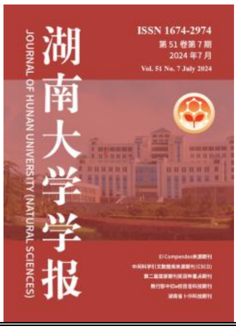


湖南大学学报（自然科学版）
Journal of Hunan University (Natural Sciences)

第 51 卷 第 7 期
2 0 2 4 年 7 月

Available online at http://jonuns.com/index.php/journal/index

Vol. 51 No. 7
July 2024

Open Access Article

https://doi.org/10.55463/issn.1674-2974.51.7.17

Harvesting Insights: Combining the IoT and a WSN for Tomato Cultivation in a Greenhouse Farming Environment

Iván Darío Aristizábal Henao, Jhon Mauricio Noguera Jimenez, Angie Paola Racines Vanegas, Jose Daniel Victoria Patiño, Angel Jose Lozada Das Dores*

Engineering Faculty, Unidad Central del Valle del Cauca, Tuluá, Colombia

* Corresponding author: alozada@uceva.edu.co

Received: May 25, 2024 / Revised: June 20, 2024 / Accepted: June 29, 2024 / Published: July 31, 2024

Abstract: The aim of this research is to simulate a wireless sensor network (WSN) and implement an internet-of-things (IoT) system to measure environmental variables, such as temperature, relative humidity, and CO2 in greenhouse farming, and to compare the plant stem lengths of tomato crops cultivated in both soil-based and hydroponic systems. The research is composed of two main stages: design and simulation of WSN, which includes the optimal placement of sensor nodes and checking communication protocols for data exchange, and implementation of the IoT system in the greenhouse by deploying physical sensor nodes, configuring the gateway, and establishing communication channels. The novelty of the research lies in the design and simulation of a WSN under the TrueTime framework (MATLAB, Simulink) prior to implementation, allowing us to avoid data loss, latency, and unnecessary implementation efforts. In addition, the evaluation of the aforementioned variables in tomato crops cultivated simultaneously in soil-based and hydroponic systems within a greenhouse was conducted to determine the most suitable method for implementation under tropical weather conditions. The research showed results similar to those of other studies regarding the simulation of a partial or complete WSN using MATLAB/Simulink. Allowing identifying that, hydroponics initially accelerates growth but later faces limitations due to root space; meanwhile, soil-based crops exhibit more uniform growth and yield larger, faster-ripening fruits. Compared to other studies, this research minimizes device quantity, reduces cost and complexity, and also successfully achieved environmental measurements, corroborating findings from other studies that also highlight the use of MATLAB/Simulink for simulating a WSN and components. The study found a match between simulated data communication and real-world data exchange between sensor nodes and gateway nodes, which is crucial for the reliability and accuracy of the sensor network. This study found that soil-based crops experienced less temperature stress due to microclimate variations, leading to uniform growth, which is an essential finding for agricultural practices. In addition, evidence indicates that both hydroponic and soil-based systems showed variations in stem size, where soil-based crops had larger stems at the end of the study period.

Keywords: greenhouse, internet of things, wireless sensor network, Zigbee, crops.

收获见解：将物联网与 WSN 相结合，在温室农业环境中进行番茄种植

摘要：本研究的目的是模拟无线传感器网络(WSN)并实施物联网(IoT)系统，以测量温室种植中的环境变量，例如温度、相对湿度和二氧化碳，并比较土壤和水培系统中种植的番茄作物的茎长。这项研究由两个主要阶段组成：WSN 的设计和仿真，包括传感器节点的最佳放置和检查数据交换的通信协议，以及通过部署物理传感器节点、配置网关和建立通信通道

在温室中实施 IoT 系统。这项研究的新颖之处在于在实施之前在真時框架(MATLAB、Simulink)下设计和仿真 WSN，使我们能够避免数据丢失、延迟和不必要的实施工作。此外，还对温室内土壤和水培系统中同时种植的番茄作物的上述变量进行了评估，以确定在热带气候条件下实施的最合适方法。这项研究的结果与其他使用 MATLAB/Simulink 模拟部分或完整 WSN 的研究结果相似。可以确定的是，水培最初会加速生长，但后来会因根部空间而受到限制；而土壤作物生长更均匀，果实更大、成熟更快。与其他研究相比，这项研究最大限度地减少了设备数量，降低了成本和复杂性，并成功实现了环境测量，证实了其他研究的结果，这些研究也强调了使用 MATLAB/Simulink 模拟 WSN 和组件。研究发现，传感器节点和网关节点之间的模拟数据通信与真实世界数据交换相匹配，这对于传感器网络的可靠性和准确性至关重要。这项研究发现，土壤作物因微气候变化而受到的温度压力较小，从而导致生长均匀，这是农业实践的一个重要发现。此外，有证据表明，水培和土壤系统都表现出茎的大小变化，其中在研究期结束时，土壤作物的茎更大。

关键词：温室、物联网、无线传感器网络、Zigbee、农作物。

1. Introduction

Tomato crops are important ingredients in many Colombian meals because of their high content of nutrients, such as calories, carbohydrates, and fiber, and are also excellent sources of calcium, vitamin C, potassium, etc. They are one of the vegetables most commonly used in Colombian meals. Therefore, their value in Colombian food security is high.

The IoT and WSNs appear as technological options for monitoring crops such as cassava crops [1], oil palms in Colombia [2], sago palms [3], tomato crops in Malaysia [4], and brinjal crops (eggplants) in India [5].

Under this concept, it is possible to monitor several microclimate environmental conditions in greenhouse farming, such as temperature, oxygen, relative humidity, and light intensity, among others [6], [7], which is performed remotely by website platforms or mobile apps.

In addition, researchers have been implementing several technologies within the IoT or a WSN to monitor the mentioned variables in greenhouses. For instance, for wireless communications (TX/RX), they used Zigebee [8], LoRaWAN [9], and NB-IoT [10]; each offers its advantages and disadvantages, such as range, packet loss, and cost.

To measure environmental parameters, researchers have used DHT and SHT series sensors for relative humidity and temperature [11], [12], SP Lite2 pyranometers for solar radiation [12], and MSP-6 sensors for oil moisture sensors [13], among others.

According to previous research, microclimate conditions in a greenhouse affect any crop cultivated within these structures; therefore, it is essential to measure, visualize, and regulate fundamental environmental factors, including temperature, relative humidity, CO2 levels, and soil moisture, to cultivate and harvest high-quality fruits and vegetables, regardless of the conditions outside of the greenhouse.

There are countries around the world that are developing research to optimize the automation process within greenhouses to improve the harvest of fruits and vegetables. Some of these countries are India, Colombia, and China [14].

The importance of agriculture in China is highlighted because of its impact on China's economic activity and national food security [15]. In this regard, The cultivation of tomato plants in greenhouses has been optimized to increase productivity and reduce environmental impact through the use of technological innovations, including microprocessors (e.g., Raspberry Pi platforms) and cloud technologies. These advancements have been made with the understanding that tomato plants can thrive in temperatures ranging from below 0°C to above 30°C.

Advancements in agricultural technologies have led to the exploration of innovative methods for enhancing crop production and environmental monitoring. The present research endeavored to explore the operationalization of WSNs and the IoT technologies within a greenhouse context, while simultaneously examining the growth performance differential of tomato plants cultivated in soil-based and hydroponic systems.

Hypothesis 1: Implementing a WSN and the IoT systems in a greenhouse environment will result in accurate and reliable measurements of environmental variables (temperature, relative humidity, and CO2) with minimal data loss and latency when simulated under the TrueTime framework (MATLAB, Simulink) prior to physical deployment.

This hypothesis is based on the premise that advanced simulation tools, such as the TrueTime framework in MATLAB, Simulink, can effectively model the performance of WSN and IoT systems.

Hypothesis 2: Tomato crops cultivated in soil-based systems will exhibit more uniform growth, larger stem size, and less temperature stress than those grown in hydroponic systems, under the same greenhouse conditions and tropical weather, because of better microclimate regulation and root space availability.

This hypothesis is based on the understanding that soil-based systems provide a more stable microclimate and greater root space, which are essential for healthy growth of tomato plants.

This research was conducted to examine tomato plants cultivated in both soil-based and hydroponic systems under controlled climate stress in a greenhouse. The measurement of environmental variables, such as temperature, relative humidity, and CO2, was automated through the use of technologies such as the IoT WSN and Zigbee.

The simulation of a WSN was achieved through the TrueTime Framework software, which was applied to simulate communication between WSN nodes as they measured the aforementioned variables. The implementation of the entire system was then carried out to compare the plant stem lengths of tomato crops cultivated in both systems.

The academic community aspires to facilitate cooperation between academia and the quadruple helix stakeholders, including industry, government, and society, through initiatives such as this project [16].

2. Materials and Methods

A flow chart of this project, describing the methodology used, is shown in Fig. 1.

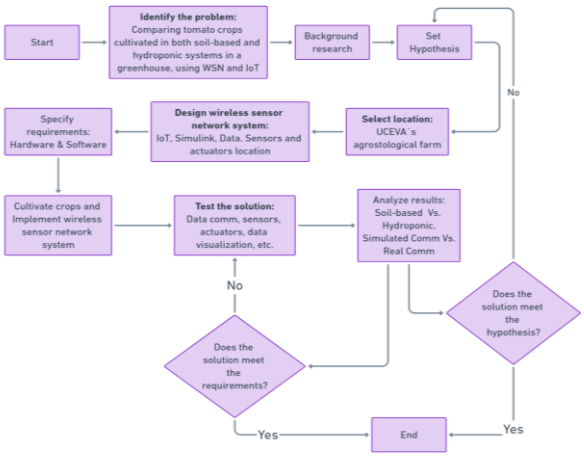


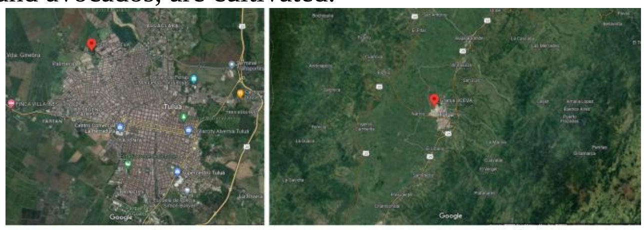
Fig. 1 Flow chart of the project (The authors)

2.1. Characteristics and Conditions of Tomato Crops under Study

This investigation examined the cultivation of the tomato variety Solanum lycopersicum in a greenhouse situated in Colombia using two systems. Specifically, the researchers compared the growth of tomatoes cultivated in a soil-based system with those grown in a hydroponic system.

An experimental investigation was conducted over a two-month period to examine the simulation and automation of system control in a greenhouse that measured environmental parameters, including the temperature, relative humidity, CO2, and tomato plant stem length. The greenhouse in the Valle del Cauca Department, Colombia, is situated in the municipality of Tuluá within the UCEVA agrostological farm, at coordinates 4°06'11.9" N 76°12'37.0" W. The climate of this region is characterized as tropical and warm throughout the year, with particularly high temperatures during the summer months in certain areas.

Fig. 2a illustrates the UCEVA farm's position relative to Tuluá's urban region to the northwest, while Fig. 2b displays Tuluá's influence area. It is evident from Fig. 2b that numerous square kilometers of natural vegetation exist within this region, where a variety of crops, such as sugarcane, potatoes, tomatoes, and avocados, are cultivated.



(a) (b)

Fig. 2 Greenhouse location (Google Maps)

The research is composed of two stages: the first is the design and simulation of the IoT and WSN system using the TrueTime Framework software, and the second is the implementation of the entire system. Fig. 3 shows the greenhouse design and dimensions, with a total area of 47.1 m^2 and height of 3.6 mts.

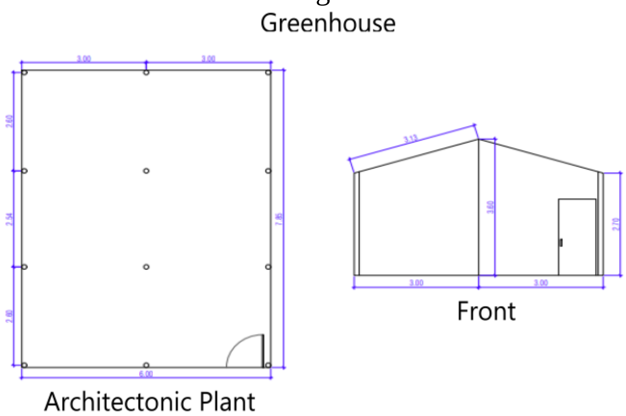


Fig. 3 Greenhouse design (The authors)

2.2. WSN Design and Simulation

It was necessary to select the environmental parameters to be measured and distribute the electronic devices (five nodes) within the greenhouse, as shown in Fig. 4. Sensor nodes (four nodes) measured the temperature, relative humidity, and CO2 (carbon dioxide) parameters for both soil-based and hydroponic systems, and all collected information was centralized by a gateway node and displayed on a website interface.

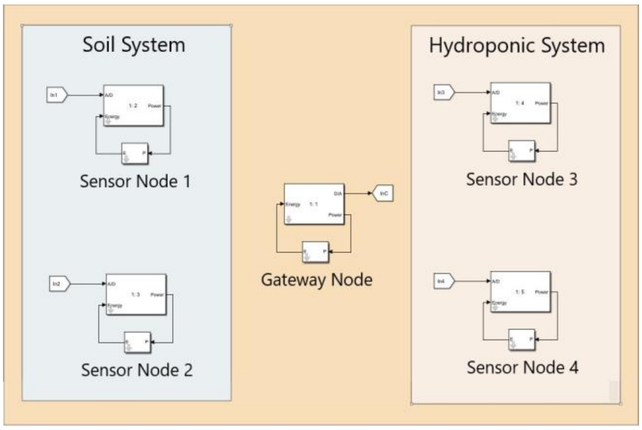


Fig. 4 WSN organization under simulation (The authors)

Each node is composed of one Xbee Module S2C, one MQ135, one DHT22, one XBIB-U-DEV module, and one Arduino Nano. The gateway node is composed of one Xbee Module S2C and one Raspberry Pi B+, which allows communication between the system and website platform. Once the components of the WSN were chosen, it was necessary to simulate the TX/RX data between the nodes. To accomplish this, the TrueTime Framework software was employed within the MATLAB/Simulink environment [17], [18] (Fig. 5).

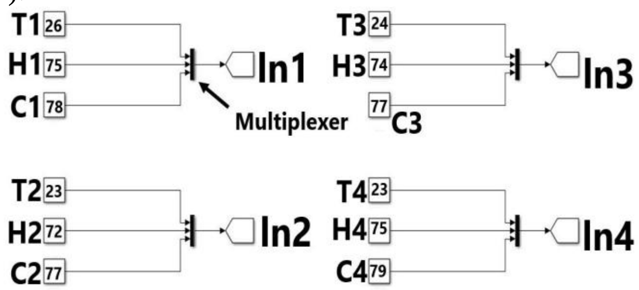


Fig. 5 Communication between sensors and nodes (The authors)

The framework capable of working with a wireless network block based on the IEEE 802.11 and IEEE 802.15.4 standards. The latter standard is used for Zigbee technology. Additionally, this framework allows for interaction with MATLAB functions, C++, and Python languages.

In the simulation diagram, each measured parameter was labeled as T1, T2, T3, and T4 for temperature; H1, H2, H3, and H4 for relative humidity; and C1, C2, C3, and C4 for CO2, as shown in Fig. 5. Each block of variables (T, H, and C) was connected to a multiplexer that allowed the three values to be grouped into a single variable labeled as "ln" (representing each Arduino Nano input).

Each "ln" organizes the information at the input of each sensor node; where "ln1" collected data from T1, H1, C1; "ln2" from T2, H2, C2, etc.

According to Fig. 6, the function of the gateway node labeled "lnC" is to receive data (T, H, and C) from the sensor nodes (ln1 to ln4) via wireless communication and transmit them as output data.

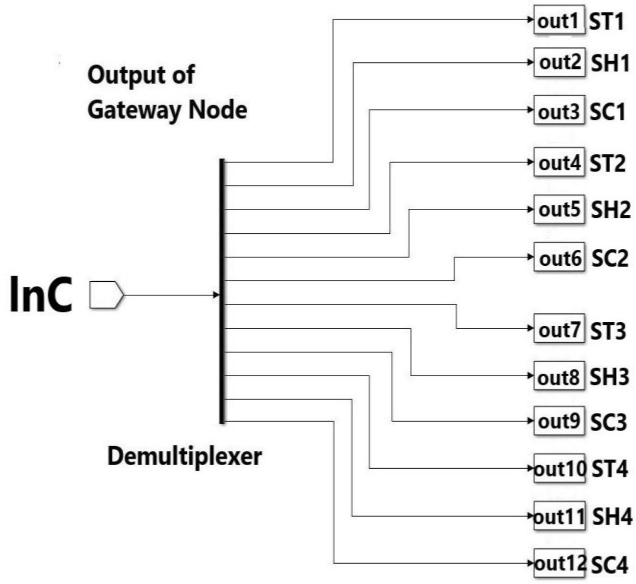


Fig. 6 Communication between the gateway node and Raspberry Pi (The authors)

It was necessary to demultiplex the data to organize and visualize them, and the output data were labeled as ST1, ST2, ST3, and ST4 for temperature; SH1, SH2, SH3, and SH4 for relative humidity; and SC1, SC2, SC3, and SC4 for CO2 values. Thus, this information should be displayed on a website.

2.3. Control System Design and Simulation

To control crop growth, it was necessary to control the irrigation system, using the temperature parameter as a reference. The control system simulation was performed in the MATLAB/Simulink environment, as shown in Fig. 7.

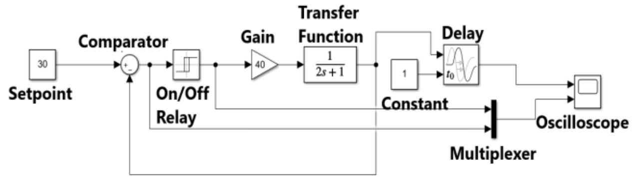


Fig. 7 Control system for the temperature variable (The authors)

The control system was composed of controller elements, such as Raspberry Pi B+ and a 5V 4-channel relay module, and controlled elements, such as electrovalves, nebulizers, and a water pump. The setpoint (sp) was fixed at 33°C as a standard operating value, and a temperature range of 20-35°C was established, which corresponds to the optimal temperature range for the crop. The hysteresis (h) value was calculated using the following equation:

$$h = \frac{h_s - h_i}{2} \quad (1)$$

According to Equation (1), it is possible to determine the value of h provided that h_s = 35 and h_i = 20, resulting in h = 7.5. This means the setpoint may vary between 20 and 35°C. To control the irrigation system, it is necessary to set several values, including the process variable (pv).

$$pv = sp - h \quad (2)$$

According to Equation (2), the value of pv is determined by substituting the values of sp and h, resulting in a value of 25.5. The irrigation system was managed when the following equation was fulfilled:

$$pv < sp - h \ \ldots\text{Irrigation off}$$
$$pv > sp - h \ \ldots\text{Irrigation on} \quad (3)$$

3. Results and Discussion

3.1. System Performance

It can be observed from Fig. 8 that the simulated communication between the sensor nodes and gateway node matched the real data behavior, which indicates the effectiveness of using the TrueTime framework for this purpose.

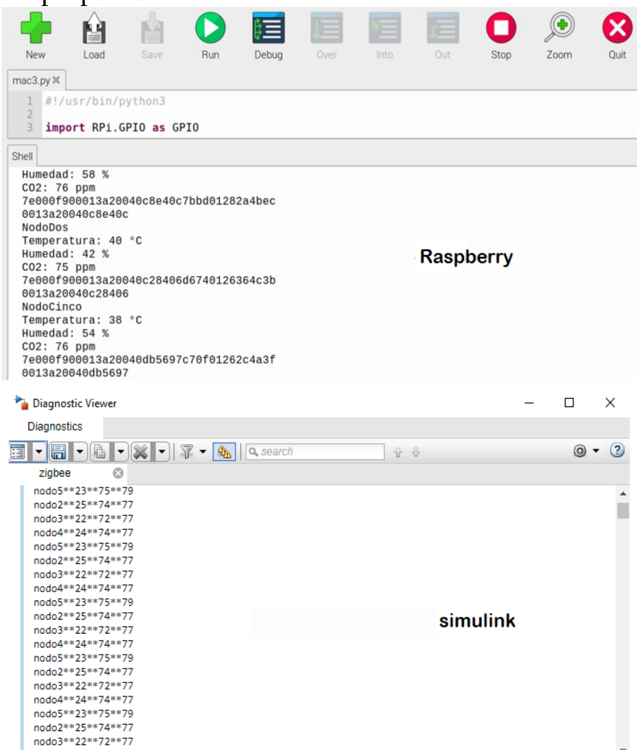


Fig. 8 Simulated and real data of the WSN (The authors)

3.2. IoT System Implementation

According to the system design previously described, Fig. 9 illustrates the positions of the sensor nodes, gateway node (that is, the WNS), and tomato crops for both hydroponic and soil-based systems (located on the right and left sides of the figure, respectively).

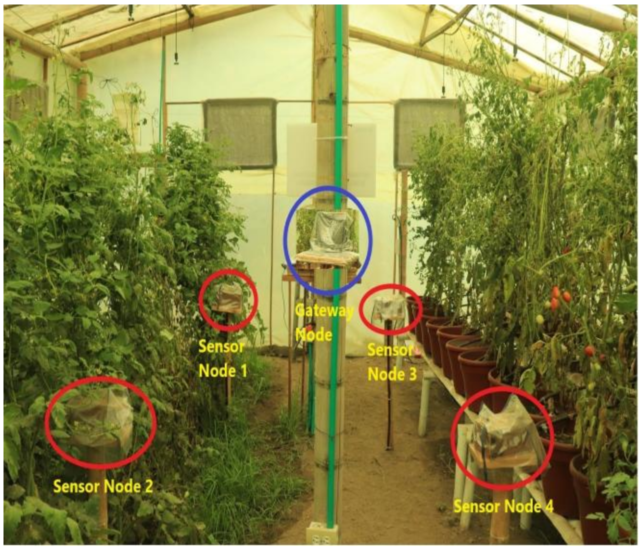


Fig. 9 IoT implementation (The authors)

Each node was protected with a plastic cover to preserve the electronics; each was placed over stacks to prevent any malfunction due to irrigation and any other environmental conditions.

Nebulizers and electrovalves were placed between the crops to optimize irrigation in a distribution similar to that shown in Fig. 10.

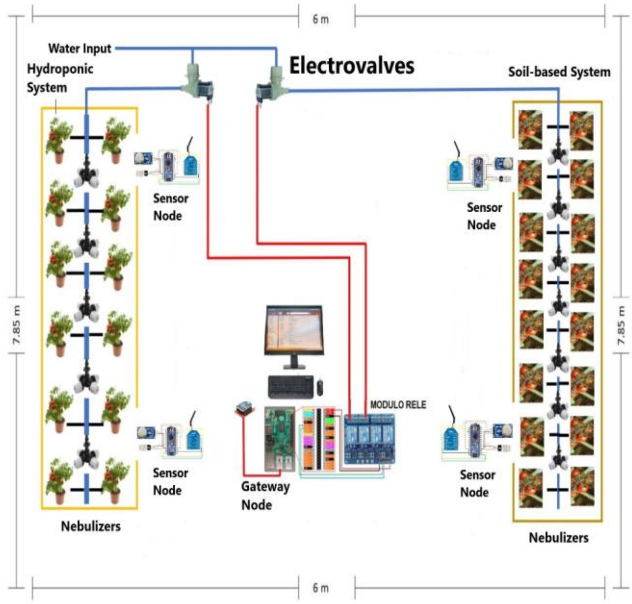


Fig. 10 Nebulizers and electrovalves' location (The authors)

An online graphical user interface (GUI) was developed to visualize the collected data from the sensor nodes (temperature, relative humidity, and CO2), including the number of the nodes, date, and time.

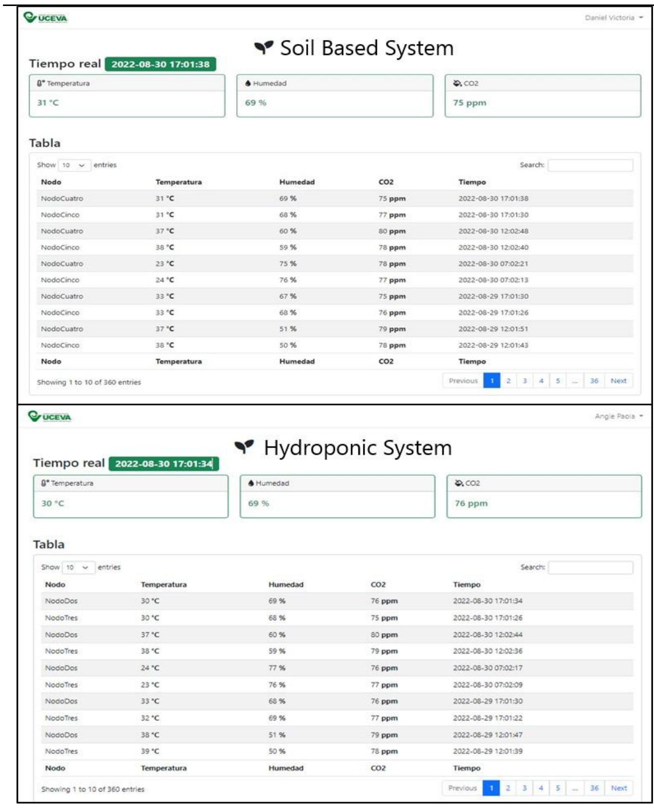


Fig. 11 Graphical user interface (The authors)

3.3. Raw Data

The environmental data obtained by the sensor nodes provided several insights into the microclimate of the greenhouse. Fig. 12 displays the fluctuations in environmental parameters, including temperature, relative humidity, and CO2, at three different time points (07:00, 12:00, and 19:00) over a two-month period. Based on these results, CO2 levels have low variation across the day (less than 10%), moving between 75 and 85 ppm.

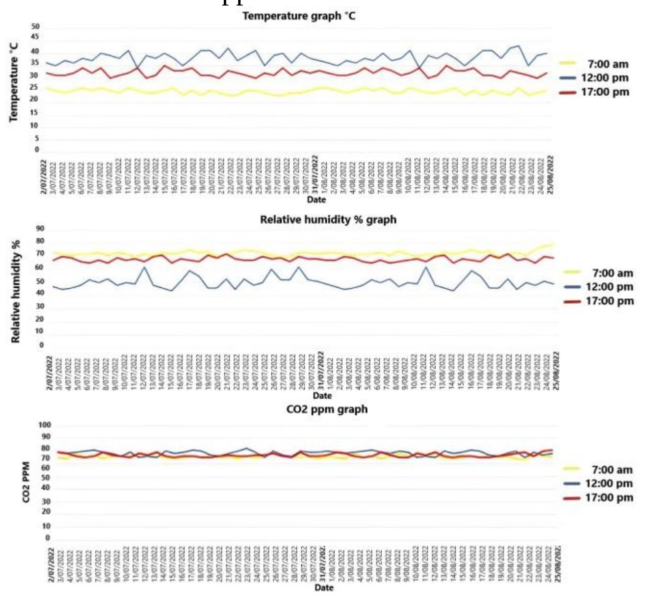


Fig. 12 Measured environmental variables (The authors)

The relative humidity showed the lowest values at noon (12:00) and the highest values in the morning (07:00) and afternoon (17:00), with the greatest variations occurring at 12:00, varying between 42% and 62% during the same period. Temperature showed the greatest differences at each time point. As expected, the lowest temperature occurs in the morning, varying from 22°C to 26°C, and the highest temperature occurs at noon, oscillating between 35°C and 42°C.

Owing to variations in temperature and relative humidity within the greenhouse, it is necessary to protect the electronic devices to endure their lifetime.

During these two months, both the hydroponic and soil-based systems showed some variations in stem size, as shown in Fig. 13.

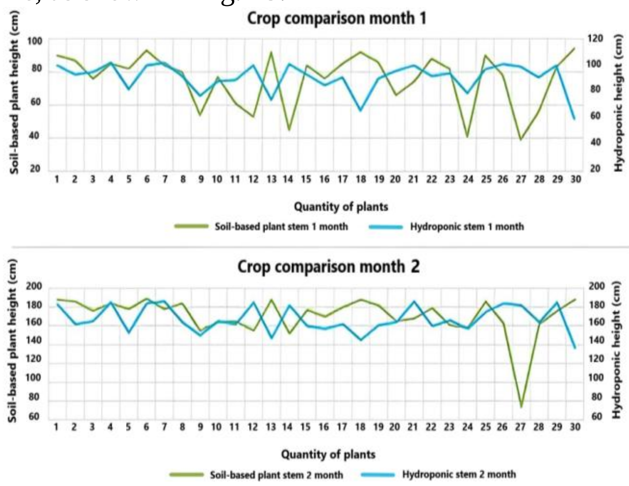


Fig. 13 Plant stem comparison (The authors)

These variations were more significant during the first month in the soil-based system than in the hydroponic system. During the second month of cultivation, the stem size of crops grown using the hydroponic method was found to be lower compared to those grown using the soil-based method. At the end of the study period, the stem size was larger in the tomato crops cultivated with soil-based structures.

WSNs were integrated with Zigbee technology, which operates under the IEEE 802.15.4 Zigbee communication protocol [19], to transmit and receive data on temperature, CO2, and humidity variables [20]. Zigbee technology enables wireless communication with lower energy consumption than Wi-Fi, but it is not suitable for transmitting large amounts of data. Nevertheless, both technologies function within the same 2.4-GHz frequency band.

Based on these technologies, we designed and simulated a network based on star topology to match the distribution of nodes.

Due to the nature of the greenhouse and its internal environment, which includes temperature, an on/off control system with hysteresis was developed and simulated in the MATLAB/Simulink software [21]. This simulation was conducted to determine the optimal temperature variation range and setpoint for crops. The control system was designed to respond to the feedback conditions derived from the sensor-measured variables.

According to techniques used for cultivating crops, such as hydroponics [22] and traditional techniques in soil, under the same physical conditions, hydroponic system crops showed faster growth during the first month than plants of the soil-based counterpart because hydroponics allows a controlled environment by taking advantage of plant resources and the recirculation of nutrients. However, it reached a point where its growth was limited because the roots no longer had room to grow, altering the development of the crop.

Soil-based systems are known to produce plants that are less affected by temperature and exhibit more uniform population growth. By the second month, the growth of these plants accelerated significantly, reaching a size comparable to that of hydroponic system plants. This allowed the soil-based plants to develop larger fruits that ripened faster, in contrast to the hydroponic crop, which produced a greater number of smaller fruits that ripened more slowly.

3.4. Comparison with Other Studies

In the context of WSNs, numerous technologies are available for collecting and transmitting data from digital sensors to an online platform. In this study, we utilized a Raspberry Pi B+ and a ZigBee gateway to accomplish this task. Other researchers have used a variety of devices such as NRF24L01, ESP8266, and STM32 to achieve similar results in their projects [23]. This research minimizes the number of devices used in the project, thereby reducing cost and complexity.

Implementing a WSN based on Zigbee technology was chosen because of its advantages such as scalability, low power consumption, and security. It is possible to connect several devices (sensors) to measure several parameters such as temperature, CO2, and PH conditions [24]. In this sense, this study attained the predicted environmental measurement and findings that align with those of [23] and [24].

Prior to implementing WSNs, a crucial step involves simulating communication between sensor nodes and gateway nodes. In this regard, the MATLAB/Simulink environment was utilized to verify whether data packages, including temperature, relative humidity, and CO2 measurements, transmitted from the sensor nodes to the gateway node were in accordance with expectations and adhered to the IEEE 802.15.4 Zigbee communication protocol.

A more in-depth study was conducted by [25], in which the entire WSN was simulated and prototyped based on previous simulation results. This approach demonstrated the effectiveness of utilizing the MATLAB/Simulink environment to save time and reduce costs while maintaining accuracy in decision-making for such systems.

On the other hand, [26] summarized several studies that used the MATLAB/Simulink environment to partially or completely simulate a WSN network and its components.

4. Conclusion

The utilization of IoT technologies in crop management involves the deployment of WSNs employing technologies such as Zigbee and Wi-Fi, which are supported by the IEEE 802.15.4 and IEEE 802.11 standards. These networks are designed to monitor various parameters, including temperature, humidity, and pH, with the aim of reducing energy consumption in sensor devices. Therefore, Zigbee technology is best suited to these conditions.

With the design and simulation of the WSN in MATLAB/Simulink using the True-Time framework, the correct transmission and reception of the information based on Zigbee technology and the IEEE 802.15.4 standard are verified during the implementation stage under star topology, where the coordinating node receives the information from the sensor nodes without errors and latency, confirming hypothesis 1; then, it is processed and visualized by connecting a Raspberry Pi B+ and a PC.

In the greenhouse, there is an effective monitoring system for temperature, humidity, and CO2 levels, which enables the use of an on/off control system to regulate temperature. By employing foggers, the temperature stress experienced by the tomato crops can be reduced, particularly in regions with high temperatures. This indicates that cherry tomatoes can be cultivated using both edaphic and hydroponic methods in such environments.

Through the examination of temperature, relative humidity, and CO2 levels in edaphic and hydroponic cultivation methods, it was observed that edaphic cultivation demonstrated a better adaptation to greenhouse conditions, which supported Hypothesis 2. Conversely, although hydroponic cultivation exhibited faster growth compared to edaphic cultivation under similar conditions, the plants experienced greater deterioration. The entire process can be remotely monitored through a web application, utilizing various wireless and storage technologies, which aligns with the principles of IoT technologies.

The literature currently available indicates the use of simulation and development of WNSs and/or the IoT for monitoring crop variables, including temperature and humidity, both within and outside of a greenhouse environment. However, the present research employs the aforementioned technologies to compare two types of cultivation, namely soil-based and hydroponic systems, within the confines of a greenhouse. This may lead to identifying the cultivation methods best suited for various crop types and climates, which can result in significant cost and effort savings when growing and harvesting high-quality products.

5. Future Research

This research uses several technologies (MATLAB/Simulink, Zigbee, etc.) to measure environmental parameters within a greenhouse to study how these parameters may affect the stem size of tomato crops.

Improving this study may involve incorporating additional technological resources, such as cameras, to employ artificial vision in analyzing various parameters, including plant length and disease prevalence in both plants and fruits. By doing so, it may be possible to minimize crop loss and optimize time and financial resources.

Factors such as the level of incident ultraviolet (UV) radiation, soil temperature and humidity, fertilizer components, automated lighting, and ventilation can contribute to extending the life of crops and improving the quality of their fruit. When these factors are monitored, they can have a significant impact on the overall success of the crop. Thus, there is a need for extensive research to examine how all these parameters collectively influence a specific crop variety in a greenhouse located in the tropics, taking into account the effects of climate change and the continuous rise in global temperatures.

On the other hand, artificial intelligence can utilize the collected data to create predictive models and automate actions related to the management of the greenhouse system, including irrigation and light control.

References

[1] CAICEDO-ORTIZ J. G., DE-LA-HOZ-FRANCO E., MORALES ORTEGA R., PIÑERES-ESPITIA G., COMBITA-NIÑO H., ESTÉVEZ F., and CAMA-PINTO A. Monitoring system for agronomic variables based in WSN technology on cassava crops. *Computers and Electronics in Agriculture*, 2018, 145: 275–281. https://doi.org/10.1016/j.compag.2018.01.004

[2] CULMAN M., DE FARIAS C. M., BAYONA C., and CABRERA CRUZ J. D. Using agrometeorological data to assist irrigation management in oil palm crops: A decision support method and results from crop model simulation. *Agricultural Water Management*, 2019, 213: 1047–1062. https://doi.org/10.1016/j.agwat.2018.09.052

[3] KHO E. P., CHUA S. N. D., LIM S. F., LAU L. C., and GANI M. T. N. Development of young sago palm environmental monitoring system with wireless sensor networks. *Computers and Electronics in Agriculture*, 2022, 193: 106723. https://doi.org/10.1016/j.compag.2022.106723

[4] SHAMSHIRI R. R., BOJIC I., VAN HENTEN E., BALASUNDRAM S. K., DWORAK V., SULTAN M., and WELTZIEN C. Model-based evaluation of greenhouse microclimate using IoT-Sensor data fusion for energy efficient crop production. *Journal of Cleaner Production*, 2020, 263: 121303. https://doi.org/10.1016/j.jclepro.2020.121303

[5] KAUR N., & DEEP G. IoT-Based Brinjal Crop Monitoring System. In: GUPTA D., DE ALBUQUERQUE V. H. C., KHANNA A., and MEHTA P. L. (eds.) *Smart Sensors for Industrial Internet of Things*. Springer, Cham, 2021: 231–247. https://doi.org/10.1007/978-3-030-52624-5_15

[6] MAIOLO L., & POLESE D. Advances in Sensing Technologies for Smart Monitoring in Precise Agriculture. *Proceedings of the 10th International Conference on Sensor Networks*, 2021, 1: 151–158. https://doi.org/10.5220/0010415401510158

[7] KOLAPKAR M. M., & SAYYAD S. B. Greenhouse Microclimate Study for Humidity, Temperature and Soil Moisture Using Agricultural Wireless Sensor Network System. In: SANTOSH K. C., & GAWALI B. (eds.) *Recent Trends in Image Processing and Pattern Recognition.* Springer, Singapore, 2021: 278–289. https://doi.org/10.1007/978-981-16-0493-5_25

[8] TANG R., ARIDAS N. K., and ABU TALIP M. S. Design of Wireless Sensor Network for Agricultural Greenhouse Based on Improved Zigbee Protocol. *Agriculture*, 2023, 13(8): 1518. https://doi.org/10.3390/agriculture13081518

[9] VALENTE A., COSTA C., PEREIRA L., SOARES B., LIMA J., and SOARES S. A LoRaWAN IoT System for Smart Agriculture for Vine Water Status Determination. *Agriculture*, 2022, 12(10): 1695. https://doi.org/10.3390/agriculture12101695

[10] NIU L. Design of intelligent agricultural environmental big data collection system based on ZigBee and NB-IoT. Proceedings of the IEEE 2nd International Conference on Electrical Engineering, Big Data and Algorithms, Changchun, 2023, pp. 1299–1304. https://doi.org/10.1109/EEBDA56825.2023.10090649

[11] LIM H., PINONTOAN R., and URANUS H. P. Hydroponic vegetable cultivation with nutrient film technique system in a greenhouse based on the Internet of Things. *AIP Conference Proceedings*, 2022, 2659: 060018. https://doi.org/10.1063/5.0118502

[12] FERENTINOS K. P., KATSOULAS N., TZOUNIS A., BARTZANAS T., and KITTAS C. Wireless sensor networks for greenhouse climate and plant condition assessment. *Biosystems Engineering*, 2017, 153: 70–81. https://doi.org/10.1016/j.biosystemseng.2016.11.005

[13] THENE M. E., & MATHABA T. N. D. Analysing the Design of a Solar Energy Harvesting Wireless Sensor Node for Agricultural Applications. Proceedings of the International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems, Durban, 2022, pp. 1–6. https://doi.org/10.1109/icABCD54961.2022.9856301

[14] LIN Y. Q., & SHEN H. Design of Greenhouse Monitoring System Based on ZigBee Technology. Proceedings of the 3rd International Conference on Information Science, Parallel and Distributed Systems, Guangzhou, 2022, pp. 252–256. https://doi.org/10.1109/ISPDS56360.2022.9874013

[15] OECD. *Agricultural Policy Monitoring and Evaluation 2022: Reforming Agricultural Policies for Climate Change Mitigation.* OECD Publishing, Paris, 2022. https://doi.org/10.1787/7f4542bf-en

[16] LOZADA-DAS-DORES Á. J., CASALLAS-RESTREPO R. E., BEDOYA-GARCÍA J. A., CASTELLANOS-GARZÓN J. A., and REY-PIEDRAHITA A. Dispensador de cajetillas de cigarrillos para Mipyme

como experiencia de relación academia-sector productivo, Tuluá. *Revista Científica*, 2021, 43(1): 109–123. https://doi.org/10.14483/23448350.17642.
[17] CERVIN A., HENRIKSSON D., LINCOLN B., EKER J., and ARZEN K. E. How does control timing affect performance? Analysis and simulation of timing using Jitterbug and TrueTime. *IEEE Control Systems*, 2003, 23(3): 16–30. https://doi.org/10.1109/mcs.2003.1200240
[18] DEPARTMENT OF AUTOMATIC CONTROL. *TrueTime*, 2022. https://www.control.lth.se/?id=108009
[19] NUNEZ V. J. M., FONTHAL R. F., and QUEZADA L. Y. M. Design and Implementation of WSN and IoT for Precision Agriculture in Tomato Crops. Proceedings of the IEEE ANDESCON, Santiago de Cali, 2018, pp. 1–5. https://doi.org/10.1109/ANDESCON.2018.8564674
[20] PRAKASH S. Zigbee based Wireless Sensor Network Architecture for Agriculture Applications. Proceedings of the 3rd International Conference on Smart Systems and Inventive Technology, Tirunelveli, 2020, pp. 709–712. https://doi.org/10.1109/ICSSIT48917.2020.9214086
[21] LI B., & ALLEYNE A. G. Optimal on-off control of an air conditioning and refrigeration system. Proceedings of the American Control Conference, Baltimore, Maryland, 2010, pp. 5892–5897. https://doi.org/10.1109/ACC.2010.5531215
[22] BAKHTAR N., CHHABRIA V., CHOUGLE I., VIDHRANI H., and HANDE R. IoT based Hydroponic Farm. Proceedings of the International Conference on Smart Systems and Inventive Technology, Tirunelveli, 2018, pp. 205–209. https://doi.org/10.1109/ICSSIT.2018.8748447
[23] SONG Y., BI J., and WANG X. Design and implementation of intelligent monitoring system for agricultural environment in IoT. *Internet of Things*, 2024, 25: 101029. https://doi.org/10.1016/j.iot.2023.101029
[24] WANG Z. Greenhouse data acquisition system based on ZigBee wireless sensor network to promote the development of agricultural economy. *Environmental Technology & Innovation*, 2021, 24: 101689. https://doi.org/10.1016/j.eti.2021.101689
[25] ABDAL-KADHIM A. M., & LEONG K. S. Design and Model of Low-Power Wireless Sensor Node Powered by Hybrid Heterogeneous Energy Harvesters with Energy Gap Coverage. Proceedings of the IEEE International Conference on Sensors and Nanotechnology, Penang, 2019, pp. 1–4. https://doi.org/10.1109/SENSORSNANO44414.2019.8940103
[26] SHARMA R., VASHISHT V., and SINGH U. Modelling and simulation frameworks for wireless sensor networks: a comparative study. *IET Wireless Sensor Systems*, 2020, 10(5): 181–197. https://doi.org/10.1049/iet-wss.2020.0046

参考文:

[1] CAICEDO-ORTIZ J. G.、DE-LA-HOZ-FRANCO E.、MORALES ORTEGA R.、PIÑERES-ESPITIA G.、COMBITA-NIÑO H.、ESTÉVEZ F. 和 CAMA-PINTO A. 基于 WSN 技术的木薯作物农艺变量监测系统。农业计算机和电子技术，2018 年，145：275–281。https://doi.org/10.1016/j.compag.2018.01.004
[2] CULMAN M.、DE FARIAS C. M.、BAYONA C. 和 CABRERA CRUZ J. D. 使用农业气象数据协助油棕作物灌溉管理：一种决策支持方法和作物模型模拟结果。农业水资源管理，2019，213：1047–1062。https://doi.org/10.1016/j.agwat.2018.09.052
[3] KHO E. P.、CHUA S. N. D.、LIM S. F.、LAU L. C. 和 GANI M. T. N. 利用无线传感器网络开发幼树棕榈环境监测系统。农业计算机和电子技术，2022 年，193：106723。https://doi.org/10.1016/j.compag.2022.106723
[4] SHAMSHIRI R. R.、BOJIC I.、VAN HENTEN E.、BALASUNDRAM S. K.、DWORAK V.、SULTAN M. 和 WELTZIEN C. 基于模型的温室微气候评估，使用 IoT-传感器数据融合实现节能作物生产。清洁生产杂志，2020 年，263：121303。https://doi.org/10.1016/j.jclepro.2020.121303
[5] KAUR N. 和 DEEP G. 基于物联网的茄子作物监测系统。引自：GUPTA D.、DE ALBUQUERQUE V. H. C.、KHANNA A. 和 MEHTA P. L. (eds.) 工业物联网智能传感器。施普林格，占婆，2021 年：231–247。https://doi.org/10.1007/978-3-030-52624-5_15
[6] MAIOLO L. 和 POLESE D. 精准农业智能监测传感技术进展。第 10 届国际传感器网络会议论文集，2021 年，1：151–158。https://doi.org/10.5220/0010415401510158
[7] KOLAPKAR M. M. 和 SAYYAD S. B. 使用农业无线传感器网络系统进行温室微气候湿度、温度和土壤水分研究。在：SANTOSH K. C. 和 GAWALI B. (eds.) 图像处理和模式识别的最新趋势。施普林格，新加坡，2021 年：278–289。https://doi.org/10.1007/978-981-16-0493-5_25
[8] TANG R.、ARIDAS N. K. 和 ABU TALIP M. S. 基于改进的 Zigbee 协议的农业温室无线传感器网络设计。农业，2023 年，13(8)：1518。https://doi.org/10.3390/agriculture13081518
[9] VALENTE A.、COSTA C.、PEREIRA L.、SOARES B.、LIMA J. 和 SOARES S. 用于智能农业的 LoRaWAN 物联网系统，用于葡萄树水分状况测定。农业，2022 年，12(10)：1695。https://doi.org/10.3390/agriculture12101695
[10] NIU L. 基于 ZigBee 和 NB-IoT 的智能农业环境大数据采集系统设计。IEEE 第二届电气工程、大数据和算法国际会议论文集，长春，2023 年，第 1299-1304 页。https://doi.org/10.1109/EEBDA56825.2023.10090649
[11] LIM H.、PINONTOAN R. 和 URANUS H. P. 基于物联网的温室水培蔬菜种植营养膜技术系统。AIP 会议论文集，2022 年，2659：060018。https://doi.org/10.1063/5.0118502

[12] FERENTINOS K. P.、KATSOULAS N.、TZOUNIS A.、BARTZANAS T. 和 KITTAS C. 用于温室气候和植物状况评估的无线传感器网络。生物系统工程，2017 年，153 : 70-81 。https://doi.org/10.1016/j.biosystemseng.2016.11.005

[13] THENE M. E. 和 MATHABA T. N. D. 分析用于农业应用的太阳能收集无线传感器节点的设计。人工智能、大数据、计算和数据通信系统国际会议论文集，德班，2022 年 , 第 1-6 页 。https://doi.org/10.1109/icABCD54961.2022.9856301

[14] LIN Y. Q. 和 SHEN H. 基于 ZigBee 技术的温室监控系统设计。第三届信息科学、并行和分布式系统国际会议论文集，广州，2022 年，第 252-256 页。https://doi.org/10.1109/ISPDS56360.2022.9874013

[15] 经合组织。2022 年农业政策监测和评估：改革农业政策以减缓气候变化。经合组织出版，巴黎，2022 年。https://doi.org/10.1787/7f4542bf-en

[16] LOZADA-DAS-DORES Á。 J.、CASALLAS-RESTREPO R. E.、BEDOYA-GARCÍA J. A.、CASTELLANOS-GARZÓN J. A. 和 REY-PIEDRAHITA A. 与米皮梅相关的小雪茄分配器，图卢阿。科学杂志，2021 , 43(1) : 109–123 。https://doi.org/10.14483/23448350.17642。

[17] CERVIN A.、HENRIKSSON D.、LINCOLN B.、EKER J. 和 ARZEN K. E. 控制时序如何影响性能？使用吉特巴舞和真時分析和模拟时序。IEEE 控制系统，2003 , 23(3) : 16–30 。https://doi.org/10.1109/mcs.2003.1200240

[18] 自动控制部门。真時，2022 年。https://www.control.lth.se/?id=108009

[19] NUNEZ V. J. M.、FONTHAL R. F. 和 QUEZADA L. Y. M. 番茄作物精准农业的 WSN 和 IoT 设计和实施。IEEE ANDESCON 论文集，圣地亚哥德卡利，2018 年，第 1-5 页 。https://doi.org/10.1109/ANDESCON.2018.8564674

[20] PRAKASH S. 基于 Zigbee 的农业应用无线传感器网络架构。第三届智能系统和发明技术国际会议论文集，蒂鲁内尔维利，2020 年，第 709-712 页。https://doi.org/10.1109/ICSSIT48917.2020.9214086

[21] LI B. 和 ALLEYNE A. G. 空调和制冷系统的最佳开关控制。美国控制会议论文集，马里兰州巴尔的摩，2010 年 , 第 5892-5897 页 。https://doi.org/10.1109/ACC.2010.5531215

[22] BAKHTAR N.、CHHABRIA V.、CHOUGLE I.、VIDHRANI H. 和 HANDE R. 基于物联网的水培农场。智能系统和发明技术国际会议论文集，蒂鲁内尔维利，2018 年 , 第 205-209 页 。https://doi.org/10.1109/ICSSIT.2018.8748447

[23] 宋英，毕建军，王鑫。物联网农业环境智能监测系统设计与实现。物联网，2024，25：101029。https://doi.org/10.1016/j.iot.2023.101029

[24] 王哲。基于 ZigBee 无线传感器网络的温室数据采集系统促进农业经济发展。环境技术与创新，2021 年，24 ：101689。https://doi.org/10.1016/j.eti.2021.101689

[25] ABDAL-KADHIM A. M. 和 LEONG K. S. 由具有能量间隙覆盖的混合异构能量收集器供电的低功耗无线传感器节点的设计和模型。IEEE 国际传感器和纳米技术会议论文集，槟城，2019 年，第 1-4 页。https://doi.org/10.1109/SENSORSNANO44414.2019.8940103

[26] SHARMA R.、VASHISHT V. 和 SINGH U. 无线传感器网络的建模和仿真框架：一项比较研究。IET 无线传感器系统 , 2020 , 10(5): 181–197 。https://doi.org/10.1049/iet-wss.2020.0046