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Impact of natural-white and red-blue light-emitting diode lighting on hydroponic basil growth and energy efficiency

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ABSTRACT

Advanced phosphor-converted white light-emitting diodes (pc-WLEDs) have been developed to mimic the natural sunlight spectrum, potentially enhancing plant growth compared to traditional red-blue (R-B) LEDs. This study aimed to compare the effects of natural-white pc-WLED (nsW-pcLED) and conventional R-B LED (R:B 3.24) on the growth, yield, and energy efficiency of hydroponically grown sweet basil. It was cultivated in a deep-water culture system under identical conditions with a photosynthetic photon flux density (PPFD) of 200±10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and a 16/8 light/dark photoperiod over 28 days. Key growth parameters, including plant height, stem diameter, leaf number, and plant fresh weight (PFW), were measured, while energy consumption was recorded to assess efficiency. Results indicated that nsW-pcLED significantly enhanced growth, with plants achieving an average height of 44.30±1.51 cm, stem diameter of 6.68±0.21 mm, and a PFW of 34.20±6.12 g, compared to 35.88±4.05 cm, 4.66±0.88 mm, and 23.02±5.26 g under R-B LED ($p < 0.05$), respectively. The nsW-pcLED treatment produced an average net growth of 1,221 $g \cdot m^{-2}$ versus 536.43 $g \cdot m^{-2}$ for R-B LED and delivered 33.05 $g \cdot m^{-2} \cdot kW \cdot h^{-1}$ compared to 11.17 $g \cdot m^{-2} \cdot kW \cdot h^{-1}$, while consuming 23% less energy. These findings highlight nsW-pcLED's superior performance for indoor hydroponic cultivation. Future studies should explore its application in large-scale systems and across diverse crop species.

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1. INTRODUCTION

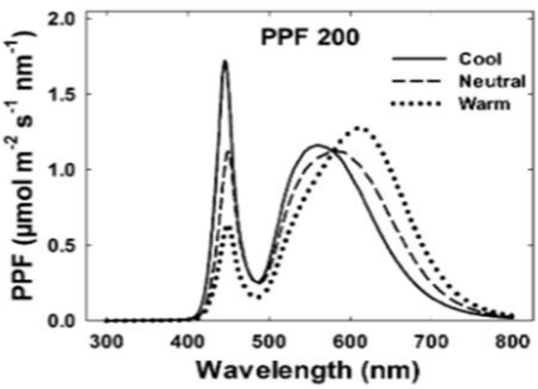
Since 1990, light-emitting diodes (LEDs) have been increasingly used in horticulture and vegetation production across various platforms, including closed-growth chambers, indoor vertical farms, greenhouses, and plant factories with artificial light [1]–[3]. Indoor cultivation of salad vegetables, such as red-leaf lettuce, green oak lettuce, cos lettuce, and basil, is now a common practice. Numerous studies have shown that blue LEDs (B) with wavelengths of 400-500 nm and red LEDs (R) with wavelengths of 600-700 nm significantly enhance photosynthesis, stimulate chlorophyll and beta-carotene production, and activate certain parts of the phytochrome system from red to infrared light [4], [5]. Moreover, LED horticultural lighting is more energy-efficient [6] and promotes better average plant growth per unit of energy [7] compared to fluorescent, incandescent, and high-intensity discharge (HID) lamps.

Several studies have reported on the influence of the red-to-blue (R:B) light ratio on plant growth. The R:B ratio between 2.2 and ≥3 was found to positively impact the yield of various crops and vegetables, while also providing good energy efficiency in indoor lettuce cultivation [8]–[10]. The use of red and blue LED technology requires integrating two distinct types of LEDs within a single lighting fixture, as no single-chip LED can produce a combined red-blue spectrum. Consequently, assembling such LED fixtures involves a relatively complex design and installation process.

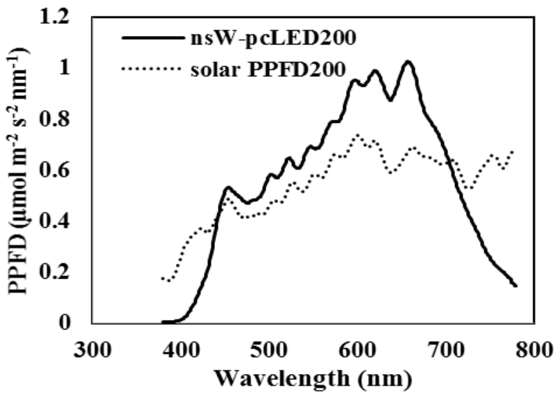
Subsequently, phosphor-converted white LED (pc-WLED) technology was introduced, typically producing either warm or cool white light [11], as illustrated in the spectral data in Figure 1. The spectrum of pc-WLEDs consists of a peak in the blue region (450 nm) combined with an orange-red component (600 nm), resulting in white light emission as Figure 1(a). A study conducted by [6] utilized pc-WLEDs emitting white light within the 400-700 nm wavelength range as a substitute for combining red and blue lighting in lettuce cultivation. These findings revealed that the broad-spectrum white light from pc-WLEDs could effectively promote plant growth and offer greater energy efficiency compared to traditional red-blue LED lighting systems for horticulture. Additionally, pc-WLEDs provide high-quality white light which is beneficial for both human vision and plant development [12].

Currently, the advanced phosphor-converted white LED (pc-WLED) technology has been developed to produce a light spectrum that closely mimics the natural sunlight spectrum. The natural-white pc-WLED (nsW-pcLED) spectrum closely mimics the natural sunlight over 400-700 nm, delivering the photosynthetic photon flux density (PPFD) comparable to natural light and covering the entire photosynthetically active radiation (PAR) spectrum (Figure 1(b)). This technology was first reported by Nakajima *et al*. [13] in 2014. Zheng *et al*. [14] applied this technology in the development of a solar simulator for photovoltaic devices. However, there have not been reports of this technology for supplemental lighting in greenhouse cultivation.

Based on the aforementioned rationale and background, the authors were motivated to further investigate this topic and address the following research questions. The first research question is "Will nsW-pcLED produce different plant yield and growth compared to R-B LED in indoor cultivation?". The second question is "Which light source between nsW-pcLED or R-B LED provides better average plant growth per unit of energy?". The author aimed to conduct an experiment comparing the growth and yield of a sample plant grown under R-B light with an R:B ratio of 3.24 to that of nsW-pcLED, both with the same PPFD in the PAR range. The results will report on the average plant growth per unit of energy [7], [15] between the two LED light sources.



(a)



(b)

Figure 1. Comparative spectrum of 200 µmol m^{-2} s^{-1} of (a) cool white and warm white LEDs [11] and (b) natural-sun-white LEDs and solar natural light (measurement)

2. MATERIALS AND METHOD

2.1. Light sources

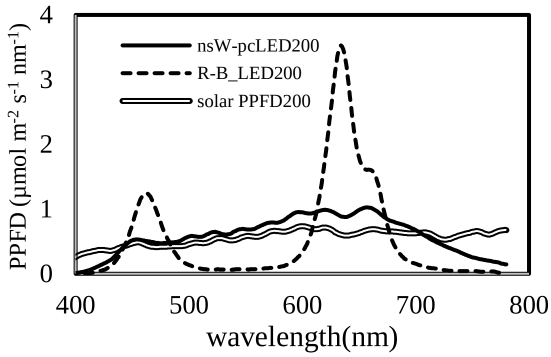
Two types of LED lamps were used in the experiment: i) R-B LED luminaire and ii) nsW-pcLED luminaire. The research followed a posttest-only design with two experimental groups. Each group received the same PPFD of 200±10 µmol m^{-2} s^{-1}, with a lighting period of 16 hours per day. The plants were harvested after seeding four weeks. The experimental system details were as follows:

2.1.1. R-B LED luminaire

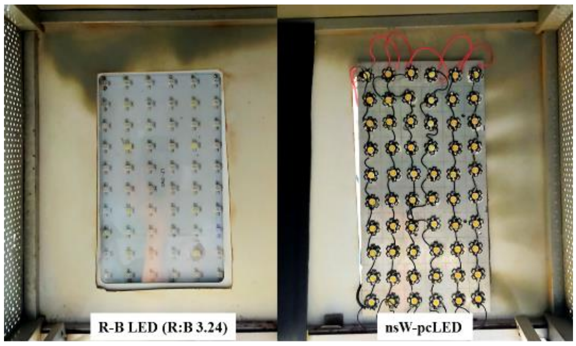
The control group used a commercial type of R-B LED growing light model LZ-ZWD (Guangdong, China) as a light source (430~450, 620~630, 650~670 nm). That was a total of 60 LEDs, 3 watts each. Figure 2 shows the LED light sources and spectral distribution. The light source area was 21×31 cm. The spectral distribution of R-B LED is shown in Figure 2(a) (dot line). The measured power consumption of R-B LED was 107.18 W.

2.1.2. nsW-pcLED luminaire

This experiment used a custom light source that included the nsW-pcLED (LC-3FE504-G24) 3 V 300 mA of 60 units (LCFOCUS, China). It connected 6 circuits in series with 10 LEDs and connected each circuit in parallel. The LEDs were mounted on a heat sink with a forced-air-cooling system. The lighting area was 17×34 cm. The spectral distributions of light are shown in Figure 2(a) (black line). The solar spectrum (dual lines) is displayed for comparison. The measured power consumption of this lamp was 82.50 W. The solar spectrum was recorded in Nonthaburi, Thailand, on August 12, 2022, at 10:00 AM. The luminaires of the R-B LED and nsW-pcLED are shown in Figure 2(b), left and right, respectively.



(a)



(b)

Figure 2. LED light sources and spectral distribution of (a) spectral PPFD comparison of R-B LED, nsW-pcLED, and solar spectrum at 200 μmol m^{-2} s^{-1} and (b) R-B LED and nsW-pcLED luminaires

2.2. Plant

The experimental plant used in this study was sweet basil (*Ocimum basilicum* L.), with five samples assigned to each group. The plants were cultivated using a hydroponic deep-water culture (DWC) system. The sweet basil seeds were sourced from Chia Tai Co., Ltd, Thailand. Sweet basil was selected for this experiment due to its global popularity, high harvest index, ease of cultivation, adaptability to hydroponic systems, and high profitability margin [16].

2.3. Measurements and statistic

The effects of different light sources on plant growth were investigated. The measurement of this system revealed its capability and efficiency. In this section, it presented the light quality, plant yield, and growth characteristics.

2.3.1. Light quality, plant yield, and growth characteristic

The research method was a post-test-only design. There were two experimental groups. Each group had the same PPFD, which is 200±10 µmol m^{-2} s^{-1}. The lighting period was 16 h d^{-1}. The experiment was made in the laboratory with T=27±2 °C, RH=60±10%. The harvesting time was 4 weeks after transplants. The spectral distribution (SPD), PPFD, and the percentages of blue, green, red, and far-red light, along with the red-to-blue light ratio (R:B), were measured and analyzed using a lighting passport pro spectroradiometer (Asensetek, Taiwan). The following plant growth parameters were also assessed: leaf number (LN), stem diameter (SD), plant height (PH), root fresh weight (RFW), and plant fresh weight (PFW). Growth measurements were recorded weekly from five sample plants in each group (n=5). At the end of the fourth week (the 28th day), PFW (without roots) and RFW were measured using a digital balance. The stem diameter was measured using a digital vernier caliper.

2.3.2. Average growth per unit of energy

The light source was connected to a kWh meter that measured energy consumption in kilowatt-hours (kWh) per crop. The kWh per crop was then used to calculate the average plant growth per kWh in grams per square meter per kWh (g m^{-2} kWh^{-1}). This unit facilitates the comparison of total PFW (g) in a given cultivation area (m^2) per unit of energy (kWh). In this study, the cultivation area for each experimental group was equal, measuring 0.14 m^2 (0.4×0.35 m).

2.3.3. Statistical analysis

Plant samples will be collected from five plants in each group to investigate LN, SD, PH, RFW, and PFW. Significant differences will be analyzed using a t-test (p=0.05). IBM SPSS Statistics software will be utilized for the analysis.

3. RESULTS AND DISCUSSION

The choice of light source is a critical factor in indoor plant cultivation. In this section, discussed the analysis of the light-quality growth and yield of sweet basil. It showed the experimental data under the proposed light source.

3.1. Analysis of the light quality

According to Table 1, the total PPFD in the 400-700 nm range of nsW-pcLED is equal to that of R-B LED, measuring 200±10 µmol m^{-2} s^{-1}. The PPFD of red (R) and blue (B) light emitted by the R-B LED is 158 and 125% higher, respectively, compared to nsW-pcLED. In contrast, the PPFD of far-red (FR) and green (G) light from the R-B LED is 15.42 and 14.09%, respectively, lower than that of nsW-pcLED. The R:B ratio for nsW-pcLED is 2.56, whereas that of R-B LED is 3.24, both of which are suitable for indoor plant cultivation or plant factory applications [10]. Additionally, the R:FR ratio for nsW-pcLED is 3.19, significantly lower than the R-B LED's ratio of 35.21. This suggests that nsW-pcLED lighting is more likely to enhance plant yield [17], as its relatively lower FR-Blue ratio is considered beneficial for plant growth compared to R-B LEDs.

Lastly, the daily light integral (DLI) [18] was “the daily accumulated photosynthetically available number of photons delivered to a given area over the course of one day.” The DLI from both LED luminaires was approximately 17 mol m^{-2} d^{-1} (Table 1), which was reasonably high and aligns with the results of the study [14]. This indicated that both types of light sources provided DLI values suitable for plant growth consistent with the DLI specifications outlined by Faust and Logan [18] and Dou *et al*. [19].

In conclusion, both nsW-pcLED and R-B LED lighting systems used in this study provided appropriate light intensity and DLI for plant growth. However, significant differences in PPFD were observed between these two light sources. Specifically, nsW-pcLED exhibited higher PPFD values for FR and green (G) light compared to R-B LED. In contrast, while the R-B LED had a significantly higher PPFD for red (R) light, it revealed considerably lower PPFD values for green and FR light.

Table 1. Measurement and calculation results of light quality of nsW-pcLED and R-B LED

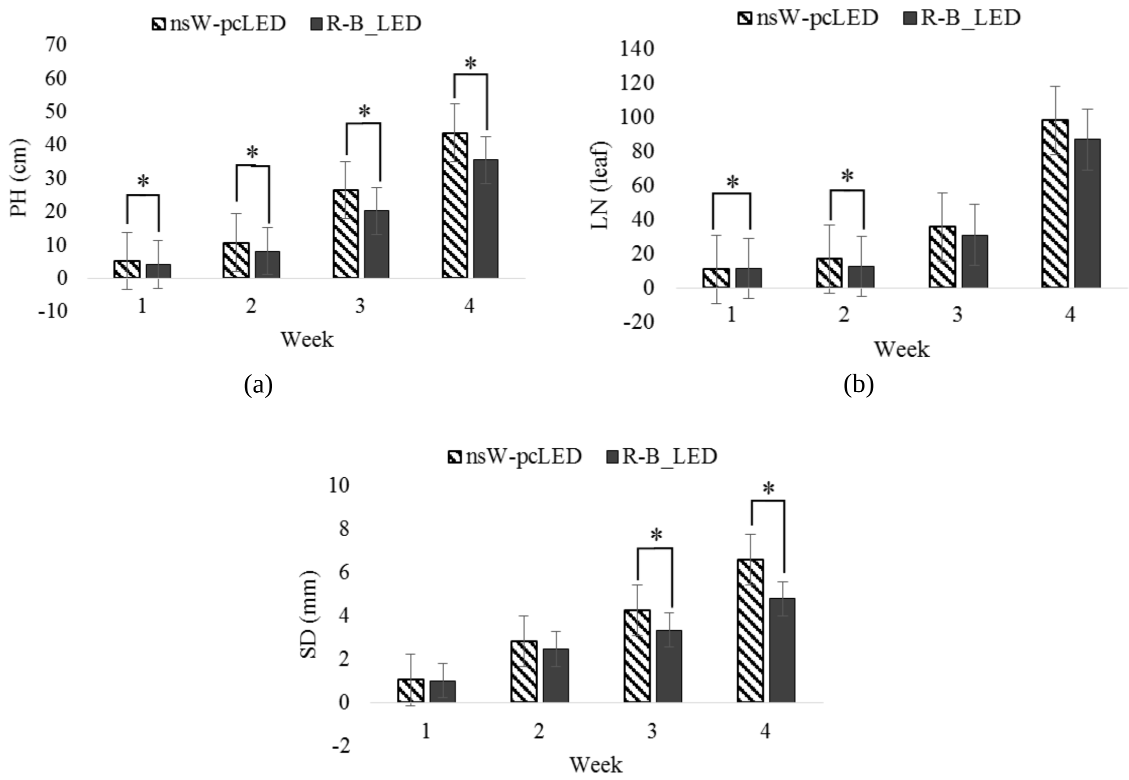
Parameter	nsW-pcLED	R-B LED	Unit
B (400-500 nm)	35.19	44.03	
G (500-600 nm)	71.36	10.05	
R (600-700 nm)	90.19	142.67	µmol $m^{-2}s^{-1}$
FR (700-800 nm)	28.26	4.36	
PPFD (400-700 nm)	196.75	196.77	
Total (400-800 nm)	225.01	201.13	
Total	100.00	100.00	
B	15.64	21.89	
G	31.71	4.99	fraction (%)
R	40.08	70.93	
FR	12.56	2.16	
R:B ratio	2.56	3.24	
R:FR ratio	3.19	35.21	mol m^{-2} d^{-1}
DLI	17.19	17.00	

3.2. Growth and yield of the sweet basil

The experiment involved controlling specific growth parameters. In this section, it explained the growth and yield of sweet basil and the energy consumption of the light source. It discusses and displays the basil trees that grew under the proposed light source.

3.2.1. Growth and development

In this experiment, Figure 3 shows the growth of basil in both groups was normal. The PH curve corresponded to the typical growth curve of plants (Figure 3(a)). The growth and height of the basil gradually increased from the first week to the second week, with both LN (Figure 3(b)), and SD (Figure 3(c)) following the same trend. This growth had become more pronounced in the third and the fourth week. The results indicated that, after the second week, the growth of sweet basil in terms of PH and SD under nsW-pcLED was significantly higher than that under R-B LED, showing a significant difference at $p < 0.05$. The LN during the first two weeks showed a significant difference ($p < 0.05$) between both treatments and afterward, the LN of sweet basil under nsW-pcLED tended to be higher than the one under R-B LED. The statistically significant difference by comparing the average PH, LN, and SD between nsW-pcLED and R-B LED (R:B 3.24), with $p < 0.05$ and $n=5$ is shown in Figure 3.



(c)

Figure 3. Growth and development of the sweet basil over 4 weeks of the experiment of (a) PH vs time, (b) LN vs time, and (c) SD vs time

3.2.2. Yield of the sweet basil

At the end of the fourth week (the 28th day), the sweet basil under nsW-pcLED demonstrated an average leaf number of 95.00±9.38, which, although higher than the 81.00±11.7 leaves observed under R-B LED, was not a statistically significant difference (Table 2). In contrast, the plant height under nsW-pcLED (44.30±1.51 cm) was significantly greater than that under R-B LED (35.88±4.05 cm) at $p < 0.05$. These results were consistent with [19], which indicated that the green basil grown under a R40G15B32 treatment (with a PPFD nearly identical to that of nsW-pcLED) achieved greater plant height compared to the plant grown under an R:B ratio of 3.17 (R76B24).

The SD of sweet basil under nsW-pcLED (6.68±0.21 mm) was significantly higher than under R-B LED (4.66±0.88 mm) at $p < 0.05$. The yield of sweet basil was expressed in terms of PFW (g). PFW were collected excluding the roots from sweet basil in both groups of 5 plants. The results showed that the PFW of sweet basil under nsW-pcLED (34.20±6.12 g) was higher than the PFW under R-B LED (23.02±5.26 g) with a statistically significant difference at $p < 0.05$. For RFW, the analysis results showed no statistically significant differences. However, the RFW of the plants under nsW-pcLED was approximately 30% heavier.

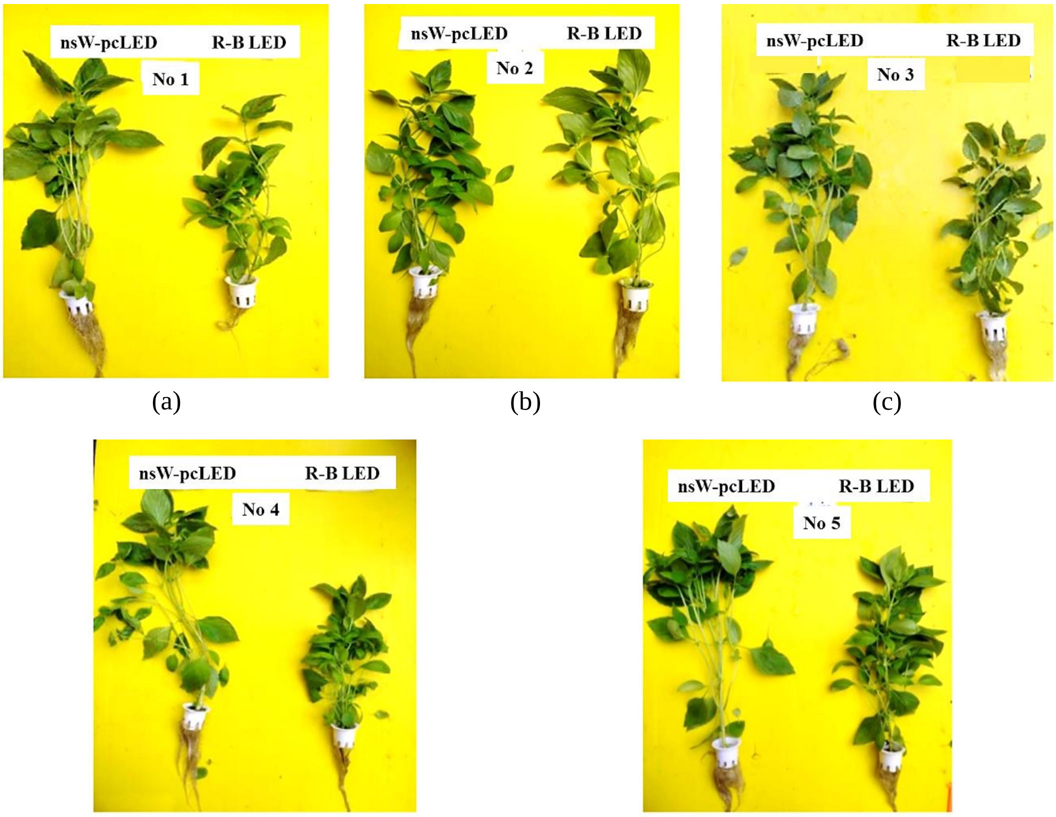
Table 2. Statistical analysis of LN, PH, SD, PFW, and RFW of the sweet basil on the 28th day

	LN (leaf)	PH (cm)	PFW (g)	RFW (g)	SD (mm)
nsW-pcLED	95.00±9.38	44.30±1.51	34.20±6.12	13.24±1.53	6.68±0.21
R-B LED	81.00±11.7	35.88±4.05	23.02±5.26	10.06±3.56	4.66±0.88
t-test	ns	0.007	0.015	ns	0.006

Significant difference (p <0.05), ns is not a significant difference *(p ≥0.05)*. Standard error: LN=6.73, PH=8.42, PFW=3.61, RFW=1.73, and SD=0.41.

Figure 4 illustrates the growth, morphology, and yield of the sweet basil in both experimental groups. The results indicated that the plants under nsW-pcLED lighting, at 200±10 μmol m^{-2} s^{-1} with a 16/8 light/dark photoperiod, manifested significantly greater plant height, stem diameter, and plant fresh weight compared to plants grown under R-B LED lighting under identical light intensity, photoperiod, and environmental conditions ($p < 0.05$). Moreover, the stem, leaf, and root characteristics, presented in Figures 4(a)-4(e) for each plant number, further substantiate these statistical findings.

In general, PFW showed a strong positive correlation with PH and SD in this study. The average PFW under nsW-pcLED was significantly heavier than under the R-B LED. The higher photon flux of FR from nsW-pcLED, was approximately 6.48 times greater than that of the R-B LED (Table 1). This finding was consistent with the results of studies [17] and [20], which concluded that the R-B light with increasing FR boosted lettuce leaf fresh weight by approximately 30%. It also aligned with the conclusions of the study by [21], which found that LEDs with wavelengths of 610-720 nm (R and FR) increased leaf number and size, while FR in the 720-800 nm range induced stem elongation in sweet basil plants. Additionally, the green light emitted by the nsW-pcLED, with its higher G PPFD, may also contribute to the increased PFW of sweet basil, consistent with the report by [22]. These findings were consistent with the study by [17], which reported the effect of FR light on the yield of four lettuce species and also aligned with the report by [23] on the impact of the FR spectra on the yield of both sweet basil and holy basil.



(a) (b) (c) (d) (e)

Figure 4. Comparison of the morphology of the sweet basil under nsW-pcLED and R-B LED (R: B 3.24) on the 28th day of the experiment (n=10) of (a) plant number 1, (b) plant number 2, (c) plant number 3, (d) plant number 4, and (e) plant number 5

3.2.3. Average growth per unit of energy

After 28 days, the data were collected on several key parameters, including total PFW, total energy consumption, average net growth (g m^{-2}), and average growth per unit of energy. Table 3 summarizes both the measured and calculated values for these parameters across the two experimental groups. Specifically, the average net growth of the sweet basil under nsW-pcLED conditions was approximately 1,221 g m^{-2}, whereas it under R-B LED conditions (R:B 3.24) was approximately 536.43 g m^{-2}. Furthermore, the net energy consumption for the nsW-pcLED treatment was about 36.96 kWh, in contrast to 48.02 kWh for the R-B LED treatment. These results demonstrated that nsW-pcLED not only enhanced biomass production but also improved energy efficiency, highlighting its potential advantages for indoor horticultural applications.

The results indicated that the conversion efficiency, from electrical energy to light and subsequently from light to plant yield (g), differed significantly between the two LED light sources. Specifically, the sweet basil grown under nsW-pcLED exhibited an average net growth that was 227% higher than that under R-B LED. The average growth per unit of energy for the sweet basil under nsW-pcLED was 33.05 g m^{-2} kWh^{-1}, approximately 295% higher than the 11.17 g m^{-2} kWh^{-1} observed with R-B LED (R:B 3.24). These findings aligned with the results reported by [7]. Additionally, nsW-pcLED consumed 23% less electricity than R-B LED (R:B 3.24) while it was producing 227% higher yields of sweet basil.

Using LEDs as a light source for indoor cultivation was an effective solution for energy savings in modern agriculture and sustainability. Horticultural LEDs exhibited higher energy efficiency compared to fluorescent lamps, with an improvement of 17% [24], and they were 70% more efficient than high-intensity discharge (HID) lamps [25]. LED did not only reduce power consumption compared to other light bulbs but it also provided higher plant yields per unit of energy than fluorescent and HID lights [24]. Based on the results of this study, the authors suggested that white LEDs (WLEDs) with a PPFD spectrum similar to that of natural sunlight significantly enhanced the yield of hydroponic sweet basil and demonstrated greater cost-effectiveness in average growth per unit of energy compared to R-B LED (R:B 3.24).

Table 3. Net energy consumption of the light source, PFW, and average growth per unit of energy

LED type	Net energy consumption (kWh)	Total PFW (g)	Area (m^2)	Average net growth (g m^{-2})	Average growth per unit of energy (g m^{-2} kWh^{-1})
nsW-pcLED	36.96	171.00	0.14	1,221.00	33.05
R-B LED	48.02	75.10	0.14	536.43	11.17

4. CONCLUSION

This study demonstrated that nsW-pcLED lighting, which closely mimicked the natural sunlight spectrum, significantly enhanced the growth and yield of hydroponic sweet basil compared to conventional R-B LED lighting. Despite comparable PPFD levels within the PAR range, nsW-pcLED delivered notably higher levels of far-red and green light, leading to significant improvements in plant height, stem diameter, and plant fresh weight. Specifically, the sweet basil grown under nsW-pcLED achieved an average net growth of 1,221 g m^{-2}, approximately 227% higher than that observed under R-B LED (536.43 g m^{-2}), while also exhibiting an average growth per unit of energy that was roughly 295% higher (33.05 g m^{-2} kWh^{-1} vs. 11.17 g m^{-2} kWh^{-1}, respectively). Additionally, nsW-pcLED consumed 23% less electrical energy than the R-B LED system, underscoring its superior energy efficiency. These findings highlight the potential benefits of nsW-pcLED lighting in indoor horticultural applications, offering a viable pathway toward increased crop productivity and energy savings in modern agriculture. The enhanced performance of nsW-pcLED supports sustainable cultivation practices in controlled environments and aligns with previous research indicating the crucial role of far-red and green wavelengths in promoting plant growth. Future studies should expand this research to include a broader range of crop species and longer cultivation periods. These studies should also focus on optimizing spectral parameters and conducting economic feasibility analyses for large-scale applications. Such investigations will ultimately elucidate the benefits and practical applications of nsW-pcLED technology in advancing sustainable indoor agriculture.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Napat Watjanatepin	✓	✓							✓		✓	✓		✓

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

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

As this study did not involve the collection of personal information that could identify individuals, informed consent was not applicable.

ETHICAL APPROVAL

As this study did not involve research on humans or animals, the section on ethical approval is not applicable.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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