a LoRaWAN gateway located at a much greater distance. Therefore, this type of sensor node (also called a local coordinator node) includes both LoRaWAN and IEEE 802.15.4 transceivers and is part of a star network. The data accumulated by the sensor nodes are collected sequentially by the LoRaWAN gateway located at the base station, which then outputs the data to the management user interface. This interface displays the status of the wireless network infrastructure and the readings from the IoT sensor nodes. The user application can retrieve data from the user interface. The LoRaWAN gateway manages the LoRaWAN star network and includes a photosynthetically active radiation (PAR) sensor. This sensor measures part of the incident solar energy that drives photosynthesis in plants, which is important for many ecophysiological models, and some plant biophysical variables depend on this radiation [7].

4. Hardware infrastructure

The main requirements of devices that constitute the developed WSN are the use of robust radio technology, reduced size, and low cost. Furthermore, the electronics used in devices, such as sensors and their interfacing circuits, microcontrollers, and transceivers, are low-power devices that reduce energy requirements. The network is designed to be easily scalable.

4.1. Wireless sensor nodes

The developed solution is a compact, low-cost, and low power-consumption system that enables easy integration of sensor nodes in cropped fields. Some devices that represent the network nodes contain two transceivers, allowing them to be connected through either an LR-WPAN (IEEE 802.15.4) or an LPWAN (LoRaWAN) link. These dual nodes, which represent the cluster heads (or local coordinators) in the network, are built using a single printed circuit board, and a microcontroller is used to manage both transceivers. Other sensor nodes are end devices that include an IEEE 802.15.4 transceiver and the required sensors, creating an 802.15.4 beaconed network with a tree topology. Finally, a LoRaWAN gateway or base station provides services to all devices belonging to its coverage area using a star network topology. The LoRaWAN gateway provides users with remote access to sensor information through communication networks such as the Internet or mobile networks.

Each wireless sensor node consists of a soil moisture probe, temperature probe, NPK soil sensor, microcontroller for data acquisition, and one or two radio transceivers. The sensor measurements gathered by these end devices are transmitted to a local coordinator node using an IEEE 802.15.4 tree-network topology. A star network topology is used to communicate between the local coordinator nodes and data receiver (gateway) via the LoRaWAN protocol.

The design of the IEEE 802.15.4 sensor nodes (end devices) and hardware building blocks are shown in Fig. 2. These nodes contain an 8-bit ATmega128RFA1 microcontroller from Atmel (San Jose, CA, USA) that manages the communication stack of the IEEE 802.15.4 standard and samples the sensors. The ATmega128RFA1 is an energy-efficient 8-bit microcontroller with a high-speed transceiver designed for ZigBee and IEEE 802.15.4 protocols in the 2.4-GHz ISM band. This transceiver offers robust wireless communication at high data rates and requires minimal external components. This device combines outstanding RF performance with low cost, compact size, and low power consumption. To optimise energy usage, the sensor node is powered only during specific periods for data collection. Once this process is complete, the node enters a deep-sleep mode until the next data-gathering cycle. Moreover, each wireless sensor node consists of a set of sensors with digital outputs that measures the required parameters, that is, moisture and temperature (TP9602 from Telaire) and an NPK sensor for detecting the content of nitrogen, phosphorus, and potassium in the soil. The sensor node is powered by a 3.7-V (2600 mAH) battery with a Microchip MCP73831 charge controller. Nevertheless, full energy autonomy is guaranteed by operating a photovoltaic solar panel.

The local coordinator nodes are structured in a multiprocessor architecture and include the same sensors as the aforementioned IEEE 802.15.4 sensor nodes shown in Fig. 3. The role of the main 8-bit ATmega328P microcontroller from Atmel is to directly collect the measurements of the previously mentioned parameters of interest from the IEEE 802.15.4 transceiver (ATmega128RFA1) and the associated data of the sensor nodes (end devices) in the IEEE 802.15.4 network. The main microcontroller then transmits the data to the Microchip RN2483 433/868 MHz LoRa technology transceiver via a serial peripheral interface (SPI), with the latter sending the data wirelessly to the gateway. The current design focuses on low power requirements with less priority given to aspects such as wireless communication performance. Thus, the selected LoRa transceiver module is an easy-to-use solution that provides high network capacity and low-power long-range wireless data transmission. The power supply system is the same as that of the IEEE 802.15.4 sensor nodes. The sensor and coordinator nodes are encapsulated in a waterproof container.

Regarding the power consumption analysis, a small 1.5 W solar panel provides energy to a lithium battery (18,650 cell) with a voltage of 3.7 V and a capacity of 2600 mAh through a battery charging circuit. The average energy consumption for the IEEE 802.15.4 sensor nodes and local coordinator nodes is quite low, around 0.53 mAh and 0.55 mAh respectively, thanks to hardware and software strategies like low-power components, switching, and sleep modes. As a result, both types of nodes are only active for about 8 s every ten minutes during their sampling periods, allowing time for sensors like the NPK sensor to settle. While the solar panel keeps the battery charged to ensure the system can operate independently of external power, it can run continuously for up to 156 days without additional charging if the battery discharge is limited to 80 %, in case of bad weather or if the panel fails.

4.2. Processing unit

The processing unit comprises a LoRaWAN gateway and a control terminal. The gateway receives all data sent by the local coordinator nodes and communicates with the control terminal or monitoring computer in charge of managing the network using the monitoring application. The connection between the gateway and control terminal, where the data are assessed and processed, is performed using a UART. Fig. 4 shows an image of the gateway node. This node is governed by an RN2483 LoRa transceiver and sends data via serial communication to the control terminal implemented by a Raspberry Pi. The boards are placed on top of each other. Similar to sensor or local coordinator nodes, an antenna is connected through an SMA connector. The gateway node is fed from the control terminal through an external power supply. The control terminal sends an alert to the user when the threshold values of the measured parameters are exceeded, thereby reducing irrigation costs.

This node also includes a non-certified RY-GH PAR sensor from NONG-IOT to measure the in-field PAR. The pre-calibration performed on this sensor is insufficient to accurately record the PAR values and allow its distribution without a calibration certificate. To obtain accurate data, the equipment required a calibration phase as described in Appendix A.

5. Firmware

Hardware components were chosen to minimise power consumption; however, firmware strategies were also applied to further extend the autonomy of the system. Given the large number of nodes in a WSN, it is crucial to deploy and configure sensor nodes with minimal manual intervention. The initialisation and configuration parameters may vary based on various factors, even outside the sensor network. Regarding the two wireless communications standards used in this work, below we describe some details that have been taken into account for the firmware development of the network nodes. In accordance with the IEEE 802.15.4 LR-WPAN, the protocol specification of the MAC (medium access control) layer for the end devices (sensor nodes) includes two operational modes: an asynchronous beaconless mode and a synchronous beacon-enabled mode. In the beaconless mode, nodes must remain constantly attentive for potential transmissions from other devices, significantly impacting battery life. This asynchronous method necessitates for the nodes to be almost perpetually in receive mode, waiting for data from other network devices. The channel access is regulated through an unslotted carrier-sense multiple access with collision avoidance (CSMA-CA) protocol. Conversely, the beacon-enabled mode offers a synchronous method for data transmission between the transmitter and receiver, it uses a slotted CSMA-CA channel access mechanism, and it has been chosen in this work as it allows enabling efficient and coordinated sleep/wakeup periods for the sensor nodes. The beacon-enabled mode favours battery-powered devices since these devices will spend most of their operational life in a sleep state, allowing the designer to decide on the balance between battery consumption and message latency. Thus, parameters considered in the IEEE 802.15.4 standard such as, beacon interval (BI), superframe duration (SD), beacon order (BO) and the superframe order (SO), have been set to adapt the MAC layer and strike a balance between high-quality radio resources and energy needs for the intended application.

Fig. 5(a) shows a flowchart of the end devices. To ensure correct data transmission, communication between the local coordinator and sensor nodes was synchronised using the beacon-enabled mode of the IEEE 802.15.4 standard. Each IEEE 802.15.4 network was managed by its local coordinator node. Its tasks include assigning addresses to associated sensor nodes and periodically sending frames for synchronisation.

Fig. 5(a) shows the structure of a superframe that allows sensor nodes to track beacons. This approach grants sensor-node media access during the active period of the superframe while enabling low-power modes during the inactive period when transmissions are prohibited. A device can also utilise preassigned slots of the active superframe (guaranteed time slots - GTS) to transmit data to the associated node. The initial step for the IEEE 802.15.4 sensor node, as depicted in Fig. 5(a), is to attempt network association by transmitting an association frame, also referred to as a broadcast (or association beacon within the standard). The association of the sensor nodes is confirmed upon receiving a response from the coordinator. Subsequently, the sensor node wakes from the sleep mode to read the data, which are then sent to the local coordinator node. The sensor node then returns to the sleep mode for a specified duration based on the desired sampling rate to conserve energy. After successfully transmitting data, the sensor node awaits an acknowledgement (ACK) beacon before repeating the process. The radio transceiver of the sensor nodes exchanges data with the local coordinator node at 2.4 GHz.

Fig. 5(b) shows the flowchart for the local coordinator node (IEEE 802.15.4 and LoRaWAN). After setting the parameters associated with the IEEE 802.15.4 standard for network creation (beacon order, superframe order, channel, or network name, among others) and the LoRaWAN protocol, the coordinator node awaits a beacon from an end device (IEEE 802.15.4 sensor node). Upon receiving the initial broadcast (association beacon) from the end device, the coordinator associates the MAC address with the sensor node, sends an association beacon, and waits for the device to respond. Once the sensor node confirms the association, the local coordinator waits according to the BO and SO parameters which define the interval between the beacons and the time during which the end device can transmit, respectively, before sending a data-request beacon [17]. Upon sending the beacon, the coordinator receives an ACK from the sensor node, thereby enabling data transmission to the microcontroller. If no data are received, another beacon is sent. Finally, the microcontroller transmits the data to the LoRa transceiver and then to the gateway. For the LoRa network configuration, parameters such as spreading factor (SF), channel bandwidth (BW), transmission power (TP), carrier frequency (CF), coding rate (CR), payload, and preamble length, were set to determine the data rate, signal airtime and power consumption, duty cycle, and the time between the sending of messages. The 868 MHz CF was utilized due to it being one of the two license-free radio frequency bands in the sub-gigahertz range available in Europe. A 125 kHz bandwidth was selected to provide an adequate bitrate and sufficient sensitivity for detecting the radio signal. The LoRaWAN wireless communication network has been dimensioned following the recommendations of [35].

Regarding the LoRaWAN gateway firmware, several libraries were used in the development of the application in Python (virtual environment) within the Raspberry PI: ctypes, Pandas, MySQL, signal, threads, os, time, numpy, libbcm2835, dash, and MatPlotLib. To avoid memory problems, a Python program was created with three threads that ran concurrently and managed the memory usage as shown in Fig. 6(a). The first thread, “Read TTL” (Fig. 6b), is responsible for receiving information from the UART port and saving it in a volatile memory area. The second thread, “Write BD” (Fig. 6c), collects the information vector, calculates the maximum, minimum, and average values of the received data and saves them in the database. Finally, the “Real-Read BD” thread (Fig. 6d) is responsible for real-time monitoring of the information entered into the database. The database consists of information columns for each monitored sensor and two search indices. The first index is used to determine the amount of information contained in the table, and the second is the timestamp entered when writing information. This information is useful for locating data during specific time periods or creating historical records.

The use of Python threads was necessary to manage the data received by the LoRa module and easily control the database. The synergy between the input and plotting of information is essential for the end user to obtain the expected results from the complete system. The data are received by the serial port, stored in the RAM, and then passed from one variable to another to delete the data from the input variable. Once the data are obtained in a second variable, they can be displayed in real time and saved. This allows data to be monitored in real time and provides access to historical data to study plant growth.

6. Experimental results

6.1. Field test

The automated irrigation system was tested in a strawberry plantation located in Matalascañas, Huelva, southwestern Spain (37° 5′ 20.796′’ N, 6° 32′ 26.737′’ W) close to the Doñana National Park.

Fig. 7 shows images in the field of the sensor and local coordinator nodes and the PAR sensor on the roof of an INTA building. The calibration of the radiometer for the measurement of PAR relative is described in detail in Appendix A. Fig. 8 shows the test of the NPK sensor throughout a one-day period and the data collected along with the time the plants were fertilised.

6.2. Web application and results

Graphical user interface (GUI) software was developed for real-time monitoring and programming of irrigation based on soil moisture, temperature data, and the content of nitrogen, phosphorus, and potassium in the soil. The LoRaWAN gateway receives and sends the information of each node to an MySQL database. The web application is used to query the database to show selected data to the user. Moreover, the web application displays the information of the PAR sensor and the geographic location of the devices. The software application permits the user to visualise graphically the data from each wireless node online using any Internet device. The received information is relevant for decision making or for taking appropriate actions. The GUI was developed in Python and is shown in Fig. 9. The user can choose the measurements to be displayed and the corresponding date using a calendar. Several tabs provide the measured parameters for each wireless sensor node. The development of servers, databases, and GUIs has facilitated real-time monitoring. This interface enables users to easily visualise and access data from any sensor or coordinator node.

Despite advancements in optimising irrigation for strawberry cultivation, most companies still rely on traditional monitoring methods such as periodic observations. The developed combined sensor network provided real-time data on crop variables, enabling the estimation of water requirements with minimal human intervention. This allows farmers to ensure optimal cultivation conditions for strawberries in real-time.

7. Discussion and future scope

The test and experimental outcomes validate the effective performance of the deployed WSN and its value for real-time measurement of various variables in strawberry farming. This is particularly important in an environment where advanced monitoring and control methods are scarcely used, as farmers tend to be skeptical and resistant, relying primarily on empirical knowledge and experience for decision-making.

The developed monitoring system efficiently integrates low-cost sensors with a tailored WSN solution, utilizing two wireless communication standards. It incorporates low-latency techniques for real-time monitoring and calibrates the devices to ensure reliable

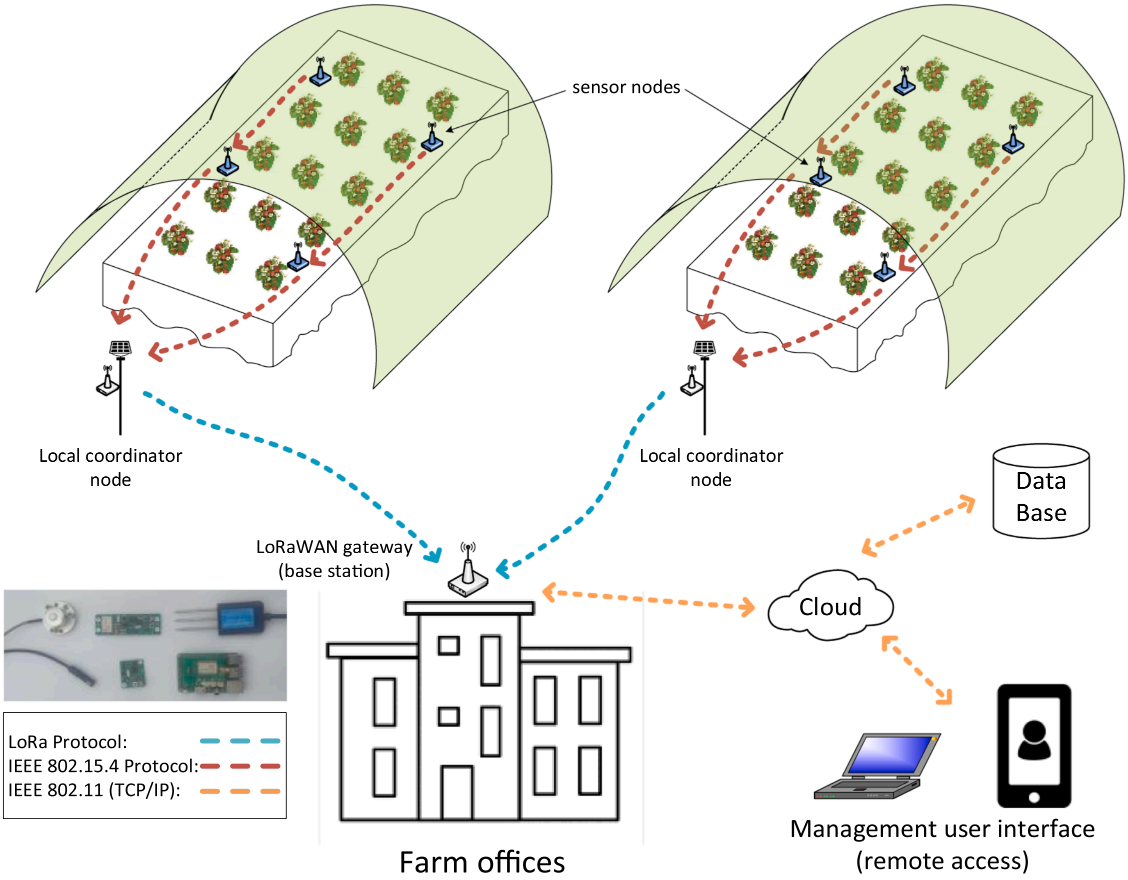


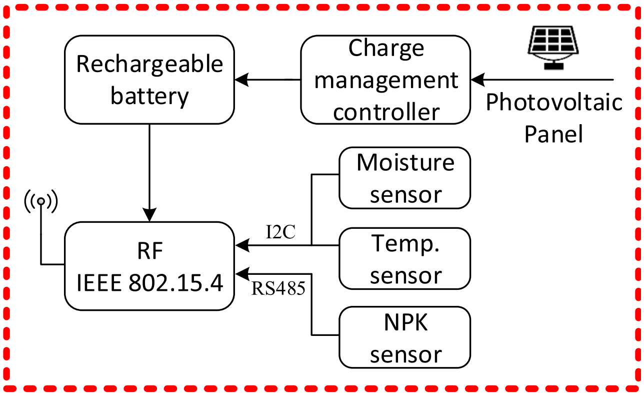
Fig. 1. System overview.

data collection. Power management strategies are also implemented, given the use of battery-powered devices. As a result, the self-sustaining wireless sensor network operates autonomously without time constraints, with the battery continuously charged during daylight through a photovoltaic panel. This approach combines energy-efficient hardware designs with optimized operation techniques at the firmware level, achieving effective power management. By selecting low-power hardware components with adjustable power states and sleep modes, the system ensures optimal energy consumption. Additionally, the hardware is built using affordable commercial off-the-shelf components. An algorithm was developed with threshold values of the main crop parameters that was programmed into the gateway to control water quantity. The designed system allows end users to monitor crop conditions remotely more easily and can alert the user if the monitoring data exceed predefined values for a certain time.

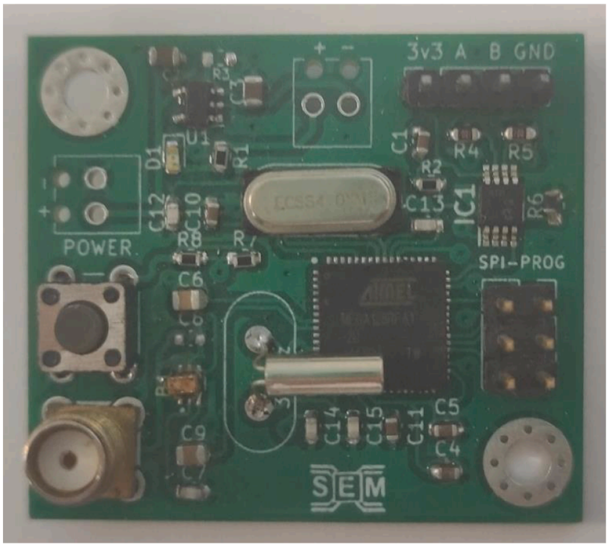
The inclusion of two wireless standards enhances the flexibility of the system, enabling it to adapt to diverse environments by taking advantage of the benefits of both. The interoperability between these networks is addressed at the device level using tree and star topologies, leading to an independent design and deployment of each of the networks. To this end, an IEEE 802.15.4 network is combined with LoRaWAN, and dual nodes are incorporated to act as cluster heads (local coordinators). This efficient integration mechanism enables resource sharing and information exchange, thereby avoiding increased costs, resource wastage, and the reduced lifespan of standalone terminals.

Laboratory and field tests confirmed a data transfer success rate of 97.5 % to the gateway, even in challenging conditions with obstacles between the network nodes. Regarding coverage, successful data transmission was achieved up to 60 m between IEEE 802.15.4 sensor nodes (end devices) and a local coordinator node, and approximately 2 km in direct line between the gateway and local coordinator nodes in the LoRaWAN star network. These coverage ranges are primarily a tradeoff between power consumption and data rate. The real time monitoring is achieved configuring a latency below 100 ms including measurements of time-of-air (ToA). Parameters, such as, beacon order and superframe order defined in the IEEE 802.15.4 standard, have been set to determine the time between beacons and the time in which the end device (sensor node) can transmit, using a beacon-enabled mode with guaranteed time slot. Regarding the latency in LoRaWAN, the duty cycle (DC) is a crucial parameter that must not surpass 1 % as per ETSI (European Telecommunications Standards Institute), and requires meticulous network design. Factors such as message sending frequency, ToA, SF, BW, CR, and payload have been taken into consideration.

The IEEE 802.15.4 sensor nodes and local coordinator nodes are only active for 8 s every ten minutes (sampling time) taking into account the settling time of some sensors. The average energy consumption of the IEEE 802.15.4 sensor nodes is only 0.53 mAh and for



(a)

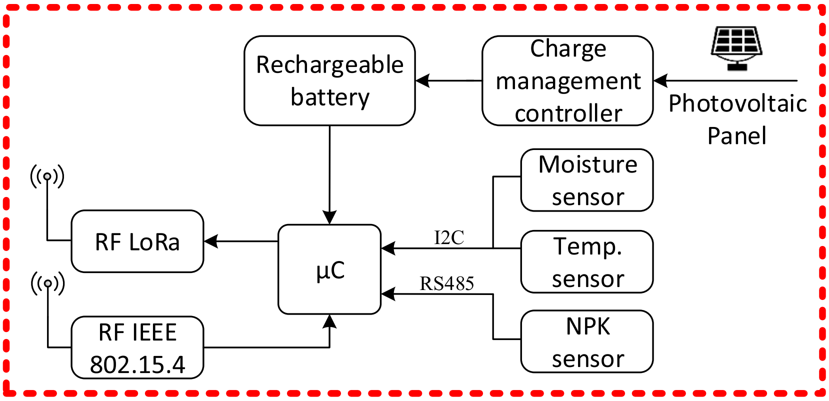


(b)

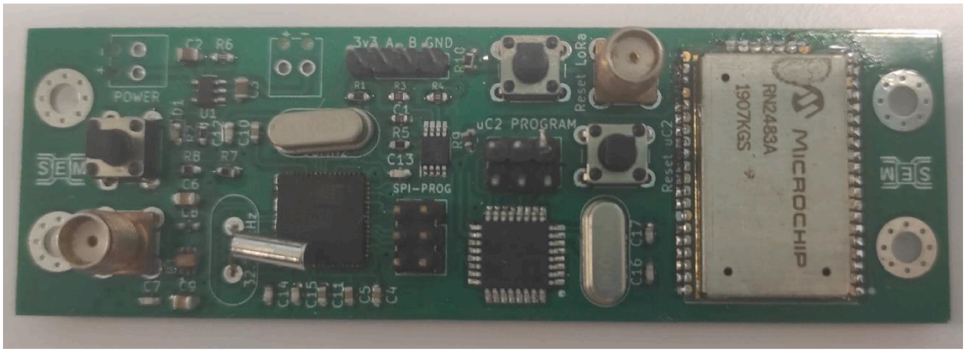
Fig. 2. IEEE 802.15.4 sensor node (end device): (a) hardware block design and (b) PCB.

the local coordinator nodes is 0.55 mAh due to the mentioned hardware and firmware strategies (low power devices, switches and sleep mode, respectively). Even though the battery is kept charged by the photovoltaic panel to ensure full energy autonomy, in case the recharging process is disrupted due to adverse weather conditions or a failure of the panel, the system can continue operating for up to 156 days without an external power source. Due to its energy autonomy and low cost, the system has the potential to be useful in geographically isolated areas with limited water resources. The combination of both types of wireless technologies makes the system versatile enough to be deployed on different types of crops and in plantations of varying sizes and locations.

This project aims to build upon the existing work by redesigning the network to include a larger number of deployable sensor nodes. Additionally, it involves integrating various types of sensors into each node to monitor other crop parameters, such as wind speed, pH levels, precipitation, zinc, magnesium, sulfur, boron, calcium, and organic carbon. These enhancements can provide a more comprehensive understanding of crop growth and plant health. As a result, the scope of the system expands the work area to be instrumented and can be applied to a wider variety of crops. To support the increased data flow from the larger network, it might be beneficial to use a more powerful microcontroller for the sensor nodes and a gateway with higher processing capacity. Finally, to improve crop recommendations, the versatility of the proposed system must extend beyond mere monitoring and control of the main crop parameters, and the integration of artificial intelligence (AI) would provide decision-farmers with the best crop yield prediction advice [3,4]. Therefore, for a complete smart farming, future integration of IoT, combined wireless technologies, and machine learning and AI techniques will enhance agricultural productivity and profitability while reducing resource use and minimizing environmental impact [36].



(a)



(b)

Fig. 3. Local coordinator node (IEEE 802.15.4 and LoRaWAN): (a) hardware block design and (b) PCB.

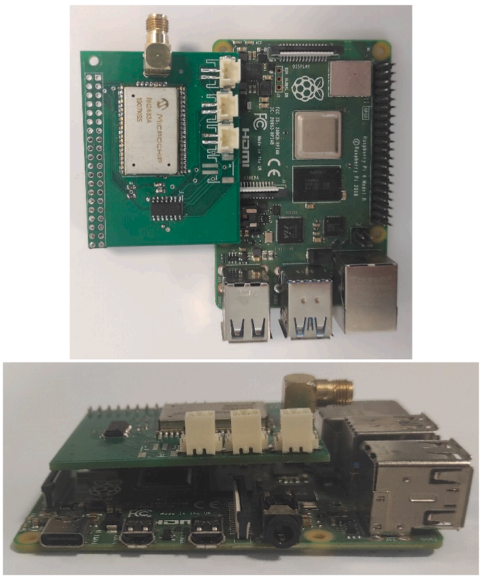


Fig. 4. LoRaWAN gateway node PCB.

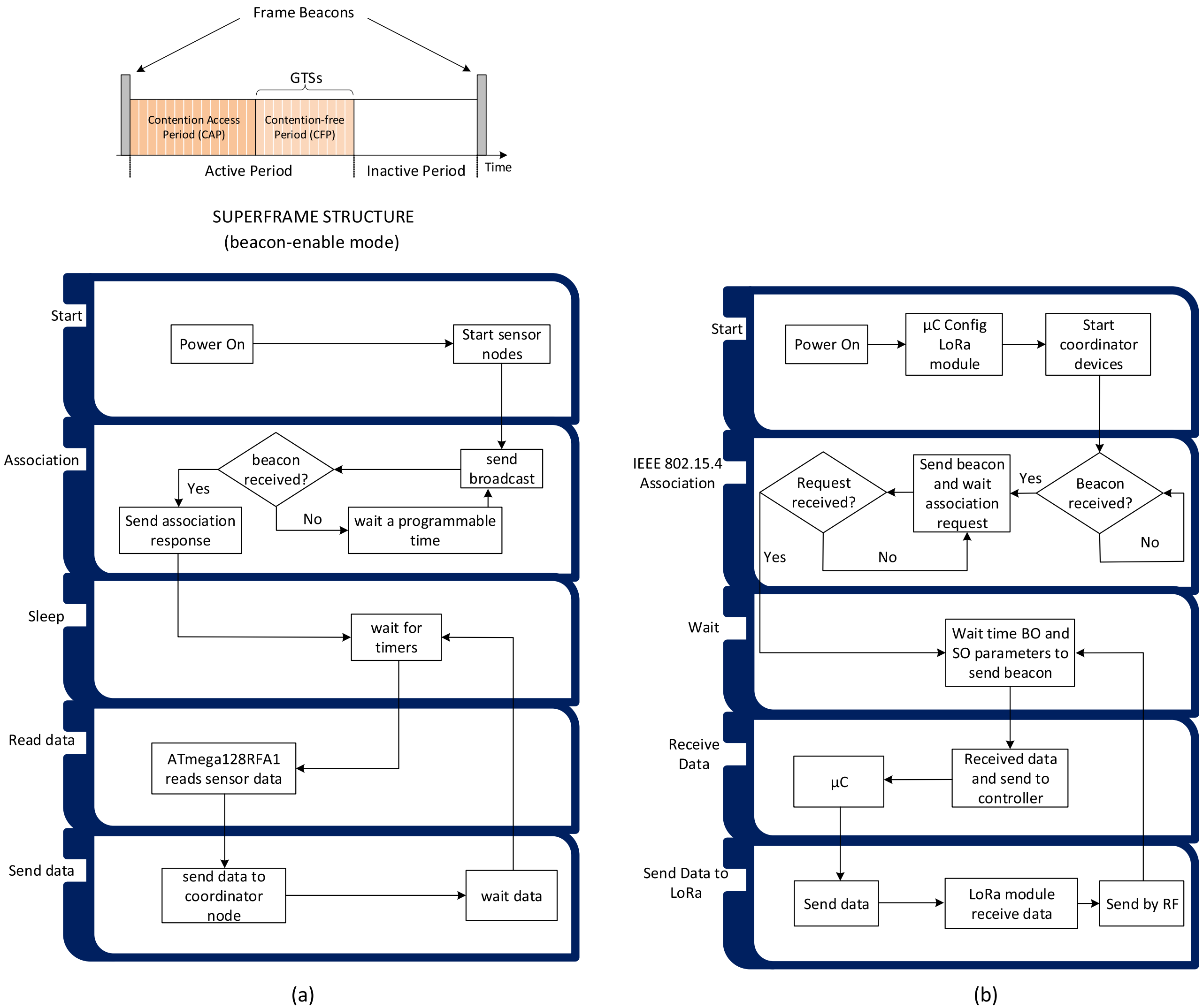


Fig. 5. (a) Flow diagram of IEEE 802.15.4 sensor node (end device) and structure of superframe in beacon-enable mode. (b) Flow diagram of local coordinator node (IEEE 802.15.4 and LoRaWAN).

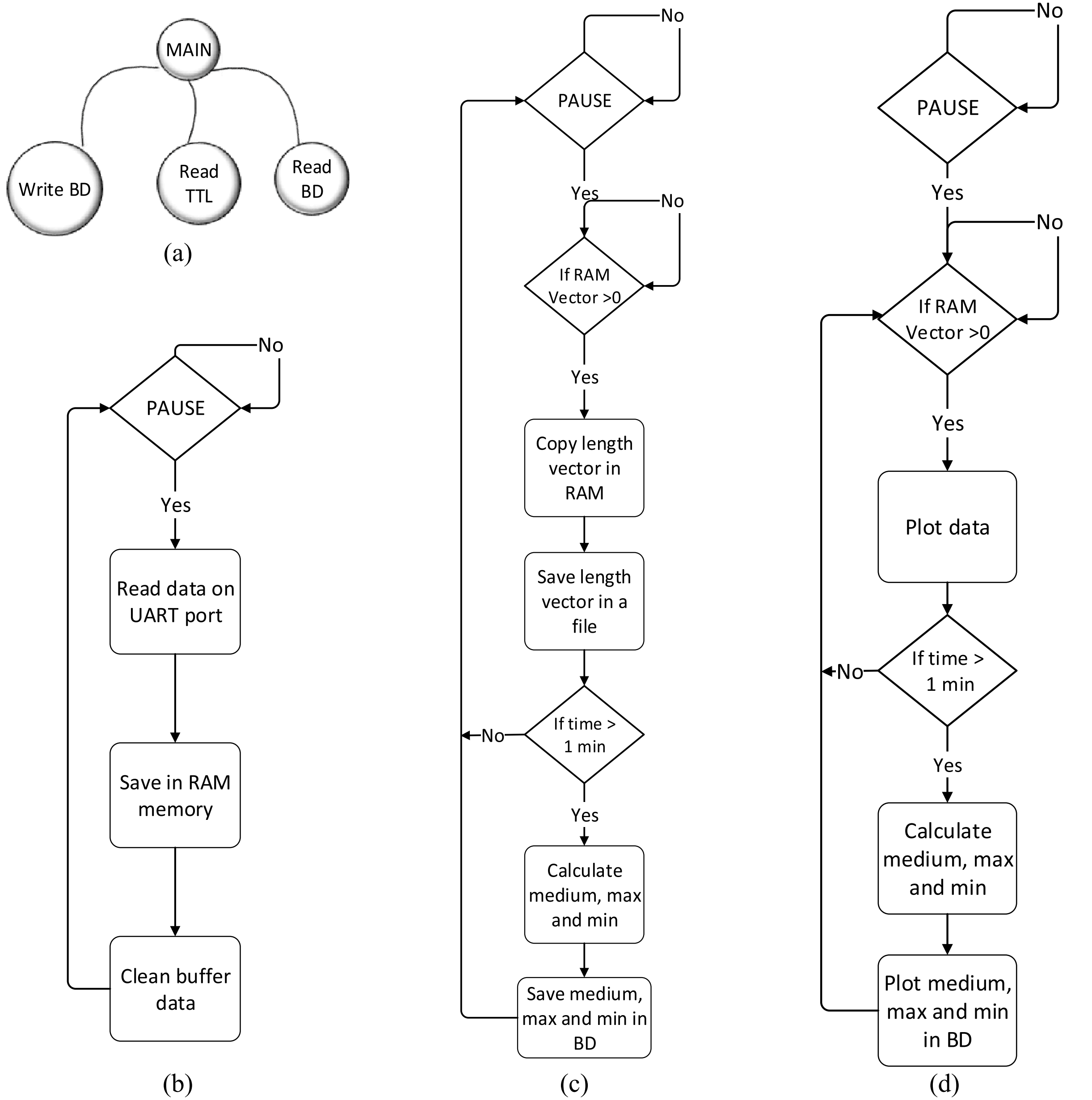


Fig. 6. LoRaWAN gateway firmware: (a) main program, (b) read TTL thread, (c) save (write) BD thread, and (d) plot data (read) DB thread.

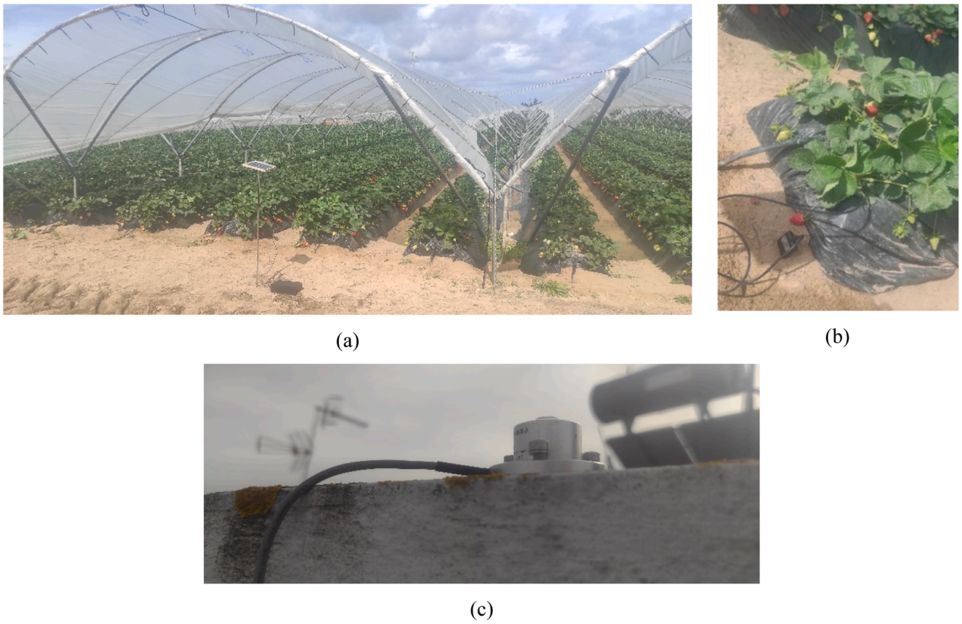


Fig. 7. Automated irrigation system for experimental production: (a) greenhouse for strawberry production, (b) image of device in field, and (c) image of PAR sensor on roof of INTA building.

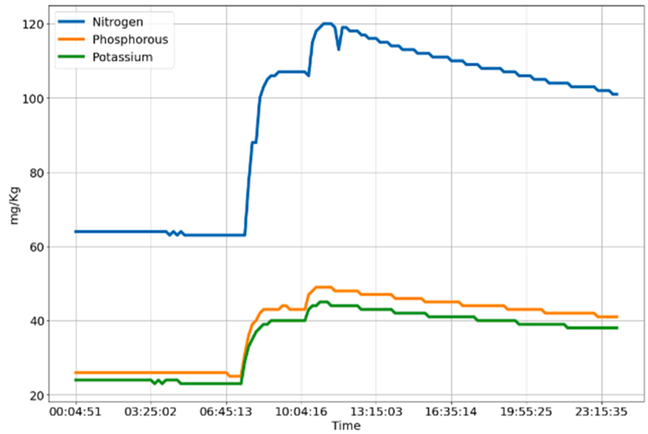


Fig. 8. Registered data from one-day monitoring process: nitrogen, phosphorous, and potassium.

8. Conclusions

The design of mixed networks at the device level, where traditional LR-WPAN technologies can be integrated with recent LPWAN protocols, is addressed, allowing for the use of a combined network according to the precepts of low power consumption that takes advantage of each technology involved. A WSN system utilises devices that satisfy the stringent requirements of robust radio technology, low cost, and compact size. Low-power electronics are used in sensors, conditioning interfaces, microcontrollers, and transceivers to ensure efficient energy management. Moreover, at firmware level the wireless communications based on the IEEE 802.15.4 standard have been programmed in the synchronous operation mode using beacons to allows sensor nodes to sleep between transmissions, resulting in energy savings. The proposed architecture is based on different nodes equipped with one or two wireless technologies and several commercial sensors for measuring some variables that affect the growing process of the crop. Data signals from the WSNs to the processing central unit were successfully interfaced using LoRa wireless communication. A graphical user interface offers consultation and analysis of data from any device. Moreover, this processing unit also include a PAR sensor calibrated by intercomparison with a reference equipment. This type of sensor complements the information of the sensors placed in the root zone of the plants as the sunlight is a key parameter required for the photosynthesis process, and can help to control the crop growth by monitoring plant biophysical variables. Therefore, the network design is highly scalable and accommodates an increasing number of

Fig. 9. (a) GUI of the irrigation system, (b) and (c) temperature and soil moisture collected data of different wireless sensor nodes, (d) Measured data of PAR sensor over two days gathered by LoRaWAN gateway node, (e) Geographic location of devices in the southwestern Spain close to the Doñana National Park and Atlantic Ocean in a strawberry plantation.

nodes and the integration of new sensors. These sensors can monitor additional parameters of interest remotely, thereby enhancing the overall functionality of the system.

CRediT authorship contribution statement

J. Medina-García: Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **J.A. Gómez-Galán:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation. **J.M. Vilaplana-Guerrero:** Validation, Supervision, Methodology, Data curation. **J.A. Bogeat:** Validation, Supervision, Methodology, Data curation.

Declaration of competing interest

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

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Appendix A. Calibration of PAR sensor

Photosynthetically active radiation (PAR) is the amount of solar radiation capable of inducing photosynthetic activity in plants. This radiation corresponds to a spectral range of 400–700 nm and is expressed in the photosynthetic flux density unit μmol•m^{-2}•s^{-1}, equal to microEinsteins per m^{-2}•s, because photosynthesis is a quantum process. Because PAR is related to global solar radiation, measurements are highly dependent on the solar elevation angle. This angle varies throughout the day, and its calculation depends on the latitude, date and time of year. A broadband radiometer was used to measure this radiation.

This section describes the calibration of the radiometer for the measurement of PAR relative to the simultaneous measurements of solar global irradiance. For this purpose, an intercomparison between these two instruments was performed at the El Arenosillo observatory/INTA (National Institute of Aerospace Technology), which is a public research organisation dependent on the Spanish Ministry of Defence. This observatory is located in Huelva in the Andalusian region of southwest Spain. Many authors have related total global solar radiation measurements to PAR measurements [13,14,32,37]. The following equation was reported in [13]:

$$Q_p = R_s * \varepsilon, \tag{A.1}$$

where (R_s) is the global radiation measured with a pyranometer and Q_p is the PAR. The values of ε are dependent on atmospheric parameters and are determined according to the following parameterisation described in the literature as a function of the air mass factor (m) and precipitable water vapour (w) as

$$\varepsilon = 0.991[a(m) + b(m)w^{c(m)}], \tag{A.2}$$

where

$$a(m) = 1.834 - 0.0631m - 0.0175m^2 + 0.00354m^3 - 2.69 * 10^{-4}m^{-4} + 7.63 * 10^{-6}m^5,$$

$$b(m) = 0.111 + 0.1023m - 0.0225m^2 + 0.00297m^3 - 2.06 * 10^{-4}m^{-4} + 5.79 * 10^{-6}m^5,$$

$$c(m) = 0.365 - 0.0661m + 0.0182m^2 - 0.00271m^3 + 2.04 * 10^{-4}m^{-4} - 6.02 * 10^{-6}m^5.$$

Taking into account the days with average daily water-vapour values greater than 1.5 cm and solar zenith angles between $\pm 65^\circ$, values of ε very close to 2 μmol/W•s were obtained as shown in Fig. A.1, demonstrating that it is ideal for modelling atmospheric effects.

Regarding units, we start with the variable ε where (1) defines it as $\varepsilon = \mu E/J$. Knowing that 1 W= 1 J/s, it can be said that 1 J= 1 W•s and 1 μE = 1 μmol, therefore, $\varepsilon = \mu mol/Ws$. The global radiation is represented as $R_S = W/m^2$. Thus, PAR is the result of $Q_p = R_S * \varepsilon$, and the units will be determined in $Q_p = \mu mol/m^2.s$. When calculating the calibration constant, the function *constant* = *(PAR in μV)/* Q_p is used, whereby the units given in the calibration constants are *constant* = *(μV•m^2•s)/(μmol)*.

To perform the calibration, the RY-GY radiometer from NONG-IOT was installed on the roof of the main building at the atmospheric observatory of INTA/El Arenosillo, and Kipp and Zonen CMP21 pyranometers were used as reference radiometers. Simultaneous data were collected from 17/01/2024 to 06/02/2024 on January 22nd and 28th. These dates were chosen because the amount of precipitable water vapour did not exceed the 1.5-cm threshold established in (1) to perform good calibration. Finally, 28 January 2024 was selected to perform the calibration, with 150 simultaneous measurements for zenith angles of <60° The following values were obtained as a function of the solar zenith angle (SZA): RY-GH = (302.81−4.1086*SZA) $\mu V/\left(\frac{\mu mol}{sm^2}\right)$ with a correlation factor of the regression R2 = 0.9834, yielding an error of 0.79903 %.

Fig. A.2 shows the intercomparison in W/m^2 between the RY-GY radiometer and the reference pyranometer on 28 January. Fig. A.3 shows the calculated error of intercomparison.

To consolidate the obtained values, another day was used. Fig. A.4 shows the measures of the RY-GY radiometer in units of PAR ($\mu mol/m^2 \bullet s$) for this day, and Fig. A.5 shows the intercomparison with the reference pyranometer where the value of ε was not calculated because it was taken as a constant according to [13]. Fig. A.5 shows that the error was in the same range as that calculated in Fig. A.3.

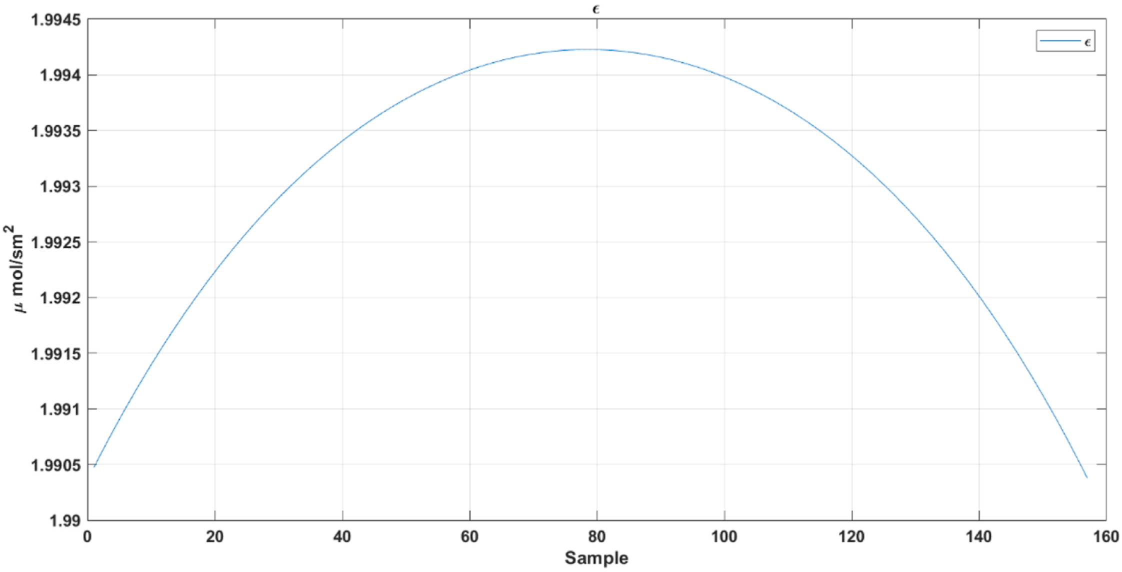

Fig. A.1. ε values.

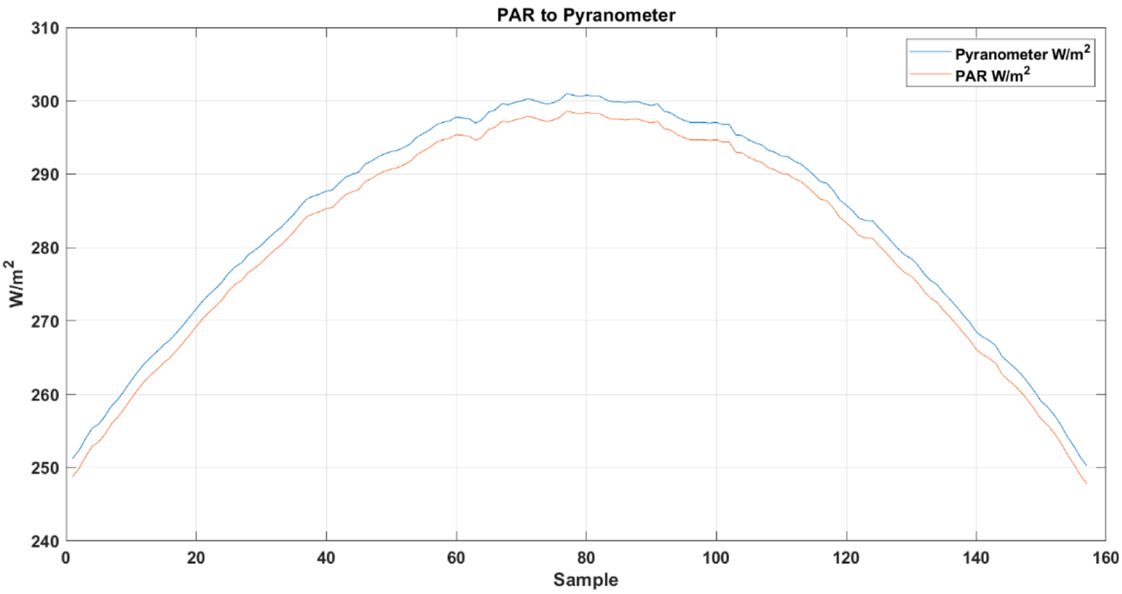

Fig. A.2. Intercomparison between RY-GH radiometer and reference pyranometer.

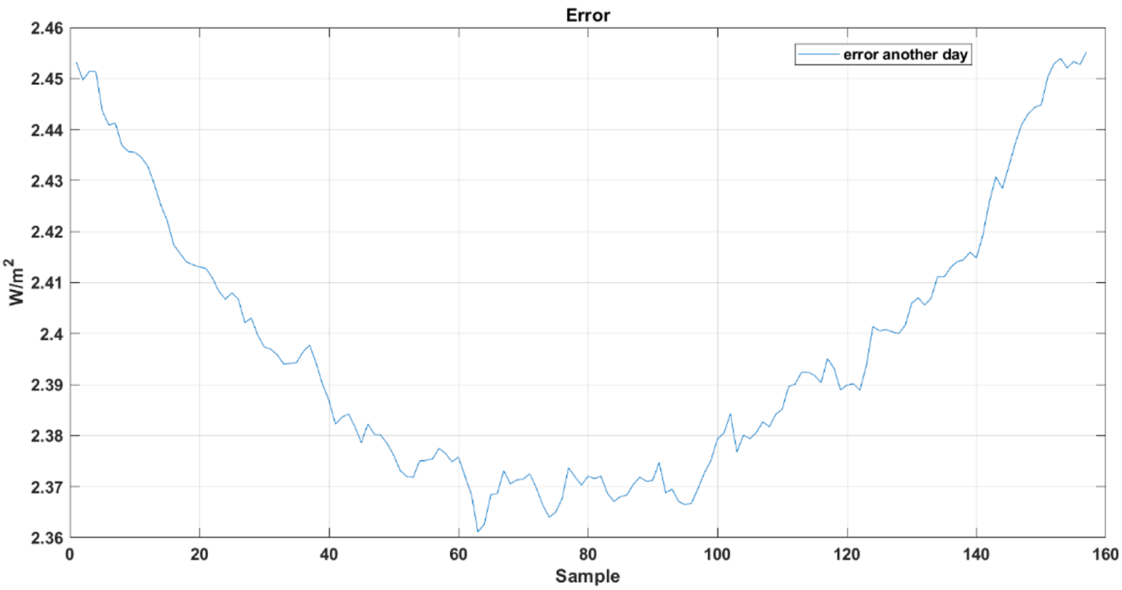

Fig. A.3. Calculated error of intercomparison in Fig. A.2.

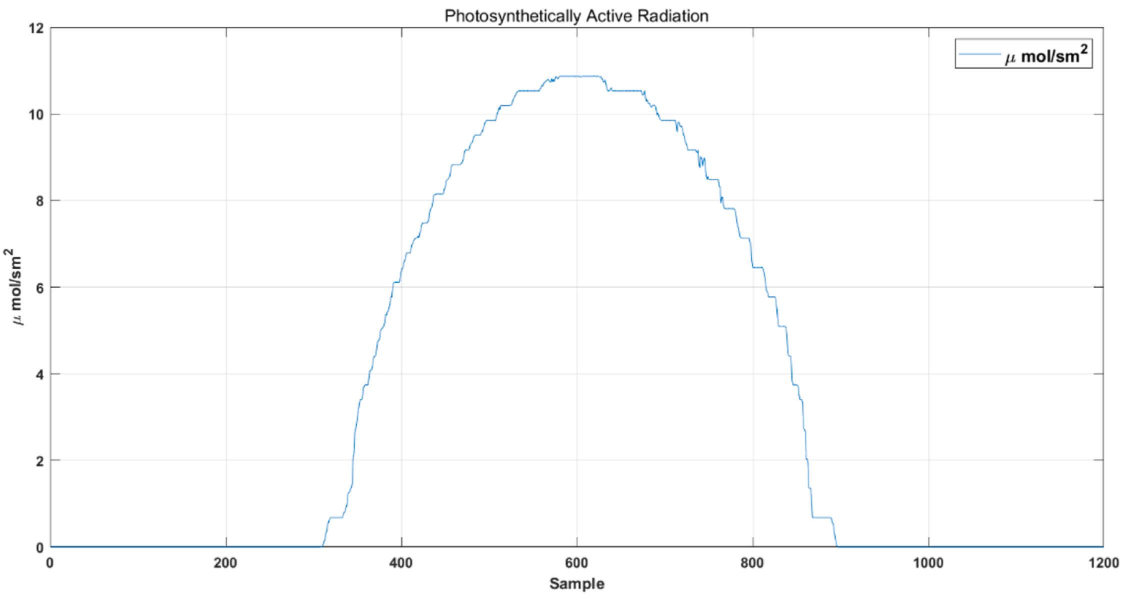

Fig. A.4. Measurements of RY-GY radiometer in units of PAR (μmol/m^2•s) on a day other than that of calibration.

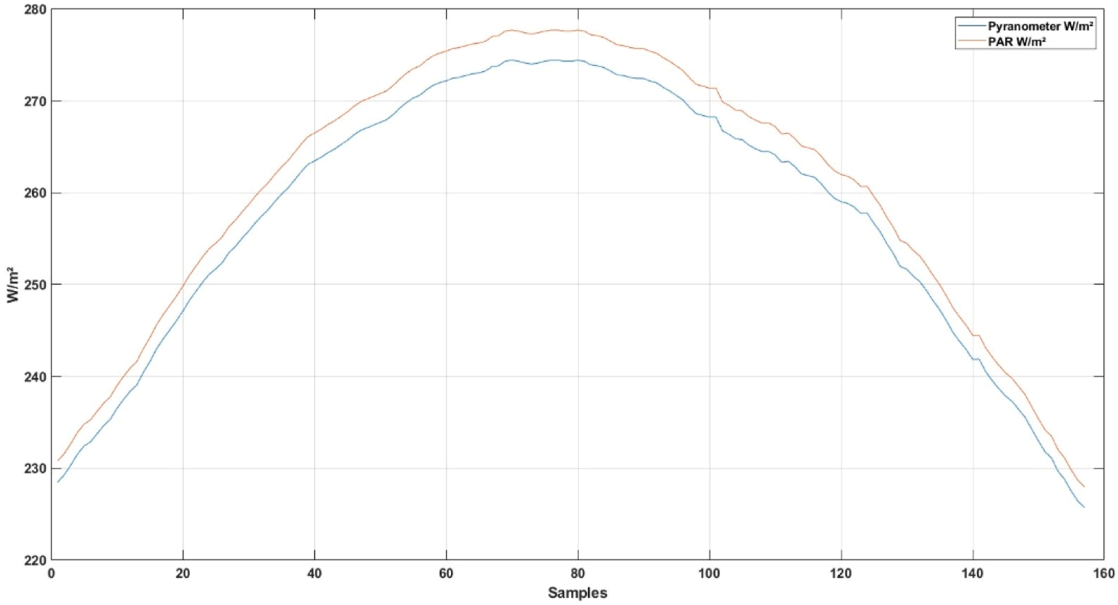

Fig. A.5. Comparison of PAR and global irradiance on a day other than that of calibration.

Data availability

No data was used for the research described in the article.

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