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Enhancing greenhouse management: assessing sensor accuracy and device transmission in strawberry cultivation

Otimização do manejo de estufas: avaliando a precisão de sensores e a transmissão de dispositivos em cultivo do morangueiro

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The large-scale use of water resources represents one of the drawbacks of horticulture specially the strawberry cultivation. Irrigation and management systems using IoT technologies have increasingly been used in agriculture, presenting greater efficiency potential in water consumption, and productivity and quality of agricultural products. This study aimed to develop and evaluate an environmental monitoring system integrating data acquisition and transmission using LoRa technology, applied to strawberry cultivation under greenhouse conditions. The accuracy of the data through sensors and the accuracy rate of sending the data were evaluated. The sensor STH20 was compared with a weather station and the DS18b20 with geothermometers. The accuracy rate of sending data was analyzed for its efficiency, the packages sent fewer acknowledge messages (confirmation uplink). The SHT20 sensor showed no significant difference in relation to the air temperature data collected, only in relation to relative humidity due to the lack of protection of the sensor. The DS18b20 sensors also showed accuracy for measuring substrate temperature compared with geothermometers. The proposed LoRa technology system presented an accurate data-sending effectiveness rate about the environment in which the devices were inserted and their hardware configuration. The system can be used in greenhouse production system as management improvement strategy in consonance with global development objectives.
Keywords: *Fragaria* X *ananassa* Duch., water, data-sending.

A utilização em larga escala dos recursos hídricos representa um dos inconvenientes da horticultura, especialmente do cultivo do morango. Sistemas de irrigação e gestão utilizando tecnologias IoT têm sido cada vez mais utilizados na agricultura, apresentando maior potencial de eficiência no consumo de água, e na produtividade e qualidade dos produtos agrícolas. Este estudo teve como objetivo desenvolver e avaliar um sistema de monitoramento ambiental, integrando a aquisição e a transmissão de dados utilizando a tecnologia LoRa, aplicado ao cultivo de morangueiro em casa de vegetação. Foram avaliadas a precisão dos dados através dos sensores e a taxa de precisão do envio dos dados. O sensor STH20 foi comparado com uma estação meteorológica e o DS18b20 com geotermômetros. A taxa de precisão do envio de dados foi analisada quanto à sua eficiência no envio dos pacotes (uplink de confirmação). O sensor SHT20 não apresentou diferença significativa em relação aos dados de temperatura do ar coletados, apenas em relação à umidade relativa devido à falta de proteção do sensor. Os sensores DS18b20 também apresentaram precisão na medição da temperatura do substrato em comparação com os geotermômetros. O sistema de tecnologia LoRa proposto apresentou taxa de efetividade no envio de dados precisos sobre o ambiente em que os dispositivos foram inseridos e sua configuração de hardware. O sistema pode ser utilizado em sistemas de produção em estufas como estratégia de melhoria de gestão em consonância com os objetivos de desenvolvimento global.
Palavras-chave: *Fragaria* X *ananassa* Duch., água, envio de dados.

1. INTRODUCTION

Valued for its rich nutritional content - including health-beneficial biomolecules such as anthocyanins, vitamin C, β-carotene, and others - the strawberry (*Fragaria* X *ananassa* Duch.) stands as a principal horticultural crop in numerous global agroecosystems [1]. In Brazil, strawberry production is predominantly carried out in soil and open fields, however a shift towards greenhouse cultivation is noticeable. Within this context, greenhouse cultivation techniques and irrigation management are often implemented based on empirical knowledge. Given the global water scarcity and the prevalent use of irrigation depths that exceed the actual water needs of strawberries, appropriate irrigation management is an essential factor for enhancing both crop yield and water use efficiency [2, 3]. Proper irrigation also plays a crucial role in achieving superior fruit quality by influencing sugar content. For example, sugar content might rise under deficient irrigation conditions, while the acid concentration may increase when water absorption is limited [4]. However, irrigation is still carried out without technical parameters in most rural properties, leading to the inefficient use of freshwater resources, especially when considering that agriculture accounts for 70% of global water consumption [5].

Improving water use efficiency in agriculture, particularly in horticulture, is a pressing challenge, especially since many systems operate under greenhouse conditions. Several technologies may be used to reduce the water dependency in crop production. One among them is real-time irrigation that can contribute to water savings [3]. Therefore, the integration of affordable and precise technological innovations is pivotal to enhance water use efficiency and optimize productive resources. Monitoring the environment within a greenhouse is another essential factor. For instance, the microclimate inside the greenhouse is influenced by variables such as air temperature, relative humidity, carbon dioxide concentration, and irradiation [6]. Real-time measurement of these factors, including relative humidity, air temperature and substrate temperature, allows for quicker environmental assessment, ultimately benefiting crop growth [7].

Data collection and transmission stations face challenges such as limited connectivity, the necessity to transmit data across vast distances, and the high cost of sensors. Moreover, for an irrigation system to function optimally, the data collected, and its transmission must be dependable. With the progression of technology, innovative solutions have emerged to enhance irrigation. The Internet of Things (IoT) is becoming a staple in agriculture. Devices equipped with sensors can gather diverse data types, aiding in more informed decision-making for crop cultivation. Among the available technologies, LoRa stands out as a wireless communication technology. It boasts long-range capabilities, low power consumption, and a cost-effective price point compared to similar technologies.

The Long-distance communication technology, LoRa, is pivotal in agriculture for collecting precise meteorological data, which is essential for various decision-making aid systems. LoRa operates under an open standard protocol, utilizing the capabilities of the LoRa module and the LoRaWAN protocol. Typically, LoRaWAN networks employ a star network topology, centralizing gateways to receive data from end-devices. This architecture ensures optimal long-distance communication and commendable battery life. A functional LoRaWAN network hinges on three crucial components: 1) End-devices: these low-energy consumption devices are data collectors or actuators; they communicate with gateways using the LoRaWAN protocol; 2) gateways: facilitating communication between the LoRaWAN protocol with end-devices and servers, usually via mediums like 3G or WiFi; 3) servers: these entities process data received from gateways; they can be private or public, offering visualization and registration of end-device data [8].

However, the high acquisition costs of irrigation systems and meteorological stations limit their accessibility for many producers. Another challenge is real-time data transmission; conventional meteorological stations often need to catch up in providing instantaneous updates. In irrigation management, real-time data collection is crucial, enabling prompt crop management adjustments as conditions change. This research also seeks to anticipate potential issues with data and transmission devices for a future intelligent irrigation system. Notably, there needs to be more literature concerning the accuracy of such sensors [9], a critical aspect of obtaining trustworthy data.

This study aims to enhance greenhouse management practices. Specifically, we are examining the impact of device transmission on package delivery effectiveness and assessing the accuracy of both the substrate temperature sensor and the air temperature and relative humidity sensor in strawberry cultivation under greenhouse conditions.

2. MATERIAL AND METHODS

2.1 Plant material and growing environment

A prototype of the final devices was placed in a greenhouse with strawberries, a 'San Andreas' cultivar, in the municipality of Passo Fundo (28º15'41"S; 52º24'45"W), Rio Grande do Sul (RS), Brazil. According to the Köppen climate classification, Passo Fundo is characterized by the climate type Cfa, with no defined dry season and hot summer [10]. Figure 1 shows the locations of the end-devices in the greenhouse and the gateway in the Agronomy Department at the University of Passo Fundo.

The study was conducted from May (autumn) 2021 to January (summer) 2022 in a greenhouse (430 m^2) with a semicircular roof covered with a low-density polyethylene film installed in a northwest-southeast direction. The greenhouse was not heated. Ventilation control was performed manually by opening and closing the side plastic (curtains). In addition, at each front end, the structure contained two zenith windows for internal air renewal [11].

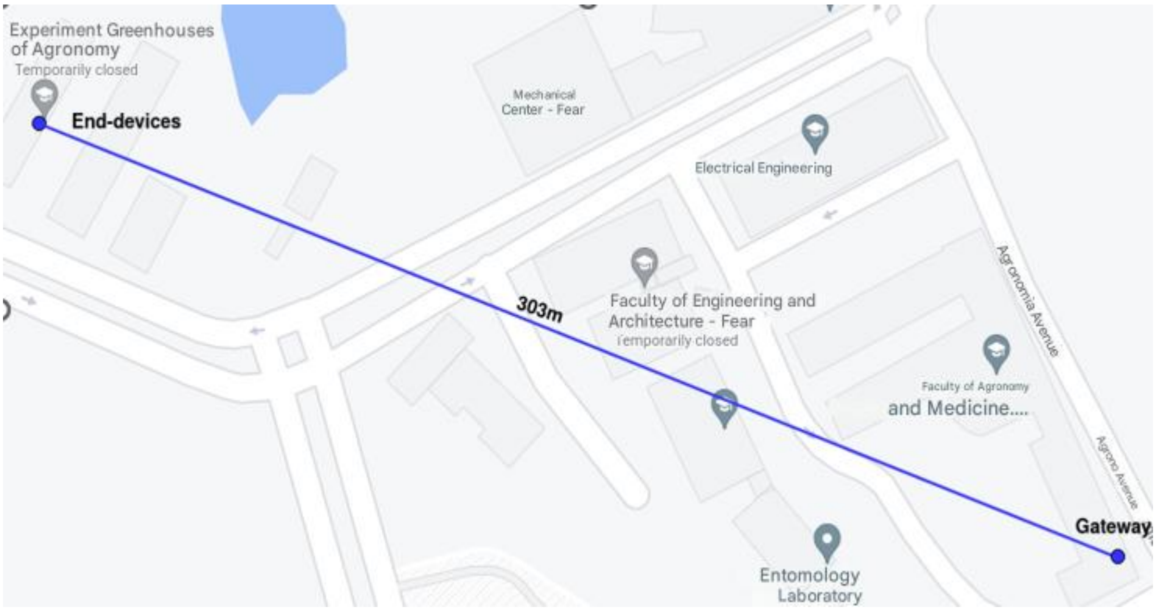

Figure 1: Location of the end-devices and gateway in the University of Passo Fundo.

The strawberry daughter plants were transplanted in May 2022 in containers (1 m long and 0.5 m wide) containing the Dallemole® substrate, composed of pine bark, rice husk, rice ash, and organic compost class A. The daughter plants were spaced 0.17 m apart and arranged in a planting row.

Using localized irrigation (1.41 $L.h^{-1}$ per dripper), the irrigation regime consisted of activating the system seven times a day. We provided nutrient solutions to the plants weekly [12]. With a weather station (WatchDog), the air temperature and relative humidity were monitored.

2.2 Hardware

The Arduino Nano with Atmega328p processor was used to control the sensor data collection and transmission. SHT20 and DS18b20 were the sensors that read air relative humidity, air temperature, and substrate temperature, respectively.

For message transmissions, the LoRa transceiver RFM95 was used. The RFM95 can send messages in the Brazilian unlicensed bands AU915. The antenna was a wire, an Omnidirectional antenna. The gateway to receive all end-device messages was the Dragino LPS8N.

Three end-devices were put to the test. One with the SHT20 sensor and the other two with two substrate temperature sensors, in which each sensor was inserted in a row of containers with the substrate. Each device was configured to send a message every thirty minutes. The frequency and Spreading Factor configured were the AU915 and SF10. The collecting device was installed in the central position of the strawberry greenhouse.

The data collected from the STH20 sensor was compared with the data from the weather station inside the greenhouse. For the DS18b20 sensors, two geothermometers were placed on the substrate close to each digital sensor, ensuring an accurate comparison and validation of the temperature and humidity readings within the greenhouse environment.

2.3 LoRa server and dashboard

ChirpStack was the LoRa server installed on the Digital Ocean server. It features several integrations; however, for the initial test, Datacake[2] was chosen for data visualization, where dashboards displaying the collected values were developed. Additionally, the system was programmed to send weekly reports summarizing the data collected from the sensors. This setup not only facilitated detailed monitoring and analysis of sensor data but also enhanced the project's overall data management and visualization capabilities.

ChirpStack is an open-source LoRaWAN Network Server for setting up LoRaWAN networks, managing gateways, devices, and tenants, and integrating data with major cloud providers, databases, and services for device data handling [13]. Datacake is a versatile, low-code IoT platform designed for ease of use, requiring no programming expertise and minimal time investment. This platform enables the rapid creation of custom IoT applications, which can be seamlessly integrated into a white-label IoT solution with a simple click [14].

2.4 Data analysis

Sixty-seven samples were collected from the SHT20 sensor across different times and days, and subsequently compared with data from the automatic weather station. For the DS18b20 sensor, samples were collected in coordination with geothermometer readings and subsequently compared with them. The data from both the SHT20 and DS18b20 sensors underwent a Shapiro-Wilk test to assess normality. A T-test was conducted upon establishing the data's normality; for data that did not meet this criterion, the Wilcoxon test was applied to handle non-normalized data. This analytical process was carried out using RStudio [15], ensuring a rigorous examination of the sensor data's statistical properties.

3. RESULTS AND DICUSSION

The monitoring system employing LoRa technology delivered encouraging outcomes. Initially, the system was straightforward to set up, enhancing its utility. It facilitated the acquisition of real-time data critical for decision-making processes in the greenhouse. This data, particularly regarding air temperature and humidity, directly informed the automated management of the greenhouse curtains. This automation played a crucial role in sustaining the ideal meteorological conditions necessary for the cultivation and development of strawberries.

The transmission capabilities and the reliability of sensors were also tested. We examined the connectivity between the end-devices and the gateway, specifically focusing on identifying packet loss. Additionally, we evaluated the accuracy of sensors, with particular attention given to the SHT20 sensor for measuring relative humidity and air temperature.

Each end-device was configured to use confirmed uplink messages, allowing monitoring of successful transmissions by cross-referencing the uplink messages sent with the downlink messages received from the network server. However, one of the end-devices, equipped with a substrate temperature sensor, experienced operational difficulties. It stopped transmitting messages one week after the transmissions began. Despite having replaced the battery, the device stopped transmitting messages shortly thereafter.

Analysis of data transmission up to January 17, 2023 revealed the performance of the devices with respect to message loss. The device equipped with DS18b20 sensor (Figure 2) sent a total of 5,676 uplink messages. Thus, 2,076 of these messages received successful downlinks, resulting in a message loss rate of 63.42%. In comparison, the device equipped with the SHT20 sensor (Figure 3) transmitted a total of 3,659 uplink messages, with 2,315 successfully acknowledged by downlink responses. This corresponds to a loss of 1,344 messages and a message loss rate of 36.17%.

Figure 2: Illustration of a device equipped with substrate temperature sensors.

Figure 3: Device equipped with the SHT20 sensor to measure air temperature and relative humidity.

The issue identified in the system pertained to message losses originating from the data collection device. The weak sensitivity of the antennas, attributed to their wire configuration and low gain, resulted in numerous lost packets. In the study by Magro et al. (2022) [16], a LoRaWAN message repeater device was developed to extend the coverage of the technology. This device was inserted into the network 240 m away from the gateway and, in the most unfavorable scenario, exhibited an uplink packet loss rate of 4.65%. Discrepancies in message loss behavior could potentially be attributed to the arrangement of devices within the network and the presence of dense environmental elements such as buildings and trees at the University of Passo Fundo. Thus, the placement of the gateway plays a significant role in facilitating effective message exchanges.

The end-device equipped with substrate temperature sensors (Figure 2) experienced a higher message loss rate compared to the end-device used for measuring air temperature and relative humidity (Figure 3). Variations in height and positioning of the devices could have contributed to this increased loss rate.

The system's performance in strawberry cultivation demonstrated efficient functionality and robustness during initial testing in message transmission. The incidence of lost messages is expected to decrease following the implementation of antennas and relocation of the gateway to an area with reduced interference for message transmission. The system boasts easy installation; once the data collection device (end-device) is installed in the greenhouse, it promptly transmits collected data to the internet-accessible gateway, providing real-time information to producers. This capability facilitates swift decision-making and helps prevent potential issues in the future.

Analysis of data transmission up to January 17, 2023, revealed the compartment depicted in (Figures 2 and 3). Integration with Datacake facilitated the development of dashboards that visually presented collected data, enabling real-time observation of air temperature and relative humidity (Figure 4A), as well as substrate temperature (Figure 4B). This underscores the system's capability for real-time environmental monitoring, despite the noted challenges in message transmission.

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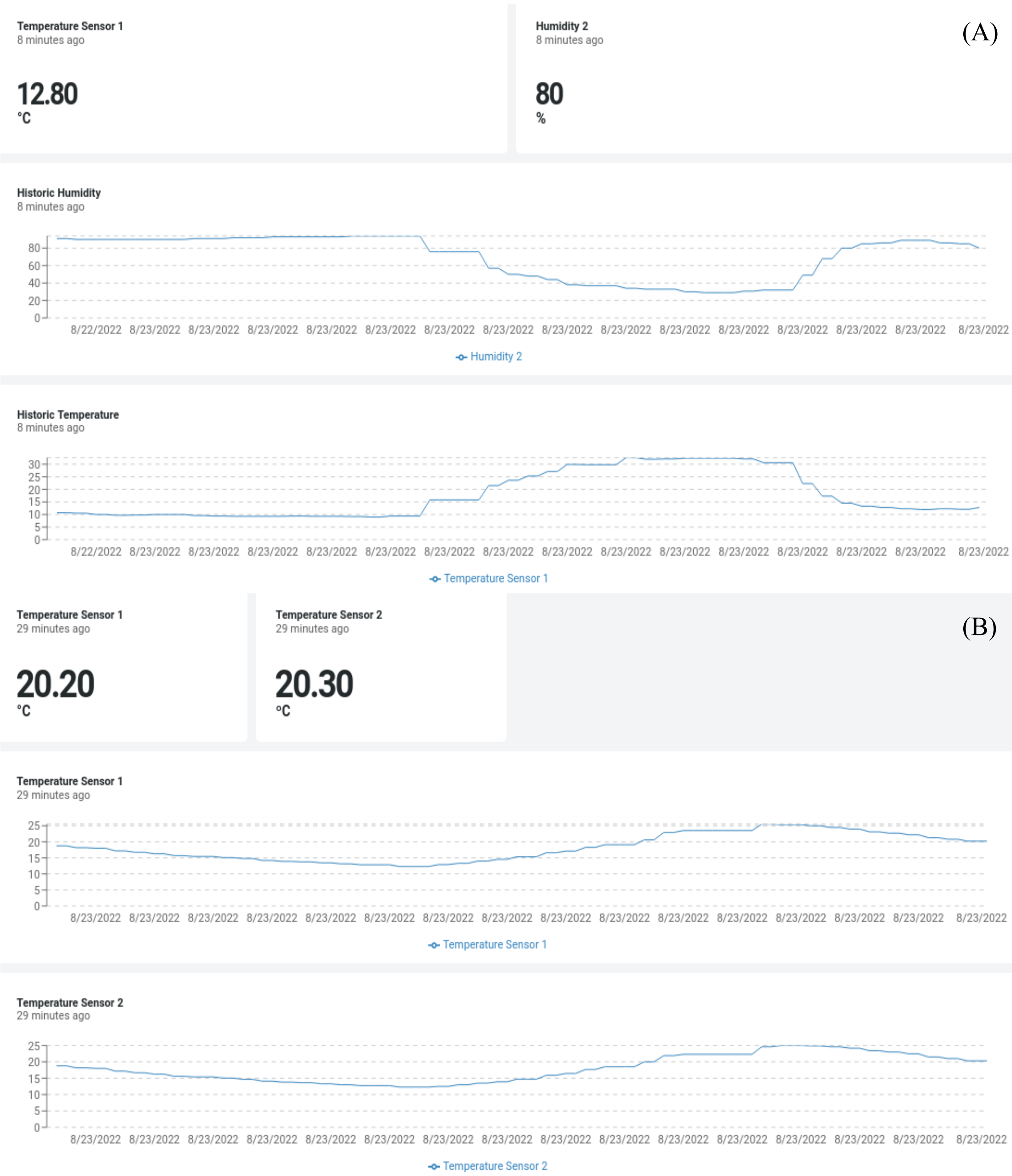
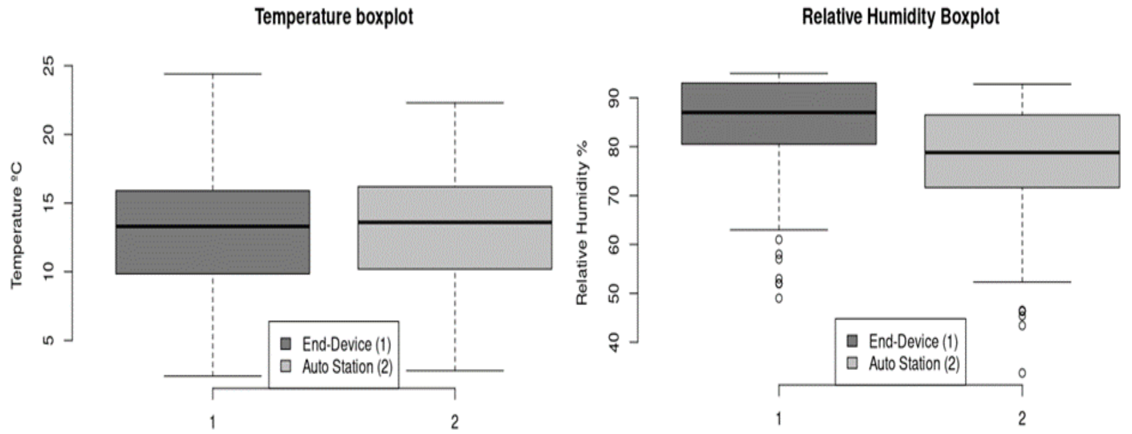


Figure 4: Dashboard with Datacake integration representing the air temperature and relative humidity sensor (A) and the substrate temperature of one end-device (B).

The accuracy of air temperature and relative humidity measurements was investigated to determine the suitability of the SHT20 sensor for practical applications and its potential to enhance management and irrigation system. Given the lack of normality in the data, the Wilcoxon test was applied. The results indicated that there was no significant difference between the air temperature data ($p>0.70$) (Figure 5A), whereas the relative humidity data showed a significant difference ($p<0.5$) (Figure 5B).



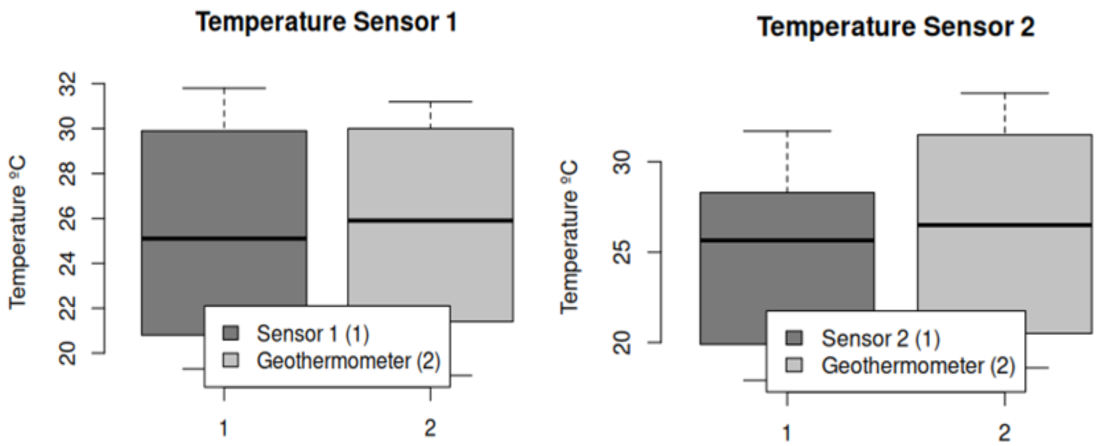
(A) (B)

Figure 5: Air temperature (A) and relative humidity (B) from the SHT20 sensor (1) and automatic station (2).

The analysis comparing the air temperature and relative humidity measured by the SHT20 sensor with the automatic station revealed varying results. While there was no significant difference in air temperature readings between the SHT20 sensor and the automatic station, the sensor's measurements showed a lower median, first quartile, and third quartile (Figure 5A). Additionally, there was a wider range of measured values, indicated by the higher maximum and minimum values recorded. This disparity may be attributed to the sensor's greater exposure to environmental energy exchanges compared to the automatic station, which is equipped with multiple protective plates. Consequently, the SHT20 sensor demonstrated high accuracy in measuring air temperature and can serve as a cost-effective alternative with low energy consumption and the ability to transmit data over long distances, thereby contributing to greenhouse management [7].

Relative humidity exhibits an inverse correlation with air temperature, which may account for the higher relative humidity values recorded by the SHT20 compared to the automatic station (Figure 5B). However, the obtained values were consistently higher, with a median of 89%, surpassing the meteorological station measurement of 78.8% (Figure 5B), indicating the low accuracy of this sensor in measuring air relative humidity. The SHT20 sensor was exposed without any protective shelter to shield it from direct solar radiation and wind, factors that could potentially influence the recorded air relative humidity values. Given the wide array of sensors available on the market, ensuring their adequate accuracy is crucial for obtaining precise data to inform management practices. This critical evaluation has been overlooked or underreported in most studies involving IoT [17-20]. Consequently, researchers may opt for more accurate sensors or consider implementing adaptations, such as constructing a shelter, which could be explored in future research.

The Figure 6 shows the boxplot comparing substrate temperature sensors with the geothermometers. Following the confirmation of data normality, a T-test was conducted (with a significance level of 5%), revealing no significant difference for Sensor 1 ($p>0.97$) and Sensor 2 ($p>0.49$).



(A) (B)

Figure 6: Comparison of Substrate Temperature between Sensor and Geothermometer 1 (A) and Sensor and Geothermometer 2 (B).

The DS18b20 sensor did not exhibit significant differences compared to the geothermometer data (Figure 6) and therefore can be considered suitable for future research. Both sensors recorded lower temperatures compared to the geothermometers, which can be attributed to the sensors being fully submerged and shielded from direct solar radiation. While the tests revealed no discrepancies between the DS18b20 sensor and the geothermometer, geothermometer 1 consistently recorded lower temperature values. This variation may be explained by differences in leaf area, with the plant associated with geothermometer 1 having a larger leaf surface area compared to the one monitored by geothermometer 2.

The sensors selected were chosen with the aim of constructing a low-cost system. Consequently, both the SHT20 and DS18b20 sensors underwent testing to assess the accuracy of the collected data in comparison to a reference. Only the relative humidity readings exhibited unsatisfactory values, which will be addressed through the implementation of sensor protection measures. Nonetheless, employing these end-devices in strawberry greenhouses can provide producers with reliable and cost-effective data, with the most expensive device featuring the SHT20 sensor not exceeding $35.00 USD.

The mean absolute difference between the air temperature measured by the SHT20 sensor and the substrate temperature measured by two DS18b20 sensors decreased from October (8.5 ºC) to January (5.1 ºC) (Figure 7). Substrate temperature variations were more pronounced during October and November, exhibiting greater amplitude (Figures 7A and 7B). The lowest thermal amplitude of substrate temperature occurred in December and January, coinciding with reduced daily air temperature variation during this period, thereby minimizing differences between these variables (Figures 7C and 7D).

The mean difference between air temperature and substrate temperature (Figure 7) exceeded the 4 ºC mean difference reported by Gavilán (2004) [21]. Additionally, when considering daily variability, variations of over 15 ºC were observed in October (Figure 7A) and over 10 ºC in November, December, and January (Figures 7 B, C, D), particularly at the onset of the night period. This phenomenon is attributed to the sudden decrease in air temperature following the reduction and subsequent absence of solar radiation, resulting in a negative radiation balance that leads to surface cooling and, consequently, cooling of the surrounding air. While this cooling effect is somewhat delayed in the substrate, occurring around 20:00 hours in October and November (Figures 7A and 7B) and around 21:00 hours in December and January (Figures 7C and 7D), due to the predominantly slow conduction-based heat flux within the substrate. Additionally, considering that the last irrigation occurred at 17:00 hours, thermal conductivity tends to decrease with greater airspace, particularly in substrates with high total porosity [22].

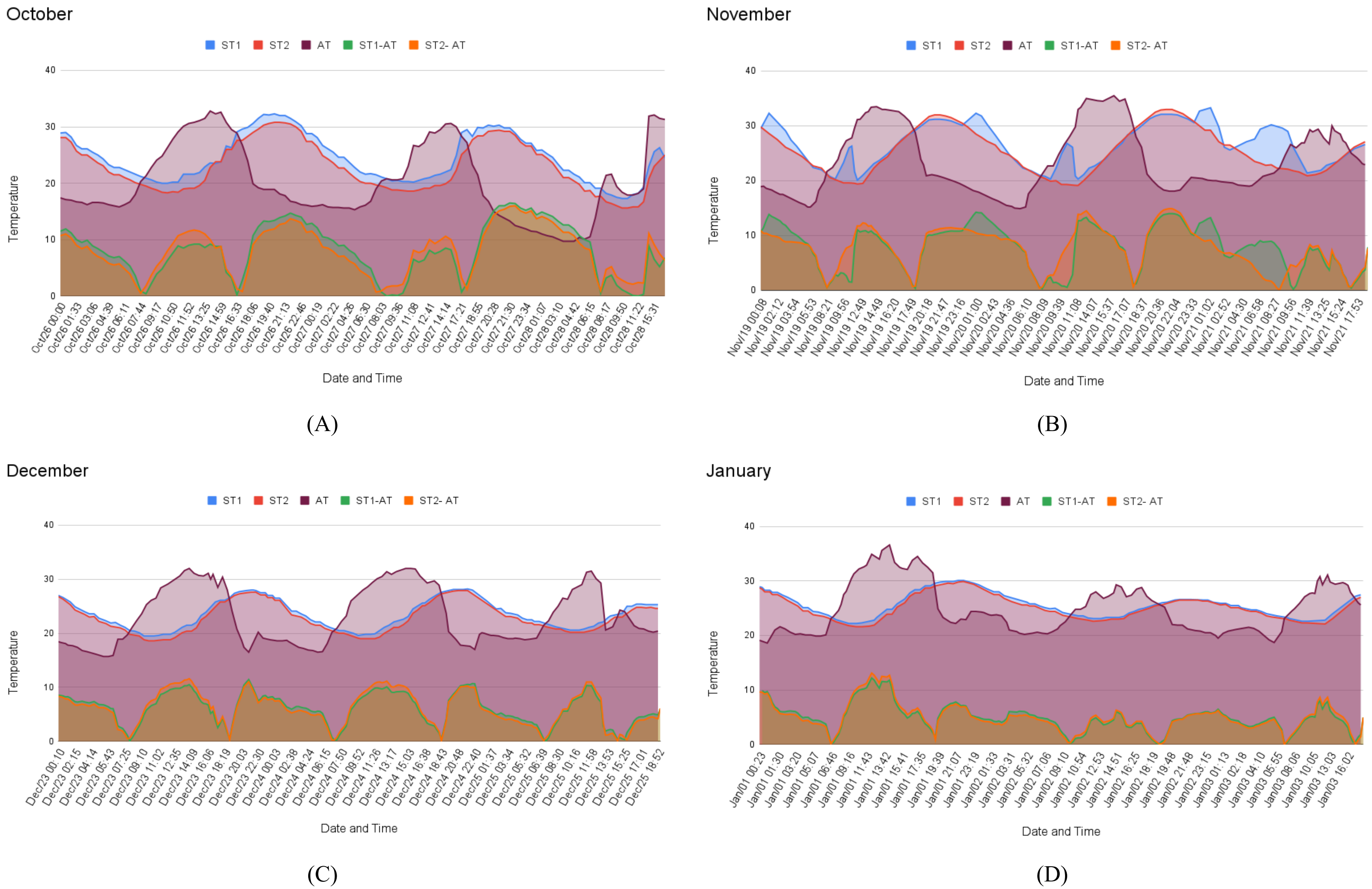


Figure 7: Variation of air temperature measured by the SHT20 sensor and substrate temperature measured by two soil temperature sensors and absolute temperature difference over a three-day period in October (A), November (B) and December (C) 2022 and January (D) 2023, in a strawberry cultivation under greenhouse conditions. ST1 and ST2 represent the substrate temperature, while AT corresponds to the air temperature measured by the SHT20 sensor.

This same pattern was observed in the early morning, where air temperature rises rapidly while substrate temperature shows a delayed increase (Figure 7). It is noteworthy that the substrate temperature consistently fell within a range considered above ideal for strawberry cultivation in substrates, ranging from 18 to 24 ºC [23, 24]. In December and January (Figures 7 C and 7D), despite frequent drip irrigation occurring eight times between 08:00 and 17:00, which contributes to substrate cooling, the maximum temperature still approached 30 ºC. Conversely, during October and November, despite lower solar radiation availability, substrate temperature exhibited greater fluctuations, often dropping below 20 ºC at night and exceeding 30 ºC during the day. This pronounced daytime heating may be linked to reduced irrigation frequency during this period. Fluctuations in root zone temperature can negatively impact root and shoot dry weight, leaf area, and the uptake of certain nutrients [23]. Moreover, substrate temperatures above 30 ºC can inhibit root respiration and strawberry growth [25]. Therefore, to prevent substrate temperature from exceeding the critical threshold of 30 ºC, alternatives such as shading or increasing real-time irrigation frequency without altering the applied depth can be considered, provided they do not promote root disease occurrence.

The expenses associated with establishing and maintaining the necessary infrastructure for data collection and transmission, including sensors, connectivity, and data storage and processing systems, can often pose a significant barrier for farmers, particularly in low-income countries. Despite the availability of numerous low-cost IoT devices, their reliability and accuracy may not always meet the standards required for agricultural applications. This research represents an attempt to use LoRa technology, with low-cost and high-accuracy sensors, as a tool to monitor the microclimate in a greenhouse in strawberry cultivated on substrate. Our findings will enable strawberry producers to implement more efficient water management strategies by monitoring substrate temperature, air temperature, and relative humidity, thus aligning with the sustainability goals of agricultural ecosystems. In the future, the integration of sensors for solar radiation, soil moisture, and other parameters will allow for precise and reliable long-term monitoring of irrigation practices. Additionally, the development of algorithms capable of utilizing this data to optimize irrigation scheduling and enhance water use efficiency holds promise for further advancements in agricultural sustainability.

4. CONCLUSION

The proposed data collection system utilizing LoRa technology exhibited message loss rates of 36.17% and 63.42%, attributable to the network device arrangement. While providing real-time data to enhance environmental monitoring within the greenhouse, the system experiences a notable percentage of lost packages. In the updated version, antennas will be integrated into the end-devices to enhance package transmission efficiency, and the gateway location will be optimized. Furthermore, new devices will be developed using Arduino Pro Mini to reduce battery energy consumption.

Regarding the sensors, both tested sensors, SHT20 and DS18b20, provided accurate results. However, there was a statistical difference observed in the relative humidity readings from the SHT20 sensor. To address this, a shelter will be developed for the sensor.

The proposed system demonstrates promising utility in strawberry cultivation within greenhouse conditions. For example, we have illustrated the overall ease of operation for crop management. Currently in its initial phase, the collection system will undergo improvements in both transmission and the collection of additional variables. Subsequently, the gathered data will be utilized to feed a deep-learning model for predicting irrigation needs and determining the required water quantity.

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