Impact of artificial light color on microgreen green spinach growth in an IoT-controlled environment

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Article Info

Article history:

Received May 25, 2025
Revised Jul 27, 2025
Accepted Oct 14, 2025

Keywords:

Artificial lighting
Microcontroller
Microgreen
Moisture Sensor
Soil moisture sensor
Temperature sensor

ABSTRACT

This study investigates the effect of different artificial colors red-blue and white on the growth of green spinach microgreens under an internet of things (IoT) based controlled environment and integrated sensors: DHT22 for temperature and humidity, and YL-69 for soil moisture. The experiment compared plant growth in two lighting scenarios over 10 days evaluating parameters including plant height and number of leaves. Results indicate that spinach microgreens grown under red-blue LED light achieved a slightly higher average height of 4.6cm and more leaves of 50 compared to white LED light with an average height of 4.5cm and 36 leaves. Although the difference between the two lighting conditions appears minor, a t-test was conducted to determine statistical significance. The results show that the difference in the number of leaves is statistically significant, suggesting that morphological responses particularly leaf growth take precedence over vertical steam elongation as an adaptive strategy to optimize environmental conditions.

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1. INTRODUCTION

Cultivation of plants has a significant advancement through the implementation of internet of things (IoT) particularly in smart farming. Utilizing sensors, smart farming systems can create and maintain optimal environments for plant growth, ensuring factors such as temperature, humidity, and soil moisture are precisely controlled [1]–[8]. The main goal of using IoT in agriculture enhances efficiency and productivity through real-time monitoring and automation. By integrating these technologies, farmers can monitor and manage crops more efficiently, leading to increased yields and reduced resource wastage [9]–[15]. IoT plays an important role by using different physical objects to increase the quantity and quality of the crops. Smart farming refers to using technology in agricultural activities such as remote controlling, sensing hardwares, wireless monitoring and many more [16]. Nowadays with the increasing number of populations, there is a shortage of land mostly in urban areas. Many urban places in Indonesia are facing this problem, it would be hard to cultivate plants in an area where there are not many lands [17], [18]. Smart indoor microgreen contributes a role giving a chance to cultivate plants in an urban area.

Land use is not only limited to agriculture or gardening activities to meet food needs, but it can also be utilized in other ways, such as by implementing an urban agriculture. One method of urban agriculture that can be applied in limited spaces is indoor farming. Indoor farming is the utilization of land within the home in areas that can be optimized. By doing so, the need for vegetables for daily consumption can be met. When conducted in a controlled environment, it supports optimal plant growth in an enclosed space. The implementation of indoor farming in a home setting has limitations in terms of planting area. Plants generally require a considerable amount of space, so an alternative that can be used is microgreens.

This project proposes developing an automated smart indoor farming including the controlling and monitoring unit, this will overcome the challenges faced in urban areas because of its shortage of land in cultivating plants. Vertically smart indoor farming is a solution to the absence of land and eases the process of cultivation, this project uses microcontroller ESP32 as the main control unit to connect to a cloud platform. Temperature, humidity and soil moisture sensor as an actuating unit used to control the growth process. However, one of the primary challenges in artificial lighting for indoor farming is selecting the optimal light color. According to Yeh and Chung [19], LED has been proposed as a primary light source for optimizing energy conversion and the nutrient supply. The use of two different light colors to fully understand the most effective color optimizing photosynthesis and plant development.

2. RELATED WORKS

Study from Burattini *et al.* [20] highlights the importance of artificial lighting used in greenhouses when sunlight radiation is insufficient for plant growth. Additional lighting is often required during winter in Nordic regions. Plant growth depends on the duration of light available during the day, so artificial light impacts energy consumption. The study used two lighting conditions with warm white light and cold white light on spinach plants. The results indicated that using cold white light for a total period of two months resulted in more optimal growth.

Tang *et al.* [21] examined how the intensity of light lamp was measured for growing water spinach in a closed environment. Ten containers were used, each with varying wattages of white and yellow fluorescent lamps. The growth of the plants was assessed based on root weight, root length, number of leaves, and plant height. The conclusion was that the 42-watt white lamp provided the most optimal plant growth results. Meanwhile, Abdelkader *et al.* [22] addresses the broader issue of low vegetable consumption, citing The World Health Organization (WHO) has stated that the recommended consumption of vegetables and fruits for a healthy life is 400 grams per day, while actual consumption falls short at around 208.89 grams. The reason for this problem is that the high price of vegetables causes people to focus more on carbohydrate-rich foods. The methods used include literature studies and design methods that encompass system design, hardware design, and IoT architecture design frameworks. It is expected that the design provided can produce vegetables in urban areas. Study from Jiang *et al.* [23] explores the use of energy-efficient light technology which has advanced for use in homes and offices. The focus of this research is the development and implementation of energy-saving lighting and experimentation on its effects on plants. The creation of an IoT system architecture is prepared for indoor use, equipped with several sensors, including RGB, UV Index, PAR quantum, temperature, humidity, soil moisture, and a camera. This experiment demonstrates how adaptive lighting can support efficient indoor plant growth. Similarly, Budavári *et al.* [24] emphasizes the role of IoT in addressing future food demands, projecting the need to feed 9.6 billion people by 2050. IoT highlights the importance and potential it can offer for economic and industrial development. The study describes a smart farming system that uses sensors (such as pH and soil moisture), an ESP32 microcontroller and a drip irrigation setup to enhance cultivation.

Improving spinach cultivation using artificial lighting which [25] focuses on a specific variety called “Disease-resistant 388” from the Netherlands, typically grown in open fields. Addressing inconsistencies in natural sunlight, researchers designed a specialized growth rack equipped with LED chips in red, blue and green. The research results show that a light ratio of red: blue=4:1 with a lighting duration of 13/11 hours per day allows the plants to grow more optimally. Meanwhile, Simanungkalit *et al.* [26] explores innovative solutions to global food insecurity is an important issue that affects the global population, with the number of people suffering from hunger increasing every year. Developing a smart system to monitor and control farming in a closed environment, such as agricultural boxes that do not receive sunlight, is essential. By using sensors to monitor key conditions such as temperature, humidity, lighting and water levels. The system ensures efficient, controlled cultivation, offering a promising alternative for sustainable food production.

The growth performance of green spinach with a particular focus on leaf development, which is a key indicator of vegetative health and productivity. Isaza *et al.* [27] has shown that environmental factors such as light spectrum, nutrient availability and temperature significantly influence the number and size of spinach leaves. Generally, optimal growth conditions promote a higher number of leaves indicating plant development. Studies comparing traditional soil-based cultivation with hydroponic systems have reported that hydroponically grown spinach often produces more leaves in shorter time due to consistent nutrient supply and water availability [28], [29].

3. METHOD

3.1. System design

In this paper, the smart indoor microgreen system is composed of two levels shown in Figure 1. The first level is a red-blue LED light scenario, and the second level is a white LED light scenario. Each level consists of a microgreen tray which is connected to a pipe by a water pump. Both scenarios are treated the same way with a difference in LED light color. Hardware components are connected to the microcontroller which is on the very top level to program each component works according to the program. The microcontroller collects data from sensors which are transmitted to a database for real-time monitoring using Blynk app. This integration of sensors, actuators, and IoT technology enables users to monitor and manage microgreen conditions efficiently, supporting consistent and controlled growth without requiring constant physical presence.

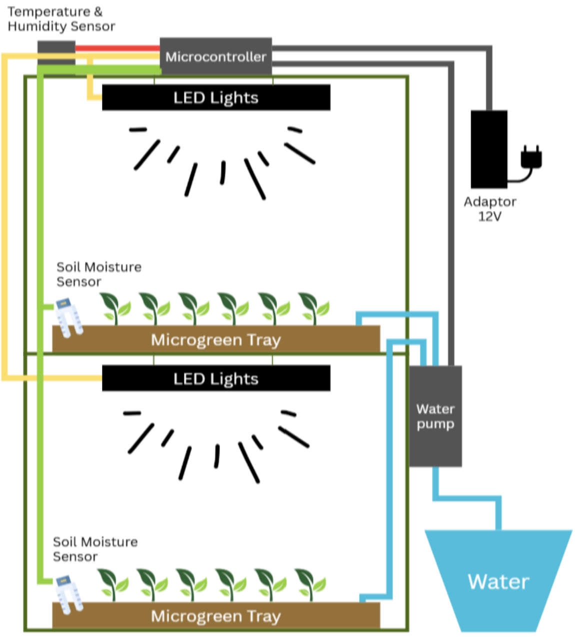


Figure 1. Smart indoor microgreen system design

3.2. Hardware planning

Figure 2 shows the architecture diagram for a smart indoor microgreen system using IoT. The system consists of both hardware and software. The main controller which connects to all the hardware is the ESP32 microcontroller which has in-build Wi-Fi. The system is controlled via the Blynk application. Moreover, each actuator is connected using a relay module which then connects to the breadboard and then connected to the microcontroller. The smart indoor microgreen system proposed in this paper is divided into two parts which are controlling and monitoring. The ability to control the system is primarily responsible for turning on and off water pumps that can be controlled via a smartphone. The monitoring allows the user to observe the condition of the microgreen plant. Table 1 shows a list of hardware components used in this research.

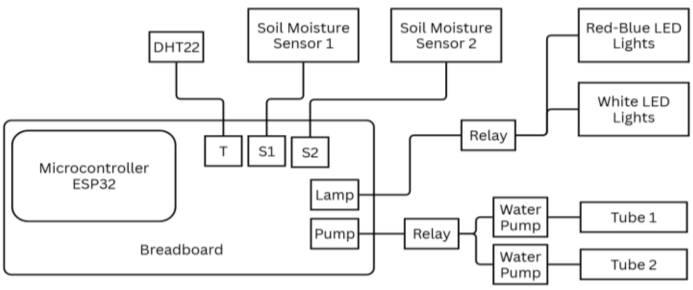


Figure 2. Architecture diagram smart indoor microgreen system

Table 1. List of hardware components used for developing smart agriculture microgreen system

Hardware components	Functions
ESP32 microcontroller	ESP32 is a versatile microcontroller widely used in Internet of Things (IoT). Features a built in Wi-Fi and Bluetooth capabilities which make it compatible with connected devices. It provides low power consumption with a wide range I/O pins that support various sensors and actuators.
DHT22 temperature and humidity sensor	DHT22 is a digital sensor used to measure temperature and humidity. It provides a precise measurement over a wide range with a temperature from -40 Celsius to 80 Celcius and a humidity level from 0% to 100%.
YL-69 soil moisture	Soil moisture is designed to measure the water content of soil. The sensor provides an output that can be read by microcontrollers which allows it to be used in agricultural application.
4 relay module	An electronic component used to control multiple devices through a microcontroller that allows a high-power electricity loads to be connected. The module can be activated by the digital outputs of a microcontroller. It is used often in automation systems, home security and Internet of Things (IoT) applications which provide to control various electronic devices.
LED lights red-blue and White	An energy light source is used for plants to give an effective growth process. Having low power consumption, it is efficient to be used in indoor farming. The ability to relate to IoT devices gives it an advantage to developing a smart indoor farming system.
Water Pump	A device used to move water from one place to another via a tube. Powered by electricity, depends on its size the power consumption varieties. The pump is designed by creating a pressure difference allowing water to flow through pipes or hoses.

3.3. Application for controlling and monitoring

The flowchart of the smart indoor microgreen system process is shown in Figure 3. This flowchart represents the sequence of steps taken in implementing the system. The flowchart shows how the system will operate. First the Blynk app will verify the connection with the microcontroller and sensors connected via Wi-Fi. Then the app will check to verify that your phone is connected to the internet. If it has internet connection, it will start to read all the information given by the hardware and display it on your smartphone. Then, users can remotely control and monitor the smart indoor microgreen system via smartphone. This is a simple and easy procedure for this project, which will make growing microgreen plants more efficient and effective.

Configuring the Blynk application for controlling and monitoring the implemented system by accessing the platform website blynk.io to initiate a new project. It is essential to specify the data streams for each sensor which are connected to allow the application to receive data from the microcontroller. The application will generate unique authentication token which must be incorporated into the microcontroller source code programmed in Arduino IDE. Blynk applications could be accessed from a smartphone that enables users to design their control dan monitor dashboard by integrating various widgets. The project can be executed by activating the application, thereby enabling controlling and monitoring of the smart indoor microgreen system.

Within the Blynk interface will display the data streams which were established to read data of each sensor. The process is shown in Figure 3 in which the user can display the dashboard in the Blynk app and could manually control the water pump. Displayed in the Blynk application are data information from each sensor which are temperature, humidity, soil moisture 1, soil moisture 2, water pump 1 and water pump 2. Information displayed are received real-time in which correspond to the hardware connected.

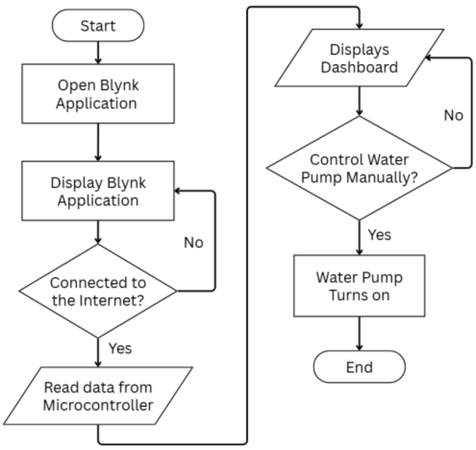


Figure 3. Application process of the smart indoor microgreen system

4. RESULTS AND DISCUSSION

The implementation of the Smart Indoor microgreen system hardware model is shown in Figures 4 and 5. The structured model for this system consists of 4 levels, on the very top is the hardware system in which the microcontroller connects with all the sensors and actuators. The second and third level are the microgreen growing placements with a red-blue light on the second and white light on the third. Lastly at the very bottom is placed a bucket of water where a water pump will transfer the water to the microgreen tray via tubes. The structure is made in a vertical position for maintaining the challenges of limited land in urban areas.

Figure 6 shows the Blynk control and monitor displays on the smartphone. This is how the display shows will look on the smartphone screen. The smart indoor microgreen system data information will be shown via the Blynk application where it will display temperature, humidity, soil moisture 1, soil moisture 2, water pump 1 button and water pump 2 button. The data is manipulated from the hardware connected to the microcontroller which has all the connected sensors and actuators. Several tests were conducted on manipulating the environment to measure their functionality.

Figure 4. Structure model

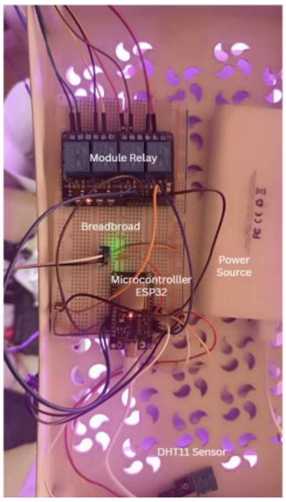


Figure 5. System hardware model

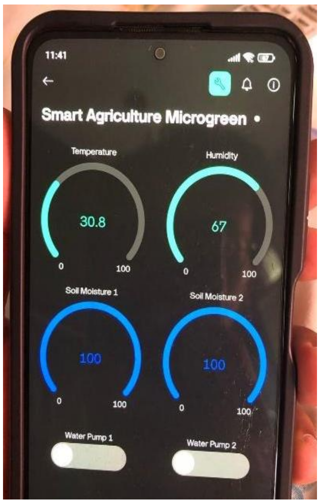


Figure 6. Blynk app display on a smartphone

This paper's main contribution is its emphasis on indoor farming and light color effect on plants between both light color exposures shown in Figure 7. Figure 8 shows the result of the use of smart indoor microgreen system that could be seen on green tray that is exposed to red-blue light. For more detailed results, Figure 9 shows a close-up image of the white light exposure where the plants show more blossom than in Figure 8. It is shown that the red-blue light exposure has a better effect on these microgreen plants rather than the white light exposure. Detailed comparative analysis will be explained in Figures 10 and 11.

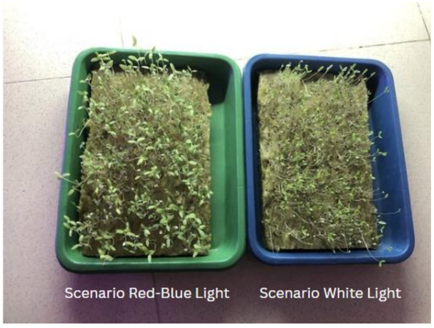


Figure 7. Plant growth comparison

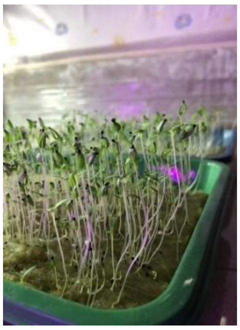
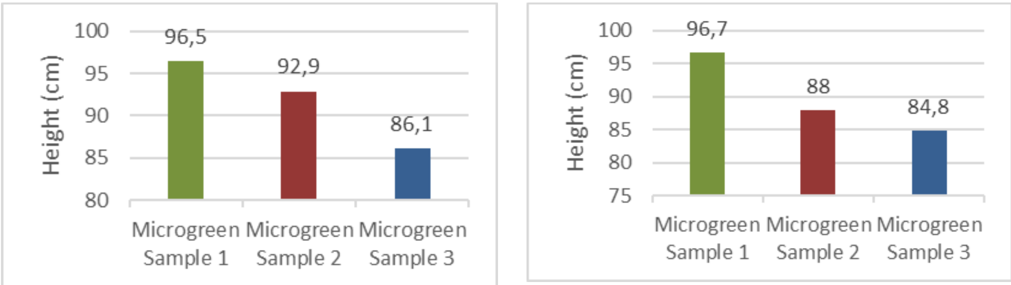


Figure 8. Scenario red-blue light exposed plant

Figure 9. Scenario white light exposed plant

Following the explanation of the Plant growth comparison between two light color scenarios, detailed comparative analysis is explained with a comparative between height and number of leaves. Microgreen plants are different than normal growing plants which requires much detail in analyzing the plants' growth. Analysis was carried out by taking 20 samples of stems for each tray and 3 tests are conducted to ensure the optimal analysis. Each 20 samples were measured for their height and their number of leaves; the height is measured with a unit of Centimeters and the number of leaves is measured with each leaves counted.

Implementing random sampling for each tray shown in Figure 10. Figure 10(a) shows the average plant height from each microgreen sample exposed to red-blue light and Figure 10(b) shows the average plant height from each microgreen sample exposed to white light. Each sample is taken 20 samples which will be calculated its heigh with a unit centimeter. While a visual comparison between the two light treatments suggests only minor differences, variations in the average plant height are noticeable. This observation highlights the importance of conducting statistical analysis using t-test method. Evaluating significantly thereby testing the hypothesis regarding the effect of light color on microgreen growth.



(a) (b)

Figure 10. Plant height exposure to (a) red-blue light and (b) white light

Following from the comparison of height between red-blue and white light from Figure 10(a) and Figure 10(b). For better analysis to know the significant difference between these two light colors it is necessary to conduct a statistical analysis using a t-test method. Determining the hypothesis of significance plant height which are H_0= There is no difference in microgreen growth between red-blue light and white light and H_1= There is a difference in microgreen growth between red-blue light and white light. Calculating from the formula below, in (1) and (2) focuses on calculating the Mean. In (3) and (4) calculate the standard deviation to be able to calculate the T value in formula (5). Lastly, calculating the degree of freedom in formula (6) to obtain the right p-value in the t-table.

Calculating the average (mean):

$$\underline{X}_1 = \frac{96.5+92.9+86.1}{3} = \frac{275.5}{3} = 91.83 \quad (1)$$

$$\underline{X}_2 = \frac{96.7+88+84.8}{3} = \frac{269.5}{3} = 89.83 \quad (2)$$

Calculating the standard deviation:

$$s_1 = \sqrt{\frac{(96.5-91.83)^2+(92.9-91.83)^2+(92.9-91.83)^2}{2}} = \sqrt{\frac{21.84+1.15+32.82}{2}} = \sqrt{\frac{55.81}{2}} = \sqrt{27.905} \approx 5.28 \quad (3)$$

$$s_2 = \sqrt{\frac{(96.7-89.83)^2+(88-89.83)^2+(84.8-89.83)^2}{2}} = \sqrt{\frac{47.16+3.34+25.20}{2}} = \sqrt{\frac{75.70}{2}} = \sqrt{37.85} \approx 6.15 \quad (4)$$

Calculating the t value:

$$s_1 = \frac{91.83-89.83}{\sqrt{\frac{5.28^2}{3}+\frac{6.15^2}{3}}} = \frac{2}{\sqrt{\frac{27.91}{3}+\frac{37.85}{3}}} = \frac{2}{\sqrt{9.303+12.617}} = \frac{2}{\sqrt{21.92}} = \frac{2}{4.68} \approx 0.427 \quad (5)$$

Calculating the degree of freedom (*df*):

$$df = n_1 + n_2 - 2 = 3 + 3 - 2 = 4 \quad (6)$$

It can be seen from the value of t ≈ 0.427 dan the value of df = 4, then if adjusted to the t-table that the t value is very small and the p-value is much greater than 0.05. From this conclusion indicates the t-test calculation by accepting H_0, meaning there is no significant difference in the heigh of microgreen plant growth between red-blue and white lighting.

Occurring for the number of leaves with a random sampling is implemented for each tray shown in Figure 11. Figure 11(a) shows the numbers of leaves from the exposure of red-blue light from each microgreen sample and Figure 11(b) shows the number of leaves from the exposure of white light from each microgreen sample. A total of 20 individual samples were randomly selected from each tray, and the number of leaves per sample was recorded. Although the visual differences between red-blue and white light treatments appear minimal, there is some variation in the average number of leaves. This also suggests the need for a statistical analysis to determine whether these differences are significant. Therefore, a t-test will be employed to test the hypothesis and assess whether the variation in the number of leaves between two light colors is statistically significant.

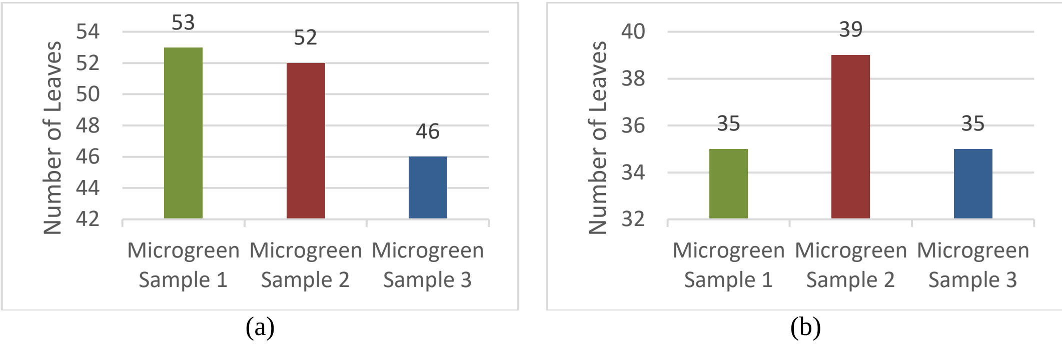


Figure 11. Plant number of leaves exposure: (a) red-blue light and (b) white light

Comparison between the number of leaves between two light colors shown in Figure 11(a) and Figure 11(b). White light exposure shows a smaller number of leaves compared to red-blue light, this is proven the red-blue light shows better growth than the white light, but it is still necessary to conduct a statistical analysis using t-test method to determine the significant comparison. H_0= There is no difference in microgreen growth between red-blue light and white light and H_1= There is a difference in microgreen growth between red-blue light and white light. Calculating from the formula shown below, in (1) and (2) focus on calculating the Mean. In (3) and (4) calculate the standard deviation to be able to calculate the T value in (5). Lastly, calculating the degree of freedom in (6) to obtain the right p-value in the t-table.

Calculating the average (mean):

$$\underline{X}_1 = \frac{53+52+46}{3} = \frac{151}{3} = 50.33 \quad (7)$$

$$\underline{X}_2 = \frac{35+39+35}{3} = \frac{109}{3} = 36.33 \quad (8)$$

Calculating the standard deviation:

$$s_1 = \sqrt{\frac{(53-50.33)^2+(52-50.33)^2+(46-50.33)^2}{2}} = \sqrt{\frac{7.11+2.78+18.75}{2}} = \sqrt{\frac{28.64}{2}} = \sqrt{14.32} \approx 3.78 \quad (9)$$

$$s_2 = \sqrt{\frac{(35-36.33)^2+(39-36.33)^2+(35-36.33)^2}{2}} = \sqrt{\frac{1.78+7.11+1.78}{2}} = \sqrt{\frac{10.67}{2}} = \sqrt{5.33} \approx 2.31 \quad (10)$$

Calculating the t value:

$$s_1 = \frac{50.33-36.33}{\sqrt{\frac{3.78^2}{3}+\frac{2.31^2}{3}}} = \frac{14}{\sqrt{\frac{14.29}{3}+\frac{5.33}{3}}} = \frac{14}{\sqrt{4.76+1.78}} = \frac{14}{\sqrt{6.54}} = \frac{14}{2.56} \approx 5.47 \quad (11)$$

Calculating the degree of freedom (df):

$$df = n_1 + n_2 - 2 = 3 + 3 - 2 = 4 \quad (12)$$

It is proven from the calculation above that the value of t≈5.47 with a value of df=4, adjusted to the distribution table which the value of t is smaller than 0.01. This indicates the analysis proven to accept H_1 means there is a significant difference between the number of leaves in microgreen plant growth between red-blue and white lighting.

5. CONCLUSION

In conclusion, the smart agriculture microgreen system using IoT hardware has functioned as programmed within the setpoint and accomplished its objectives. Those appliances can be monitored and controlled successfully. According to the study’s findings, this smart agriculture microgreen system has obtained a functional IoT system. Overall, the implemented system has worked according to the user’s expectations which can be monitored and controlled over by a smartphone user. Other findings which were obtained by comparing light red-blue color and white color, both scenarios in growing microgreen plants have shown almost a comparable result in which it is needed for an analysis statistical test. Implementing t-test has proven the calculation for plant height with a t value of 0.427 and accepting H_0 meaning there is no significant difference. However, the calculation for number of leaves with a t value of 5.47 and accepting H_1 meaning there is a significant difference. Based on the results of statistical analysis, red-blue lighting significantly increased the number of leaves in green spinach plants without being accompanied by significant increase in plant height. This indicates that the plant growth response is more focused on leaf development than stems. Morphologically, spinach is a plant whose leaves are consumed and tends to allocate more resources on leaves to photosynthetic than vertical growth. Compared with vertical growth in stems, leaf growth shows a higher priority in the adaptation strategy to their growing environment.

FUNDING INFORMATION

The authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials. The file contains raw measurements of microgreen growth under red-blue and white light conditions, across three experimental replicates. Each sheet (microgreen_sample_1, microgreen_sample_2, and microgreen_sample_3) includes detailed data on plant height and number of leaves for both lighting treatments.

REFERENCES

[1] L. Kumar *et al*., "Internet of things (IoT) for smart precision farming and agricultural systems productivity: a review," *Internation Journal of Engineering Applied Science and Technology*, vol. 5, no. 9, pp. 141-146, 2021, doi: 10.33564/IJEAST.2021.v05i09.022.

[2] Riyan *et al.,* "The Effect of UV Light in Accelerating IoT-Based Hydroponic Plant Growth," *Engineering Proceedings*, vol. 107, no. 1, pp. 29, Aug. 2025, doi: 10.3390/engproc2025107029.

[3] D. Y. Setyawan, "Internet of things (IoT) application in smart farming to optimize tomato growth," *Proceeding International Conference on Information Technology and Business*, pp. 81–90, 2022.

[4] A. Mohan *et al.*, "Automation of hydroponic microgreen farming using IoT," *SSRN Electronic Journal*, 2024, doi: 10.2139/ssrn.4483782.

[5] F. Evan, N. Anisa, S. J. Nurfitriyani, and J. Alexandra, "IoT architectural design for microgreens cultivation," in *Proceedings of 2022 International Conference on Information Management and Technology, ICIMTech 2022*, IEEE, Aug. 2022, pp. 225–230. doi: 10.1109/ICIMTech55957.2022.9915013.

[6] J. Boobalan, V. Jacintha, J. Nagarajan, K. Thangayogesh, and S. Tamilarasu, "An IoT based agriculture monitoring system," in *Proceedings of the 2018 IEEE International Conference on Communication and Signal Processing, ICCSP 2018*, IEEE, Apr. 2018, pp. 594–598. doi: 10.1109/ICCSP.2018.8524490.

[7] M. Dholu and K. A. Ghodinde, "Internet of things (IoT) for precision agriculture application," in *Proceedings of the 2nd International Conference on Trends in Electronics and Informatics, ICOEI 2018*, IEEE, May 2018, pp. 339–342. doi: 10.1109/ICOEI.2018.8553720.

[8] M. Ayaz, M. Ammad-Uddin, Z. Sharif, A. Mansour, and E. H. M. Aggoune, "Internet-of-things (IoT)-based smart agriculture: toward making the fields talk," *IEEE Access*, vol. 7, pp. 129551–129583, 2019, doi: 10.1109/ACCESS.2019.2932609.

[9] M. Bacco, P. Barsocchi, E. Ferro, A. Gotta, and M. Ruggeri, "The digitisation of agriculture: a survey of research activities on smart farming," *Array*, vol. 3–4, p. 100009, Sep. 2019, doi: 10.1016/j.array.2019.100009.

[10] T. Ahsan, M. Khan, M. Ahmed, T. Zafar, and A. Javeed, "Applications of Artificial Intelligence in Crop Disease Diagnose and Management," *International Journal of Scientific & Engineering Research*, vol. 13, no. 2, pp. 1000–1015, 2022.

[11] M. Javaid, A. Haleem, R. P. Singh, and R. Suman, "Enhancing smart farming through the applications of Agriculture 4.0 technologies," *International Journal of Intelligent Networks*, vol. 3, pp. 150–164, 2022, doi: 10.1016/j.ijin.2022.09.004.

[12] A. L. Qohar and Suharjito, "Smart agriculture for optimizing photosynthesis using internet of things and fuzzy logic," *International Journal of Electrical and Computer Engineering*, vol. 12, no. 5, pp. 5467–5480, Oct. 2022, doi: 10.11591/ijece.v12i5.pp5467-5480.

[13] A. Goap, D. Sharma, A. K. Shukla, and C. R. Krishna, "An IoT based smart irrigation management system using Machine learning and open source technologies," *Computers and Electronics in Agriculture*, vol. 155, pp. 41–49, Dec. 2018, doi: 10.1016/j.compag.2018.09.040.

[14] R. Veerachamy, R. Ramar, S. Balaji, and L. Sharmila, "Autonomous application controls on smart irrigation," *Computers and Electrical Engineering*, vol. 100, p. 107855, May 2022, doi: 10.1016/j.compeleceng.2022.107855.

[15] K. Sharma and S. K. Shivandu, "Integrating artificial intelligence and internet of things (IoT) for enhanced crop monitoring and management in precision agriculture," *Sensors International*, vol. 5, p. 100292, 2024, doi: 10.1016/j.sintl.2024.100292.

[16] K. A. Omar, A. D. Malik, A. Jamil, and H. M. Gheni, "Faulty sensor detection using multi-variate sensors in internet of things (IoTs)," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 18, no. 3, pp. 1391–1399, Jun. 2020, doi: 10.11591/ijeecs.v18.i3.pp1391-1399.

[17] C. G. W. Dona, G. Mohan, and K. Fukushi, "Promoting urban agriculture and its opportunities and challenges—a global review," *Sustainability (Switzerland)*, vol. 13, no. 17, p. 9609, Aug. 2021, doi: 10.3390/su13179609.

[18] A. Saputra, O. S. Abdoellah, and G. L. Utama, "Challenges and opportunities of urban agriculture programme implementation in Indonesia: social, economic, and environmental perspectives," *Local Environment*, vol. 29, no. 11, pp. 1490–1498, Nov. 2024, doi: 10.1080/13549839.2024.2402716.

[19] N. Yeh and J. P. Chung, "High-brightness LEDs-energy efficient lighting sources and their potential in indoor plant cultivation," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2175–2180, Oct. 2009, doi: 10.1016/j.rser.2009.01.027.

[20] C. Burattini, B. Mattoni, and F. Bisegna, "The impact of spectral composition of white LEDs on spinach (spinacia oleracea) growth and development," *Energies*, vol. 10, no. 12, p. 1383, Sep. 2017, doi: 10.3390/en10091383..

[21] Tang W *et al*., "Effect of Light Intensity on Morphology, Photosynthesis and Carbon Metabolism of Alfalfa (Medicago sativa) Seedlings" *Plants (Basel)*, vol. 11, no. 13, p. 1688, Jun. 2022, doi: 10.3390/plants11131688.

[22] H. Abdelkader *et al*., "Energy-Efficient IoT-Based Light Control System in Smart Indoor Agriculture," *Sensors*, vol. 23, no. 18, pp. 7670, Sep. 2023, doi: 10.3390/s23187670

[23] J. Jiang, M. Moallem, and Y. Zhengi, "An intelligent IoT-enabled lighting system for energy-efficient crop production," *Journal of Daylighting*, vol. 8, no. 1, pp. 86–99, Feb. 2021, doi: 10.15627/jd.2021.6.

[24] Budavári *et al*., "An Overview on the Use of Artificial Lighting for Sustainable Lettuce and Microgreens Production in an Indoor Vertical Farming System," *Horticulturae*, vol. 10, no. 9, pp. 938, 2024, doi: 10.3390/horticulturae10090938.

[25] T. Zou, C. Huang, P. Wu, L. Ge, and Y. Xu, "Optimization of artificial light for spinach growth in plant factory based on orthogonal test," *Plants*, vol. 9, no. 4, p. 490, Apr. 2020, doi: 10.3390/plants9040490.

[26] E. Simanungkalit *et al*., "Smart Garden on Chili Plants Based on IoT," *International Journal of Research in Vocational Studies (IJRVOCAS)*, vol. 3, no. 4, pp. 46-51, Jan. 2024, doi: 10.53893/ijrvocas.v3i4.146.

[27] C. Isaza, A. M. Aleman-Trejo, C. F. Ramirez-Gutierrez, J. P. Zavala de Paz, J. A. Rizzo-Sierra, and K. Anaya, "Spinach (Spinacia oleracea L.) growth model in indoor controlled environment using agriculture 4.0," *Sensors*, vol. 25, no. 6, p. 1684, Mar. 2025, doi: 10.3390/s25061684.

[28] T. P. D. Nguyen *et al*., "Growth and quality of hydroponic cultivated spinach (Spinacia oleracea L.) affected by the light intensity of red and blue LEDs," *Sains Malaysiana*, vol. 51, no. 2, pp. 473–483, Feb. 2022, doi: 10.17576/jsm-2022-5102-12.

[29] T. P. Nguyen, "Growth and quality characteristics of spinach (Spinacia oleraceae L.) in various substrate cultures," *Dong Thap University Journal of Science*, vol. 10, no. 5, pp. 55–61, Oct. 2021, doi: 10.52714/dthu.10.5.2021.895.

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