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Photoperiod Extension Enhances Lettuce Performance Across LED Spectra in an Indoor Vertical Farming Setup

Fajar Riyadi[1], **Wiwin Dyah Ully Parwati**[1], **Yovi Avianto**[1*]
[1]Program Studi Agroteknologi, Fakultas Pertanian, INSTIPER Yogyakarta, Yogyakarta, Indonesia;

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*Corresponding Author: **Yovi Avianto**, Program Studi Agroteknologi, Fakultas Pertanian, INSTIPER Yogyakarta, Yogyakarta, Indonesia;
Email: yovi@instiperjogja.ac.id

Abstract: Artificial lighting is a key factor in indoor vertical farming because light spectrum and photoperiod strongly regulate plant growth, biomass accumulation, and pigment formation. Lettuce is highly responsive to light manipulation, making it an important model crop for evaluating lighting strategies that can improve productivity and quality under controlled environments. This study evaluated the effects of LED light color and photoperiod on the growth, yield, and pigment content of lettuce (*Lactuca sativa* L.) cultivated in an indoor vertical farming system in Yogyakarta, Indonesia (November 2025 – January 2026). A 3 × 3 factorial experiment arranged in a nested design was conducted with three light colors (white, blue, and green) and three photoperiods (8, 12, and 16 h). Data were analyzed using ANOVA ($\alpha = 0.05$), followed by Tukey's HSD when significant differences were detected. Growth and yield were assessed using stem diameter, plant height, number of leaves, leaf area, root length, fresh weight, and dry weight, while physiological responses were evaluated using chlorophyll a, chlorophyll b, and total chlorophyll. Significant light color × photoperiod interactions were observed for stem diameter, root length, fresh and dry weight, and chlorophyll contents. Overall, white light produced superior lettuce performance compared with blue and green light, particularly under a 16-h photoperiod. The combination of white light and a 16-h photoperiod resulted in the highest biomass accumulation and pigment content, indicating that optimizing both light spectrum and photoperiod is critical to improve lettuce productivity and quality in indoor vertical farming.

Keywords: Biomass yield; Indoor Vertical Farming; Light Spectrum; Lettuce; Photoperiod.

Introduction

Lettuce (*Lactuca sativa* L.) is a widely consumed leafy vegetable and is commonly associated with temperate growing conditions (Thomas et al., 2021). Lettuce contributes important nutrients to the human diet. Per 100 g, it contains 15 kcal, 0.2 g fat, 2.9 g carbohydrates, 1.2 g protein, 1 mg iron, 25 mg phosphorus, 22 mg calcium, 540 IU vitamin A, 0.04 mg vitamin B1 (thiamine), and 8 mg vitamin C (Novriani, 2014). Demand is rising in the culinary sector, including restaurants, hotels, and catering services, for lettuce as a fresh side dish and salad ingredient (Medina-Lozano et al., 2021).

Lettuce production in Indonesia increasingly faces structural constraints. Agricultural land conversion reduces planting area and intensifies competition for resources (Choi et al., 2020). Climate change adds further pressure on open-field systems. Higher climate variability and more frequent extreme events reduce yield stability and increase production risks (Ghorbani et al., 2024; Tran et al., 2025). Soil degradation linked to unsustainable practices can further constrain productivity. These conditions weaken the reliability of the conventional supply (Tran et al., 2025).

Indoor vertical farming is a practical option for leafy vegetable production in urban and peri-urban settings. It supports cultivation

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in limited spaces through vertical structures and controlled environments (Fei et al., 2025; Sengodan, 2022). According to Hadikusuma et al. (2024) Indoor systems enable tighter control of temperature, humidity, irrigation, and nutrient delivery, and this system receives little direct sunlight. However, the absence of direct sunlight means that artificial lighting becomes a primary driver of photosynthesis, morphology, biomass accumulation, and pigment formation in lettuce (Li et al., 2025). Therefore, optimizing lighting strategies is central to improving productivity and resource-use efficiency in indoor systems (Boros et al., 2023; Pennisi et al., 2019).

Among controllable lighting factors, light spectrum (color/wavelength composition) and photoperiod (daily lighting duration) are two key management levers. Spectrum regulates photoreceptor responses that shape morphology and pigment biosynthesis, while photoperiod determines daily carbon assimilation time (Matsuda et al., 2014; Pashkovskiy et al., 2023). In indoor lettuce, changes in spectral composition and red–blue balance can modify growth, yield, and resource-use efficiency (Pennisi et al., 2019). Light environment also affects quality attributes, including antioxidant-related traits and pigment profiles (Carotti et al., 2021; Mohammed et al., 2023).

Recent studies expand attention beyond classic red–blue systems, such as those done by García-Caparrós et al. (2020) and Gao et al. (2022). White LEDs are widely applied in vertical farming because they provide broader spectral coverage and practical visibility for crop inspection. White-light configurations with specific blue or green components can improve growth and quality responses in lettuce (Nguyen et al., 2021). Green wavebands are physiologically active and may influence canopy light distribution and plant responses (Alrajhi et al., 2023; Smith et al., 2017). Reported effects vary with wavelength range, intensity, and cultivar. A recent review emphasizes that spectrum optimization should be evaluated alongside operational constraints, including energy efficiency and crop target traits (Boros et al., 2023).

Evidence from Indonesia also supports the importance of managing artificial lighting and photoperiod for lettuce in indoor or semi-indoor systems. Red–blue LED supplementation at night has been reported to affect lettuce production in modified floating hydroponics (Suhandoko et al., 2018). Studies in Indonesian plant-factory contexts by Widodo et al. (2022) show that different photoperiod regimes can alter growth performance and energy-use efficiency. Other local reports by Supriani et al. (2021) highlight responses of lettuce to LED treatments and additional nighttime lighting in hydroponic systems. These findings support the role of lighting management, while indicating variability across systems and treatments.

Research remains limited for tropical indoor vertical farming conditions that test implementable spectrum options and practical photoperiod durations in one factorial framework. Many published experiments emphasize red–blue ratios, different waveband combinations, or photoperiod patterns that are not aligned with common operational choices for small-to-medium indoor farms (Nguyen et al., 2021; Pennisi et al., 2019; Widodo et al., 2022).

The objective of this study is to evaluate the effects of three LED light colors (white, blue, and green) and three photoperiod durations (8, 12, and 16 h) on lettuce growth, yield, and pigment-related traits in an indoor vertical farming system. The work provides a direct comparison among feasible spectrum options for indoor growers. It quantifies light color × photoperiod interactions on key agronomic and physiological indicators. The results support lighting decisions for indoor lettuce production in Indonesia.

Materials and Methods

Study Site and Period

This experiment was conducted in an indoor room located at Depok District, Sleman Regency, Special Region of Yogyakarta, Indonesia (-7.765653, 110.420729). The study lasted for three months, from system preparation to harvest, from November 2025 to January 2026, covering system preparation, seedling establishment, transplanting, and harvest. The cultivation room was a closed indoor space with no direct sunlight exposure, where crop growth relied entirely on artificial LED lighting. The hydroponic racks were placed on a level floor and arranged to minimize shading among tiers. The room was kept in a clean and protected condition to reduce contamination and pest entry. Ambient temperature and relative humidity were monitored during cultivation using a DHT11 sensor connected to an ESP32 microcontroller.

Materials and Equipments

The equipment used in this study included PVC pipes (paralon), LED lamps (white: 400–700 nm; blue: 400–500 nm; green: 500–600 nm; 15 W), electrical cables, a drill, pH meter, EC meter, hoses, a ruler, seedling trays, cardboard sheets, scissors, a knife, a hammer, net pots, a graduated (measuring) cylinder, a digital/analytical balance, a spectrophotometer (Spectronic 21D Milton Roy), a relay module, an ESP32 microcontroller, and a DHT11 temperature–humidity sensor. The materials used comprised cocopeat as the seedling medium, hydroponic AB-mix nutrient solution, base water, lettuce seeds (*Lactuca sativa* L., cv. Sonybel), adhesive glue, aluminum foil, styrofoam sheets, nails, adhesive tape, strings, and acetone solution for pigment extraction.

Experimental Design and Cultivation

The experiment was conducted as a controlled indoor study using a 3 × 3 factorial design with two treatment factors. The first factor was LED light color (W) with three levels: white (W1; 400–700 nm), blue (W2; 400–500 nm), and green (W3; 500–600 nm). The second factor was photoperiod (P) with three levels: 8 h day^{-1} (P1), 12 h day^{-1} (P2), and 16 h day^{-1} (P3). Each treatment combination was replicated three times, resulting in 27 experimental units.

Hydroponic cultivation was carried out using a multi-tier rack system consisting of three racks, each with three tiers (Figure 1). Plants were grown in PVC channels (3-inch diameter, 1 m length) with a 15 cm plant spacing. Each tier was equipped with two LED lamps positioned 30 cm above the canopy to provide uniform illumination within the tier. Photoperiod treatments were applied using an ESP32 microcontroller programmed via the Arduino IDE and connected to a relay module to automatically control lamp on–off schedules according to the assigned treatment (8, 12, or 16 h per day). Temperature and relative humidity in the cultivation room were monitored using a DHT11 sensor integrated with the ESP32 system.

Seeds of lettuce (*Lactuca sativa* L., cv. Sonybel) were germinated in cocopeat and maintained under standard nursery conditions. During the seedling phase, plants received hydroponic AB-mix solution maintained at approximately 500 ppm. Seedlings were transplanted at 25 days after sowing into a wick hydroponic system using net pots. After transplanting, plants were grown using AB-mix solution maintained at 800–900 ppm, with daily monitoring to maintain nutrient concentration within the target range. The nutrient solution was prepared using clean water and adjusted as needed based on EC/ppm readings. The pH and EC/ppm were monitored routinely to minimize nutrient stress and maintain stable growing conditions throughout the experiment.

Figure 1. Multi-tier rack system for plant factory

Measurements

Plant growth and yield were evaluated using standard horticultural measurements. Plant height (cm) and number of leaves (leaves $plant^{-1}$) were recorded weekly throughout the cultivation period. Plant height was measured from the stem base at the growing surface to the highest point of the canopy. Leaf number included all fully expanded leaves per plant. At harvest (35 DAT), the following parameters were measured: stem diameter (mm), root length (cm), fresh weight (g), and dry weight (g). Stem diameter was measured at the mid-stem section using a vernier caliper after leaf removal. Root length was measured from the stem base to the longest root tip. Fresh weight was recorded after plants were cleaned of cocopeat residues and separated from the wick material. Dry weight was determined after oven-drying plant material at 70 °C until constant weight, followed by weighing using an analytical balance.

Chlorophyll Determination (Combs Method)

Leaf chlorophyll content was quantified by spectrophotometry using the Combs method with acetone extraction. A representative fresh leaf sample was collected at harvest. The tissue was homogenized in acetone to extract photosynthetic pigments, and the extract was clarified before measurement. Absorbance was measured using a spectrophotometer at 663 nm and 645 nm, corresponding to chlorophyll a and chlorophyll b absorption peaks in acetone extracts.

Chlorophyll concentration was calculated using the following equations:

- Chlorophyll a (mg L^{-1})
  $Chl\ \ = 12.7(A_{663}) - 2.69(A_{645})$
- Chlorophyll b (mg L^{-1})
  $Chl\ b = 22.9(A_{645}) - 4.68(A_{663})$
- Total chlorophyll (mg L^{-1})
  $Chl_{total} = 20.2(A_{645}) + 8.02(A_{663})$

Chlorophyll values were expressed on a fresh-weight basis using:

$$\text{Chlorophyll (mg g}^{-1}\text{ FW)} = \frac{C \times V}{1000 \times W}$$

where C is chlorophyll concentration (mg L^{-1}), V is extract volume (mL), and W is leaf fresh weight (g). Chlorophyll a, chlorophyll b, and total chlorophyll were reported consistently using the same unit system to support comparison among treatments.

Analisis Data

Data were analyzed using two-way analysis of variance (ANOVA) at $\alpha = 0.05$ to test the main effects of LED light color (W), photoperiod (P), and their interaction (W × P). Before ANOVA, data were evaluated for compliance with key assumptions. Normality of residuals and homogeneity of variance were checked using appropriate diagnostic procedures; data that did not meet assumptions were transformed as needed before analysis.

When ANOVA indicated significant effects, treatment means were separated using Tukey's Honestly Significant Difference Test (HSD) at $\alpha = 0.05$. For variables measured weekly (plant height and leaf number). Harvest variables were analyzed using final measurements at harvest. All statistical analyses were conducted using standard statistical software R version 4.5.1.

Results and Discussion

Results

The factorial analysis revealed that responses in root length, stem diameter, fresh weight, and dry weight were shaped by a clear light color × photoperiod interaction (Tables 1–4). In practical terms, the magnitude of photoperiod effects depended on the light spectrum, and the advantage of a given spectrum became more evident under specific lighting durations. In contrast, plant height and leaf number followed a simpler pattern. These traits responded primarily to photoperiod rather than to light color, with no interaction detected (Tables 5–6).

Table 1. Effects of LED light color and photoperiod on root length (cm)

Light Spectra	Photoperiod			Mean
	8 h	12 h	16 h	
White	17.66 ^{bc}	18.50 ^{bc}	23.83 ^{a}	20.00
Blue	17.90 ^{bc}	20.00 ^{abc}	17.33 ^{c}	18.41
Green	10.16 ^{d}	15.50 ^{c}	22.83 ^{ab}	16.16
Mean	15.24	18.00	21.33	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Table 2. Effects of LED light color and photoperiod on stem diameter (mm)

Light Spectra	Photoperiod			Mean
	8 h	12 h	16 h	
White	5.90 ^{bc}	6.80 ^{ab}	7.40 ^{a}	6.70
Blue	5.20 ^{cd}	5.23 ^{cd}	6.33 ^{b}	5.58
Green	2.66 ^{e}	4.46 ^{d}	5.96 ^{bc}	4.25
Mean	4.58	5.50	6.56	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Across the dataset, extending the photoperiod produced a consistent upward shift in plant performance. This tendency appeared not only in biomass traits but also in structural traits. Mean values increased from 8 h to 16 h in root length (15.24 to 21.33 cm), stem diameter (4.58 to 6.56 mm), fresh weight (23.33 to 46.89 g), and dry weight (1.03 to 1.93 g) (Tables 1‑4). The same directional response was also observed for plant height (13.05 to 14.97 cm) and leaf number (17.00 to 20.00 leaves) (Tables 5‑6). This parallel increase indicates that a longer daily lighting period supported both the development of plant structure and the accumulation of harvestable biomass.

Table 3. Effects of LED light color and photoperiod on fresh weight (g)

Light Spectra	Photoperiod			Mean
	8 h	12 h	16 h	
White	35.33 ^{c}	51.00 ^{b}	73.00 ^{a}	53.11
Blue	23.66 ^{de}	31.33 ^{cd}	36.00 ^{c}	30.33
Green	11.00 ^{f}	19.33 ^{ef}	31.66 ^{cd}	20.66
Mean	23.33	33.89	46.89	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Table 4. Effects of LED light color and photoperiod on dry weight (g)

Light Spectra	Photoperiod			Mean
	8 h	12 h	16 h	
White	1.72 ^{bc}	2.66 ^{a}	2.70 ^{a}	2,36
Blue	0.95 ^{de}	1.29 ^{cd}	1.24 ^{cd}	1.16
Green	0.42 ^{f}	0.73 ^{e}f	1.84 ^{b}	1.00
Mean	1.03	1.56	1.93	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

The interaction effects become clearer when viewing organ development and biomass formation as connected processes. Treatments that promoted thicker stems tended to coincide with higher fresh and dry mass, suggesting that structural reinforcement was aligned with stronger overall growth. This alignment was most visible under white light, where the increment from 8 h to 16 h was expressed simultaneously in stem diameter (5.90 to 7.40 mm) and in biomass accumulation (fresh weight 35.33 to 73.00 g; dry weight 1.72 to 2.70 g) (Tables 2‑4). The same treatment progression also coincided with a marked enhancement of root length (17.66 to 23.83 cm) (Table 1), indicating that belowground development strengthened alongside aboveground biomass formation rather than trading off against it.

Blue light produced a different growth signature. Under 12 h, blue reached its highest root length within the blue series (20.00 cm), yet the response did not continue in the same direction at 16 h (17.33 cm) (Table 1). This divergence illustrates the interaction: extending photoperiod did not uniformly amplify root extension under all spectra. Despite that, stem diameter and biomass under blue still rose from 8 h to 16 h (stem diameter 5.20 to 6.33 mm; fresh weight 23.66 to 36.00 g) (Tables 2‑3), indicating that additional lighting time under blue was expressed more reliably in shoot thickening and fresh mass than in root elongation.

Green light showed the strongest dependence on photoperiod. Under 8 h, green produced relatively modest structural and yield outcomes, but the shift toward 16 h was accompanied by a pronounced improvement in multiple traits at once. Root length increased sharply (10.16 to 22.83 cm) and stem diameter also advanced (2.66 to 5.96 mm) (Tables 1‑2). This coordinated improvement was reflected in harvest indices as well, with fresh weight rising (11.00 to 31.66 g) and dry weight increasing (0.42 to 1.84 g) (Tables 3‑4). The pattern suggests that, within the green spectrum used here, longer lighting duration was necessary to translate the treatment into meaningful plant growth across organs.

Table 5. Effects of LED light color and photoperiod on plant height (cm)

Light Spectra	Photoperiod			Mean
	8 h	12 h	16 h	
White	12.23	14.06	14.83	13.71 ^{a}
Blue	13.26	13.93	15.50	14.23 ^{a}
Green	13.66	14.36	14.60	14.21 ^{a}
Mean	13.05 ^{c}	14.12 ^{b}	14.97 ^{a}	(-)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Plant height and leaf number, by

comparison, behaved more like time-driven vegetative indicators. Height remained statistically similar across light colors, yet it increased with photoperiod, indicating that extending daily light exposure consistently promoted vertical growth regardless of spectrum (Table 5). Leaf number followed the same logic. It was relatively stable across colors but increased with longer photoperiod (Table 6). These two parameters, therefore, tracked the general developmental acceleration provided by longer daily lighting.

Table 6. Effects of LED light color and photoperiod on the number of leaves (leaves plant^{-1})

Light Spectra	**Photoperiod**			**Mean**
	8 h	**12 h**	**16 h**	
White	19.66	22.66	23.66	22.00 ^{a}
Blue	17.33	17.66	18.00	17.66 ^{a}
Green	14.00	16.66	18.33	16.33 ^{a}
Mean	17.00 ^{b}	19.00 ^{ab}	20.00 ^{a}	(-)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Table 7. Effects of LED light color and photoperiod on the chlorophyll a content (mg L^{-1})

Light Spectra	**Photoperiod**			**Mean**
	8 h	12 h	16 h	
White	25.23 ^{a}	25.21 ^{a}	25.41 ^{a}	25.28
Blue	20.26 ^{c}	25.36 ^{a}	22.63 ^{b}	22.75
Green	11.25 ^{e}	19.49 ^{d}	24.77 ^{a}	18.50
Mean	18.91	23.35	24.27	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Taken together, the results indicate a coherent growth trajectory under extended photoperiods. Longer lighting duration supported faster vegetative development (more leaves and greater height), while simultaneously enabling greater structural investment (larger stem diameter) and higher harvestable biomass (fresh and dry weight). The interaction observed in Tables 1–4 adds an important nuance: light color influenced how efficiently additional lighting time was converted into root development and biomass. White light expressed the most synchronized gains across roots, stems, and biomass as photoperiod increased. Green light required longer exposure before comparable improvements emerged. Blue light produced intermediate outcomes, with some traits responding strongly while others showed a less linear pattern.

Table 8. Effects of LED light color and photoperiod on the chlorophyll b content (mg L^{-1})

Light Spectra	**Photoperiod**			**Mean**
	8 h	12 h	16 h	
White	20.68 ^{c}	19.16 ^{d}	26.03 ^{a}	21.96
Blue	11.19 ^{g}	21.44 ^{b}	16.67 ^{f}	16.43
Green	5.86 ^{i}	10.46 ^{h}	18.36 ^{e}	11.56
Mean	12.57	17.02	20.35	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Table 9. Effects of LED light color and photoperiod on the total chlorophyll content (mg L^{-1})

Light Spectra	Photoperiod			**Mean**
	8 h	12 h	16 h	
White	45.93 b	44.36 c	51.44 a	47.24
Blue	31.47 f	46.81 b	39.29 e	39.19
Green	17.12 h	29.99 g	43.14 d	30.08
Mean	31.51	40.39	44.62	(+)

Note: Values followed by the same letter in the same row and column are not significantly different according to HSD at 5%.

Chlorophyll a, chlorophyll b, and total chlorophyll were all influenced by the interaction between LED light color and photoperiod (Table 7–9), indicating that pigment formation depended on the combined effect of spectrum and lighting duration. In general, chlorophyll content increased as the photoperiod became longer, especially under white and green light. Under white light, chlorophyll a remained relatively stable across photoperiods, while chlorophyll b and total chlorophyll reached higher values at 16 h, suggesting that broad-spectrum light supported a strong and consistent pigment system, particularly when daily illumination was extended.

Under blue light, chlorophyll a, chlorophyll b, and total chlorophyll tended to peak at 12 h rather than 16 h, showing that the response under this spectrum was not always linear. Under green light, all chlorophyll fractions increased markedly with longer photoperiod, indicating that extended exposure was needed before this spectrum could support greater pigment accumulation. Overall, these results show that longer daily lighting generally enhanced the photosynthetic pigment pool, although the magnitude of the response varied among light spectra.

The chlorophyll response was closely related to the growth and yield patterns observed in the previous parameters. Treatments that produced higher chlorophyll levels, particularly under white light with a 16 h photoperiod, also tended to produce greater root length, stem diameter, fresh weight, and dry weight. This relationship suggests that a stronger pigment system increased light-harvesting capacity and supported higher daily photosynthetic rates, which were then translated into greater assimilate production and biomass accumulation. The same trend helps explain why extended photoperiod improved vegetative performance across the experiment. As chlorophyll content increased, the plants were better able to support structural growth and biomass formation. In this way, pigment accumulation did not stand as an isolated response, but rather formed part of the same physiological sequence that linked light treatment to stronger root development, thicker stems, and higher final yield.

Discussion

Light color and photoperiod jointly determined lettuce performance in the indoor system because both factors regulated the daily supply of usable light and the developmental signals received by shoots and roots. A longer photoperiod generally increased total daily light, which in turn supported greater photosynthesis and biomass formation. At the same time, white light provided a broader spectrum that more closely resembled natural light and therefore supported more balanced growth across plant organs. This general pattern agrees with controlled-environment studies showing that lettuce growth is strongly influenced by cumulative daily light and that a 16 h photoperiod is often effective for maximizing growth and quality under artificial lighting (Boros et al., 2023; Yudina et al., 2023).

The interaction found for root length indicates that belowground growth depended on both light quality and lighting duration. Root elongation is closely tied to the availability of photosynthates because root tissues depend on assimilates produced in the canopy. When the photoperiod was extended, the plants had a longer photosynthetic window and thus a greater carbon supply for root extension and recovery after transplanting.

This explains why the treatment that promoted stronger canopy performance also supported longer roots. The same interpretation is consistent with Nurdianna et al. (2018), who reported that light spectrum and photoperiod affect root growth and nutrient uptake efficiency in hydroponic systems. Evidence from hydroponic lettuce studies by Zhang et al. (2018) also shows that the light environment can alter root-related carbon dynamics, which supports the close link between improved canopy assimilation and stronger root development observed in this study.

Figure 2. Representative growth performance of lettuce under different LED light spectra, arranged from left to right as white, blue, and green light treatments

Stem diameter followed a pattern similar to root length, which suggests that structural reinforcement developed together with improved carbon acquisition. A thicker stem reflects stronger cell division and cell enlargement, both of which require a sufficient supply of assimilates. In this study, the treatments that increased stem diameter also tended to produce greater fresh and dry weight, indicating that plants were not only building larger canopies but also investing in stronger supporting tissues. The advantage of white light can be explained by its wider spectral range, which supports more stable vegetative growth than narrow-band light alone.

This interpretation is in line with Alrajhi et al. (2023), who reported that broad-spectrum light can support stable vegetative development.

Fresh weight and dry weight clearly reflected the cumulative effect of longer daily lighting. Fresh weight represents both structural biomass and tissue water content, whereas dry weight reflects net carbon gain after excluding water. When both parameters increase in the same direction, it indicates that the plants are not only retaining more water but also producing more structural biomass. This was exactly the pattern observed under the longer photoperiods, especially under white light. The increase in fresh weight is consistent with improved photosynthesis, higher assimilate production, and better tissue hydration, while the increase in dry weight indicates more efficient conversion of assimilates into new plant tissues. This supports the view that photoperiod extension increased daily carbon assimilation and biomass accumulation. Yudina et al. (2023) similarly reported that increasing illumination duration stimulated dry weight accumulation in lettuce, while Jasenovska et al. (2024) found that white light promoted higher fresh biomass than monochromatic environments.

The green-light treatment showed a particularly strong dependence on photoperiod. Under the shorter photoperiod, green light produced weaker growth responses, but those responses improved substantially when the photoperiod was extended (Figure 2). This phenomenon can be explained by the optical behavior of green light in leaves. Green wavelengths are absorbed less strongly at the leaf surface than red or blue light, yet they penetrate more deeply into leaf tissues and canopies. Because of this, green light can contribute to whole-canopy photosynthesis when the total photon supply is sufficient. In other words, green light may become more useful when plants receive it for a longer time. Liu & Van Iersel (2021) explained that green light can excite chlorophyll in deeper leaf layers despite its lower surface absorptance, which helps explain why a longer photoperiod improved growth and biomass even under the green spectrum in this study.

Plant height and number of leaves did not show interaction effects, but both increased with photoperiod. These two traits mainly describe developmental progression and canopy expansion, so their positive response to longer daily lighting indicates that plants had more time to assimilate carbon and sustain organ formation. Height is closely related to cell elongation and is influenced by assimilate availability as well as hormonal regulation, especially auxin- and gibberellin-related growth processes (Avianto et al., 2025). The descriptive tendency for blue light to produce taller plants, while white light produced stronger biomass and structural traits, suggests that some spectral conditions favored shoot elongation more than balanced dry matter production. This helps explain why the tallest plants were not always the heaviest. A similar distinction between morphology and biomass has been widely described in controlled-environment studies, where spectrum shapes architecture while total daily light largely determines biomass formation. Cho et al. (2020) and Zhang et al. (2018) also showed that photoperiod and daily light input regulate lettuce growth and quality in plant factory systems.

The chlorophyll response strengthens the interpretation above. Chlorophyll a, chlorophyll b, and total chlorophyll all increased in general as the photoperiod became longer, although the size of the increase varied among spectra. Under white light, pigment levels were maintained at relatively high values and became stronger at 16 h, especially for chlorophyll b and total chlorophyll. Under green light, pigment accumulation rose markedly as lighting duration increased, indicating that this spectrum required a longer exposure to support a stronger light-harvesting system. Under blue light, the pigment response was less linear, with intermediate photoperiods sometimes producing the highest values.

Even so, the overall trend shows that longer daily lighting expanded the photosynthetic pigment pool. This matters because pigment accumulation is not an isolated response (Avianto, 2025). Higher chlorophyll content improves light capture, which increases photosynthetic capacity and helps explain why the treatments with stronger pigment formation also tended to produce longer roots, thicker stems, and greater fresh and dry biomass (Avianto & Susila, 2024). Thus, the pigment data provide a physiological bridge between the light treatment and the growth responses observed in the previous parameters (Avianto et al., 2024; Avianto & Saputra, 2024).

Taken together, the results suggest a connected growth sequence rather than separate trait responses. After transplanting, lettuce first needs to restore root function so that water and nutrient uptake can stabilize. Once this belowground recovery is improved, leaf function and pigment adjustment become more effective, allowing greater light capture and stronger daily photosynthesis. The increase in assimilate supply then supports canopy expansion, stem thickening, and continued root development. Finally, these cumulative processes are expressed as higher fresh weight and dry weight. In this study, the white-light treatment under a 16 h photoperiod appeared to support this sequence most effectively because it combined a broad spectrum with a longer daily assimilation period. This pattern is fully consistent with plant-factory literature emphasizing that light quality and photoperiod should be optimized together to achieve high productivity and balanced growth under artificial lighting**.**

Conclusion

This study demonstrated that LED light color and photoperiod significantly influenced lettuce growth, yield, and pigment-related traits in the indoor vertical farming system. Significant interactions between the two factors were observed for root length, stem diameter, fresh weight, dry weight, and chlorophyll content, indicating that lettuce responses depended on the combination of spectrum and lighting duration. The combination of white LED light and a 16 h photoperiod was the most effective treatment for improving lettuce growth, yield, and photosynthetic pigment formation under the conditions of this study.

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