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Smart Hydroponic Farming System Integrated with LED Grow Lights

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ABSTRACT

Vertical farming, including hydroponics, is a growing trend in the agricultural sector due to the increasing demand for food and urbanisation. Thus, hydroponics can save space and achieve faster plant growth compared to traditional farming methods. The concept of smart farming has been applied in this study to improve the ease of control and monitoring of hydroponic systems. The effects of light-emitting diodes (LEDs), light distance, and colour (purple and white) on water spinach growth in a hydroponic system were investigated. Additionally, an Internet of Things (IoT) controller was developed and implemented to facilitate the use of the system in an indoor hydroponic-based environment system. Based on the results, the distance between the LED light of 15 cm and the plants and the colour of the LED light (white) can positively impact plant growth in a hydroponic system. Using an IoT controller also allows for continuous monitoring and control of factors that influence plant growth. Hence, this research would catalyse the local smart hydroponic farming system for improved deliverables.

Keywords: Grow light, hydroponic, IoT controller, light emitting diodes, smart farming

INTRODUCTION

Soilless agriculture can be traced back to ancient Egyptian civilisation, as depicted in a painting in the Temple of Deir el Bahari (Torabi et al., 2012). Irish scientist Robert Boyle subsequently conducted the first known experiment on growing plants with submerged roots. John Woodward's experiments in 1699 demonstrated that soil

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and water could provide essential nutrients for plant growth. This observation led to the development of mineral nutrient solutions by Julius von Sachs, now widely used in soilless agriculture worldwide (De Rijck & Schrevens, 1998; Suryaningprang et al., 2021). Before 1929, the study of hydroponics was primarily focused on biological research. Nonetheless, William Frederick Gericke's efforts in the late 1920s began exploring hydroponics's commercial potential and the hydroponic system's development as it is known today (Torabi et al., 2012).

Hydroponics has emerged as a potential solution to meet the increasing demand for food due to rapid population growth and the limited availability of land for agriculture due to urbanisation (Lem et al., 2014; Satterthwaite et al., 2010). The term "hydroponics" comes from the Greek words "*hydro,*" which is water, and "*ponos,*" which is labour. It is a method of growing plants by immersing their roots in a nutrient solution. Hydroponics offers several advantages, such as the ability to grow plants in a smaller space by placing them closer together, the ability to control the climate through temperature, humidity, and light exposure, and improved nutrient efficiency and overall growth rates (Balashova et al., 2019; Magwaza et al., 2020). Nevertheless, hydroponics requires specialised knowledge and time to maintain the appropriate pH levels, nutrient concentrations, and water levels for optimal plant growth. In hydroponics systems, the roots of the plants are directly immersed in a nutrient solution, which must be carefully monitored. The nutrient solution must contain 13 essential macro- and micronutrients necessary for plant growth, including Ca, N, Mg, K, P, S, B, Cl, Cu, Fe, Mn, Mo, and Zn (Bugbee, 2004). Two factors that must be regularly checked in hydroponic systems are the pH level of the nutrient solution and the electrical conductivity (EC). The pH level is not essential for plant growth but determines the availability of nutrients in the solution. The EC of the nutrient solution indicates the number of ions in the root zone (Al Meselmani, 2022).

In hydroponic systems, there were approximately six system types which could generally be classified, such as Deep Water Culture (DWC) (Hamza et al., 2022; Janeczko & Timmons, 2019), Nutrient Film Technique (NFT) (Suryaningprang et al., 2021), drip irrigation (Taofik et al., 2019), ebb and flow (flood and drain) (Setiawan et al., 2022), aeroponics (Wang et al., 2019; Wimmerova et al., 2022), and wick system (Hartanti & Sulistyowati, 2022). In the DWC technique, plant roots were submerged in nutrient-rich water while plants floated in the solution. Although DWC was simple to install and maintain, the oxygen levels in the water were challenging to control. Meanwhile, NFT plants were inserted in a narrow channel, where a thin layer of the nutritional solution ran over their roots. NFT was water-efficient and suitable for the cultivation of small plants. Nonetheless, it was challenging to maintain consistent nutrient levels. For drip irrigation, a network of tubes with miniature drippers allowed a nutrient solution to drip onto the roots of the plants.

Drip irrigation was versatile and simple to install but required proper and advanced planning to avoid wastage. Alternatively, plants in ebb and flow were cultivated in a growing medium-filled tray. Periodically, the tray was saturated with a nutritious solution and then emptied. Despite the ebb and flow method being advantageous for growing huge plants and mechanised, it was prone to clogging. Plant roots were suspended in air and sprayed with nourishing in aeroponics. Aeroponics could generate rapid growth rates and great yields, but its setup was more difficult and costly. Lastly, the wick system involved plants in a growing medium and a wick transported nutrient solution from a reservoir to the plants' roots. This simple method required low maintenance, but wick systems were unsuitable for larger plants. Therefore, the choice of the hydroponic system relied on several criteria, including the type of plants being produced, the available space and resources, and the grower's experience level (Namgyel et al., 2018).

Light-emitting diodes (LEDs) are semiconductor devices that emit light through electroluminescence. The first LED was discovered by James Biard et al. in 1961, but it was not until 1944 that Shuji Nakamura developed an LED with a high-brightness blue colour suitable for plant growth (Gupta & Agarwal, 2017). LED lights are more efficient than other types of artificial lighting because they use less power but have a longer lifespan. Additionally, LEDs emit specific wavelengths, while the placement of LEDs plays a significant role in plant growth. The optimal placement of LEDs depends on the type of plant, the LED itself, the coverage area, the environmental conditions, and manufacturer recommendations (Dunn & Mills-Ibibofori, 2016). If the LED is placed too close to the plants, it can burn them, but if placed too far, the plants will grow weak due to insufficient light. Previous studies have shown that the absorption peaks of chlorophylls are in the red and blue regions (625–675 nm and 425–475 nm) (Gupta & Agarwal, 2017). On the contrary, the blue region produced a higher peak than the red region. Additionally, the peaks of phytochrome are in the red and far-red regions (660 and 730 nm, respectively) (Gupta & Agarwal, 2017). Another study found that wavelengths between 400–520 nm reported the highest absorption rate of chlorophyll and carotenoids, pigments found in plants (Xu et al., 2016). In contrast, the 610–720 nm wavelength produced a low absorption rate of chlorophyll but a high absorption rate of phytochrome (Runkle, 2016). Therefore, plants grown under red LED lights (600–700 nm) tend to be tall but have smaller leaves.

Smart farming utilises the Internet of Things (IoT) and big data analytics to monitor crops and their environment to improve sustainability in the agriculture sector (Din et al., 2018; Madushanki et al., 2019; Paul & Jeyaraj, 2019). IoT can help farmers address traditional farming challenges such as drought response, irrigation, yield, and pest control (Ayaz et al., 2019). Smart farming technologies differ from conventional farming methods. They are being increasingly adopted, as the global smart farming market is predicted to grow 19.3% annually from 2017 to 2022. Some applications of smart farming in hydroponic systems include crop disease and pest management. The Food and Agriculture Organisation of the United Nations (FAO) estimates that 20 to 40% of global crop yields are lost due to damage caused by plant pests and diseases (Gráda, 1992). Pesticides and agrochemicals are essential for increasing crop yield, but their use can also harm the environment. Thus, IoT-based devices can monitor crop disease and pest management, providing real-time monitoring and disease forecasting that is more effective than traditional methods. Devices such as field sensors and remote sensing satellites can provide real-time monitoring.

Several IoT-based devices were employed to monitor crop disease and pest control in hydroponic farming (Mamatha & Kavitha, 2023). These devices collected and transmitted data on environmental elements that affected crop health to a central monitoring system. Smart pest monitoring systems utilise cameras and sensors to identify and monitor the movement of pests in a field of crops (Ullo & Sinha, 2020). Additionally, they could detect individual species of problems and inform farmers to take the necessary measures. For automated weather stations, the sensors capture data on temperature, humidity, precipitation, wind speed, and other meteorological characteristics (Dunaieva et al., 2021). In addition, they provided forecasts for the coming days, which assisted farmers with irrigation and pest control planning. Meanwhile, soil moisture sensors measured the soil's moisture content and provided information on the ideal irrigation period (Yu et al., 2021). This data aided farmers in avoiding excessive irrigation, which resulted in waterlogging and pest infestations. In drone-based imaging systems, drones with cameras and sensors supply crop fields with high-resolution photographs (Chan et al., 2021). This information identified regions of an area infested with pests or illnesses, allowing for specific measures to eradicate the infestation. Thus, IoT-based devices for monitoring crop disease and pest control provide real-time data, limit toxic pesticides and agrochemicals use, and help farmers optimise irrigation and pest control (Khan et al., 2021). By embracing these technologies, farmers could increase their yields and contribute to the agriculture industry's sustainable growth.

Another use of smart farming is in fertiliser (nutrient solution). Fertilisers provide essential nutrients for plant growth, but excessive use can harm the environment. Smart farming technologies, such as the Normalised Difference Vegetation Index (NDVI), can help estimate the amount of fertiliser plants need without causing harm (Zhou et al., 2021). Yield monitoring, forecasting, and harvesting are efficient examples of smart farming. Yield monitoring involves analysing various aspects of agricultural yield, while yield forecasting predicts yield before the harvest. A yield monitoring, forecasting, and harvesting system provides real-time data that can be used to estimate production and yield quality. Sensors and technologies such as auto-pumps and auto-LEDs can be applied to optimise hydroponic systems, especially in small-scale hydroponic farms. These features allow the user to control the pump and LED from their smartphone. Some sensors that can be used in hydroponic systems include pH, electrical conductivity (EC), temperature and humidity, and water level sensors. These sensors can provide real-time data to help monitor and maintain optimal conditions for plant growth in hydroponic systems.

This study aimed to examine the effects of LED light distance and colour on the growth of water spinach in a hydroponic system. Furthermore, an IoT controller was installed to facilitate the usage of the system in an indoor hydroponic-based environment system. The distance and colour of LED light were expected to influence the growth of water spinach in a hydroponic system. An IoT controller would allow for continuous monitoring and adjustment of growth-influencing parameters. The optimal distance for LED lighting was determined to be 15 cm, and white LED lighting was more conducive to plant growth than purple LED lighting. In addition, the IoT-controlled smart farming system accurately monitored the environment, pH level of the nutrient solution, and amount of nutrients, enabling continuous monitoring and optimisation of these elements for plant growth. Hence, this study contributes to developing an efficient hydroponic system and introducing new paths for local smart farming.

MATERIALS AND METHODS

The Distance Between White LED and Plant for Plant Growth

The distance between White LED lights and plants was investigated to determine the optimal distance for plant growth in this study. A hydroponic system with four trays was used, three equipped with LED lights and one without LED lights (Figure 1). The LED lights were white and were turned on for 14 hours daily, from 7 am to 9 pm. The plant was water spinach, grown in rockwool as the growing medium. The plants underwent a 10-day germination process without LED lights and a 20-day germination process with LED lights. On day 30, the water spinach was harvested, and the experiment was completed. The width and height of the plants were measured every five days starting from day 11.

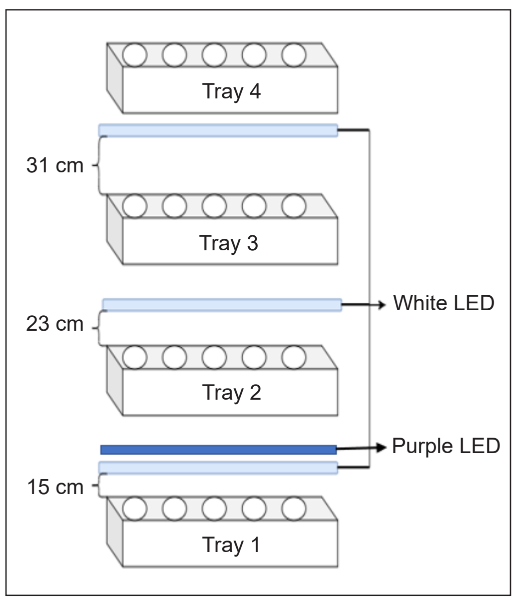


Figure 1. Schematic diagram of the hydroponic system used for LED testing

The LED Colour for Plant Growth

Following the completion of the first part of the study, the effect of LED colour on plant growth was investigated using the recommended distance between LED lights and plants from the first part. For this part of the study, only one tray was used and equipped with purple LED lights, as revealed in Figure 1. Like the last part, the LED lights were turned on every day from 7 am to 9 pm. The plant was water spinach, grown in rockwool as the growing medium. The plants underwent a 10-day germination process without LED lights and a 20-day germination process with LED lights. The width and height of the plants were measured every five days starting from day 11.

IoT Controller for Hydroponic System

The IoT controller used in this study was based on the NodeMCU platform, which features an ESP8266 Wi-Fi-enabled chip, has simple, Arduino-like hardware input/output capabilities, and is cost-effective. The Blynk application interfered with the IoT controller, providing device management, private clouds, machine learning, and data analytics capabilities. The system employed three sensors: a DHT22 sensor, a pH sensor, and a water float sensor. The flow chart of the IoT controller is illustrated in Figure 2.

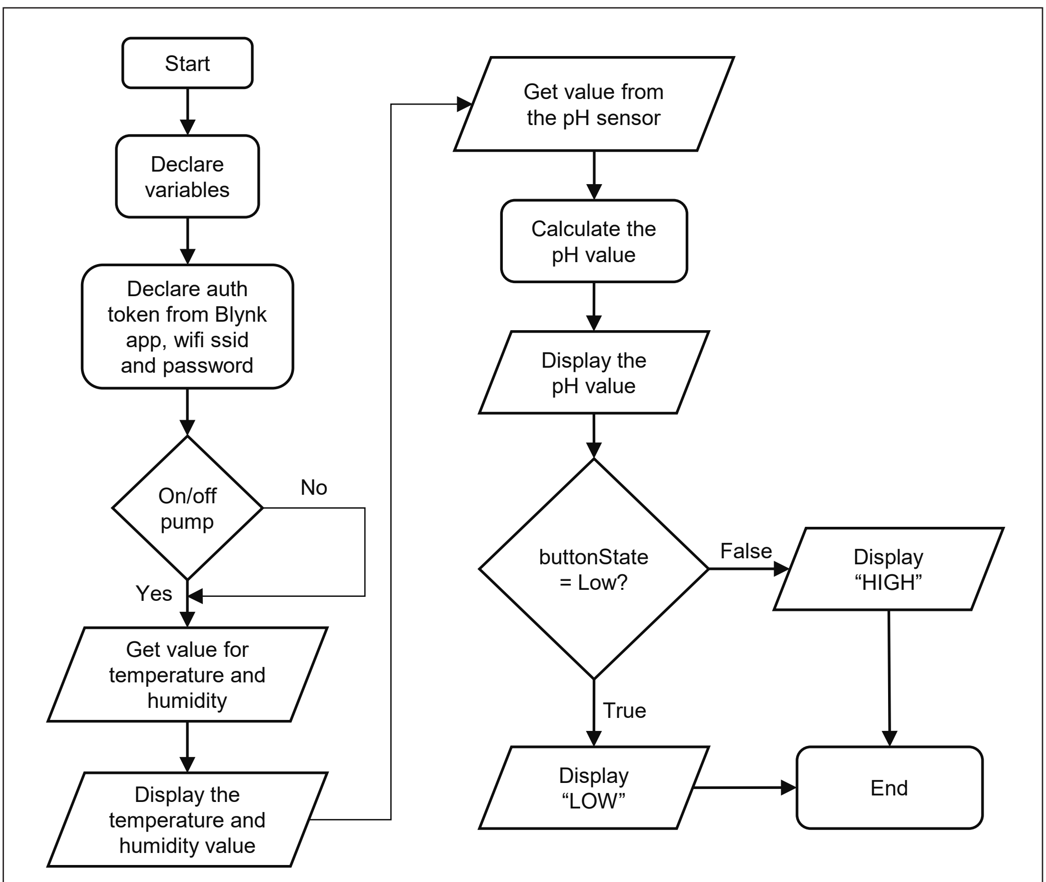


Figure 2. Schematic flow chart of the overall system in this study

RESULTS AND DISCUSSION

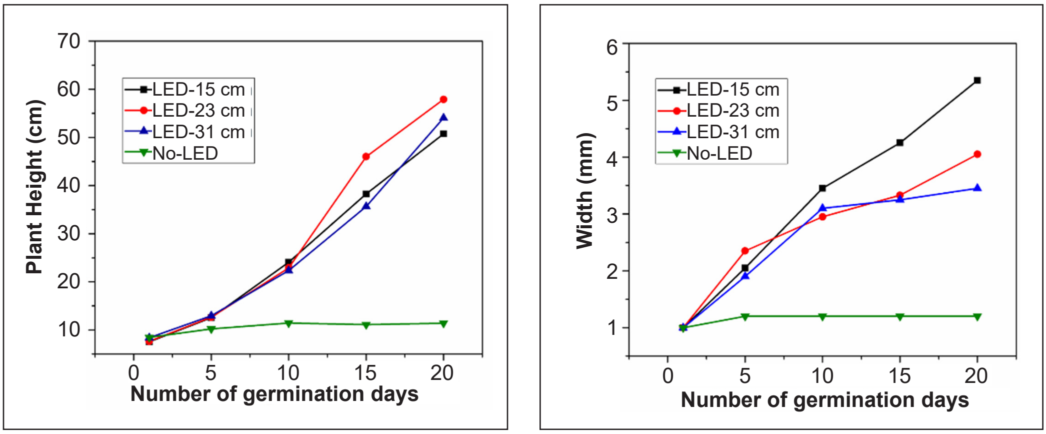
Optimised Distance Between White LED and Plant for Plant Growth

The height and width of the plants for the different distances between the white LED and the plants are tabulated in Table 1. The "LED-15 cm" condition represents 15 cm between the LED lights and plants, the "LED-23 cm" condition represents 23 cm, and the "LED-31 cm" condition represents 31 cm. The "No-LED" condition represents the absence of LED lights.

Table 1
Summary of the height and width of the plants for the varying distances between the white LED source and the plants within 20 days

Number of Germination Days	Parameters	Sample Name			
		LED-15 cm	LED-23 cm	LED-31 cm	No-LED
Day 1	Height (cm)	07.55	07.65	08.40	08.45
	Width (mm)	01.00	01.00	01.00	01.00
Day 5	Height (cm)	12.55	12.65	12.94	10.25
	Width (mm)	02.05	02.35	01.90	01.20
Day 10	Height (cm)	24.05	22.90	22.35	11.45
	Width (mm)	03.45	02.95	03.10	01.20
Day 15	Height (cm)	38.25	46.00	35.65	11.10
	Width (mm)	04.25	03.33	03.25	01.20
Day 20	Height (cm)	50.75	57.90	54.05	11.4
	Width (mm)	05.35	04.05	03.45	01.20

Figure 3 presents the investigation results of the optimal distance between LED lights and plants for plant growth. As demonstrated in Figure 3, the height of the plants under the LED-15 cm condition increased steadily while the width increased sharply. These plants



(a) (b)

Figure 3. Graphs indicating the optimal distance between LED lights and plants for plant growth, which includes (a) height (cm) versus days and (b) width (mm) versus days

had the widest and strongest stems compared to the other conditions. The height and width of the plants under the LED-23 cm and LED-31 cm conditions also increased steadily. In contrast, these plants were taller with thin stems, causing them to bend. Alternatively, the height and width of the plant under No-LED increased for the first five days and remained constant until the end of the experiment (Day 20).

Based on the results, it was concluded that the LED 15 cm distance was optimal for water spinach growth. Although not tall, it produced solid stems and large leaves, essential for water spinach (Figure 4) (Khwankaew et al., 2018). It is important to note that the optimal LED distance may vary for other plant species and LED types, depending on the plant type, LED type, coverage area, environmental conditions, and manufacturer recommendations (Runkle, 2016).

Table 2 summarises the light intensity at each distance, measured using a lux meter positioned at the pot level facing the LED source at noon. Since No-LED

Table 2
Summary of the intensity of light for each distance between LED and plants

Distance between LED and water spinach	Intensity (l×)
No-LED	154.05
LED-15 cm	2.129×10^3
LED-23 cm	1.764×10^3
LED-31 cm	1.545×10^3

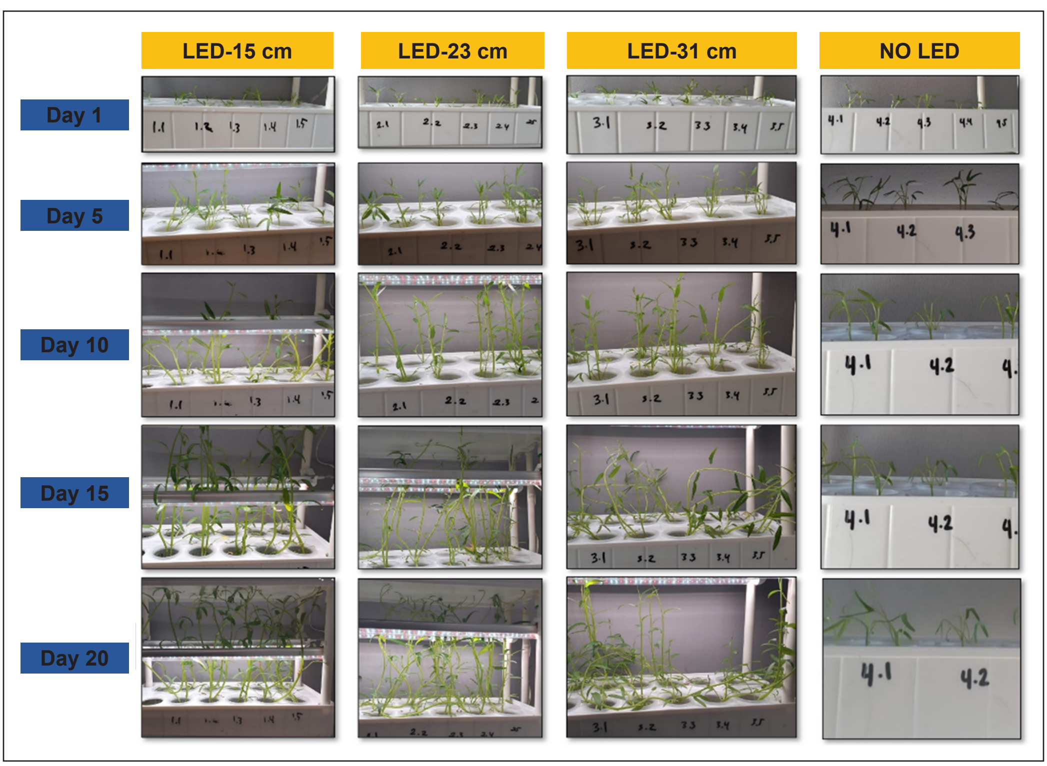


Figure 4. Photographs of water spinach plant growth under the influence of the white LED source and without LED

conditions produced very low light intensity, it is obvious the water spinach plant could not significantly grow within the germination period. The highest intensity was recorded for the LED-15 cm condition, which confirmed the most optimised condition for the water spinach growth compared to LED-23 cm and LED-31 cm conditions.

Influence of Purple and White LED Colours for Plant Growth

This part studied two LED colours: white LED and purple LED. The LED-15 cm distance was selected throughout this experiment based on the results. Thus, the results are tabulated in Table 3.

Even though the height and width of plants grown under white LED were slightly smaller than those grown under purple LED (Figure 5), the plants grown under white LED produced bigger leaves than those grown under purple LED. For water spinach, the number and size of the leaves are more important than the size of the stem, as most people eat the leaves. Therefore, it can be concluded that white LED is better compared to purple LED for plant growth for water spinach.

Based on the information given by the manufacturer, the purple LED consists of 4 blue and 11 red LED lights. The wavelengths for blue and red LED are 450 and 660 nm, respectively. Since the white LED came together with the hydroponic system, the wavelength of the white LED was unknown. Based on the literature, the wavelength of white LED varied between 365–445 nm depending on the amount of phosphor used and 465 nm for GaN-based LED (Al Shafouri et al., 2018; Singh, 2009). Bian et al. (2018) stated that the photosynthesis rate of plants grown under the white LED was higher than those produced under the purple LED. Another study also found the highest absorption peak in the blue region (425–475 nm). Other than that, it was also found that the peaks of phytochrome absorption are in the red and far-red regions (660 and 730 nm, respectively) (Gupta & Agarwal, 2017).

Table 3
Summary of the height and width of the plants under purple and white LED sources within 20 days

Number of Germination Days	Parameters	LED source	
		White	Purple
Day 1	Height (cm)	07.55	09.77
	Width (mm)	01.00	02.00
Day 5	Height (cm)	12.55	16.33
	Width (mm)	02.05	03.20
Day 10	Height (cm)	24.05	22.53
	Width (mm)	03.45	04.00
Day 15	Height (cm)	38.25	36.13
	Width (mm)	04.25	04.60
Day 20	Height (cm)	50.75	58.87
	Width (mm)	05.35	04.60

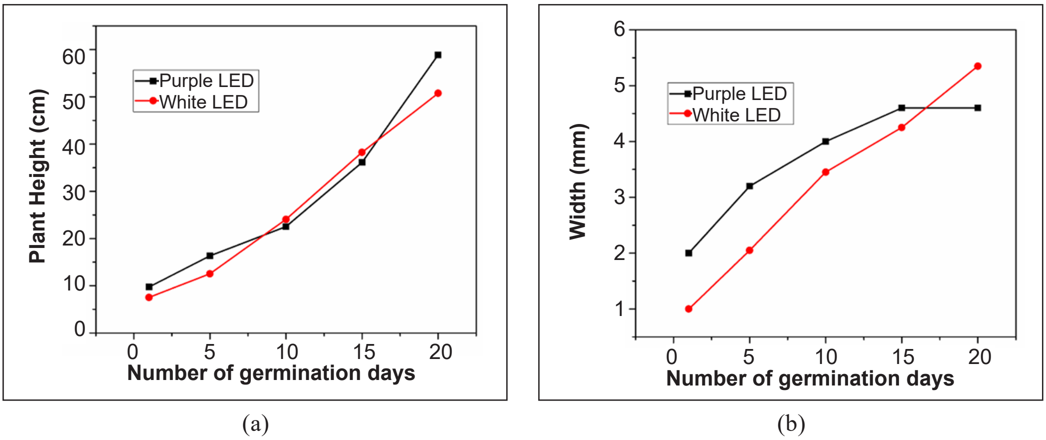


Figure 5. Graphs indicating the (a) height and (b) width variations under white and purple LED sources for plant growth

Another researchers also found that the wavelength between 400–520 nm produced the largest absorption of chlorophyll and carotenoids, a pigment found in plants (Ayaz et al., 2019). In contrast, a wavelength of 610–720 nm produced a low chlorophyll absorption rate but a high phytochrome absorption rate (Gráda, 1992). Therefore, the plants grown under red LED (600–700 nm) are tall but produce smaller leaves. White LEDs' wavelength falls under the wavelength range with large chlorophyll absorption. One of the lights, purple LED, also falls under the wavelength with high chlorophyll absorption, which is blue. However, there were only four blue LEDs out of 11 LEDs. The remaining LEDs were red, which falls under the wavelength range with a low chlorophyll absorption rate. Since the percentage of the blue LED is much smaller than the red LED, purple LED plants were taller but produced smaller leaves (Figure 6).

Although water spinach plants were demonstrated to grow effectively under white LED, it was known that different plants might have specific light requirements. The ideal wavelengths for photosynthesis varied among plant species, as did the maximum absorption rates of chlorophyll and carotenoids. It was reported that the best LED wavelengths for leafy greens, such as lettuce and spinach, were in the blue and red spectra, with a chlorophyll absorption peak around 450–460 nm and 660–680 nm (Gao et al., 2020). Some research suggested that green light (500–550 nm) could boost some plants' development and nutritional value. Herbs, such as basil and mint, were discovered to require ideal LED wavelengths comparable to those for leafy greens, with chlorophyll absorption peaking between 450–460 nm and 660–680 nm (Kondratieva et al., 2022). Conversely, herbs could benefit from increased blue light, as it might stimulate the formation of essential oils.

Fruit-bearing plants, such as tomatoes and peppers, demonstrated a greater need for red light, with chlorophyll absorption peaking between 660 and 680 nm (Ngcobo et al.,

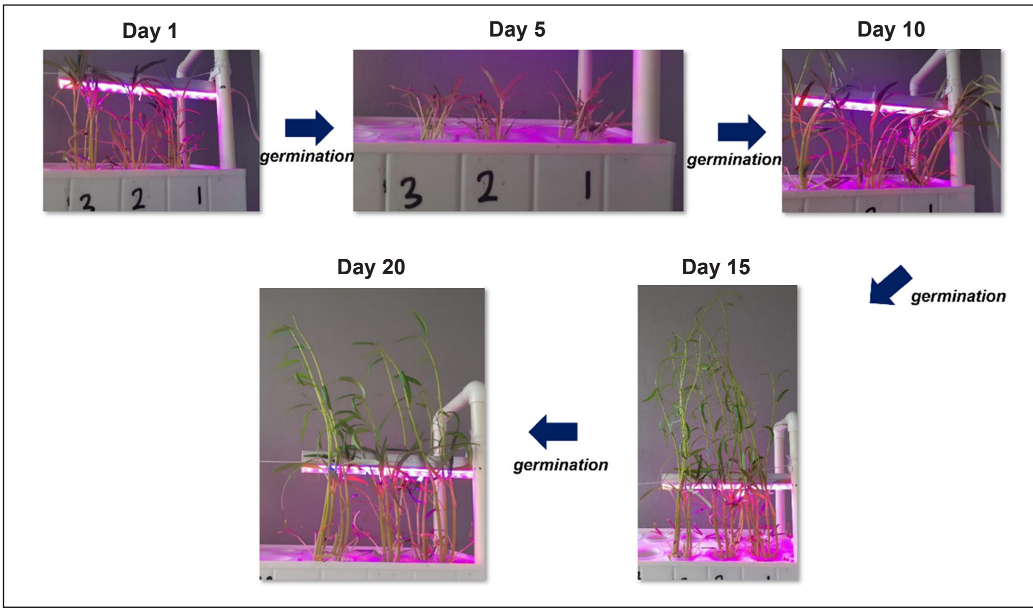


Figure 6. Photographs of water spinach plant growth under the purple LED source in this study

2022). However, they also required blue light with a peak absorption rate of 450–460 nm for vegetative growth. Root vegetables, such as carrots and potatoes, produced a lower demand for blue light but still required some development (Kim & Son, 2022). Important red light had a peak absorption rate for chlorophyll between 660 and 680 nm. Far-red light (about 730–740 nm) could boost root development in some plants (Bantis et al., 2020). For producers to optimise plant growth and output under artificial lighting conditions, it was essential to comprehend different crops' individual light spectrum needs. Hence, assessing light intensity and spectrum could assist producers in ensuring that their plants receive the optimal quantity and quality of light for optimal growth and development.

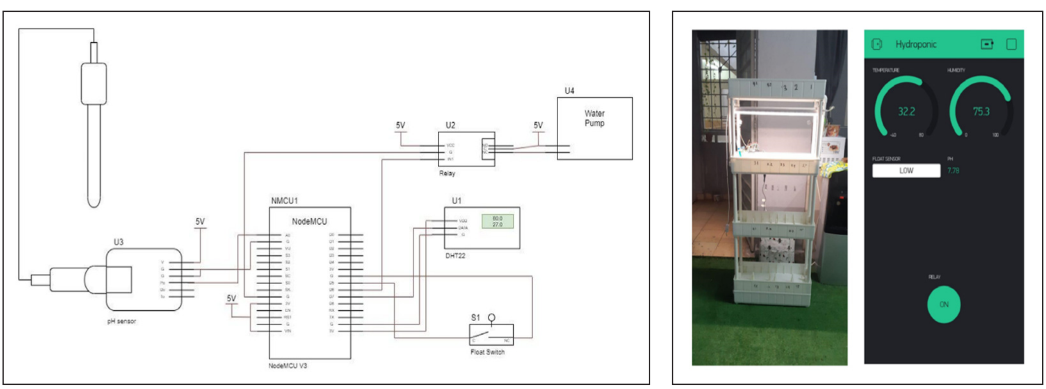
Integrating IoT Controller for Hydroponic System

The IoT is a network of interconnected objects, devices, vehicles, equipment, and buildings that exchange information through sensors and software. Five key technologies that enable the IoT, particularly in agricultural engineering, are as follows:

1. Wireless Sensor Networks (WSN) are infrastructure-less networks that use a variety of sensors to monitor factors such as temperature, humidity, and pH with water levels to transmit data for observation or analysis (Patel & Kumar, 2018; Rathinam et al., 2019).
2. Cloud Computing (CC) delivers computing services over the internet. In this project, the user used Blynk to monitor crops and their environment (Darwish et al., 2019; Namani & Gonen, 2020).

3. Embedded systems combine hardware and software to monitor hydroponic systems (Susanto et al., 2021). A NodeMCU in this system, which can be programmed using the Arduino language, was used.
4. Big data analytics examines large and varied data sets to uncover new insights (Coble et al., 2018; Huang et al., 2018). It can increase crop efficiency by collecting data from sensors and using the data to prevent events that could negatively impact crop cultivation.
5. Communication protocols are rules for transmitting data between nodes in a network (Thakur et al., 2019). They define data exchange formats, encoding, and addressing.

This study used a relay and three sensors (DHT22, pH sensor, and water float sensor). The relay can be connected to a pump or LED light to automate these systems. The schematic diagram is observed in Figure 7a. After the IoT controller was developed, it was implemented in the hydroponic system, as depicted in Figure 7b. Hence, real-time data was successfully integrated into the smart hydroponic system. When the application display was switched on, data was recorded, such as the temperature of 32.2ºC, 75.3% humidity, high float sensor, the pH level of 7.53, and the relay was switched off. Based on the integration, this system can assist the development of future smart farming, particularly for local farmers and industries.



(a) (b)

Figure 7. (a) Schematic diagram of the IoT system used in this study. (b) Photographs of the smart hydroponic system and the Blynk application

CONCLUSION

In conclusion, the distance and colour of the LED light source toward the growth of water spinach in a hydroponic system were successfully demonstrated in this study. Based on the results, the distance of 15 cm between the LED light source and the plants was indicated to be the most optimal value. Furthermore, the white LED light was more suitable for plant growth than the purple LED light owing to the increased number and size of the water spinach leaves. A successful IoT controller was also effectively integrated into this study, which included several sensors for temperature, humidity, pH, and water level. These parameters are important factors for the growth of water spinach plants in the hydroponic system. The smart farming system efficiently measured the environment, the pH level of the nutrient solution, and the number of nutrients. Thus, the embedment of the IoT controller allowed for continuous monitoring and optimisation of these factors to necessitate plant growth. This research would allow for future developments of a local smart hydroponic farming technology for the agricultural sector.

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REFERENCES

Al Meselmani, M. A. (2022). Nutrient solution for hydroponics. In P. M. Turan, A. P. S. Argin, P. E. Yildirim & D. A. Güneş (Eds.), *Soilless Culture [Working Title]* (p. Ch. 3). IntechOpen. https://doi.org/10.5772/intechopen.101604

Al Shafouri, M., Ahmed, N. M., Hassan, Z., & Almessiere, M. A. (2018). The effect of the wavelength of the LED used to pump phosphor produced from curcuminoids dye extracted from turmeric (*Curcuma Longa* L.) to Produce white light. In *IOP Conference Series: Materials Science and Engineering* (Vol. 454, No. 1, p. 012048). IOP Publishing. https://doi.org/10.1088/1757-899X/454/1/012048

Ayaz, M., Ammad-Uddin, M., Sharif, Z., Mansour, A., & Aggoune, E. H. M. (2019). Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE Access, 7*, 129551-129583. https://doi.org/10.1109/ACCESS.2019.2932609

Balashova, I., Sirota, S., & Pinchuk, Y. (2019). Vertical vegetable growing: Creating tomato varieties for multi-tiered hydroponic installations. *IOP Conference Series: Earth and Environmental Science, 395*(1), Article 012079. https://doi.org/10.1088/1755-1315/395/1/012079

Bantis, F., Fotelli, M., Ilić, Z. S., & Koukounaras, A. (2020). Physiological and phytochemical responses of spinach baby leaves grown in a PFAL system with leds and saline nutrient solution. *Agriculture, 10*(11), Article 574. https://doi.org/10.3390/agriculture10110574

Bian, Z., Jiang, N., Grundy, S., & Lu, C. (2018). Uncovering LED light effects on plant growth: New angles and perspectives - LED light for improving plant growth, nutrition and energy-use efficiency. *Acta Horticulturae, 1227*(1227), 491-498. https://doi.org/10.17660/ActaHortic.2018.1227.62

Bugbee, B. (2004). Nutrient management in recirculating hydroponic culture. *Acta Horticulturae, 648*(648), 99-112. https://doi.org/10.17660/ActaHortic.2004.648.12

Chan, Y. K., Koo, V. C., Choong, E. H. K., & Lim, C. S. (2021). The Drone Based Hyperspectral Imaging System for Precision Agriculture. *Natural Volatiles & Essential Oils Journal, 8*(5), 5561-5573.

Coble, K. H., Mishra, A. K., Ferrell, S., & Griffin, T. (2018). Big data in agriculture: A challenge for the future. *Applied Economic Perspectives and Policy, 40*(1), 79-96. https://doi.org/10.1093/aepp/ppx056

Darwish, A., Hassanien, A. E., Elhoseny, M., Sangaiah, A. K., & Muhammad, K. (2019). The impact of the hybrid platform of internet of things and cloud computing on healthcare systems: opportunities, challenges, and open problems. *Journal of Ambient Intelligence and Humanized Computing, 10*(10), 4151-4166. https://doi.org/10.1007/s12652-017-0659-1

De Rijck, G., & Schrevens, E. (1998). Comparison of the mineral composition of twelve standard nutrient solutions. *Journal of Plant Nutrition, 21*(10), 2115-2125. https://doi.org/10.1080/01904169809365548

Din, S., Paul, A., Ahmad, A., Gupta, B. B., & Rho, S. (2018). Service orchestration of optimizing continuous features in industrial surveillance using big data based fog-enabled Internet of Things. *IEEE Access, 6*, 21582-21591. https://doi.org/10.1109/ACCESS.2018.2800758

Dunaieva, I., Vecherkov, V., Filina, Y., Popovych, V., Barbotkina, E., Pashtetsky, V., Terleev, V., Mirschel, W., & Akimov, L. (2021). Review of automatized meteorological stations use for agricultural purposes. In *IOP Conference Series: Earth and Environmental Science* (Vol. 937, No. 3, p. 032097). IOP Publishing. https://doi.org/10.1088/1755-1315/937/3/032097

Dunn, B., & Mills-Ibibofori, T. (2016). *LED Lighting for Plant Production*. Division of Agricultural Sciences and Natural Resources. https://doi.org/10.13140/RG.2.2.28851.84000

Gao, W., He, D., Ji, F., Zhang, S., & Zheng, J. (2020). Effects of daily light integral and LED spectrum on growth and nutritional quality of hydroponic spinach. *Agronomy, 10*(8), Article 1082. https://doi.org/10.3390/agronomy10081082

Gráda, C. Ó. (1992). *Ireland's Great Famine*. Department of Economics University College Dublin.

Gupta, S. D., & Agarwal, A. (2017). Artificial lighting system for plant growth and development: Chronological advancement, working principles, and comparative assessment. In S. D. Gupta (Ed.), *Light Emitting Diodes for Agriculture* (pp. 1-25). Springer. https://doi.org/10.1007/978-981-10-5807-3_1

Hamza, A., Abdelraouf, R. E., Helmy, Y. I., & El-Sawy, S. M. M. (2022). Using deep water culture as one of the important hydroponic systems for saving water, mineral fertilizers and improving the productivity of lettuce crop. *International Journal of Health Sciences, 6*, 2311-2331. https://doi.org/10.53730/ijhs.v6nS9.12932

Hartanti, A., & Sulistyowati, R. (2022). The effectiveness of using types of containers and consentration AB mix on the growth and production of white packcoy (*Brassica rapa* L.) Var. dakota uses wick system hydroponics. *Nabatia, 10*(2), 101-109. https://doi.org/10.21070/nabatia.v10i2.1613

Huang, Y., Chen, Z., Yu, T., Huang, X., & Gu, X. (2018). Agricultural remote sensing big data: Management and applications. *Journal of Integrative Agriculture, 17*(9), 1915-1931. https://doi.org/10.1016/S2095-3119(17)61859-8

Janeczko, D. B., & Timmons, M. B. (2019). Effects of seeding pattern and cultivar on productivity of baby spinach (*Spinacia oleracea*) grown hydroponically in deep-water culture. *Horticulturae, 5*(1), Article 20. https://doi.org/10.3390/horticulturae5010020

Khan, N., Ray, R. L., Sargani, G. R., Ihtisham, M., Khayyam, M., & Ismail, S. (2021). Current progress and future prospects of agriculture technology: Gateway to sustainable agriculture. *Sustainability, 13*(9), Article 4883. https://doi.org/10.3390/su13094883

Khwankaew, J., Nguyen, D. T., Kagawa, N., Takagaki, M., Maharjan, G., & Lu, N. (2018). Growth and nutrient level of water spinach (*Ipomoea aquatica* Forssk.) in response to LED light quality in a plant factory. *Acta Horticulturae, 1227*, 653-660. https://doi.org/10.17660/ActaHortic.2018.1227.83

Kim, D., & Son, J. E. (2022). Adding far-red to red, blue supplemental light-emitting diode interlighting improved sweet pepper yield but attenuated carotenoid content. *Frontiers in Plant Science, 13*, Article 938199. https://doi.org/10.3389/fpls.2022.938199

Kondratieva, V. V., Voronkova, T. V., Semenova, M. V., Olekhnovich, L. S., & Shelepova, O. V. (2022). Effect of LEDs on the growth and physiological responses of sweet basil (*Ocimum basilicum* L.). *IOP Conference Series: Earth and Environmental Science*, *1045*(1), Article 12090. https://doi.org/10.1088/1755-1315/1045/1/012090

Lem, A., Bjørndal, A., & Lappo, T. (2014). Economic analysis of supply and demand for food up to 2030. In *FAO Fisheries and Aquaculture Circular (FAO) eng no. 1089* (Vol. 1089, Issue 1089). Food and Agriculture Organization.

Madushanki, A. A. R., Halgamuge, M. N., Wirasagoda, W. A. H. S., & Syed, A. (2019). Adoption of the Internet of Things (IoT) in agriculture and smart farming towards urban greening: A review. *International Journal of Advanced Computer Science and Applications, 10*(4), 11-28. https://doi.org/10.14569/IJACSA.2019.0100402

Magwaza, S. T., Magwaza, L. S., Odindo, A. O., & Mditshwa, A. (2020). Hydroponic technology as decentralised system for domestic wastewater treatment and vegetable production in urban agriculture: A review. *Science of The Total Environment, 698*, Article 134154. https://doi.org/10.1016/j.scitotenv.2019.134154

Mamatha, V., & Kavitha, J. C. (2023). Machine learning based crop growth management in greenhouse environment using hydroponics farming techniques. *Measurement: Sensors, 25*, Article 100665. https://doi.org/https://doi.org/10.1016/j.measen.2023.100665

Namani, S., & Gonen, B. (2020). Smart agriculture based on IoT and cloud computing. In *2020 3rd International Conference on Information and Computer Technologies (ICICT)* (pp. 553-556). IEEE Publishing. https://doi.org/10.1109/ICICT50521.2020.00094

Namgyel, T., Siyang, S., Khunarak, C., Pobkrut, T., Norbu, J., Chaiyasit, T., & Kerdcharoen, T. (2018). IoT based hydroponic system with supplementary LED light for smart home farming of lettuce. In *2018 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)* (pp. 221-224). IEEE Publishing. https://doi.org/10.1109/ECTICon.2018.8619983

Ngcobo, B. L., Bertling, I., & Clulow, A. D. (2022). Artificial daylength enhancement (pre-sunrise and post-sunset) with blue and red led lights affects tomato plant development, yield, and fruit nutritional quality. *Horticulture, Environment, and Biotechnology, 63*(6), 847-856. https://doi.org/10.1007/s13580-022-00447-1

Patel, N. R., & Kumar, S. (2018). Wireless sensor networks' challenges and future prospects. *2018* In *International Conference on System Modeling & Advancement in Research Trends (SMART)* (pp. 60-65). IEEE Publishing. https://doi.org/10.1109/SYSMART.2018.8746937

Paul, A., & Jeyaraj, R. (2019). Internet of Things: A primer. *Human Behavior and Emerging Technologies, 1*(1), 37-47. https://doi.org/https://doi.org/10.1002/hbe2.133

Rathinam, D. D. K., Surendran, D., Shilpa, A., Grace, A. S., & Sherin, J. (2019). Modern agriculture using wireless sensor network (WSN). In *2019 5th International Conference on Advanced Computing & Communication Systems (ICACCS)* (pp. 515-519). IEEE Publishing. https://doi.org/10.1109/ICACCS.2019.8728284

Runkle, E. (2016). *Red Light and Plant Growth*. GPN Magazine. https://gpnmag.com/wp-content/uploads/2016/08/GPNAugust_TechSpeak.pdf

Satterthwaite, D., McGranahan, G., & Tacoli, C. (2010). Urbanization and its implications for food and farming. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1554), 2809-2820. https://doi.org/10.1098/rstb.2010.0136

Setiawan, D., Siswati, L., & Ariyanto, A. (2022). Water pump control system in hydroponic plants using the ebb and flow method. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1041, No. 1, p. 012020). IOP Publishing. https://doi.org/10.1088/1755-1315/1041/1/012020

Singh, S. (2009). Basics of light emitting diodes, characterizations and applications. In *Handbook of Light Emitting and Schottky Diode Research* (pp. 1-36). Nova Science Publishers

Suryaningprang, A., Suteja, J., Mulyaningrum, M., & Herlinawati, E. (2021). Hydroponic: Empowering local farmer knowhow to gain value added on agriculture commodity. *Budapest International Research and Critics Institute (BIRCI-Journal): Humanities and Social Sciences, 4*(1), 787-796. https://doi.org/10.33258/birci.v4i1.1676

Susanto, F., Nurtantio, P., Soeleman, M. A., Sunarya, P. A., Pujino, & Nursasongko, E. (2021). P2P for prototype embedded system information on agriculture result using IoT. In *2021 International Seminar on Application for Technology of Information and Communication (ISemantic)* (pp. 348-352). IEEE Publishing. https://doi.org/10.1109/iSemantic52711.2021.9573206

Taofik, A., Frasetya, B., Nugraha, R., & Sudrajat, A. (2019). The effects of subtrat composition on the growth of *Brassica oleraceae* Var. Achepala with drip hydroponic. In *Journal of Physics: Conference Series* (Vol. 1402, No. 3, p. 033031). IOP Publishing. https://doi.org/10.1088/1742-6596/1402/3/033031

Thakur, D., Kumar, Y., Kumar, A., & Singh, P. K. (2019). Applicability of wireless sensor networks in precision agriculture: A review. *Wireless Personal Communications, 107*(1), 471-512. https://doi.org/10.1007/s11277-019-06285-2

Torabi, M., Mokhtarzadeh, A., & Mahlooji, M. (2012). The role of hydroponics technique as a standard methodology in various aspects of plant biology researches. In T. Asao (Ed.), *Hydroponics - A Standard Methodology for Plant Biological Researches* (pp. 113-134). InTech. https://doi.org/10.5772/36612

Ullo, S. L., & Sinha, G. R. (2020). Advances in smart environment monitoring systems using IoT and sensors. *Sensors, 20*(11), Article 3113. https://doi.org/10.3390/s20113113

Wang, M., Dong, C., & Gao, W. (2019). Evaluation of the growth, photosynthetic characteristics, antioxidant capacity, biomass yield and quality of tomato using aeroponics, hydroponics and porous tube-vermiculite systems in bio-regenerative life support systems. *Life Sciences in Space Research, 22*, 68-75. https://doi.org/10.1016/j.lssr.2019.07.008

Wimmerova, L., Keken, Z., Solcova, O., Bartos, L., & Spacilova, M. (2022). A comparative LCA of aeroponic, hydroponic, and soil cultivations of bioactive substance producing plants. *Sustainability*, *14*(4), Article 2421. https://doi.org/10.3390/su14042421

Xu, Y., Chang, Y., Chen, G., & Lin, H. (2016). The research on LED supplementary lighting system for plants. *Optik, 127*(18), 7193-7201. https://doi.org/10.1016/j.ijleo.2016.05.056

Yu, L., Gao, W., R Shamshiri, R., Tao, S., Ren, Y., Zhang, Y., & Su, G. (2021). *Review of Research Progress on Soil Moisture Sensor Technology*. Verlag nicht ermittelbar. http://dx.doi.org/10.34657/10037

Zhou, J., Chen, J., Chen, X., Zhu, X., Qiu, Y., Song, H., Rao, Y., Zhang, C., Cao, X., & Cui, X. (2021). Sensitivity of six typical spatiotemporal fusion methods to different influential factors: A comparative study for a normalized difference vegetation index time series reconstruction. *Remote Sensing of Environment, 252*, Article 112130. https://doi.org/10.1016/j.rse.2020.112130