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Wireless Sensor Networks and IoT Applied to Fruit Tree Cultivation in Boyacá, Colombia: An Innovative Approach in Agriculture

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***Abstract*– This study introduces the application of wireless sensor network (WSN) and Internet of Things (IoT) technologies in fruit crop agriculture to enhance technological practices. The primary goal is to achieve real-time monitoring of critical variables such as soil moisture, relative humidity, and ambient and soil temperatures, employing a WSN based on IoT architecture. The case study delves into the cultivation plot, presenting a comprehensive examination of the WSN's architecture, network dimensioning, selection and implementation of sensing and wireless communication devices, and the control platform. The work includes a graphical data interface, allowing for the graphic representation of recorded variables at a 30-minute resolution. These records offer valuable insights into environmental conditions, aiding farmers in decision-making processes. Results affirm the effectiveness of WSN implementation for monitoring agricultural variables, providing continuous real-time data acquisition and transmission. This capability enables farmers to make informed decisions promptly, optimizing fruit crop performance. In conclusion, the study underscores the significance and potential of WSN technology and IoT in agriculture, showcasing its value as a tool for efficient monitoring and data collection at San Isidro Farm. This technological approach holds promise for enhancing productivity, profitability, and sustainable resource management in agriculture.**

***Keywords*-- Wireless Sensor Networks, Wireless Communication, Agriculture 4.0, IoT, ZigBee.**

I. INTRODUCTION

Agriculture has long played a pivotal role in the advancement of societies, with Colombia witnessing its evolution over decades, contributing significantly to the nation's development. However, farmers often lack dedicated information systems, relying on empirical knowledge and acquired beliefs, leading to uncertainties and imprecise production predictions [1], [2], [3].

Despite the sector's importance, numerous fertile regions in the country still adhere to traditional approaches and employ rudimentary methods, negatively impacting the environment, inefficient energy resource consumption, and decreasing productivity and various socioeconomic aspects.

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Consequently, there is a clear imperative to develop monitoring systems for assessing the environmental conditions of agricultural lands and cultivation areas [4].

Wireless Sensor Networks (WSNs) offer versatile applications, providing real-time information across several engineering systems. From intelligent building control to healthcare systems and environmental monitoring, WSNs exhibit virtually limitless applications. With electronic circuits becoming more affordable, smaller, and energy-efficient, coupled with the evolution of user-friendly wireless communication protocols and the internet, the emergence of additional WSN applications is highly likely [5] – [7].

A notable advantage of WSNs is their newfound freedom from energy consumption limitations, thanks to advancements in microelectronic systems that now consume from a few milliwatts to tens of micro-watts. This work elucidates the fundamental principles of WSNs and IoT technologies in the context of a case study in the agricultural sector, focusing on monitoring variables in fruit crops. pH sensors and electrical conductivity sensors have been deployed for soil and vegetation analysis, detecting changes in physical or chemical variables of plants, soil, or the environment.

The fundamental operating characteristics of wireless sensors used and the architecture of the wireless communication network are presented. The WSN structure is examined to understand the relationship between sensor signal power and data transmission efficiency. The article concludes with a detailed analysis and discussion of the study's results and conclusions, encompassing the applied WSN topology, sensors used, and the evaluation of data transmission quality in a fruit crop.

II. MATERIAL AND METHODS

A. Site Selection for the Study

The Colombian agricultural sector, playing a fundamental role in the domestic market, confronts challenges regarding competitiveness. The advent of new technologies across various domains narrows trade opportunities for those who do not include cutting-edge technology in their production processes.

Among the myriad technologies available for designing crop monitoring systems, wireless sensor networks (WSNs) stand out. These networks, comprising small electronic devices communicating with the outside world, are integral to the new era of wireless communication technologies known as the Internet of Things (IoT) [8] – [15].

WSNs involve sensors linked to a node, enabling communication over distances of up to hundreds of meters. The environmental variables monitored depend on the sensor's nature, encompassing parameters like humidity, temperature, pH, and relative humidity [16], [17]. The adoption of these monitoring systems significantly contributes to improving productivity and efficiency in crop production. Wireless technology is crucial for enabling communication among intelligent objects (sensors) and their connection to the internet, underscoring the scalability of WSNs as a technology integral to IoT.

Modern agricultural practices grounded in wireless sensor technology have the potential to boost productivity, achieve economies of scale, and foster community prosperity. Fig. 1 illustrates a wireless sensor network system integrated with IoT in agriculture, measuring soil, plant, and air parameters.

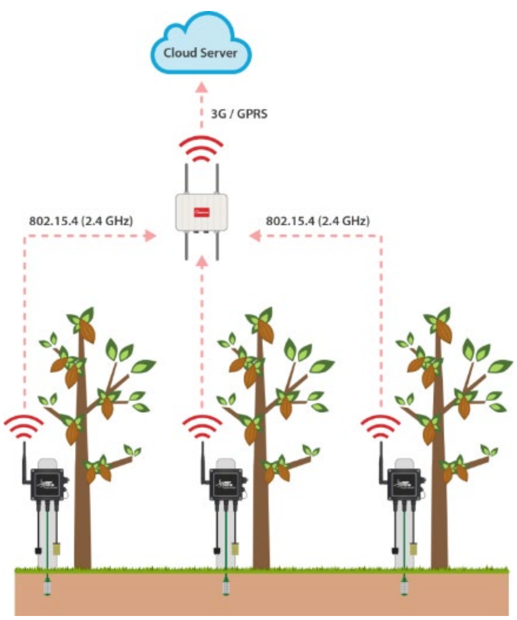

Fig. 1 WSN integrating IoT and agriculture adapted from [18].

When applying WSNs in the agricultural context, a wireless sensor detects the presence of a physical property in the soil or crops and assesses its extent. This indicates that temperature, humidity, air quality, and soil fertility level, among others, can be reliably determined through wireless technology (Fig. 2).

The municipality of Soracá, located in the department of Boyacá, Colombia, houses the San Isidro Labrador-farm an agricultural practice unit where the Agronomy Engineering program conducts studies on deciduous crop production, including golden peach, black king peach, plum, and apple, among others.

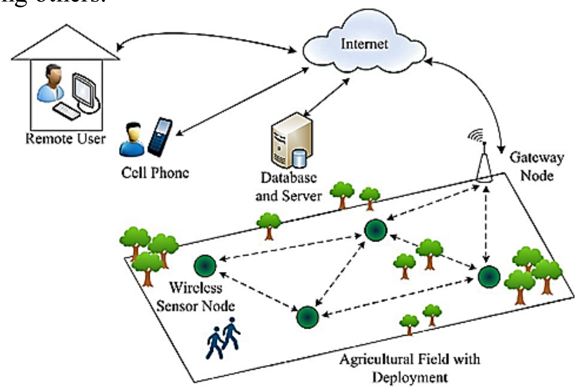

Fig. 2 Typical application of a WSN with four sensors and IoT connectivity. Adapted from [19].

Three crop lots, totaling approximately 27,524 m² (measured using Google Earth), were utilized at an average altitude of 2940 m.a.s.l., with an average annual temperature of 12.05 °C. To improve the production process, it proposed to monitor crucial variables in these fruit crops, with temperature and humidity identified as particularly relevant (Fig. 3).

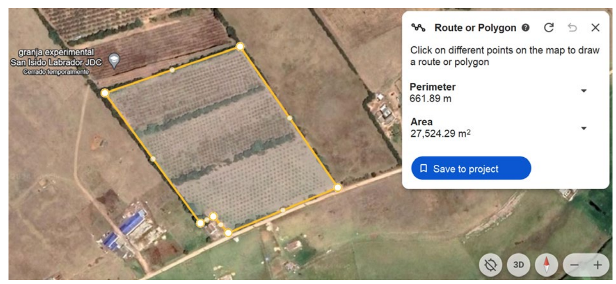

Fig. 3 San Pedro Labrador-Farm Location.

The focus of the study on a single geographical location and type of crop, specifically on an experimental fruit farm, is justified by several significant reasons. Firstly, farmers in the region are small-scale producers, whose plots are characterized by being smallholdings, implying a particular agricultural context that requires tailored and specific solutions. Secondly, site-specific agriculture is increasingly relevant in specialized crop production such as fruits, where soil conditions, climate, and other factors can vary significantly even in geographically close areas. Therefore, conducting an experimental prototype on a farm of this nature allows for the design and testing of technologies and agricultural practices that are directly applicable to the specific needs and conditions of this type of crop and the farmers who manage them.

However, current measurement methods are inadequate, relying on manual or traditional approaches. Consequently, the need arose to design a wireless sensor network that guarantees homogeneous monitoring of the variables in all growing areas. This network will gather real-time data, enabling agricultural professionals to stay informed about current and historical behavior of crop variables.

This section outlines the construction of an electronic device facilitating signal acquisition through sensors installed in the study crop. Considering the physical conditions and connectivity requirements for data and power supply, it was resolved to power the wireless sensor network using batteries. Additionally, a local webpage was implemented for visualizing the collected information.

This approach aims to enhance efficiency and accuracy in monitoring key variables for deciduous crop production at the San Isidro Labrador farm. The WSN implementation will furnish real-time data, facilitating decision-making based on current information. This development contributed to improving the quality and productivity of the test crop, optimizing the use of water and energy resources.

B. General Architecture of the WSN

Wireless sensor networks differ fundamentally from general data networks, such as the Internet, and therefore require the adoption of a distinct design paradigm. The system was structured by connecting sensor nodes through wireless transmission using the ZigBee® standard, which comprises high-level wireless communication protocols based on the IEEE 802.15.4 standard, employing XBee™ wireless transmission modules.

These integrated solutions facilitate wireless interconnection between devices and transducers by setting up fast point-to-point, multipoint or peer-to-peer networks. The system comprised one receiver node and three transmitter nodes, detailed in the block diagram illustrated in Fig. 4.

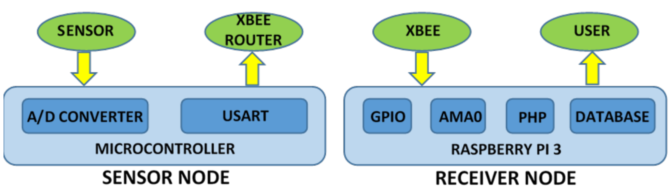

Fig. 4 ZigBee Module Block Diagram.

The initial sensing stage involves measuring various environmental variables using respective analog sensors, and this information reaches the second component of the diagram. During this stage, the analog data is converted to digital by a microcontroller, which also assumes the task of building the information transmission frame with the processed data.

Finally, the data is transmitted via the XBee™ S2C module to the nearest node for transmission and storage at the receiving node. Each sensor node is powered by batteries that have an autonomy of 200 hours. Conversely, the data-receiving node incorporates a data reception stage, with an XBee™ S2C module configured as a coordinator to organize and manage the network. This device sends the received data to a Raspberry® Pi 3, where the information is stored in a MySQL database within a local network, allowing visualization through a mobile device or computer. Similarly, the data reception node involves an XBee™ S2C module configured as a coordinator responsible for managing the network. This device forwards the received data to a Raspberry® Pi 3.

The information is then stored in a MySQL database for viewing on a web page within a local network, accessible via a mobile device or computer. The system was implemented through data acquisition and transmission stations in suitable crop areas at the San Isidro Labrador-farm in the municipality of Soracá (See Fig. 5).

Fig. 5 WSN Node Implementation in the crop site.

The potential of solar energy for the sensor nodes of WSNs used in fruit tree cultivation is substantial. The integration of solar power could enhance sustainability and reduce maintenance by providing a continuous energy supply, which is particularly crucial for long-term monitoring in the agricultural context. In this regard, each of the sensor nodes is powered by a rechargeable 12V battery and equipped with a 10W solar panel for operation.

C. Sizing and Distribution of the WSN

To determine the appropriate network size, we calculated the number of nodes needed to adequately cover the monitored crop area, ensuring to avoid information loss. Based on the tests performed, it was established that a node covering an area range of 888 m² is sufficient to guarantee satisfactory data transmission.

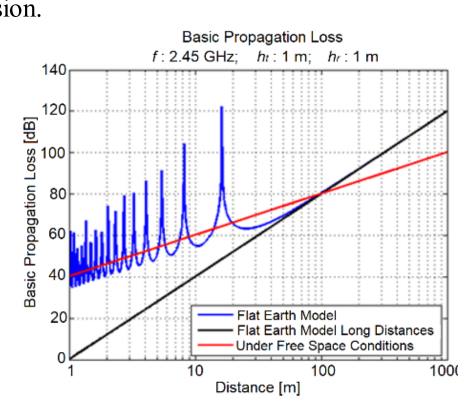

Fig. 6 Propagation models at 5.8 GHz—Path Loss & Building Penetration, adapted from [20].

Therefore, to calculate the total number of nodes N_N needed in a field, (1) is applied:

$$N_N = \frac{Total\ Area\ Crop\ (m^2)}{888(m^2)} = \frac{27524m^2}{888m^2} = 31 nodes \quad (1)$$

1) Free Space Loss (FSL): The link budget facilitates communication design for a coverage area, requiring configuration of parameters to prevent losses. Fig. 6 illustrates the common losses presented in the link budget.

The connection between the transmitter and receiver XBee™ modules, as shown in Fig. 7, graphically represents the loss budget design.

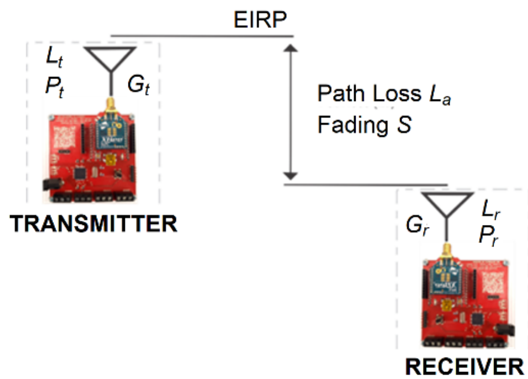

Fig. 7 Loss budget design in the WSN transceiver.

The parameters utilized in the loss budget are as follows:

P_t = Transmitter Output Power (dBm or dBW)
P_r = Receiver Power (dBm or dBW)
L_t = Transmitter losses due to connectors (dB)
G_t = Transmitter antenna gain (dB)
L_a = Free space path loss (dB)
S = Fading loss margin (dB)
G_r = Receiver antenna gain (dB)
L_r = Receiver losses due to connectors (dB)

To calculate the Effective Isotropic Radiated Power (EIRP), (2) is considered, relating the loss margin, receiver antenna gain, power, and losses, among others:

$$P_r = (P_t - L_t + G_t) - (L_a + S) + (G_r - L_r) \text{ dBm} \quad (2)$$

The EIRP was defined as:

$$EIRP = (P_t - L_t + G_t) \text{ dBm} \quad (3)$$

By replacing (2) with (3), (4) is obtained:

$$P_r = EIRP - (L_a + S) + (G_r - L_r) \text{ dBm} \quad (4)$$

Table I displays the configuration parameters of the XBee™ modules utilized in the Wireless Sensor Network. Signal loss calculations are in decibels. Substituting values defined in Table I into (3) to calculate the Effective Isotropic Radiated Power (*EIRP*) in (5) is as follows:

$$EIRP = (8 - (-1) + 3) \text{ dB} = 12 \text{ dBm} \quad (5)$$

TABLE I
SPECIFICATIONS OF XBEE™ DEVICES

Parameters	Reception	Transmission
Transmitter output power (P_t)		8 dBm
Antenna gain (G_t, G_r)	3 dB	3 dB
Fading losses (S)	24.68 dB	
Cable loss	– 1 dB	– 1 dB
Minimum reception power (P_r)	– 130 dBm	
Frequency of XBee™ modules	2.4 GHz	
Range (line of sight)	1.6 Km	1.6 Km

To calculate the Free Space Loss (L_a) in decibels, (6) is employed, where the fading loss margin (S) is determined based on the network designer's criteria and technical equipment data:

$$L_a = EIRP - S + (G_r - L_r) - P_r \text{ dB} \quad (6)$$

Substituting the values into (6):

$$L_a = 12 - 24 + 3 - (-3) - (-130) \text{ dB} = 122 \text{ dB} \quad (7)$$

The Free Space Path Loss (L_a) can also be calculated by (8):

$$L_a = 10 Log_{10}\left(\frac{4\pi f d}{c}\right)^2 \text{ dB} \quad (8)$$

Where:

L_a = Free Space Path Loss (dB)
d = Distance between the transmitter and receiver (m)
f = Signal frequency (Hz)
c = Speed of light (m/s)

By substituting the values of the variables defined in (8), the distance (d) between the central node and the sensor nodes is cleared.

$$122 \text{ dB} = 10 Log_{10}\left(\frac{4(3.14)(2.4e^9 Hz)d}{3e^8 m/s}\right)^2 \text{ dB}$$
$$10^{122/10} = \left(\frac{4(3.14)(2.4e^9)d}{3e^8 m}\right)^2 \quad (9)$$
$$d = \sqrt{156819} m = 1.25 Km$$

According to tests conducted in a rural environment with dense vegetation, the approximate coverage radius was 400 to 500 meters. Losses in signal transmission occur in the presence of obstacles between the signal emitter and transmitter since there is no direct line of sight.

2) Network Transmission Rate Calculation: To determine the network transmission rate, we consider the total percentage of possible nodes in the supervised crop, based on an area of 24,854 m². According to the manufacturer's technical specifications, the maximum number of nodes for a ZigBee® network with XBee™ modules is 64,000 devices. Within this space and under the design criteria, 31 nodes are calculated to cover the area. Table II presents the coverage percentage relative to the number of nodes in the network.

TABLE II
COVERAGE PERCENTAGE ABOUT THE NUMBER OF NODES

Number of Nodes N_N	Percentage (%)
31	100
23	75
15	50
8	25
3	10

The minimum frame is obtained when data is received from a single sensor, occupying 24 bytes, and the maximum frame is calculated when data from all four analog sensors is received, occupying 30 bytes. Table III displays the calculated data frame size.

TABLE III
CALCULATED DATA FRAME SIZE

Maximum Frame	Minimum Frame
30 bytes = 240 bits	24 bytes = 192 bits

The relation (v) between transmission rate and frame are calculated using the expression (10):

$$v = \frac{Transmission\ Rate}{Frame\ Size} \tag{10}$$

Fig. 8 illustrates the dimensioning of the Wireless Sensor Network to ensure comprehensive coverage of the entire crop area. The network operates at varying speeds, ranging from 25,000 to 80,000 bps, facilitating efficient data transmission for both minimum and maximum rates, as detailed in Table IV.

The selected speeds of 25,000 to 80,000 bps strike a balance between data transmission capacity and energy consumption. Higher speeds could result in faster data transfer but may increase power consumption, impacting the lifespan of sensor nodes. Conversely, lower speeds might conserve energy but could compromise the timely data delivery, affecting real-time monitoring and decision-making processes.

TABLE IV
CALCULATED DATA FRAME DIMENSIONS FOR THE WSN

Maximum Frame	Minimum Frame
240 bits * 31 nodes = 7440 bits	192 bits * 31 nodes = 5952 bits

Additionally, the dimensioning of the WSN considers specific crop area requirements, including size, layout, and potential obstacles. Each sensor node covers an area of 888 m^2, a measurement obtained by polygonal mapping of the plot using the Google Earth tool (Fig. 3 and Fig. 8). This area was determined to be adequate for sensor node placement considering the communication infrastructure utilized.

The nodes communicate using XBee® RF modules operating under the ZigBee® wireless communication protocol. These modules operate at a frequency of 2.4 GHz with an effective range of 1600 meters, facilitated by the installation of a 6 dBi omnidirectional antenna, providing significant signal gain.

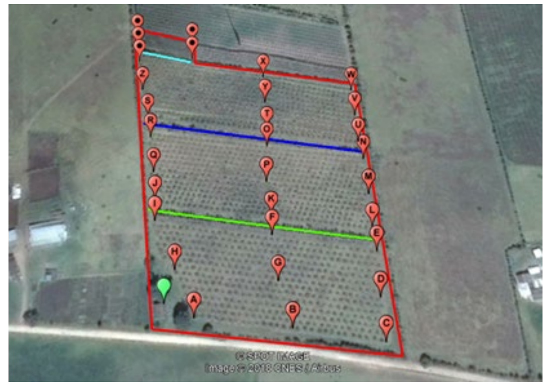

Fig. 8 WSN dimensioning in the crop.

This location enables accurate and comprehensive monitoring, facilitating proactive decision-making on irrigation, pest control, and other agricultural practices. Overall, careful WSN dimensioning, considering the speed and the coverage, enhances system efficiency and reliability. Farmers obtain timely and accurate data on plantations for efficient management of crop resources. Therefore, the frame rates are calculated as shown in Table V.

TABLE V
COMPARISON OF FRAME SPEEDS FOR THE WSN

Network Speed	Maximum Frame	Minimum Frame
250.000 bits	$\frac{250.000\ bits}{7440\ bits} = 33.6\ bps$	$\frac{250.000\ bits}{5952\ bits} = 42\ bps$
170.000 bits	$\frac{170.000\ bits}{7440\ bits} = 21.9\ bps$	$\frac{170.000\ bits}{5952\ bits} = 28,5\ bps$
140.000 bits	$\frac{140.000\ bits}{7440\ bits} = 18.1\ bps$	$\frac{140.000\ bits}{5952\ bits} = 23.5\ bps$
80.000 bits	$\frac{80.000\ bits}{7440\ bits} = 10.75\ bps$	$\frac{80.000\ bits}{5952\ bits} = 13.44\ bps$

According to the calculations, the data transmission rate for a minimum frame ranges between 42.00 and 13.44 bps, and for a maximum frame, ranges between 33.60 and 10.70 bps. The analysis indicates that the smaller the number of sensors, the greater the bandwidth in the transmitted bit frame.

3) Data Storage Interface: The data storage and visualization interface comprise a local web page where the central node communicates with the server via a web address, providing a dynamic interface for each node of the system to display the information. Fig. 9 illustrates the graphical user interface of the WSN.

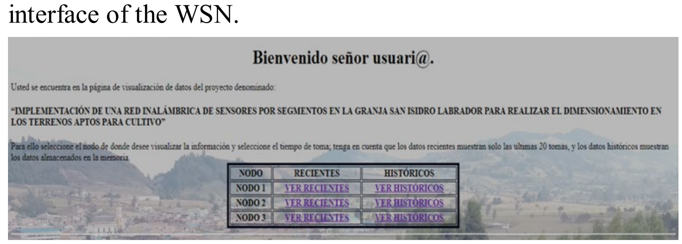

Fig. 9 WSN Graphical User Interface.

4) Analysis of WSN Behavior: A comparative analysis is conducted between the data collected by the sensor node system and a meteorological station at the same study site to validate proper functionality. Fig. 10 and Fig. 11 depict the records of soil moisture and ambient temperature, respectively, with measurements at 30-minute intervals.

The graph in Fig. 10 displays soil moisture readings throughout a day in June 2022, showcasing variations from 70% to 92%. The lowest moisture content is recorded around 3:00 AM, while the highest occurs at 9:00 PM.

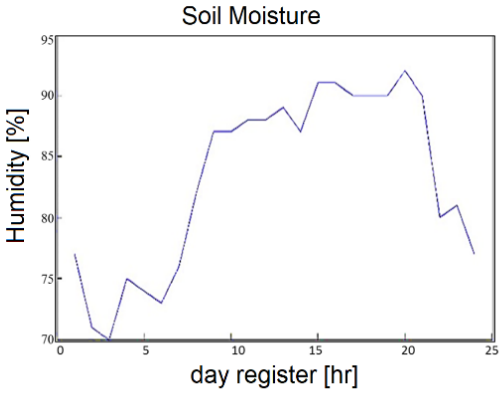

Fig. 10 Daily Behavior of soil moisture in the crop.

Additionally, Fig. 11 presents the daily average temperature record, ranging from 11 °C to 16 °C. The highest ambient temperature is recorded around 3:00 AM, while the lowest average temperature is reached at 4:00 PM.

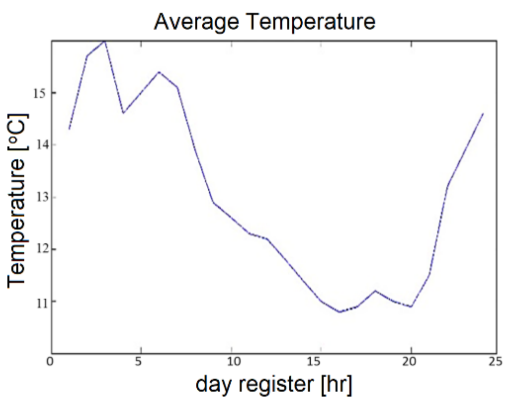

Fig. 11 Daily Behavior of ambient temperature in the crop.

These findings offer crucial insights into the environmental conditions on the analyzed day, impacting plant growth and development. Optimal soil moisture levels are vital for plant health, and the daily average temperature record provides valuable information about thermal variations throughout the day, aiding in understanding local weather patterns.

Note that these data are specific to the analyzed day in June 2022 and may vary at different times and locations. Nevertheless, these results present a snapshot of the environmental conditions on that particular day, contributing to a comprehensive understanding of the study's context and its implications on the obtained results.

III. Analysis and Discussion

Application of the Internet of Things and sensor network architecture involves numerous devices transmitting data to data centers for processing and subsequent storage. Implementing a distributed system in small sensor networks, where information is transmitted to a data fusion center, enables the data reception from sensor nodes and storage in a local database or a cloud server.

Currently, various technological platforms are available in the market, offering the flexibility to design sensor nodes according to different needs, including cost, information access, technical features, device variety, network coverage, hybrid communication protocols, and a wide range of tools for designers.

These platforms encompass wireless communication modules at the MAC layer, such as XBee™, single-board computers like Raspberry® Pi, Galileo, and pcDuino, low-power communication protocols like ZigBee®, software simulation tools like Opnet® IT, Scratch, LabVIEW™, and Proteus, open hardware platforms like Arduino™, open-source software platforms like MySQL™ and PHP, integrated development environments like Microchip® MPLAB™, Python™, and DIGI XCTU, free cloud servers like Amazon Web Services, and programmable electronic devices like Microchip® PIC and Atmel® [21 – 24].

These tools and technological platforms, accessible in terms of cost, availability, and documentation, empower the design of distributed wireless sensor network systems that integrate high-level languages with hardware devices. In this development, the Raspberry® Pi was selected as the final device for capturing WSN data due to its low cost (USD35), processor capabilities, and Ethernet interface. XBee™ Series 2 modules were chosen for implementation due to the support of the low-power IEEE 802.15.4 standard, compatibility with other devices using ZigBee® protocol, utilization of the 2.4 GHz band, and cost-effectiveness.

Furthermore, a PIC 16F1937 microcontroller was used as an embedded device for data processing before transmission to the coordinator node. The software design involved the identification of the distributed network system devices. These components were a coordinator node, multiple sensor units, and the database that stores information from these nodes. Various operating scenarios were used to characterize and test the WSN. In addition, an entity-relationship model was applied to design the database.

The system exhibits partial autonomy, because supervision focuses on the Raspberry® Pi's SD card as well as the information storage facilitating large-scale implementation. Additionally, it was implemented with the most favorable technological resources in terms of market prices, ensuring that execution does not incur a high budget while still meeting the required system characteristics, such as optimization and information processing speed. Deviating from the mentioned elements would escalate associated costs.

Unlike other designs on the market that usually prioritize robustness, this design stands out for its simplicity, straightforwardness, and ease of handling. It features minimal electrical connections and elements with low energy consumption. Moreover, this design exhibits compatibility with devices of various references or brands. The implementation involves a sensor network utilizing the ZigBee® protocol and a star topology. The coordinator node receives frames from eight sensor nodes, divided into 14 packets with a size of 50 bytes, occupying 49% of the link capacity at a transmission rate of 170 Kbps. This design covers a geographic area of 50 m², providing a scalable network with low latency.

In the specified conditions, 112 sensors are deployed across the crop area, transmitting information at a sampling rate of one second. The network's scalability is contingent on the required information amount per minute, allowing for the installation of more sensor nodes by increasing packet-sending intervals. Network reconfiguration facilitates adaptation to new working conditions. A scalable network dispose of ten sensor nodes, ten end devices, and one coordinator, supporting 280 sensors in an area of up to 15.6 km², can be achieved using the maximum Link Budget capacity. The star topology ensures data reaches in a single network hop, suitable for rapid sensing. However, possible interconnectivity problems must be considered, given that they operate in the 2.4 GHz frequency band.

The device implementation involves hardware, software, and design platforms, creating a system that captures data from a sensor node, including a sensor, a microcontroller (PIC16F1937) processing the voltage signal, and an XBee™ module wirelessly transmitting the frame to the coordinator node. The coordinator node, consisting of an XBee™ module (coordinator), forwards the frame information to a Raspberry® Pi. The Raspberry® Pi processes the information received through the Raspbian operating system, connecting to the local database named BD_sensors1 using a PHP algorithm.

This system integrates preset configurations, such as the device speed normalized at 9600 bps 8N1, device power supply between 3.3V and 5V, and synchronization between the received frame and the algorithm. Any modification to these elements would impact the data storage process.

In this development, ZigBee® is utilized as the physical layer and data link protocol for the wireless network nodes in the orchard. Once the data is collected within the local network, higher-level data transmission protocols such as MQTT can be implemented to send this data to cloud servers or other devices across the global network via the internet. This enables an efficient and scalable integration within agricultural environments and broader IoT applications. The adoption of such protocols offers the potential to optimize data flow from sensor nodes to the end-user interface, facilitating real-time remote monitoring, ensuring data availability for analysis, and enabling timely decision-making for fruit cultivation based on cloud-based platforms.

The economic viability assessment of implementing an IoT-based wireless sensor system in fruit cultivation reveals promising prospects for farmers. With low-cost commercial electronic components and freely accessible software, the implementation proposal proves economically favorable, with an effective cost per node of just 50 USD. This financial accessibility presents a tangible opportunity to enhance agricultural efficiency and productivity while reducing operational costs associated with crop monitoring and management. Furthermore, by enabling more precise, real-time data collection on soil conditions, moisture levels, and other relevant factors, these wireless sensor systems have the potential to optimize resource utilization and increase crop yields, leading to long-term revenue growth for farmers. Consequently, investing in this technology can be viewed not only as a technological upgrade but also as a sound economic strategy for the agricultural sector.

A. Limitations and Future Work

An important consideration when implementing agricultural technologies is their environmental impact. As the number of nodes increases to cover greater distances, the challenge of maintaining a balance between efficiency and environmental cost arises. A sustainable approach that utilizes renewable energy sources is required to minimize energy consumption and ensure system autonomy. Furthermore, the system scalability to other types of crops needs to be investigated, taking into account variations in environmental conditions and the specific requirements of each crop.

Future developments could involve applying more specific control platforms (ESP32), which offer greater processing capacity and flexibility to adapt to different agricultural environments. Exploring emerging wireless protocols like LoRa™ could enhance coverage and communication efficiency among nodes. Additionally, integrating an intuitive graphical interface would facilitate data visualization and analysis for farmers.

To address potential challenges, the precision of collected data could be compared with that of conventional weather stations to validate the reliability of the proposed system. Furthermore, the future use of prediction and decision-making tools based on machine learning could optimize irrigation, input, and nutrient dosing, as well as early detection of pests or diseases. These advancements would not only improve agricultural efficiency and productivity but also contribute to long-term environmental conservation and sustainability.

IV. CONCLUSIONS

The crucial variables to measure at San Isidro Labrador farm include ambient temperature, soil temperature, relative humidity, and soil moisture. These measurements are essential for parameterizing fruit plant growth and monitoring variable behavior, particularly for detecting frequent frost occurrences in the crop area.

The implementation of XBee™ S2C devices alongside the ZigBee® 802.15.4 protocol proves to be a suitable technology for a wireless sensor network (WSN) in precision agriculture. The data transmission speed of up to 250 Kbps is sufficient for sending and receiving the required information, considering a sampling frequency of 2 to 3 samples per second for these variables.

These devices exhibit low power consumption, as demonstrated in prior research, contributing to extending the battery life of the WSN. WSNs present new opportunities for innovation in predictive systems and precision agriculture. Early detection of opportunistic microorganisms affecting crops and precise irrigation application when needed can optimize agricultural systems, reduce costs, and address challenges related to climate change.

WSNs are increasingly pivotal in agricultural systems, providing farmers with real-time data about their crops for quick and informed decision-making.

The integration of IoT technology in precision agriculture allows more efficient management of agricultural resources by providing detailed and up-to-date information about crop conditions. This application helps to minimize excessive use of water, fertilizers, and pesticides, promoting sustainable and environmentally friendly agriculture.

Implementing a wireless sensor network in agriculture offers enhanced monitoring and control capabilities, potentially boosting productivity and crop quality. Moreover, long-term data collection enables in-depth analysis and studies, contributing to a better understanding of patterns and trends in plant growth. This work provides valuable input for agro industrial research, the improvement of agricultural practices, and the support of technologies for making crop decisions by farmers.

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