Design and analysis plant factory with artificial light

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ABSTRACT

It has been challenging to construct an autonomously controlled plant factory with artificial light (PFAL). It is also useful in engineering and bioscience research and education. The purpose of this research is to design and construct a micro-scale plant factory with artificial light (µPFAL) with automatic environment control for a university project. Then, analyze the effectiveness of managing temperature, humidity, potential of hydrogen (pH), electrical conductivity (EC), and carbon dioxide (CO_2) on crop production, as well as the cost, and benefit of µPFAL. The µPFAL is made up of light emitting diode (LED) lighting, air condition, vertical cultivation, EC-pH regulation, a CO_2 supply unit, and environmental control and monitoring. Control was provided via Arduino with PC monitor. For economic evaluation, cost-benefit analysis was used. The results of the control environment in µPFAL were achieved with a deviation of less than 2.5%. An Arduino-based environmental control system with a computer for monitoring was suited for university's PFAL.Our µPFAL could produce 80.45 g/head fresh weight of green oak lettuce, the lettuce's yield of 19 kg/m^2/y. The payback period of µPFAL is 3.28 years, net present value of 82,543.30 THB, an internal rate of return of 24% and the benefit to cost ratio (B/C) ratio of 1.22. Future research should include solar energy to assist µPFAL in meeting its sustainable goal.

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1. INTRODUCTION

Temperature, humidity, carbon dioxide (CO_2) concentration, light, water, and nutrients are among environmental elements that influence plant growth. Depending on the season, natural plant cultivation is subjected to a variety of environmental conditions [1]. Plant growth and production are also affected by environmental changes. A closed plant production system (CPPS) is a growing system that regulates the environmental conditions best suited to each plant species. Environmental management is essential for maximizing crop output quality and quantity. Plant factory with artificial light (PFAL) is a type of CPPS that produces high-quality staple foods such as leafy vegetables, lettuce, micro greens, and herbs. This includes the cultivation of high-priced niche, medicinal, and functional plants.

Temperature is an important factor that influences to the crop production. Crisphead lettuce grown in a closed-type plant factory can achieve good head formation under high light intensities (200 µmol/m^2/s) and low temperature [18/16 °C (0-30 days after transplantation, DAT) 18/14 °C (30–60 DAT)]. It was also found that the incidence of tip burn on the leaves of lettuce at low temperatures was significantly lower than at high temperatures. [22/18 °C (0–30 DAT) → 18/16 °C (30–60 DAT)] [2]. There are studies on the growth of kale in plant factory under different temperature, humidity, and CO_2. "The optimal temperature, relative humidity, and CO_2 range for growth (20–23 °C, 85%, and 700–1,000 ppm) and total glucosinolate content (14–17 °C, 55–75%, and 1,300–1,600 ppm) were different" [3]. Optimum temperature for growing leafy vegetables, lettuce, and other vegetables in the PFAL range is between 18 to 25 °C [4].

Furthermore, crop production increases when the humidity in the air is kept at a reasonable level. However, studies have shown that fungal illnesses arise when humidity is high. When humidity is low, the plant's growth is reduced. As a result, managing the ambient temperature and humidity is an impact on plant development and productivity across the board [5]. In addition, the concentration of CO_2 influences plant development and growth [6], [7]. A sufficient CO_2 supply can enable a greater rate of photosynthesis and yield [8]. Carbon dioxide enrichment (eCO_2) could improve photosynthetic product transportation [9], encourage photosynthesis, and increase annual growth [10], [11], and yield potential will supposedly improve due to increased product accumulation. Double and quadruple the ambient CO_2 promoted morphogenesis, growth rate, and yield in lettuce [7]. It was also discovered that CO_2 enrichment enhanced the light-energy use efficiency in lettuce. The CO_2 range used for growing plants in the PFAL is approximately 400 ppm to 1,600 ppm [3], [7], [12], [13].

In PFAL, hydroponic systems are essential component. Electrical conductivity (EC), potential of hydrogen (pH), and temperature should all be measured to ensure proper water and nutrient management in a hydroponic system. Because ionic strength in nutrient solutions change over time, causing nutrient imbalance in closed hydroponic systems, all nutrients must be measured in real time [14]. To optimize nutrition is nutrient solution composition will increase productivity and the quality of plants [15]. For example, basil and lettuce growth parameters were significantly higher in the EC of 1.2 and 0.9 dS/m, respectively, among the five different EC treatments. These EC values are lower than the optimum EC value recommended in previous studies [16]. The powerful antioxidant content, phenolic compounds for each gram dry weight with EC equal to 1.24 mS/cm and EC of 1.31 mS/cm have no significant effect on red lettuce mass productivity or phenolic compound productivity [17]. The optimal EC in saffron is 0.7 dS/m, at which level the highest plant height, leaf area, biomass, photosynthetic rate, and number of daughter corms were measured. If EC is 2.1 dS/m caused oxidative stress, the growth and daughter corm productionare reduced [18].

Since 2000, monochromatic red light emitting diodes (R-LEDs) have been utilized as a complement to blue light emitting diodes (B-LEDs) in horticulture, where they can significantly boost crop yields similar to daylight [19]. There is research on monochromatic narrow-spectrum light emitting diodes (LEDs), or red blue light emitting diodes (RB-LEDs), of various proportions, as well as RB-LED applications in PFAL [20]. High performance commercial white light that covers the entire visible spectrum with phosphor technology was created in 2010. Horticultural LED illumination is achievable by transforming the monochromatic narrow-spectrum from blue LED chip to board-spectrum white light [21], namely the phosphor-converted white LED [22].

Several studies have been published recently shown that the effects of board spectrum white LEDs (W-LEDs) on lettuce growth are as good as or better than those obtained from the narrow spectrum of R-LED, B-LED, and RB-LED [21]–[25]. Later in 2019, Lee *et al.* [2] reported a study on the effect of six types of W-LEDs compared with RB-LEDs on lettuce production under CPPS. The results indicated that the board-spectrum W-LED yields significantly better lettuce than narrow-spectrum RB-LED. And among all W-LEDs, the broad-spectrum, low-peak W-LEDs of warm type performed better than the broad-spectrum, high-peak R combined with W-LEDs and the W-LED of cooler type. They concluded that the spectral distribution for W-LED to achieve high yield in lettuce production, the percentage of photosynthetic photon flux density (PPFD) of each color should be as follows: 0% < B < 30%, 0%<G< 50%, 30% < R< 70%, and 0%< Fra-red < 20%. The best percentage of PPFD from [26] is B=7.7%, G=29.8%, R=51.4% and Fra-red=11.1%.

Cost-benefit analysis (CBA) is one of the most extensively utilized tools to check the validity of the project. CBA is a business technique that is used to methodically examine and decide which projects should and should not be completed by accumulating all predicted benefits from the project and deducting all costs [27]. In this paper, CBA is used to analyze the economic value of micro-scale plant factory with artificial light (µPFAL) such as net present value (NPV), internal rate of return (IRR), benefit to cost ratio (B/C) and pay backperiod (PBP) [28]. This cost-effectiveness data is to make decisions on the development of the large scale of PFAL in the future.

Rajamangala University of Technology Suvarnabhumi (RUS) is one of 18 universities in the technology development and innovation group in Thailand. Since, RUS provides higher education for engineering sciences and agricultural technology to meet the industry 4.0, bio-circular and green economy (BCG). PFAL will be a great benefit to the development of researchers and RUS university research has never been developed before. It can precisely control various parameters and size suitable for the research study. For these reasons, PFAL requires an artificial light with the appropriate spectrum, the right amount of PPFD with energy efficient. Along with an environmental control system, it can adjust the environmental factors to cover the cultivation of plants with a variety of species. Then, the performance is assessed by a controlling temperature, humidity, and CO_2 in each harvest. Finally, CBA economic analysis is used to evaluate the payback period, value, and benefit of µPFAL.

2. MATERIALS AND METHODS

2.1. Micro-scale plant factory with artificial light concept

µPFAL, the purpose of development is used to control the growing environment for research in plant science and engineering science. The author presented under the concept of a CPPS to obtain the high-quality crop yields of ready to eat (RTE) and ready to cook (RTC) [29]. The µPFAL design concepts in this paper included i) artificial light, ii) air–condition, iii) hydroponic vertical cultivation, iv) EC and pH control, v) CO_2 supply, vi) environmental control and monitor system, and vii) cultivation room and control room [30]. In addition, µPFAL should be appropriately function for research studies in biological, engineering, science and technology, as well as for training and capacity building of smart farmers and others.

2.2. Construction of the micro-scale plant factory with artificial light

2.2.1. Light emitting diode artificial light

The authors considered W-LEDs with PPFD contents in the B, G, R, and Fr photon flux of 11%, 43%, 42%, and 5%, respectively, R:B ratio = 3.8 and broad-spectrum, low-peak W-LEDs of warm type. The light spectrum that results in good yield of lettuce, is consistent with the results of a study [2]. The measurement of spectrum distribution of the proposed LED is show in Figure 1. W-LED that used in this study is the general lighting LED lamp (T-8, 3000K, 220V, 50Hz, 22W, 2000lm). Three LED tubes was installed per bed and top mounted with 18 to 32 cm distance from hydroponic bed. The PPFD was adjusted by altering the distance from the hydroponics bed. Plant production was carried out in this paper at a PPFD of 220±10 µmol/m^{2}s. A microcontroller and a solid-state relay were used to control the light hour, in this experiment a light/dark time of 16/8 h was set [31].

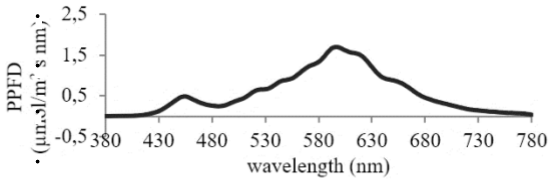


Figure 1. Measurement of the LED spectrum of our artificial light

2.2.2. Air – condition

The temperature inside the cultivation room was controlled by the Mitsubishi Econo Air MS-GN09VF (Mitsubishi-Thailand) air–conditioner with a cooling capacity of 9212 BTU/h as shown in Figure 2(a) with an energy efficiency of 13.22 BTU/h/W. This µPFAL does not require a heater to increase the temperature or to reduce the humidity within the cultivation room because the climate of Thailand is tropical climate. In general, plants grow well under the air temperature between 18 to 20 °C. The target control of temperature in this study is in range of 15 to 25 °C as shown in Table 1.

Table 1. Target control of environmental parameters in µPFAL

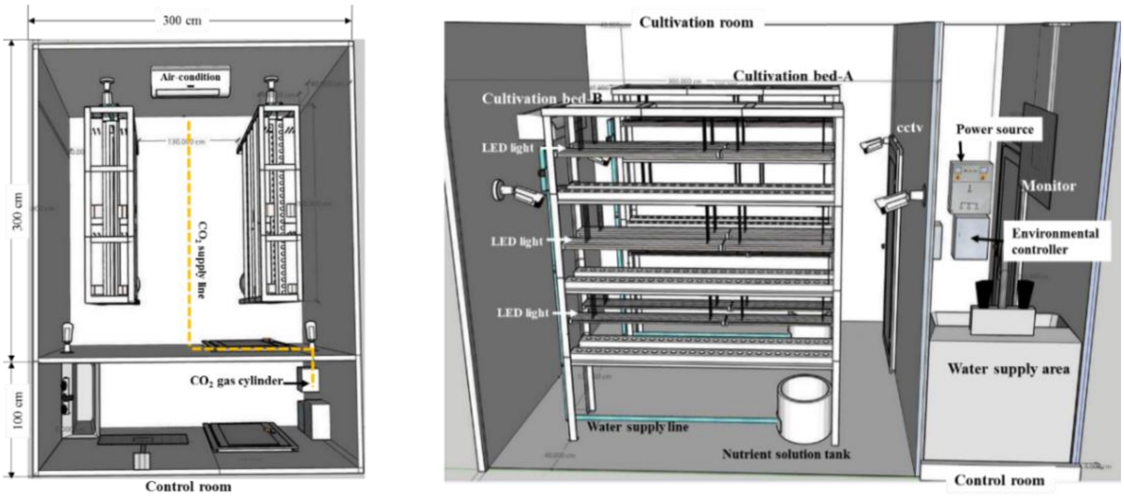
Parameter	Plant growing need	Target control	
		Range	Accuracy
Temperature (ºC)	18–20	15–25	±1
Humidity (%)	40–80	70–90	±5
CO_2 (ppm)	400–1,600	800–1,200	±100
EC (mS/cm)	0.5–3.0	1.0–2.0	±0.1
pH	6.0–7.0	5.5–6.5	±0.2

2.2.3. Cultivation room and control room

The size of the µPFAL is determined from the size of the functional area in the north of the RUS electrical engineering building. Therefore, the µPFAL is designed to 300×400 cm divided into 2 parts: cultivation room is 300×300 cm (9 m^2) and control room is 100×300 cm (3 m^2). The layout area and details are shown in Figure 2. The walls of the cultivation room were well-insulated. Polystyrene foam, 50 mm thick, is used as insulation. It is referred to as a food-grade insulated wall. The control room includes the main distribution board, the environmental controller board, the water supply area, the CO_2 gas cylinder, the PC monitoring area, and the preparing plant area as Figures 2(a) and 2(b).

2.2.4. Hydroponic vertical cultivation

There are two sets of hydroponics cultivation bed (L×W×H: 200×50×200 cm). There were cultivation bed A and B as shown in Figure 2(b). Each cultivation bed consists of 3 vertical growing tiers, each with two hydroponic tubes (one tube is 2 m. length for 16 plants). That is a total of 96-plants per crop. Therefore, the proposed µPFAL can produce 192 plants per crop. The nutrient solution tank with a capacity of 100 liters is placed under the first tier of each bed. Submerse pump circulates the nutrient solution which is controlled by EC and pH automatic dosing machine which details are described in section 2.2.7.



(a) (b)

Figure 2. Design plan and layout area of our µPFAL: (a) top view and (b) side view

2.2.5. Electrical conductivity and potential of hydrogen control

An EC and pH automatic dosing machine (model 594HD Ponpe Instruments Thailand) was installed as one machine per one water tank to facilitate study of the influence of EC and pH on plant growth and chemical compounds. Sensor data via RS485 must go through a signal converter and be processed by Arduino Mega 2,560. Then the data was displayed on the PC located in the control room. In general, the crop plants or vegetables in hydroponics will require a different nutrient solution for each plant species. That is EC between 0.5 to 3.0 mS/cm [16]–[18] and pH between 6.0 to 7.0 [31]. Our target control of EC and pH is in range of 1.0 to 2.0 mS/cm and 5.5 to 6.5, respectively, as shown in Table 1.

2.2.6. Carbon dioxide supply

Arduino-based control and data acquisition system for CO_2 supply was presented. The CO_2 supply from the external CO_2 cylinder into the cultivation room is controlled by a solid-state relay and solenoid valve through an overhead tube at the room's center top. The CO_2 in the cultivation room will remain at the desired level thanks to such a technology. Crops will often need changeable CO_2 levels between 400 and 1,600 ppm in PFAL [3], [7], [12], [13]. This study's target CO_2 control ranges from 800 ppm to 1,200 ppm as shown in Table 1.

2.2.7. Environmental control and monitor system

Figure 3 showed a diagram of an environmental control and monitor system developed in this study. PC monitoring displays temperature, humidity, CO_2, EC and pH measurements to show environment parameters. It is also a device that sets parameters that need to be controlled such as temperature and CO_2.

Visual studio programs are used to develop the user interface. Hardware interface such as all sensors, Arduino Mega 2,560 and solid-state relay output to control solenoid valve for CO_2, ventilation fan and water pump. In addition, a CCTV system is installed in the cultivation room for monitoring, operation of the control system and plant growth via PC monitor together.

There are five types of sensors used in this study: temperature, humidity, CO_2, EC, and pH. The model of all sensors and their functions are shown in Table 2. Only humidity sensors are used to measure humidity in the air and display the measured values in real-time. Other types of sensors are used to both control and monitor the environment parameters.

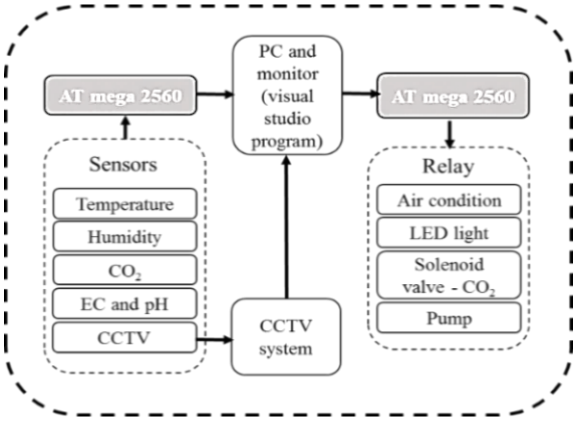


Figure 3. Diagram of an environmental control and monitor system based on Arduino mega 2560

Table 2. Sensors and their function's details

Sensors	Model	Control	Monitor
Temperature	DHT22	✓	✓
Humidity	DHT22	-	✓
CO_2	MH-Z19B WINSEN	✓	✓
EC	DFRobot Gravity	✓	✓
pH	DFRobot Gravity	✓	✓

2.3. Measurement, plant, and analysis

All 5 types of sensors in Table 2 are calibrated with standard measuring instruments and then used. The measured data from the sensor set data sampling equal to 5 min. The system will send the data to the memory card of Arduino Mega 2,560. This data was used to analyze the performance of the control system in the cultivation room environment. Spectroradiometer-lighting passport pro essence (Taiwan) was used to measure and analyze the light spectrum of LED lighting. Quantum meter-light scout (USA) was used to measure the PPFD diffuse on the hydroponics bed.

Uniformity of light on the hydroponic bed calculated in (1), recommend by the international commission on illumination (CIE) [1].

$$U = \frac{Min}{Average} \quad (1)$$

Where *U* is the uniformity of light. *Min* is the minimum of PPFD. *Average* is the average of PPFD.

The experimental plant was green oak lettuce. The author selected seeds from Chia Tai, Thailand. The experimental plant was grown in µPFAL under the following conditions: temperature 25 °C, humidity 80±10%, CO_2 1,000±100 ppm, EC1.2 and pH 6.5. Lighting period of W-LED is 16/8h, PPFD 220±10 µmol/m^{2}s. Crop production period in µPFAL was 30 days. Statistics used for data analysis were mean, standard deviation, and independent t-test. CBA was used for economic analysis.

2.4. Cost-benefit analysis

CBA has various important indicators there are NPV, IRR, B/C ratio, and PBP used in this article are utilized to analyze the profitability of a µPFAL.The NPV is the sum of all the benefits and the whole cost of the project. Adjusting all values to the current value, as stated in (2) [27].

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+k)^t} - Co \quad (2)$$

Where C_t is the net cash inflow in year 1, 2, 3, …, n. k is the discount rate or the rate of return. C_o is the initial cost of investment. n is the expected life of the investment.

IRR is the assessment that "What is the rate of return of investment?" is a random discount rate that makes NPV equal to zero. That is makes net cash in the future return the present value is equal to the initial investment. IRR (k) should be greater than the cost of financing and the more valuable that better. IRR can be determined in (3) [27].

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+k)^t} - Co = 0 \quad (3)$$

B/C is the ratio between of an absolute value of benefits and costs discount at initial year. Lastly, the PBP can be determined by dividing of initial investment by the annual cash inflow [28].

3. RESULTS AND DISCUSSION

3.1. Evaluation results of control performance

All parameters of the µPFAL used to evaluate the performance of the environmental control system include temperature, humidity, CO_2 in the cultivation room and pH, EC of fertilizer in water solution. The author experimented with the operation of the environment control system. The data received from all sensors were measured and recorded over the period of 1 crop (30 days). Those devices are not working perfectly without malfunctioning problem or any mistakes.

Figure 4 showed the measurement results of average of the temperature, humidity and CO_2 concentration. The average temperature in cultivation room was 24.5±0.88 °C, humidity in average is 87.2±7.56%, and CO_2 concentration is 977.8±99.17 ppm. The temperature and CO_2 concentration were 25 °C and 1000 ppm, respectively. These parameters corresponded to the given values indicating that the control effect was on the target [5].

To control the EC and pH of the growing solution in hydroponics, the authors used an EC and pH dosing controller can be seen in subsection 2.2. The EC and pH were set at 1.2 mS/cm and 6.0, respectively. Figure 5 showed the control's results of the EC and pH of the solution. The blue line curve showed the pH with an average pH of 6.10±0.23, the red curve was the EC value found to mean 1.23±0.04 mS/cm. It showed that the control results were on target because the EC and pH values were very close to the specified values.

The experimental control results of the temperature, CO_2, EC, and pH in Figures 4 and 5 deviated from the target values by 2%, 2.2%, 2.5%, and 1.7%, respectively. When comparing the performance of the environmental control system from Figures 4 and 5 with the author's research [5], it was found that they were consistent in the same direction with accuracy and good control response from Figures 4 and 5. Arduino-AT Mega 2,560 with wired communication to monitor at PC. The stable of environment control helped to keep plants growing in good quality and yield better indoor cultivation without environmental control [32].

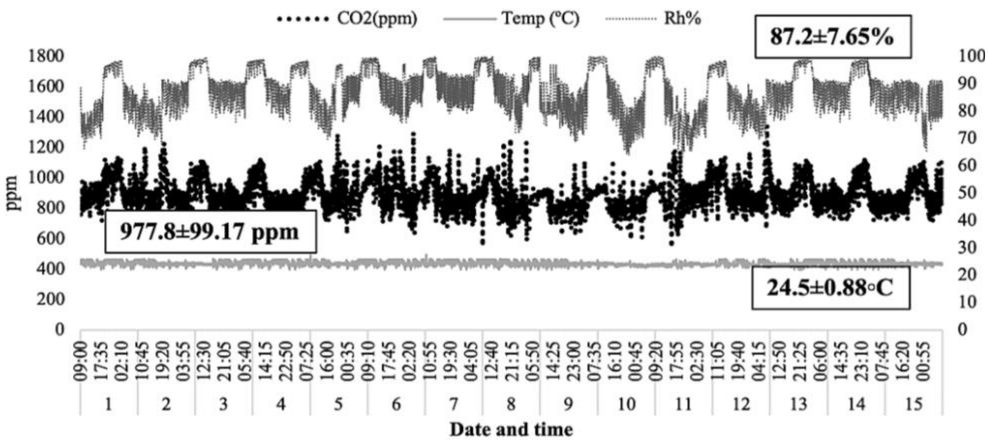


Figure 4. Temperature, humidity and CO_2 results (measured on 12 – 26 Aug, 2022)

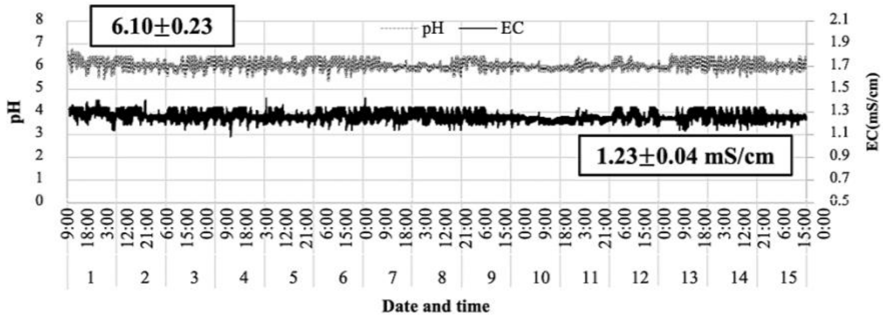


Figure 5. EC and pH experimental results (measuredt on 12 – 26 Aug, 2022)

3.2. Evaluation results of PPFD and uniformity of artificial LED light

Evaluation of PPFD on each hydroponics bed was based on cultivating layer. This ensured that the LED lighting system provided an adequate amount of photon flux and was properly distributed over the planted area. Using a Quantum meter, PPFD was measured at the planting positions (1–16) for each layer of 32 data sets in Figure 6(a). The results were then averaged. The PPFD was measured for both cultivation bed for a total of 12 data sets (n=192) of A11, A12, A21, …, A32 and B11, B12, B21, …, B32 in Figure 6(b). The analysis results showed that average PPFD on the cultivation bed-A and B is equal to 225.29±25.92 µmol/m^{2}s and 227.44±32.95 µmol/m^{2}s. The mean values were similar, as shown in Figure 7(a).

In Figure 7(a), the red line showed the average PPFD on the cultivation bed-A. The lowest value at bed A11 and A32 was 223.45 µmol/m^{2}s and the maximum value was 226.58 µmol/m^{2}s. The cultivation bed-B segment was shown with black dotted line. It was found that the lowest value at bed B31 and B32 was 224.19 µmol/m^{2}s and the maximum was 230.91 µmol/m^{2}s. The results of the analysis showed that average PPFD on the hydroponic bed of cultivation bed-A and B was equal to 225.29±25.92 µmol/m^{2}s and 227.44±32.95 µmol/m^{2}s. When testing the mean value of PPFD between cultivation bed-A and B with an independent t-test, it was not found significant different at $p>0.05$. This means that the PPFD obtained from LED lighting on those hydroponic beds was not different and met the goals in subsection 2.2.

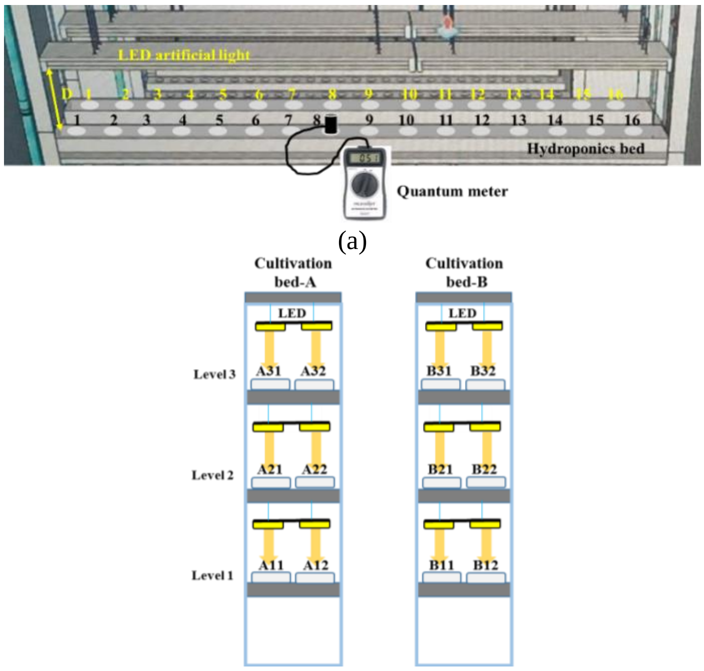
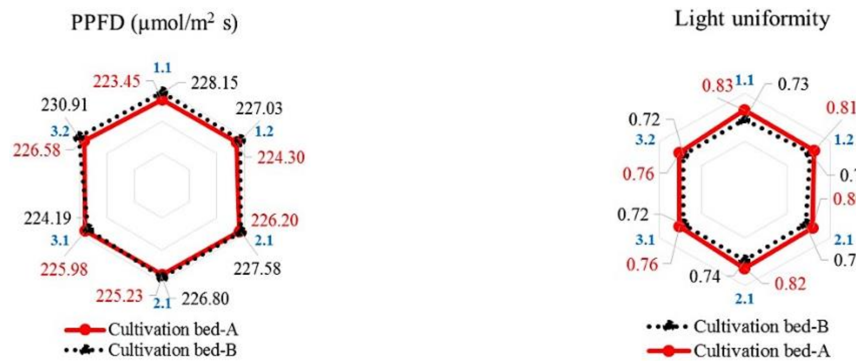


Figure 6. Measurement points of vertical cultivation, (a) PPFD measurement on hydroponic bed and (b) group of data set of cultivation bed-A and B

PPFD from the W-LED that authors proposed (225.29±25.9 to 44.227±32.95 µmol/m^{2}s, R:B 3.8 with 16/8h) was appropriate and it is likely to be believed that such a photon flux quantity would contribute the very good growth and yield of lettuce in PFAL. When comparing LED type and level of PPFD with relevant studies, it was found that W-LED application in lettuce growing in PFAL was not as significant as reported [33] in W+R LED application with R:B ratio 2.2 at 250±10µmol/m^{2}s could provide the maximum growth/quality of lettuce (cv. Ziwei) and at 200±10 µmol/m^{2}s suitable for hydroponic lettuce (cv. Fill ice) seedling production in PFAL [34]. In addition, the authors' report [35] presented that W+R LED with R:B ratio 2.7 at DLI 12.6 mol/m^{2}d (250 µmol/m^{2}s) recommended for commercial hydroponic lettuce (cv. Ziwei) cultivation in PFAL. From these studies, it can be said that W-LED and W-LED supplemented with R-LED at 200 to 250 µmol/m^{2}s was suitable for the production of various lettuce in PFAL.

The red line in Figure 7(b) indicated the uniformity on the cultivation bed-A. The minimum value at bed A31 and A11 was 0.76 and the maximum value was 0.83. The black dotted line showed the uniformity on cultivation bed-B. The minimum uniformity at bed B21 and B12 was 0.71 and the maximum was 0.77. Light uniformity of cultivation bed-A and B is about 0.797±0.03 (mean ± SD) and 0.732±0.02, respectively. When testing the mean differences of uniformity on the cultivation bed-A and B with independent t-test, the results showed that the uniformity of LED lighting distributed on the two-planting area was significantly different ($p<0.05$.). In this study, although the uniformity was statistically different, the uniformity was higher than 0.7 in Figure 7(b), which was considered to be a good fit for horticultural lighting applications. The authors have reported the results of these studies on green oak lettuce crop production in section 3.3. In general, producing plants with artificial light with uniformity lower than 50% (0.5) will show the negative result in lettuce having different head shapes and sizes. This will have an impact on crop productivity in the vertical farm [36].



(a) (b)

Figure 7. PPFD and light uniformity distribution on the cultivation bed-A and B: (a) PPFD on each hydroponic bed and (b) light uniformity on each hydroponic bed

3.3. Green oak lettuce production and price

Green oak lettuce grown under our µPFAL met the environmental conditions as specified in subsection 2.3. The environmental control system works perfectly without any power outages throughout the 30-day growing period. Lettuce yield was evaluated as fresh weight (FW) included roots. Each lettuce was removed from the bed using tissue paper to dry roots and rested in a dry clean container to drain for 5 minutes. Each lettuce was then weighed on a digital scale. The measured data were analyzed for total FW and FW per head on spread sheet program. The mean lettuce FW per head was 80.45±10.23 g in Table 3. This weight is higher than lettuce FW per head (~76g) from PFAL in Nakagusuku, Okinawa, Japan [4] using R-B LED at PPFD of 260 µmol/m^{2}s, and lower than theFW per head of lettuce from Wangree plant factory, Thailand of 20% to 45.6% [37] and also lower than PFAL (highest yield class) from Japan, Canada, and European countries [38]–[40]. This is determined by a variety of factors, including the type of plant seed. The composition of plant nutrients in fertilizer, the intensity of light, and the ambient conditions in PFAL may differ.

When operating µPFAL to produce lettuce in a year, a maximum of 11 crops could be produced, for each crop taking 30 days. The annual yields could be estimated as 169.92 kg or around 19 kg/m^2/y (169.92 kg/yof 9 m^2). This crop is lower than most PFAL-derived lettuce yields of 30–40 kg/m^2/y reported in [41]. When compared to the yield of overall means of PFALs in Japan that reported by the Japan Greenhouse Horticultural Association (JGHA) [42], it is about 2–3.5 times higher than our annual yield. This makes sense because those PFALs had total plantable area of 1,350 m^2 to 3,780 m^2 and with planting rack (1.4×6.25 m) with 8 to 12 tiers can get higher lettuce yield per square meter per year. This means that the next phase of our µPFAL development should determine the optimal number of planting layers and the optimal number of individual hydroponic beds that produce the highest lettuce yield.

The premium quality lettuce is allowed to be eaten without washing because there is no contamination from pesticides or other chemical residues. Therefore, the product has a higher price than the product obtained from other agricultural plots. The lowest purchase price per kilogram in Thailand is around 320 THB (estimated by 200% of greenhouse lettuce from NJ Hydro farm, Nonthaburi, Thailand). However, the said price is below 12 USD/kg (equivalent to 420 THB), which is the standard price estimated by authors [43]. Thus, the estimated selling price of lettuce from our µPFAL is around 54,348.80 THB for 11 crops per year (15.44 kg×11 crops×320 THB/kg).

Table 3. Lettuce yield of µPFAL during one crop of experiment (30 days)

Lettuce yield	Cultivation bed		
	A	B	A+B
Total FW(g)	7582	7865	15447
no of head	96	96	192
FW/head (mean ± SD) (g)*	78.98 ± 8.49	81.93 ± 11.98	80.45 ± 10.23

3.4. Results of economic analysis

The analyzed data consisted of i) the total initial investment of the µPFAL project, such as PFAL building construction cost (structure/wall/roof/electricity) and installation, air-conditioner, LED lighting system, vertical cultivation bed, control of environmental system and sensors, CCTV, pumping system and control (126,000 THB). ii) Annual expenses such as electricity (12 month×644 kWh×4 THB = 30,912 THB), water (260l/crops×11 crops×0.4 THB/l = 1,144 THB), fertilizer, seeds, and maintenances costs (14,144 THB). (total 46,200 THB). iii) Yearly returns, such as income from the sale of crops production (15.44 kg×7crops×320 THB/kg = 34,585.6 THB), income from reduction of university research expenditures µPFAL rental income for research purposes for off-campus individuals and income from training to develop young smart farmer (50,000 THB in estimation) and so on (total 84,585.6 THB). iv) Estimate of current salvage value when used until its maturity is 10 years, equal to 20,000 THB. Lastly, v) Minimum retail rate (MRR) loan interest rate set by Krung Thai Bank in 2023 of 6.77% [44]. PFAL lifetime estimateswere based on a study of [41] that defined an average life span of PFAL of 15 years. In this case, the authors only set it to 10 years because our µPFAL is not a commercial PFAL, so some devices are designed and built by own, not outsourcing turn-key production.

The results of the CBA analysis in Table 4 showed that over a lifetime of 10 years. The proposed µPFAL system can generate a net income equal to 38,385.60 THB/year in Table 4. This is income from cost reduction by providing research support services of the university 2 times a year, income from renting for research to external agencies at least 2 times per year and providing quality crops high premium price 6–7 crops per year. Our µPFAL can be used for trainning at least 50 smart farmer development per year. It also has an indirect benefit because it enables research on PFAL and related topics. It also creates an academic impact for RUS when research is published, and citations cannot be assessed in monetary terms.

Table 4. CBA of the µPFAL project in 10 years

Year	Cost (THB)	Benefits (THB)	Net benefits (THB)
0	126,000.00	0	-126,000.00
1	46,200.00	84,585.60	38,385.60
2	46,200.00	84,585.60	38,385.60
3	46,200.00	84,585.60	38,385.60
4	46,200.00	84,585.60	38,385.60
5	46,200.00	84,585.60	38,385.60
6	46,200.00	84,585.60	38,385.60
7	46,200.00	84,585.60	38,385.60
8	46,200.00	84,585.60	38,385.60
9	46,200.00	84,585.60	38,385.60
10	46,200.00	84,585.60	38,385.60
11	0	20,000.00	20,000.00

The proposed µPFAL system had a payback period of 3.28 years, with a NPV of 82,543.30 THB. It had an IRR of 24% and a B/C ratio of 1.22 in Table 5. Our PFAL is economically viable because its rating results correspond to the theoretical value [27], [28]. However, the analysis shows that the annual operating cost of electricity is around 65% of the total operating cost, which is higher than general PFAL electricity usage [45]. That is because the annual operation cost of our µPFAL does not consider labor cost. However, introducing renewable energy as an alternative energy [4], [46] to enhance energy efficiency will help reduce the cost of electricity. Moreover, the adoption of robot, IoT technology [37] and AI technology [47] with PFAL will increase production efficiency, productivity quality, reduce waste and reduce labor cost. However, the university should develop its own intellectual property of smart PFAL with a co-investment in research and development (RandD) with the industry sector that wants to benefit directly remains a challenge.

Table 5. The calculation results of economic analysis of our µPFAL

µPFAL	
NPV (THB)	82,543.301*
B/C ratio	1.22
IRR (%)	24**
PBP (year)	3.28

*Calculate in (1)
**Calculate in (2)

4. CONCLUSION

The results of the control environment in the cultivation room of the µPFAL were achieved with a deviation of less than or equal to 2.5% from the target value. Arduino-based environmental control with wired communication to monitor at PC is a simple, fully functional system. It is one approach that is suitable for the construction of µPFALs for university research. W-LED at 220±10 µmol/m^{2}s, R:B 3.8, 16/8 h (light/dark period), EC 1.23 mS/cm, pH 6.10, temperature 24.5 ℃, humidity 87.2%, and CO_2 977.8 ppm during 30 days in PFAL could produce the yield of green oak lettuce equal to 80.45 g/head. An estimated annual yield of 19 kg/m^2/y. Such annual yield can be increased by increasing the number of the cultivation layers and the optimal number of individual hydroponic beds under the limited area of cultivation room. The economic evaluation results showed that the proposed µPFAL had a payback period of ~3 years, NPV 82,543.30 THB, IRR of 24% and B/C ratio of 1.22. The µPFAL could produces premium quality lettuce under controlled conditions. It is also used in training to develop young smart farmer of Thailand. There are also indirect benefits such as academic impact and publication that cannot be assessed in monetary terms. The next phase of development should apply the IoT cloud based with AI technology to increase productivity and quality. Lastly, photavoltaic system should be introduced as an alternative energy supply to guide the development of µPFAL as an innovative sustainable prototype. In future studies, the life circle analysis may be evaluated to meet the creation of a sustainable PFAL system.

REFERENCES

[1] N. Watjanatepin, "Urban gardening system for home organic vegetables: LED artificial light and irrigation control," *Journal of Engineering and Technological Sciences*, vol. 52, no. 6, Nov. 2020, doi: 10.5614/j.eng.technol.sci.2020.52.6.3.
[2] R. J. Lee, S. R. Bhandari, G. Lee, and J. G. Lee, "Optimization of temperature and light, and cultivar selection for the production of high-quality head lettuce in a closed-type plant factory," *Horticulture, Environment, and Biotechnology*, vol. 60, no. 2, pp. 207–216, Apr. 2019, doi: 10.1007/s13580-018-0118-8.
[3] M. Chowdhury *et al.*, "Effects of temperature, relative humidity, and carbon dioxide concentration on growth and glucosinolate content of kale grown in a plant factory," *Foods*, vol. 10, no. 7, Jul. 2021, doi: 10.3390/foods10071524.
[4] M. Ueno and Y. Kawamitsu, "Design of a plant factory suitable for Okinawa," *Engineering and Applied Science Research*, vol. 44, no. 3, pp. 182–188, 2017, doi: 10.14456/easr.2017.27.
[5] D. K. Ryu *et al.*, "Control of temperature, humidity, and CO2 concentration in small-sized experimental plant factory," *Acta Horticulturae*, no. 1037, pp. 477–484, May 2014, doi: 10.17660/ActaHortic.2014.1037.59.
[6] E. Driesen, W. V. D. Ende, M. D. Proft, and W. Saeys, "Influence of environmental factors light, co2, temperature, and relative humidity on stomatal opening and development: a review," *Agronomy*, vol. 10, no. 12, Dec. 2020, doi: 10.3390/agronomy10121975.
[7] D. Chen, Y. Mei, Q. Liu, Y. Wu, and Z. Yang, "Carbon dioxide enrichment promoted the growth, yield, and light-use efficiency of lettuce in a plant factory with artificial lighting," *Agronomy Journal*, vol. 113, no. 6, pp. 5196–5206, Nov. 2021, doi: 10.1002/agj2.20838.
[8] X. Li *et al.*, "Light supplement and carbon dioxide enrichment affect yield and quality of off-season pepper," *Agronomy Journal*, vol. 109, no. 5, pp. 2107–2118, Sep. 2017, doi: 10.2134/agronj2017.01.0044.
[9] X. Li *et al.*, "Physiological and molecular basis of promoting leaf growth in strawberry (Fragaria ananassa Duch.) by CO2 enrichment," *Biotechnology and Biotechnological Equipment*, vol. 34, no. 1, pp. 905–917, Jan. 2020, doi: 10.1080/13102818.2020.1811766.
[10] K. A. Bishop, A. M. Betzelberger, S. P. Long, and E. A. Ainsworth, "Is there potential to adapt soybean (Glycine max Merr.) to future [CO2]? An analysis of the yield response of 18 genotypes in free-air CO2 enrichment," *Plant, Cell and Environment*, vol. 38, no. 9, pp. 1765–1774, Sep. 2015, doi: 10.1111/pce.12443.
[11] R. T. Thomas *et al.*, "Increased light-use efficiency in northern terrestrial ecosystems indicated by CO2 and greening observations," *Geophysical Research Letters*, vol. 43, no. 21, Nov. 2016, doi: 10.1002/2016GL070710.

[12] E. A. Nord, R. E. Jaramillo, and J. P. Lynch, "Response to elevated CO2 in the temperate C3 grass Festuca arundinaceae across a wide range of soils," *Frontiers in Plant Science*, vol. 6, Feb. 2015, doi: 10.3389/fpls.2015.00095.
[13] H. A. Ahmed, T. Y. -Xin, and Y. Q. -Chang, "Optimal control of environmental conditions affecting lettuce plant growth in a controlled environment with artificial lighting: a review," *South African Journal of Botany*, vol. 130, pp. 75–89, May 2020, doi: 10.1016/j.sajb.2019.12.018.
[14] J. E. Son, H. J. Kim, and T. I. Ahn, "Hydroponic systems," in *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, 2020, pp. 273–283, doi: 10.1016/B978-0-12-816691-8.00020-0.
[15] E. Gorbe and Á. Calatayud, "Optimization of nutrition in soilless systems: a review," *Advances in Botanical Research*, vo.. 53, pp. 193–245, 2010, doi: 10.1016/S0065-2296(10)53006-4.
[16] H. Hosseini, V. Mozafari, H. R. Roosta, H. Shirani, P. C. H. V. D. Vlasakker, and M. Farhangi, "Nutrient use in vertical farming: Optimal electrical conductivity of nutrient solution for growth of lettuce and basil in hydroponic cultivation," *Horticulturae*, vol. 7, no. 9, Sep. 2021, doi: 10.3390/horticulturae7090283.
[17] S. Sawatdee, C. Prommuak, T. Jarunglumlert, P. Pavasant, and A. E. Flood, "Combined effects of cations in fertilizer solution on antioxidant content in red lettuce (*Lactuca sativa L.*)," *Journal of the Science of Food and Agriculture*, vol. 101, no. 11, pp. 4632–4642, Aug. 2021, doi: 10.1002/jsfa.11106.
[18] Y. H. Dewir and A. Alsadon, "Effects of nutrient solution electrical conductivity on the leaf gas exchange, biochemical stress markers, growth, stigma yield, and daughter corm yield of saffron in a plant factory," *Horticulturae*, vol. 8, no. 8, Jul. 2022, doi: 10.3390/horticulturae8080673.
[19] E. Goto, "Effects of light quality on growth of crop plants under artificial lighting," *Environment Control in Biology*, vol. 41, no. 2, pp. 121–132, 2003, doi: 10.2525/ecb1963.41.121.
[20] T. Ouzounis, E. Rosenqvist, and C. -O. Ottosen, "Spectral effects of artificial light on plant physiology and secondary metabolism: a review," *HortScience*, vol. 50, no. 8, pp. 1128–1135, Aug. 2015, doi: 10.21273/HORTSCI.50.8.1128.
[21] J. Cho, J. H. Park, J. K. Kim, and E. F. Schubert, "White light-emitting diodes: history, progress, and future," *Laser and Photonics Reviews*, vol. 11, no. 2, Mar. 2017, doi: 10.1002/lpor.201600147.
[22] N. Watjanatepin, "Modification of growth and yield of the leafy vegetable under phosphor-converted light-emitting diode," *Polish Journal of Natural Sciences*, vol. 35, no. 2, pp. 113–128, 2021.
[23] T. Han *et al.*, "Improving 'color rendering' of LED lighting for the growth of lettuce," *Scientific Reports*, vol. 7, no. 1, Apr. 2017, doi: 10.1038/srep45944.
[24] T. Hytönen *et al.*, "Effects of LED light spectra on lettuce growth and nutritional composition," *Lighting Research and Technology*, vol. 50, no. 6, pp. 880–893, Oct. 2018, doi: 10.1177/1477153517701300.
[25] K. -H. Lin, M. -Y. Huang, W. -D. Huang, M. -H. Hsu, Z. -W. Yang, and C. -M. Yang, "The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa L. var. capitata*)," *Scientia Horticulturae*, vol. 150, pp. 86–91, Feb. 2013, doi: 10.1016/j.scienta.2012.10.002.
[26] N. Lu, S. Saengtharatip, M. Takagaki, A. Maruyama, and M. Kikuchi, "How do white LEDs' spectra affect the fresh weight of lettuce grown under artificial lighting in a plant factory? a statistical approach," *Agricultural Sciences*, vol. 10, no. 07, pp. 957–974, 2019, doi: 10.4236/as.2019.107073.
[27] V. Padmini, S. Omran, K. Chatterjee, and S. A. Khaparde, "Cost benefit analysis of smart grid: a case study from India," in *2017 North American Power Symposium (NAPS)*, IEEE, Sep. 2017, pp. 1–6, doi: 10.1109/NAPS.2017.8107212.
[28] A. Carteni, I. Henke, M. I. Di Bartolomeo, and M. Regna, "A cost-benefit analysis of a fully-automated driverless metro line in a high-density metropolitan area in Italy," in *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / IandCPS Europe)*, IEEE, Jun. 2019, pp. 1–6, doi: 10.1109/EEEIC.2019.8783471.
[29] W. Fang, "Status of plant factory industry and recent research in Taiwan," in *Proceedings of the International Symposium on Industry Status and Research and Development of Facilities*, 2018, pp. 142–154.
[30] T. Kozai and G. Niu, "Role of the plant factory with artificial lighting (PFAL) in urban areas," in *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, Elsevier, 2020, pp. 7–34, doi: 10.1016/B978-0-12-816691-8.00002-9.
[31] N. Watjanatepin and P. Sritanauthaikorn, "Increasing growth and yield of sweet basil and holy basil by application of far-red radiation for indoor horticulture," *Journal of Engineering and Applied Sciences*, vol. 15, no. 7, pp. 1709–1716, Mar. 2020, doi: 10.36478/jeasci.2020.1709.1716.
[32] W. Yongliang *et al.*, "Design of environmental control system based on embedded modbus," in *2019 Chinese Control And Decision Conference (CCDC)*, IEEE, Jun. 2019, pp. 598–601, doi: 10.1109/CCDC.2019.8832520.
[33] X. Zhang, D. He, G. Niu, Z. Yan, and J. Song, "Effects of environment lighting on the growth, photosynthesis, and quality of hydroponic lettuce in a plant factory," *International Journal of Agricultural and Biological Engineering*, vol. 11, no. 2, pp. 33–40, 2018, doi: 10.25165/j.ijabe.20181102.3240.
[34] Z. Yan, D. He, G. Niu, and H. Zhai, "Evaluation of growth and quality of hydroponic lettuce at harvest as affected by the light intensity, photoperiod and light quality at seedling stage," *Scientia Horticulturae*, vol. 248, pp. 138–144, Apr. 2019, doi: 10.1016/j.scienta.2019.01.002.
[35] Z. Yan, D. He, G. Niu, Q. Zhou, and Y. Qu, "Growth, nutritional quality, and energy use efficiency of hydroponic lettuce as influenced by daily light integrals exposed to white versus white plus red light-emitting diodes," *HortScience*, vol. 54, no. 10, pp. 1737–1744, Oct. 2019, doi: 10.21273/HORTSCI14236-19.
[36] E. Runkle, "The importance of light uniformity," *Michigan State University Extension: Floriculture Team*, Greenhouse Product News Magazine, p. 38, 2017.
[37] S. Santiteerakul, A. Sopadang, K. Yaibuathet Tippayawong, and K. Tamvimol, "The role of smart technology in sustainable agriculture: a case study of wangree plant factory," *Sustainability*, vol. 12, no. 11, Jun. 2020, doi: 10.3390/su12114640.
[38] E. Hayashi, "Selected PFALs in Japan," in *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*, Elsevier, 2020, pp. 437–454, doi: 10.1016/B978-0-12-816691-8.00030-3.
[39] J. Eaves and S. Eaves, "Comparing the profitability of a greenhouse to a vertical farm in Quebec," *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, vol. 66, no. 1, pp. 43–54, Mar. 2018, doi: 10.1111/cjag.12161.
[40] D. D. Avgoustaki and G. Xydis, "Indoor vertical farming in the urban nexus context: business growth and resource savings," *Sustainability*, vol. 12, no. 5, Mar. 2020, doi: 10.3390/su12051965.
[41] Y. Zhuang, N. Lu, S. Shimamura, A. Maruyama, M. Kikuchi, and M. Takagaki, "Economies of scale in constructing plant factories with artificial lighting and the economic viability of crop production," *Frontiers in Plant Science*, vol. 13, Sep. 2022, doi: 10.3389/fpls.2022.992194.

[42] JGHA, "Survey and case report on large-scale greenhouses and plant factories," *Japan Greenhouse Horticulture Association*, 2016. [Online]. Available: https://jgha.com/wp-content/uploads/2024/04/TM06-05-bessatsu1.pdf

[43] K. Uraisami, "How to integrate and to optimize productivity," in *Plant Factory Basics, Applications and Advances*, Elsevier, 2022, pp. 217–249, doi: 10.1016/B978-0-323-85152-7.00024-0.

[44] MB, "New loan interest rates, welcome the year 2023," *Money and Banking Online*, 2023. [Online]. Available: https://moneyandbanking.co.th/2023/16353/

[45] R. Yorifuji and S. Obara, "Economic design of artificial light plant factories based on the energy conversion efficiency of biomass," *Applied Energy*, vol. 305, Jan. 2022, doi: 10.1016/j.apenergy.2021.117850.

[46] L. Li, X. Li, C. Chong, C.-H. Wang, and X. Wang, "A decision support framework for the design and operation of sustainable urban farming systems," *Journal of Cleaner Production*, vol. 268, Sep. 2020, doi: 10.1016/j.jclepro.2020.121928.

[47] S. Vorapatratorn, "Development of automatic plant factory control systems with ai-based artificial lighting," in *2021 13th International Conference on Information Technology and Electrical Engineering (ICITEE)*, IEEE, Oct. 2021, pp. 69–73, doi: 10.1109/ICITEE53064.2021.9611820.

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