Control of a Semi-closed Plant Factory with Artificial Lighting-based on Two Different LED with NB-IoT

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ABSTRACT

Plant factory artificial light (PFAL) is an effective technique for producing large amounts of crops per area and high-quality plant growth. This work aims to construct a semi-closed PFAL growth system based on NB-IoT using two types of LED arrays: phosphor-converted LED (pc-LED) and red-blue LED (RB-LED). Next, while examining the features of the artificial light spectrum, compare the Curry leaf kale and Chinese kale in seedlings under various LED light sources. An NB-IoT module with the MAGELLAN platform monitored and controlled the temperature, humidity, and illumination of the semi-closed PFAL growing system. The results indicate that cos lettuce cultivated with pc-LEDs is likely more photosynthesis-capable than cos lettuce grown with RBLEDs. When compared to RB-LED, the average fresh weight of the cos lettuce from was significantly higher. The data gathered from the cloud system under the MAGELLAN platform during the 7-day trial, the control of lighting and watering in the semi-closed PFAL system, and the measurement results of environmental factors were all accurately completed. Organic veggies could be grown in a home or school setting using the semi-PFAL growing technique.

Keywords: Semi-closed PFAL System, Organic Lettuce, R-B LED, pc-LED, NB-IoT, MAGELLAN

1. INTRODUCTION

The problem of global warming causes changes in the global environment. As a result, agriculture has a problem of low productivity around the world. Controlling the environment in a closed cropping system is one solution to alleviate the problem. Plant factory artificial light (PFAL) is a secure technique for cultivating premium-quality of plants and vegetables. Additionally, crop yields are enhanced by more than ten times compared to conventional farming. A PFAL is a closed planting system that can completely control the environment, including light, temperature, relative humidity, plant food supply, and pests [1]. Semi-enclosed PFALs are also being developed, such as indoor vertical farming and vertical farming with artificial lighting. That is, cultivate the organic vegetables inside homes, in restaurants, and in schools [2]-[6].

The PFAL also has controls for light, temperature, humidity, carbon dioxide, and minerals. Light-emitting diodes (LED) are extensively used in artificial lighting systems because of their capacity to choose the optimal light wavelength for each plant [3]. In plant industries, artificial light is often provided by white LED, RB-LED, and red-blue-fared LED (RB+FR LED) [2]-[4]. It could help the plant's morphology and production, as well as the generation of important chemicals. It's an intriguing challenge that the authors [2] suggest a semi-enclosed PFAL in a soil-based system for domestic use that only uses RB-LEDs. Home plants will be adequately maintained, regulated, and monitored, but if modifications are made to make it simpler for people to access them through a user-friendly system. The Internet of Things (IoT) is a potential solution that is appropriate for the modern day. A semi-closed PFAL is a plant-growing system that exploits environmental factors within the home, such as temperature and relative humidity. In general, the environment in the house is ideal for the living circumstances of living things. A system like this optimizes the regulation of plant lighting intensity, illumination duration, airflow, and water. IoT is therefore a technical solution that is accurate and dependable for managing plant development and yield parameters. Furthermore, IoT is a system with crucial qualities such as quick access, smart control [7] and a user-friendly user interface.

The IoT is transforming agriculture by raising product quality, boosting company efficiency, and optimizing production processes [7]-[9]. The narrow-band Internet of Things, or NB-IoT, was created by the 3rd Generation Partnership Project (3GPP), which is in charge of defining 3G, 4G, and LTE communications. It transmits little data

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and consumes little power to link numerous devices via a mobile network [9]. In a soil-fertilizing system, the IoT receives data from sensors to process and control the operation of water pumps, ventilating fans, artificial lights, etc. In addition, the IoT will display measurement data for temperature and relative humidity in the air, soil moisture, water level, and artificial light [10].

Precision agriculture and the smart industry may both benefit from its use in conjunction with a variety of sensors. If a semi-closed PFAL of a size suitable for household use is constructed to produce organic vegetables for consumption, it will lessen the danger of ingesting filthy vegetables contaminated with germs and pollutants. It also contributes to lower future healthcare expenditures. The authors were motivated to develop a semi-closed PFAL system based on NB-IoT employing two types of LED, RB-LED and RB+FR LED, for use in real-world residential applications. The goal of this research is to use NB-IoT to build a soil-based, semi-closed PFAL. To examine the spectrum distribution qualities of these artificial lights as well as compare the growth and development of Curry leaf kale and Chinese kale in the seedling stage. The potential of NB-IoT to manage and monitor environmental factors and water in a semi-closed PFAL is then evaluated.

2. MATERIAL AND METHOD

2.1 Design of RB+FR artificial light source

The RB with FR spectrum is generally generated by a color mixing method of mixing blue, red, and FR LEDs [4]-[6]. In this paper, RB+FR artificial light generated from phosphor−converted LED (pc-LED) [9]-[14] is presented. The pc-LED in this article has a wavelength range of 380 nm to 780 nm and uses 10 W at a voltage of 220-240 Vac. The photosynthetic photon flux density (PPFD unit in µmol m^{-2} s^{-1}) was adjusted using AC Dimmer devices [7]. The authors' design comprises 15 pc-LEDs, each mounted over a 13 cm by 6 cm metal heat sink. Each column has three pc-LEDs and is organized in three rows and five columns. The LED array's lighting area is approximately 45 cm by 35 cm. A model of an RB+FR artificial light source is shown in Fig. 1. A single-phase AC dimmer module of 2 kW controls the fifth teen pc-LEDs, which have a total power of 150 W. To modify the total PPFD to meet the design goal of approximately 200 µmol m^{-2} s^{-1}.

2.2 Design of RB-artificial light source

The RB-LED used in this study mixes together R and B light at a R:B ratio of around 1.0 (R:B = 1). There are 20 sets of RB-LEDs, each consisting of two of R-LEDs and two B-LEDs connected in series. Each LED has a diameter of 6 mm and a power rating of around 2 W. The B-LED has a wavelength of 450 nm at V_F 3.4 V and I_F 700 mA, whereas the R-LED has a wavelength of 630 nm at V_F 2.4 V and I_F 700 mA. The 200 W AC-DC converter provides the 12V overall input voltage. Twenty LED units

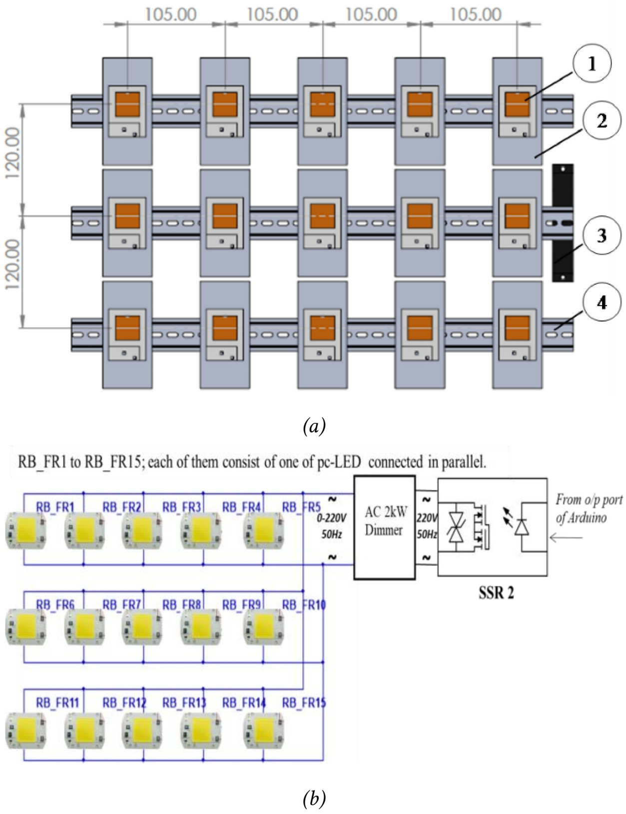


***Fig. 1**: (a) A model of RB+FR artificial light source (1) pc-LED (2) heat sink (3) ACwired terminal and (4) aluminum rail support. (b) RB+FR LED circuit diagram.*

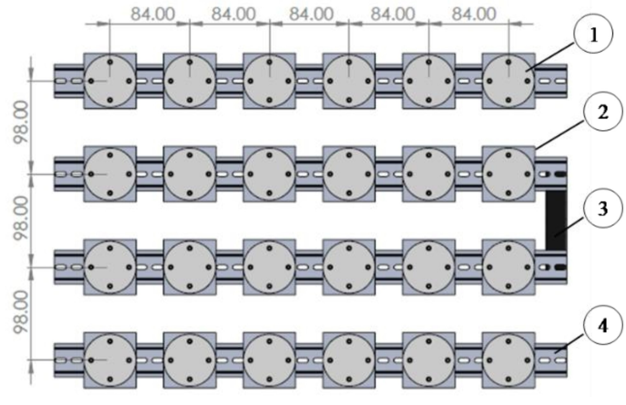
have been installed, and they are placed on an 8 cm by 9 cm aluminum heat sink. The illumination area measures 45 cm by 35 cm. The model of RB-artificial light is shown in Fig .2. The circuit diagram is shown in Fig. 2 (b). To regulate the electrical power needed by the RB-LED to construct the whole PPFD, the author's approach is about 200 mol m^{-2} s^{-1}.

2.3 Diagram of a Semi-closed PFAL system

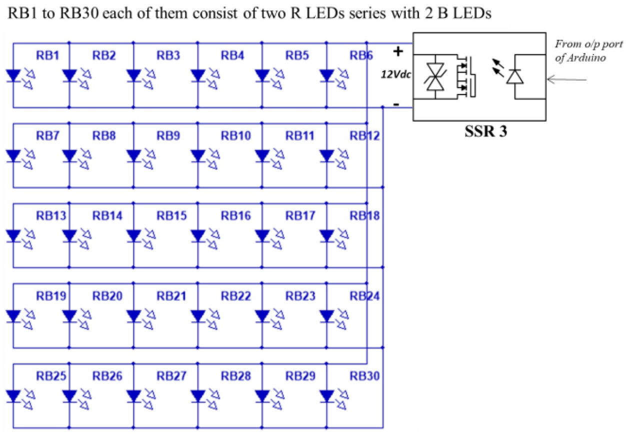
Fig. 3 shows the architecture diagram of a semi-closed PFAL growing system. The on/off operation of the pc-LED and RB-LED is managed by solid-state relays no. 2 and 3 (SSR2 and SSR3). The pc-LED lights the top planting area, while the RB-LED lights the lower floor transplant. The semi-PFAL growing system's 3 ventilation fans have their opening and shutting times set by SSR1 as well.

A light intensity control circuit for the pc-LED array uses the AC dimmer idea to operate. The SSR4 operates a water pump with on/off controls, which pumps water from the water tank at the bottom up to the plant on the plant plot. The working time is based on how much water each plant needs. The MAGELLAN platform sends some control signals to the water pump, RB-LED, and pc-LED based on the requirements of the user.

The SSR5 is designed to control the water valve to increase the quantity of water in the tank. All 5 SSRs



(a)



(b)

Fig. 2: (a)A model of RB artificial light source (1) 2R-LED combined to 2B-LED on the plate in series (2) heat sink (3) DCwired terminal and (4) aluminium rail support. (b) RB LED circuit diagram.

are controlled through the output ports of the Arduino UNO Broad. In plants, there are three types of sensors included in the control process. They consist of 2 sets of digital temperature and relative humidity sensor modules using the AM2302 module and an analog water level sensor. The BC95 AIS NB-IoT module (a MAGELLAN IoT device) is selected for data communication between the UNO microcontroller and the MAGELLAN service server IoT platform from AIS Thailand. The MAGELLAN offers an easy way to develop a dashboard and data storage with his platform and API through his IoT product. The MAGELLAN dashboard can be used to monitor and send the data to his IoT device in real time through his platform and AIS network. The users can monitor and send the command data to the PFAL in real-time through this platform from anywhere that the AIS network is supported. The details of the schematic circuit of the semi-closed PFAL control system are shown in Fig. 4.

2.4 NB-IoT based control

Because it has fewer real-world restrictions than open-access IoT, like restricting the number of sensors and cloud data storage, the authors chose an IoT control that is based on the MAGELLAN platform (AIS Thailand).

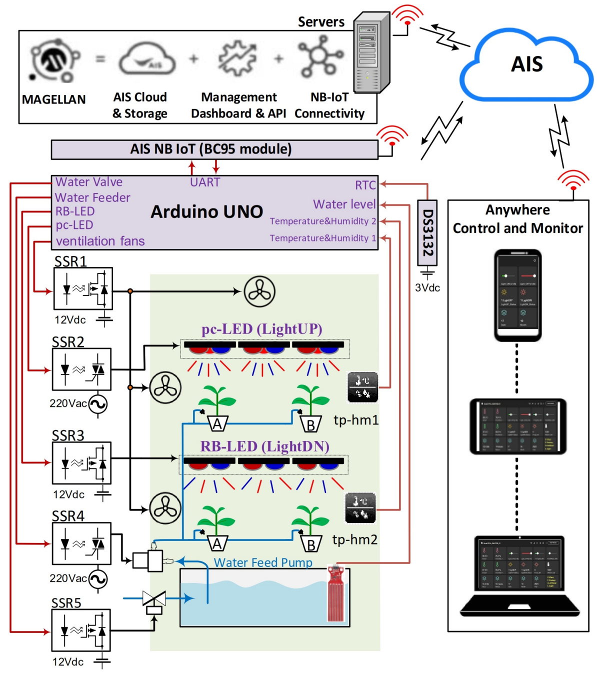


Fig. 3: Diagram of the semi-closed PFAL growing system.

A dashboard, cloud storage, and a RESTful API are further features that the MAGELLAN provides. These features let authors work on the same platform and quickly generate content by displaying sensor values. As shown in Fig. 3, the hardware of the IoT system consists of (1) a water level sensor, (2) two sets of temperature and humidity sensors, (3) 5 solid-state relays, SSR1-SSR5, (4) an NB-IoT module communication boards (BC95 module), and (5) Arduino board. A water level sensor is mounted on top of the water tank to detect and show the water level. The lower and upper plant sections have temperature and humidity sensors placed to measure and send to the MAGELLAN platform monitoring. The process control operating sequence is created by the program based on the flowchart depicted in Fig. 5, which run on an Arduino Uno board. The Magellan platform allows the user to send four real-time commands to the small PFAL-controlled sequence. They include the following: (1) the initial light start time at o'clock; (2) the initial light stop at o'clock; (3) the water feeder start time at o'clock; and (4) the water feeder "ON" duration in minutes. When the controller requests those command numbers, they are transmitted to the Arduino Uno board via the BC95 NB IoT module with the AIS communication network and standard serial communication, universal asynchronous receiver transmitter (UART), respectively. In Fig. 5, the controller obtains the reference real-time clock (RTC) from the highly accurate DS3231 module. It then uses these reference RTC hours and minutes (hour and min) to compare the commands from the administrator user on the Magellan platform (hour 1,

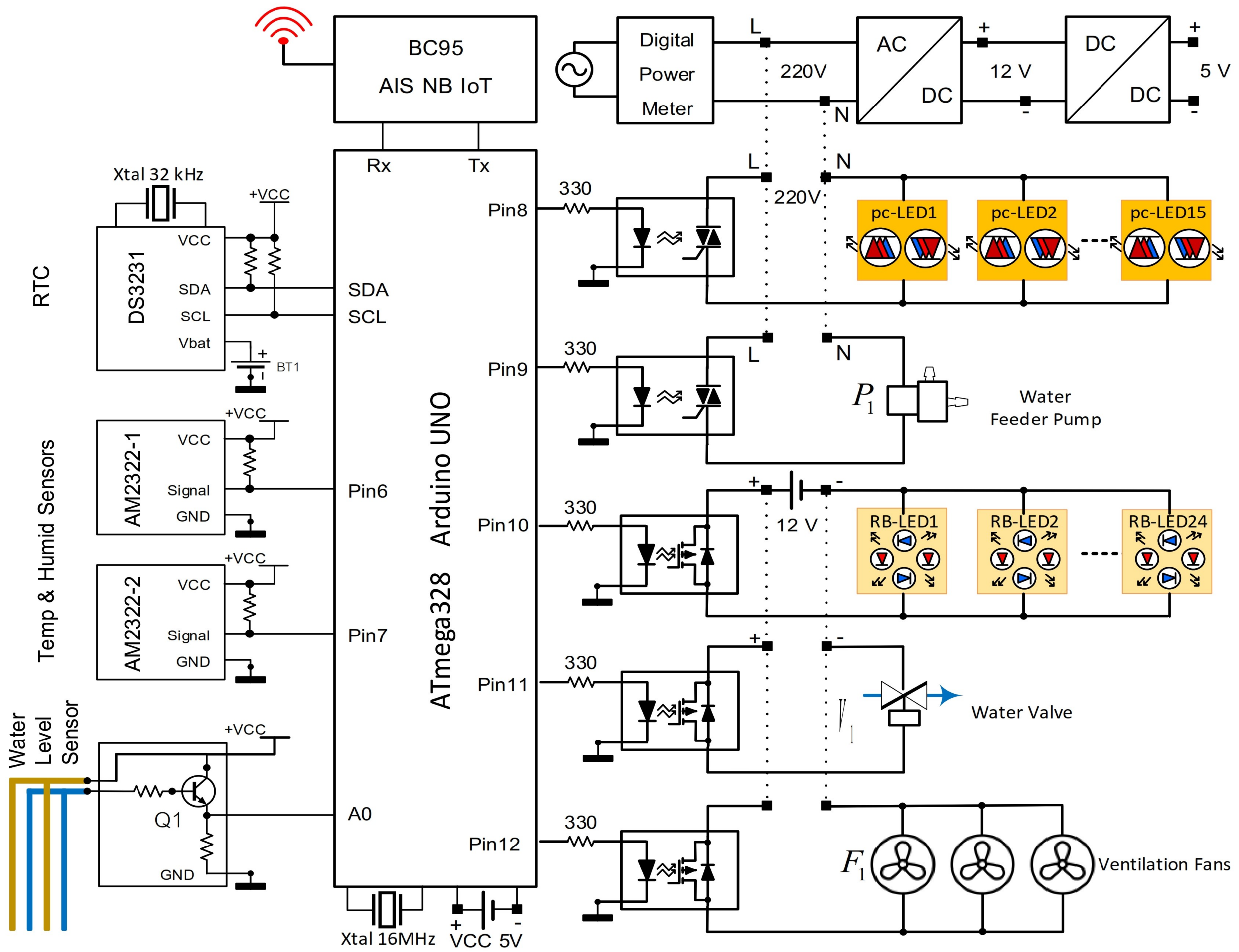


Fig. 4: Schematic circuit of the semi-closed PFAL control system.

hour 2, hour 3, min). This permits the controller to control the water feeder pump and both top and bottom artificial lights (pc-LED and RB-LED) in accordance with user requirements.

For example, H_1 is subtraction result between the real-time hour (hour) from the RTC and the artificial lights starting command hour from the Magellan dashboard (hour 1), $H_1 = hour - hour_1$. AndH_2 is subtraction result between the real time hour (hour) from the RTC and the artificial light stop command hour from the Magellan dashboard (hour 2), $H_2 = hour - hour_2$. If the $H_1$and the $H_2$are in the condition, the H_1more than or equal to zero and the $H_2$is less than or equal to zero, $H_1 >= 0$ *and* $H_2 < 0$, the artificial lights are turned on. And if the H_1or $H_2$is not in that condition, the artificial lights are turned off. In the case of the control of the water feeder pump (P_1), the condition is the same as the artificial light control condition, as shown in Fig. 5. The H_3 is subtraction result between the actual time hour (hour) and the water feeder pump beginning command hour from the Magellan dashboard (hour 3),$H_3 = hour - hour_3$. The result of subtracting the given duration time of the water feeder pump is turned on in minutes is represented by the M_1. The water feeder pump (P_1) is turned on when $H_3 >= 0$ *and* $M_1 < 0$, and turned off when $H_3 < 0$ *or* $M_1 >= 0$. In addition, the control of the water valve (V_1), TheL_1 is the result of subtracting the stated maximum water level in the tank ($level_1$) from the current water level in the tank, which is determined using the analog read from the water level sensor($level$),$L_1 = level - level_1$. Furthermore, theL_2 represents the result of subtracting the stated minimum water level in the tank($level_2$) from the current water level in the tank ($level$), which is determined using the analog read from the water level sensor. If the $L_1$is in the condition, $L_1 >= 0$ *and* $L_2 < 0$, the water valve is turned on ($V_1 = ON$).And if the L_1or $L_2$is not in that condition, the water valve is turned off ($V_1 = OFF$). By the way, to control the three ventilation fans (F_1), the condition is the same as the water valve (V_1) control condition, as shown in Fig. 5

2.5 Design of Semi-closed PFAL system

In this paper, a semi-closed PFAL refers to the PFAL that does not control temperature, relative humidity, or carbon dioxide inside the PFAL. Because this prototype is used within the home with an air conditioning system or a natural ventilation system, it provides optimal growing

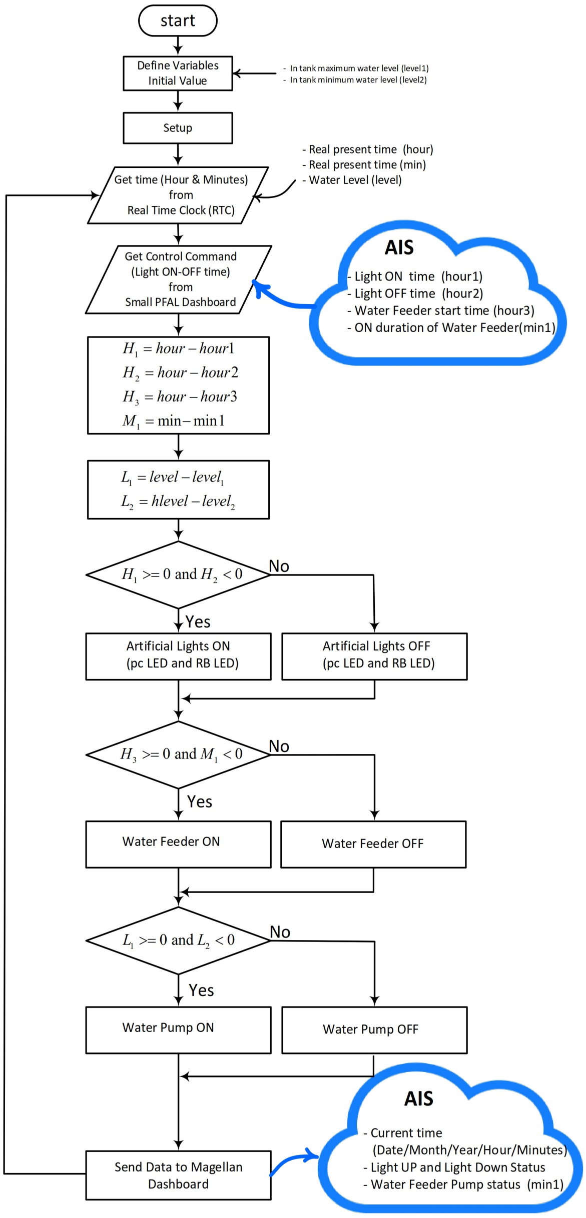


***Fig. 5**: Flowchart of the process control operating sequence obtained in Arduino uno program memory to control the proposed small PFAL.*

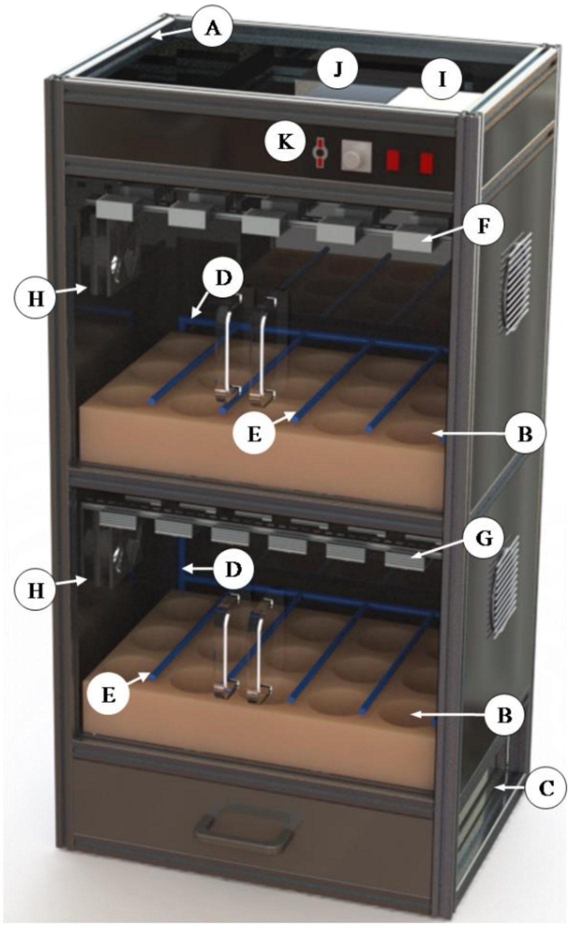


***Fig. 6**: A semi-closed PFAL prototype (A) Aluminium frame (B) soil based planting area (C) water container (D) main water pipe (E) secondary water pipe (F) R+FR artificial light (G) RB artificial light (H) ventilation fan (I) NB-IoT based control device. (J) power supply and (K) control switch.*

conditions for plants with semi-closed PFAL. Its weight-bearing structure is composed of an aluminum profile with a 3 cm × 3 cm bending area (Fig. 6.A). The frame is rectangular in design and resembles a storage cabinet. The semi-closed PFAL constructed here is 60 cm × 48cm × 140cm. It has two levels of planting space measuring approximately 55 cm by 40 cm. Each layer is made up of 12 units' 12.5 cm-diameter plastic pots for flowers (Fig. 6.B).

Because it is a plant that grows in soil. As a consequence, the author developed a 30-liter water container (Fig. 6.C) to be fitted at the bottom of the semi-closed PFAL. Water was dripped directly into each pot through a 15-mm main water pipe (Fig. 6.D) and a 6-mm secondary water pipe (Fig. 6.E) in an irrigation system. The author selected to put a 40-watt, 220-volt submerged pump within a water container. Using an NB-IoT-based control system, manage the operation of water pumps to deliver water to plants during cropping at the proper moment.

An RB+FR LED array is built at the top of the crop floor (Fig.5.F), and an RB-LED lighting system is installed on the ground level (Fig.5.G). Regulate illumination by using the system outlined in Section 2.3. The semi-closed PFAL growing system circulates like a natural environment thanks to a ventilation fan installed on one side of the prototype (Fig.5.H). It is outfitted with hardware from the NB-IoT module, Arduino boards (Fig.6.I), a power supply, and other relevant devices (Fig.6.J) on top of the structure.

2.6 Experimental and Measurement

There are two types of plants used in the experiment: Curry leaf kale (*Brassica oleracea var. acephala*) and Chinese kale (*Brassica oleracea var. albolabrin*). They were obtained from Chia Tai Co., Ltd in Thailand. Kale

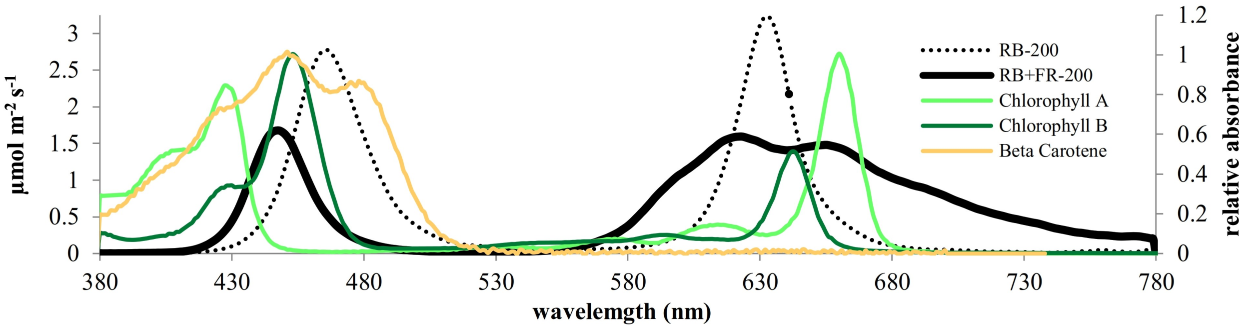


***Fig. 7**: Comparative the measurements spectrum of the RB-LED and pc-LED with the absorbance spectrum of chlorophyll a, chlorophyll b and beta carotene (reference from LUXEON Horticulture Calculator) [8].*

was chosen by the author because it is a green leafy vegetable with high nutritional value, high fiber, and low calories. It is rich in antioxidants and has a high natural vitamin C content [17]. Superfood is a common moniker for the well-liked green kale [18]. There are two experimental groups consisting of plants grown under 1) RB-LED at a PPFD of 200 µmol $m^{-2}s^{-1}$ (RB200) and 2) plants cultivated with RB+FR-LED at a PPFD of 200 µmol $m^{-2}s^{-1}$ (RB+FR200). The number of light and dark hours was 16/8. Every day, 50$\pm$5 ml of water is provided to the plants via NB-IoT control. The kale used in this study was grown in equal parts using loamy soil, compost, rice husk charcoal, coconut dust, and peat moss soil. A plant sample will be gathered from each group's twelve plants (n = 24).

The Quantum Sensor from Lighting Passport Essence-pro (Taiwan) is used to measure and the evaluate spectrum distribution of the artificial light. It has a spectrum range of 380 nm to 780 nm and a resolution of 2 nm [7].

The number of leaves (LN), plant height (PH), and growth rate (GR) were used to evaluate the growth and development of the experimental plants. The statistical approach used in the average analysis of experimental plants is the t-test ($p=0.05$). For the analysis, IBM SPSS statistics were employed [10].

The author tests the microcontroller's program and the functionality of the NB-IoT system, controller board, solid state switch, and dash board monitoring on the MAGELLAN platform. The experiment lasted 15 days when the plant was at its seedling stage, and the data was visually shown.

3. RESULTS AND DISCUSSION

3.1 Spectrum distribution comparison

The measurement discoveries of the spectrum distributions of the two LEDs indicated that the RB-LED had a greater spectrum of blue light (400-500 nm) than the RB+FR-LED. RB-LED, on the other hand, emits less red and far-red light (600-780 nm) than RB+FR-LED. When the chlorophyll a (light green line), chlorophyll b (dark green line) and carotenoid (orange line) absorption curves are compared to the two artificial light spectra. Contrary to the artificial light produced by RB-LED, it has been discovered that the light spectrum of RB+FR-LED promotes the absorption of chlorophyll a and chlorophyll b (Fig. 7). Intense red light and FR responded better to chlorophyll production, especially at wavelengths higher than 650 nm. That suggests that plants grown under semi-closed PFAL with RB+FR-LED are likely to have better photosynthesis capabilities than light from RB-LED [19]. This is because RB+FR-LED can generate higher PPFD in deep red light and FR than RB-LED, resulting in the development of some plants' stems and leaves.

The observed PPFD in the wavelength range of 400 nm to 700 nm is approximately 200 µmol m^{-2} s^{-1}. According to Fig. 8 (a), in terms of photon flux content, an RB-LED emits more blue light, but an RB+FR-LED emits much more R and FR photon flux. The ratio of red to blue light produced by RB+FR-LED and RB-LED, respectively, is 2.56 and 1.04.

When the R/B ratio of RB+FR200 is 2.56 (Fig. 8 (b)), it has a good influence on growth. and the productivity of many different types of plants, such as the growth and features of coriander [21], the growth of pepper seedlings in PFAL [22], the growth and quality of lettuce in PFAL [23], and so on. Red- FR ratio of the light output from RB+FR-LED and RB-LED is generated in ratios of 3.99 and 41.41, respectively. This demonstrates that the RB+FR-LED derived PPFD in the FR light area is roughly 14 times higher than the RB-LED. Increased FR influences plant development by promoting stem elongation and biomass partitioning on stems [19]. Increased FR favoured leaf growth with higher PPFD.

In cucumber, leaf growth increased with a rising percentage of FR at all PPFD levels, with no interaction [20]. The quantity of photosynthetically active photons gathered in a square meter over the course of a day is referred to as the daily light integral (DLI). The DLI (unit is mol m^{-2} d^{-1}), on the other hand, is the same in both LEDs. This indicates that the two groups of experimental plants received the same quantity of light or photon flux each day.

***Table 1**: Leaf number(LN) Plant heigh (PH) and Growth rate (GR) FRESH OF Curry Leaf Kale Under RB+FR 200 AND RB 200 LEDs OF PPFD OF 200 μmol m^{-2} s^{-1}.*

	LN	PH (cm)	GR (cm/day)
RB+FR200	6.167±.408	4.367±1.137	.168±.094
RB 200	6.000±.632	4.033±1.217	.110±.068
t-test	NS	NS	NS

***Table 2**: Leaf number(LN) Plant heigh (PH) and Growth rate (GR) FRESH OF Chinese Kale Under RB+FR 200 AND RB 200 LEDs OF PPFD OF 200 μmol m^{-2} s^{-1}.*

	LN	PH (cm)	GR (cm/day)
RB+FR200	5.667±.816	9.433±1.818	.320±.958
RB 200	5.167±.753	7.533± .747	.184±.599
t-test	NS	*	*

3.2 Comparative of the plant growth and development

The authors apply an independent t-test statistic to compare the differences between leaf number (LN), plant height (PH), and growth rate (GR) at $p=0.05$. The results of testing the average of the sample group (a group of 12 plants each) to study the growth of curly leaf kale grown in the seedling stage (15 days) in a semi-PFAL system showed that LN, PH, and GR under LED RB+ FR200 and RB200 were not significantly different ($p > 0.05$), as shown in Table 1.

The experiment results show that it is possible that curly leaf kale grown with red LED combined with blue LED plus fare at R/B ratio 2.56 and R/FR ratio 3.99 will have the same number of leaves and growth rate. Better than light with an R/B ratio <2.56 and an R/FR ratio >3.99. When considering plant morphology and leaf size, it can be seen that there is a chance of going in the same direction, as shown in Fig. 8.

Table 2 indicates the same study conditions for variables of growth and development in the same treatments of Curry leaf kale. The results showed that the Chinese kale had LN under LED RB+FR200 and RB200 were not significantly different. Instead, it was found that Chinese kale under RB +FR200 showed the GR and PH higher than under LED of RB200 with statistical significance ($p<0.05$). When the size of the leaves is considered (Fig. 8), it can be seen that the Chinese kale grown under RB+FR200 has bigger leaves than the Chinese kale grown under RB200. The findings of this study are congruent with those of [4], [7], and [10]. Growing plants with artificial light using red light mixed with blue and adding Fared (RB+FR) resulted in many plants with greater growth and yields than using red light mixed with blue alone. It shows a comparison of growth of Curry leaf kale and Chinese kale under RB+FR200 and RB200 at PPFD = 200 μmol m^{-2} s^{-1} as shown in Fig. 9.

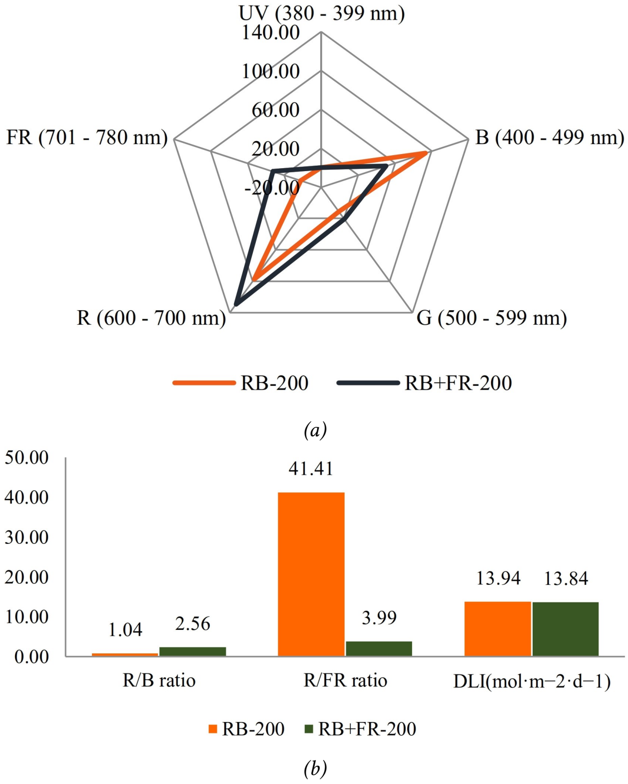
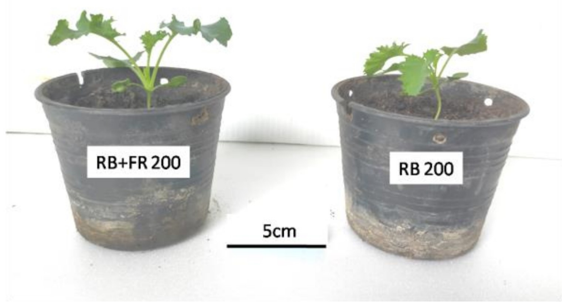


***Fig. 8**: Comparative the measurements result of light quality and PPFD of RB-LED and RB+FR-LED artificial LED light.*

3.3 Monitoring data and control platform

Fig.10 shows the real-time data on a PC of the semi-closed PFAL that is being monitored on the MAGELLAN platform. To operate the PFAL with the sliding bar, the user can apply four input commands: Light_ON, Light_OFF, Pump02_ON, and Feed water_min, which is the water feeder pump's ON time in minutes. The first two commands indicate that the artificial lights should start and stop. The data was transmitted to the controller using the AIS network and BC95 NB IoT. The output data sent by the controller is other data displayed on the website.

Fig. 11 shows the 7-day graphs that display the environmental parameter measurement results in a semi-closed PFAL system. The data was plotted on the website and gathered from a cloud system under the MAGELLAN platform. The temperature and humidity of the top plant using pc-LED (temperature 1 and humidity 1) and the bottom plant using RB-LED (temperature 2 and humidity 2) in the semi-closed PFAL growing system are represented in Fig. 11 (a) and Fig. 11(b), respectively. The pc-LED and RB-LED lighting status and the control widgets in real-time were represented in Fig. 11(c). The results of the 7-day testing showed that it worked correctly.



(a)

(b)

Fig. 9: *Comparative the morphological of sample plants under Semi-closed Plant Factory with Artificial Lighting-based on NB-IoT at PPFD = 200200 µmol m-2 s-1 (a) curry leaf kale and (b) Chinese kale.*

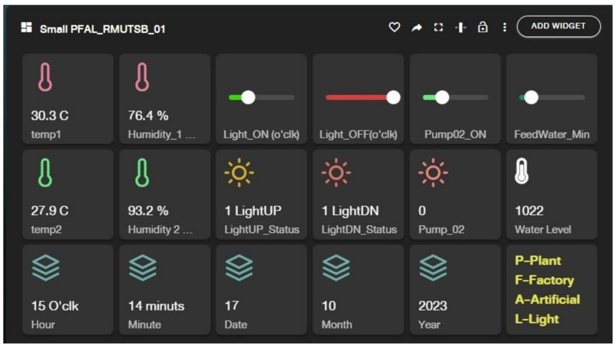


Fig. 10: *MAGELLAN dashboard developed in this study.*

On the other hand, the semi-closed PFAL system that the authors have suggested can be monitored and controlled, including the way in which the LED illumination functions. NB-IoT is a wireless communication module that is simple to access and monitor from both PCs and mobile devices. The annual cost via AIS's NB-IoT 900 MHz network is negligible in comparison to the simplicity of creating an IoT platform for managing smart agriculture in the future.

(a)

(b)

(c)

Fig. 11: *The environmental parameter measurement results in a semi-closed PFAL system are shown in the 7-day graphs. (a) temperature1 and humidity1, (b) temperature2 and humidity2 and (c) the pc-LED and RB-LED lighting status.*

4. CONCLUSION

The semi-closed PFAL growing system is appropriate for household applications. Strongly allow people to grow high-quality crops. It is safe, free of chemicals and pesticides, and promotes good health for all. The control of artificial lighting and plant watering with the NB-IoT module under the MARGELLAN platform was perfect. The semi-closed PFAL system can exchange data with other platforms, has a dashboard and has easy settings. It also reduces the time and cost of developing IoT solutions in the long run. Red light combined with blue light and fared (RB+FR) might increase the growth rate and plant height of Chinese kale. Using the RB+FR LED has the potential to raise the fresh weight of Chinese kale and Curry leaf kale. Red mixes with blue at the same PPFD as it grows with light. Because it creates several light spectrums on a single chip, the pc-LED with an R+B+FR light spectrum provides an easy-to-use alternative light source. Dimming controls can also be used to regulate the intensity of the light. The pc-LED is appropriate for indoor growing, vertical farming, supplementary light exposure in greenhouses, and other applications. The authors were successful in applying the concept of monitoring and controlling with NB-IoT to the construction of the semi-closed PFAL growing system, which is fascinating and might be used in the community or school in the future.

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