Blue LED Supplemental Lighting Enhances Flowering and Fruit Yield of 'Kuemsil' Strawberries

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Keywords. flowering phase, light-emitting diode, photoperiod, productivity, short-day plant

Abstract. **Strawberries (*Fragaria ×ananassa* Duch.) are grown in greenhouses during the winter season in Korea. Nevertheless, the light intensity in winter is lower compared with that during other seasons of the year, which can lead to inadequate photosynthesis for optimal strawberry yield. As a result, supplemental lighting is used to compensate for the lack of natural sunlight for cultivation of strawberries. However, because strawberries are classified as short-day and low-temperature plants, extending the daylength with supplemental lighting can hinder or prevent flowering. Although reports suggested that blue light can induce flowering in short-day plants, regardless of the photoperiod, few studies of strawberries have been conducted. This study was performed to assess the effects of blue light-emitting diode (LED) lights for supplemental lighting during different growth phases—after planting (AP), first flower cluster (1F), and second flower cluster (2F) phases—on flowering and fruit production of 'Kuemsil' strawberries. Untreated plants were used as control (CL). Strawberries were transplanted on 15 Sep 2023. The supplemental lighting treatments (blue LED; peak: 450 nm; photosynthetic photon flux density: 140 ± 5 μmol·m^{-2}·s^{-1}) were provided for 2 hours before sunrise and 2 hours after sunset. The photosynthetic rate of the treatment groups was significantly higher (~331%) than that of the CL group. Vegetative growth (petiole length, leaf size, and crown diameter) was significantly greater in plants grown under supplemental lighting compared with those grown under CL conditions. Except for the AP treatment group, flowering was promoted to a greater extent in the supplemental lighting treatment groups than in the CL group. The soluble solids content was significantly higher in 1F and 2F treatments than in the other treatments.**

Strawberries (*Fragaria ×ananassa* Duch.) are a high-value agricultural export. Many strawberry cultivars have been produced and distributed. Among them, the 'Kuemsil' strawberry was created to target both the domestic and export markets (Yoon et al. 2020). 'Kuemsil' strawberries are characterized by their large fruit size, low malformed fruits occurrence, and firmness of fruit that is suitable for transportation; therefore, they are currently cultivated and researched as an export strawberry (An et al. 2025; Park et al. 2020; Yoon et al. 2020). The exportation of Korean strawberries has shown a consistent upward trajectory. In 2022, the export volume was 4025 tons; however, it increased to 5012 tons and $69,270 in 2024 (Kati 2025). In South Korea, forced cultivation in greenhouses is the major cultivation method and is favored because the export unit price of strawberries is highest during the winter (Kati 2025). This cultivation method involves transplanting runner plants between August and September, enabling an earlier harvest period from October to December (Bae et al. 2019; Hwang et al. 2020; Nongnet 2024). To optimize this forced cultivation and further improve yield and quality, various advanced techniques, including the application of artificial light and precise environmental control, have been developed and implemented (Kim et al. 2010b; Park et al. 2020).

In South Korea, the interval from late fall through early spring of the subsequent year is recognized as a period characterized by diminished solar radiation; the intensity of sunlight is reduced to nearly 50% that observed during the summer months (Jee et al. 2012; Yu et al. 2023). Such low-light environments can adversely impact the size, yield, and overall quality of fruit production (Parniani et al. 2022). To mitigate these challenges, CO_2 enrichment, early morning heating, and supplemental lighting were researched for use in greenhouses cultivation to increase the photosynthesis of crops (Koo et al. 2025; Park et al. 2010). Our prior research investigated the application of combined red and blue light-emitting diode (LED) lights as a supplemental lighting strategy (Hwang et al. 2025). However, the integration of supplemental lighting for strawberry cultivation in South Korea poses significant obstacles. The predominant cultivars of strawberries cultivated under forced conditions, known as June-bearing strawberries, are classified as quantitative or facultative short-day plants (Kim et al. 2010a; Sønsteby and Heide 2008). This classification implies that the prolonged photoperiod induced by supplemental lighting may hinder the flowering process of strawberries. Research conducted by Hidaka et al. (2015) indicated that supplemental daytime LED lighting can suppress flower bud differentiation in certain Japanese strawberry cultivars. Additionally, our previous findings revealed that nighttime red–blue (RB) LED supplemental lighting also resulted in delayed flowering of strawberries (Hwang et al. 2025). Despite these challenges, it has been demonstrated that supplemental lighting can enhance fruit quality, increase yield, and improve the rate of income growth (Hidaka et al. 2015; Hwang et al. 2025). Consequently, the objective of this study is to explore solutions to the flowering inhibition associated with the use of supplemental LED lighting.

Many environmental factors, including CO_2, light, temperature, water, and nutrients, can interact with plants (Pérez-Romero et al. 2024). Among them, light plays a crucial role in shaping plant morphology and physiology (Yeh and Chung 2009). Different wavelengths of light are perceived by various photoreceptors in plants that influence their life cycle and growth patterns (Demotes-Mainard et al. 2016). For example, phytochromes primarily absorb red and far-red wavelengths, whereas cryptochromes absorb ultraviolet and blue wavelengths (Park and Jeong 2020). Although

they vary among plant species, these perceptions regulate the morphological, physiological, and biochemical characteristics of plants. Studies have shown that red light increased plant height in tomato and lettuce transplants (Lin et al. 2013; Nanya et al. 2012). Far-red light induces shade avoidance syndrome, thus promoting petiole elongation and accelerating flowering (Jeong et al. 2024; Meijer et al. 2023). Blue light promotes stomata opening, increases photosynthetic rate, and increases dry matter production in various plant species (Chen et al. 2019; Goins et al. 1997; Sharkey and Raschke 1981; Zeiger et al. 2002). To address the problem of flowering inhibition, research of the effects of blue light has been conducted. In chrysanthemums, a common short-day plant in horticulture, blue LEDs used as a night-interrupting illumination can induce flowering (Park and Jeong 2020). For ornamental flowering crops, the impact of blue light differs from its impact on fruits and vegetables. This study evaluated whether supplementary blue light delayed flowering without negatively impacting fruit yield or quality in strawberries, indicating a potentially disruptive role of blue light in controlled environment agriculture. Additionally, this research evaluated the effect of supplemental blue LED lighting on the flowering, growth, and fruit yield of 'Kuemsil' strawberries at different developmental phases. The findings of this study will contribute to mitigating flowering delays caused by supplemental lighting in strawberries and help improve the yield of greenhouse-grown strawberries during winter.

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Materials and methods

Plant material and growth conditions. During the experiment, strawberry plants (*Fragaria ×ananassa* Duch. cv. Kuemsil) with three to four leaves and a crown diameter of 9 to 10 mm were used. These plants were placed in pots (295 × 256 × 210 mm; Cheongwoon Industrial Co., Ltd., Gyeongsan, Korea) that were filled with a growing medium composed of coir (100% coir dust; Cocopeat Co., Ltd., Dummalasuriya, Sri Lanka) and perlite (New pearl shine No. 1; GFC Co., Ltd., Hongsung, Korea) in equal volumes (1:1 ratio). Transplantation occurred on 15 Sep 2023, and the plants were grown hydroponically until 20 Mar 2024, for a total of 187 d. The nutrient solution formulated by the Gyeongsangnam-do Agricultural Research and Extension contained macroelements (NO_3^- = 13.0; NH_4^+ = 1.0; $H_2PO_4^-$ = 4.0; K^+ = 6.0; Ca^{2+} = 8.0; Mg^{2+} = 4.0; SO_4^{2-} = 4.0 me·L^{-1}) and microelements (Fe = 3.0; B = 0.5; Mn = 0.5; Zn = 0.2; Cu = 0.04; Mo = 0.04 mg·L^{-1}). A pH/electrical conductivity (EC) meter (HI-98130; Hanna Instruments Co., Ltd., Woonsocket, RI, USA) was used to monitor EC and pH levels, which were maintained at 0.8 dS·m^{-1} and 5.7, respectively. The nutrient solution was supplied four times daily through drip irrigation, with each application lasting 10 min and providing 800 mL per plant. Temperature and humidity were recorded using a temperature and humidity logger (TR-76Ui; T&D Co., Ltd., Matsumoto, Japan). The average temperatures during the day and night were 22 ± 4 °C and 11 ± 5 °C (Fig. 1), while the average relative humidity levels were 40 ± 12% during the day and 64 ± 12% at night.

Supplemental lighting treatment. Plants were cultivated under structures consisting of steel pipe positioned 100 cm above the cultivation bed, with a density of 20 light bulbs per bed, using LED bulbs (peak, 450 nm; BlueUFO; D&W Co., Ltd., Gwangmyeong, Korea) (Supplemental Fig. 1). The photosynthetic photon flux density (PPFD) was 140 ± 5 μmol·m^{-2}·s^{-1}, and the light quality was predominantly blue. The PPFD was recorded using a portable luxmeter data logger (HD2102.2; Delta Ohm SrL., Caselle, Italy), while the light quality was measured using a spectroradiometer (ILT950; International Light Technologies Co., Ltd., Peabody, MA, USA). Based on data from the Korea Meteorological Administration (2024), the daily solar radiation integral in the experimental area showed a decline from October until just before January, followed by an increase starting in January of the subsequent year (Supplemental Fig. 2). Supplemental lighting was implemented during the after planting (AP) phase, first flower cluster (1F) phase, and second flower cluster (2F) phase (Fig. 2). Control plants (CL) were those that did not receive any treatment. Flowering was checked at intervals of 1 week; when a flowering plant was observed, it was considered the start of the flowering period, and supplemental lighting treatment was initiated. In line with the findings of a prior study (Hwang et al. 2022b), supplemental lighting was provided for 2 h before sunrise and 2 h after sunset. The timing for the supplemental lighting was regulated using an electrical timer outlet (SJD-CR16H; Seojin Electric Co., Ltd., Seoul, Korea). Each day, the timer was manually manipulated to activate based on the astronomical data regarding sunrise and sunset times (KASI 2023).

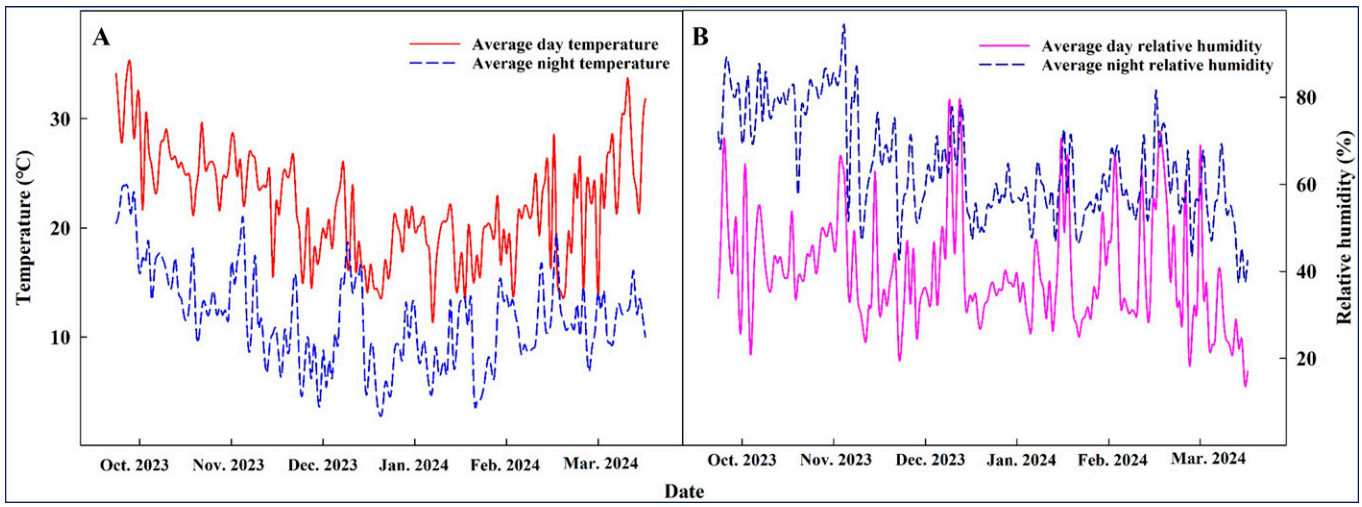

Fig. 1. Changes in average temperatures (A) and relative humidity (B) in the greenhouse.

Plant growth characteristics and flowering response. The photosynthetic rate during the supplemental lighting treatment was measured using a photosynthetic system (CIRAS-3; PP Systems, Amesbury, MA, USA) 30 min after sunset, after the 2F was observed (30 Nov 2023). Measurements of the petiole length, leaf length, leaf width, number of leaves, crown diameter, and soil plant analysis development (SPAD) values were obtained. A portable chlorophyll meter (SPAD-502; Konica Minolta Inc., Tokyo, Japan) was used to measure the chlorophyll content (SPAD value), while the crown diameter was determined with a vernier caliper (CD-20PX; Mitutoyo Co., Ltd., Kawasaki, Japan). Control measurements were performed throughout the entire experimental duration, whereas growth assessments for the AP phase, 1F phase, and 2F phase were performed after the supplemental lighting was applied. The ratios of budding and flowering plants to the total number of plants in the first, second, and third inflorescences were calculated at intervals of 1 week. Plants were classified as budding when 1 cm of the unopened flower buds became visible, and flowering plants were counted when fully developed petals were present.

Fruit characteristics and yield. Fruits that had reached over 80% maturity were collected every 2 to 3 d for each treatment group. The malformed fruits were excluding before the survey. The measurements included length, diameter, weight, firmness, soluble solids content, and acidity of the fruits. A fruit-specific firmness tester (DFT-01; Proem Co., Ltd., Seoul, Korea) was used to assess fruit firmness by inserting a 5-mm probe into a consistent area of each fruit to a depth of 7 mm. The soluble solids content was determined using a digital refractometer (PR-201a; Atago Co., Ltd., Tokyo, Japan) after extracting juice from the fruit following the removal of the 5-mm pulp from the apex of the fruit, with results reported in °Brix. Total acidity was evaluated using an acidity meter (GMK-835N; GMK Co., Ltd., Seoul, Korea) by combining 0.3 g of fruit juice with 30 mL of distilled water. The overall fruit yield was calculated through a complete enumeration survey. Strawberry samples were taken from 5 Dec 2023 to 15 Mar 2024. The fruits were categorized by their fresh weights as premium grade (>25 g), high grade (17–25 g), medium grade (10–16 g), and low grade (<10 g) (NAQS 2021). Then, the cost associated with each fruit grade was used to compute the income growth rate (Kamis 2024).

Fig. 2. Supplemental blue lighting treatment periods for 'Kuemsil' strawberry plants cultivated in a greenhouse. 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group.

Statistics. The experimental treatments were conducted using a randomized complete block design with three replications. Each treatment included 15 plants, with five plants allocated to each replicate. All experiments were conducted in triplicate. The data analysis was conducted using the Statistical Analysis System (SAS 9.4; SAS Institute Inc., Cary, NC, USA). The results of the experiments was assessed using an analysis of variance, Fisher's least significant difference tests, and Scheffé's multiple comparison procedure. A significance level of $P \leq 0.05$ was used to determine differences. Graphs were created using the SigmaPlot software (SigmaPlot 14.5; Systat Software Inc., San Jose, CA, USA). Additionally, a heatmap analysis was performed using R (version 4.2.2; R Foundation for Statistical Computing, Vienna, Austria) to

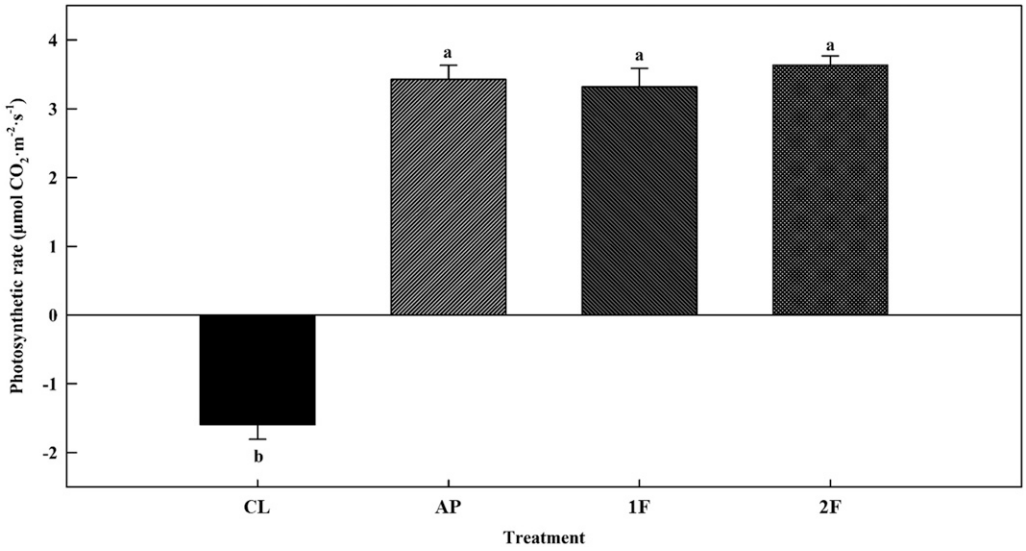

Fig. 3. Photosynthetic rate of 'Kuemsil' strawberry plants cultivated in a greenhouse as affected by supplemental blue lighting treatments 30 min after sunset at the second flower cluster phase. 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group. Vertical bars indicate the standard error of the mean values (n = 15). Lowercase letters indicate significant differences at $P \leq 0.05$ as determined by Fisher's least significant difference test.

explore the relationships between treatments and plant traits.

Results and discussion

Photosynthetic rate affected by supplemental blue LED lighting. The photosynthetic rate of strawberry plants was approximately 331% higher in the treatment groups than in the CL group during the supplemental lighting period (Fig. 3). In different growing environments, such as open-field cultivation commonly found in the United States and Spain, the amount of light available naturally varies depending on latitude, atmospheric composition, and season (Holmes 2024; Menzel 2025). However, the light environment in protected cultivation can be controlled by growers as they desire (Menzel 2025; Tang et al. 2020). Supplemental lighting during sunset and sunrise positively affects photosynthetic rate and plant growth (Goo and Park 2024; Hwang et al. 2022b; Kim et al. 2011; Tewolde et al. 2016). Blue light is associated with a high photosynthetic capacity in leaves exposed to red light (Hogewoning et al. 2010). In addition, CL exhibited negative values for photosynthetic rate. At night, an increase in CO_2 release, known as night respiration, is observed in photosynthesizing leaves (Gessler et al. 2017; Whitehead et al. 2004). The photosynthetic measuring device used in this experiment measured the photosynthetic rate through the CO_2 exchange of plants (Khan et al. 2021). The negative values observed in the CL plants indicate that respiration was more active than photosynthesis.

Plant growth characteristics affected by supplemental blue LED lighting. Strawberry plants exposed to supplemental lighting showed significantly higher vegetative growth than those in the CL treatment (Fig. 4). No significant differences were observed in the SPAD values between treatments. Supplemental lighting improved the photosynthetic rate of strawberries for a more extended period than the CL (Fig. 3). Photosynthesis enables plants to capture light energy and convert it into biochemical energy, thereby enhancing the growth of organs, such as leaves, crowns, and flowers (Evans 2013; Hidaka et al. 2013). Exposure of short-day plants to long-day conditions can enhance leaf length, width, and number (Higuchi et al. 2012; Hwang et al. 2022a). Blue light promotes stomatal opening, which improves the transportation and distribution of photosynthetic assimilation products and increases dry matter production (Senger 1982; Terfa et al. 2013). Consequently, the enhancement of vegetative organ development among the treatment groups was attributed to enhanced photosynthesis resulting from supplemental lighting. This development could provide stronger light and CO_2 capacity for assimilate production, potentially influencing reproductive organ development (Davarzani et al. 2023; Shamsabad et al. 2022).

Flowering response affected by supplemental blue LED lighting. Blue supplemental lighting showed faster flowering than AP (Fig. 5). Blue light photoreceptors, cryptochromes, are involved in flowering (Fankhauser and Ulm 2011; Hirose et al. 2006). Among the cryptochromes, Cry1 and Cry2 are involved in plant de-etiolation and are recognized as physiological mechanisms that regulate flowering timing in response to light (Khanna et al. 2003). Cry2 is considered the primary blue light receptor that promotes flowering. For flowering in plants, the accumulation of CO protein through a process involving an unidentified gene, *ELF4*, is necessary for flowering (Doyle et al. 2002). Cry2 stabilizes the synthesized CO protein (Thomas 2006). This is the primary reason why blue light receptors and cryptochromes are reportedly associated with flowering in plants. Yoshida et al. (2016) reported that blue LED promotes flowering of everbearing strawberry and found high expression levels of *FvFT1* and *FvCO* genes, which influence flowering. Jeong et al. (2014) reported that blue light increases shoot growth without flower

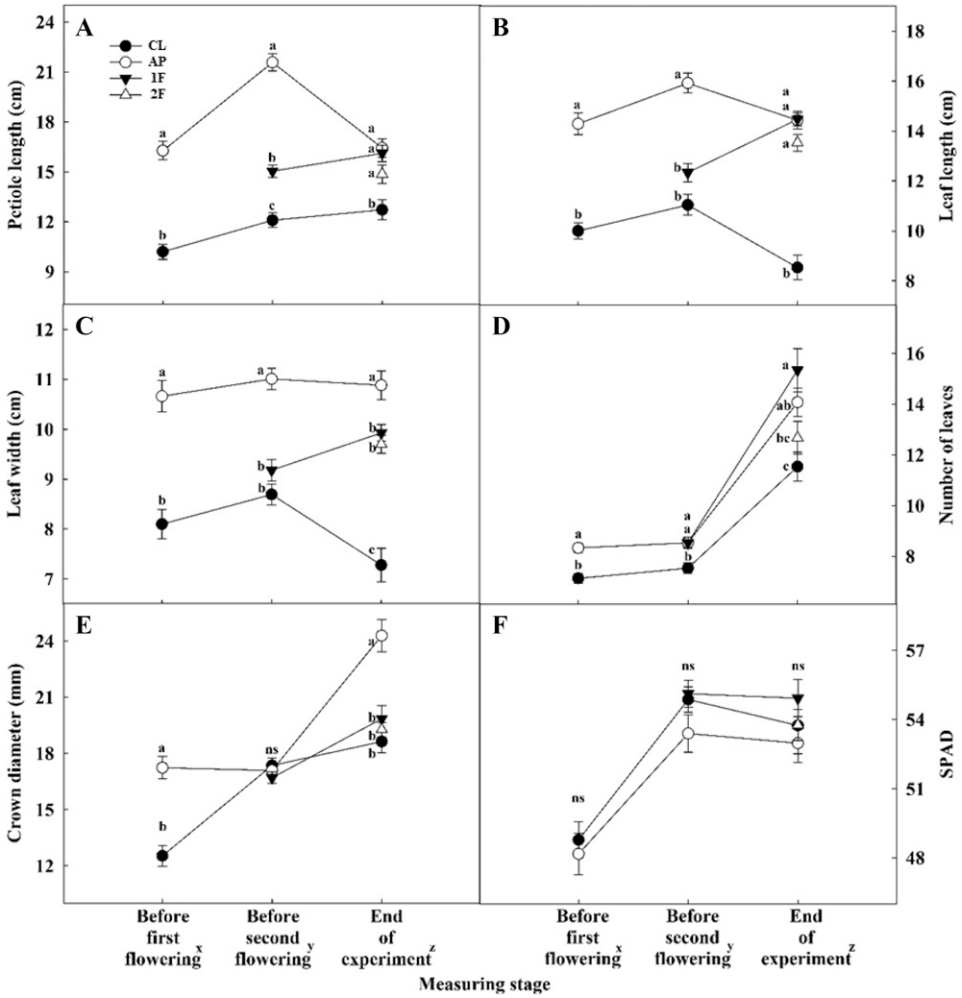

Fig. 4. Petiole length (A), leaf length (B), leaf width (C), number of leaves (D), crown diameter (E), and soil plant analysis development (SPAD) (F) values of 'Kuemsil' strawberry plants cultivated in a greenhouse with and without blue supplemental lighting. 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group. Vertical bars indicate the standard error of the mean values (n = 15). Lowercase letters indicate significant differences at $P \leq 0.05$ as determined by Fisher's least significant difference test. x, y, and z represent at 46, 67, and 188 d after transplanting, respectively.

inhibition in chrysanthemums, which are typical short-day plants. Park and Jeong (2020) demonstrated that chrysanthemum flowering could be induced under blue supplemental lighting. In contrast, AP exhibited the slowest flowering compared with the other treatments, including CL. In fruit and vegetable plants, balancing vegetative and reproductive growth is crucial to determining subsequent flowering and fruit yield (Hwang et al. 2006). Although strawberry plants can grow both vegetatively and reproductively at the same time (Lee et al. 2019), AP appears to prioritize vegetative growth over the other treatments, potentially causing delayed flowering (Fig. 4). Therefore, considering the balance between vegetative and reproductive growth, blue supplemental lighting is recommended after 1F.

Fruit characteristics affected by supplemental blue LED lighting. No significant differences were observed in fruit length, diameter, weight, or firmness between the treatments (Table 1). However, supplemental lighting treatments tended to increase the soluble solids content and acidity compared with CL. Plant organs can be classified based on the supply and demand of the assimilation products (Heuvelink and Buiskool 1995). Fruits demand assimilation products supplied by the leaves, and more active leaves can produce increased amounts of assimilation products for utilization by the fruits (Dejong et al. 1987; Roussos et al. 2009). Plants treated with supplemental lighting exhibited superior shoot growth compared with those in the CL group (Fig. 4). Therefore, the enhanced development of vegetative organs was considered to result in the production of better quality fruits in the treatment groups compared with the untreated CL group. Hidaka et al. (2013) reported improved fruit quality, including increased fruit weight and soluble solids content, of strawberries treated with supplemental LED lighting. Qiu et al. (2024) and Pérez-Romero et al. (2024) reported that supplemental LED light significantly enhanced the soluble solids content and functional compounds of strawberry fruit attributable to improved shoot development and

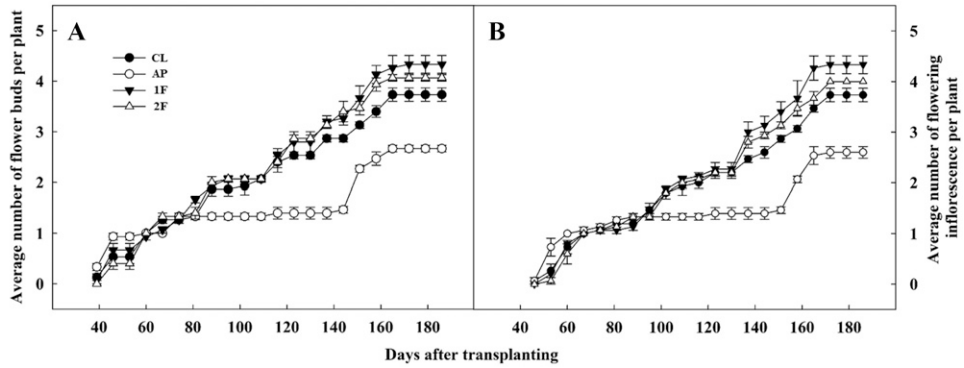

Fig. 5. Average number of flower buds per plant (A) and average number of flowering inflorescences per plant (B) of 'Kuemsil' strawberry plants cultivated in a greenhouse under blue supplemental lighting treatments. 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group. Vertical bars indicate the standard error of the mean values (n = 15).

Table 1. Fruit characteristics of 'Kuemsil' strawberries cultivated in a greenhouse as affected by blue supplemental lighting treatments (n = 15).

Treatment[i]	Fruit length (mm)	Fruit diam (mm)	Fruit wt (g)	Fruit firmness (N/Φ5 mm)	Soluble solids content (°Brix)	Acidity (%)
CL	40.73	30.77	16.41	4.35	12.02 b[ii]	0.76 b
AP	41.98	33.25	17.14	4.15	12.15 ab	0.83 a
1F	42.63	32.34	18.54	4.21	12.83 a	0.89 a
2F	40.63	30.77	16.61	4.23	12.63 a	0.82 a

[i] 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group.
[ii] Lowercase letters indicate significant differences calculated by Scheffé's multiple comparison procedure at $P \leq 0.05$.

increased nitrogen uptake. Blue light has been shown to enhance photosynthetic rate and dry matter production (Chen et al. 2019; Goins et al. 1997; Sharkey and Raschke 1981; Zeiger et al. 2002). Exposure of plants to blue light can influence metabolic pathways and increase the levels of metabolic compounds (Nascimento et al. 2013; Stutte et al. 2009). In strawberries, blue light exposure has been associated with increased organic acid and sugar content (Xu et al. 2014). Therefore, blue supplemental lighting can enhance fruit quality.

Fruit yield affected by supplemental blue LED lighting. Commercial yield and income growth rates were increased by supplemental blue lighting compared with CL (Fig. 6). The fruit yield of AP was significantly lower than that of 1F and 2F plants because of the delay in flowering (Fig. 5), which can be attributed to the allocation of assimilation products to vegetative parts rather than reproductive organs (Fig. 4). The 1F treatment produced the highest

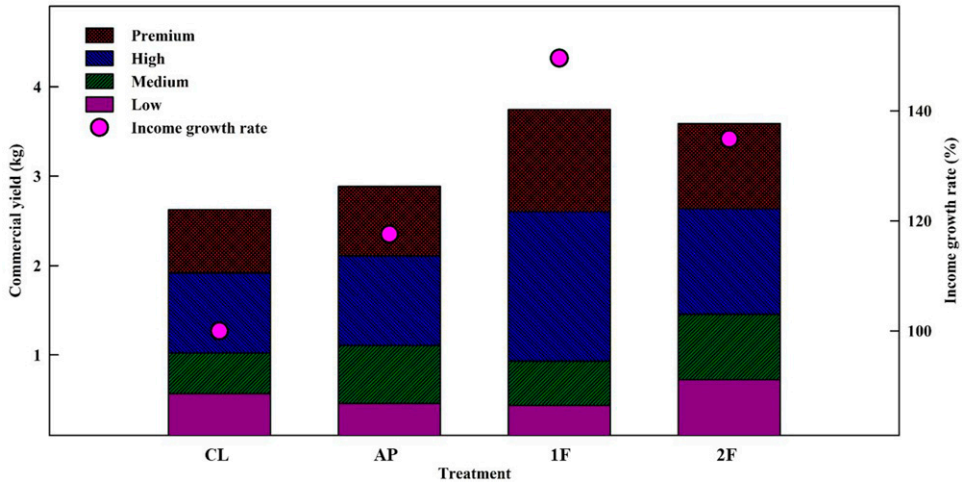

Fig. 6. Commercial yield and income growth rate of 'Kuemsil' strawberry plants cultivated in a greenhouse under blue supplemental lighting treatments. 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group.

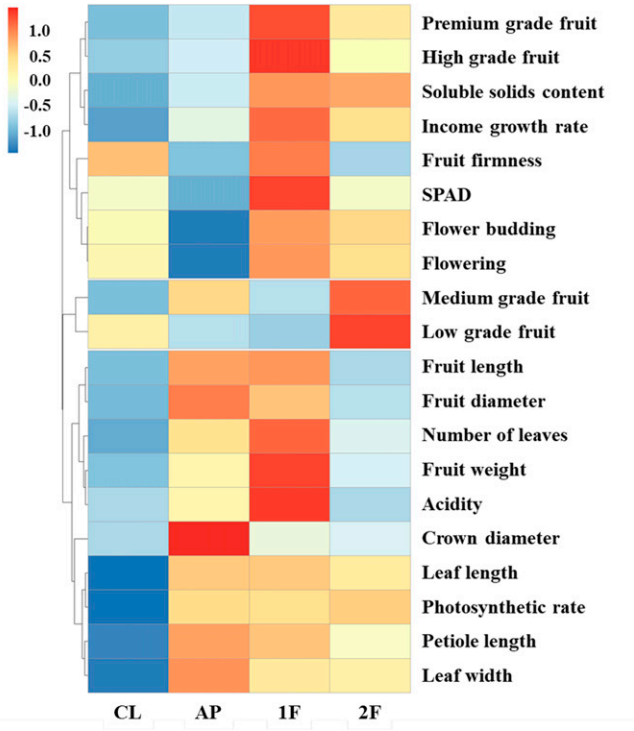

Fig. 7. Heatmap analysis presenting the correlation among supplemental blue lighting treatments and 'Kuemsil' strawberry plant traits. The color bar explains the correlation between variables. Red indicates a positive correlation, blue indicates a negative correlation, and yellow indicates a weak correlation. 1F = supplemental lighting treatment commenced at the first flower cluster phase; 2F = supplemental lighting treatment commenced at the second flower cluster phase; AP = supplemental lighting treatment commenced after the planting phase; CL = control group.

commercial yields of premium-grade and high-grade fruits. Supplemental lighting enhances photosynthesis and increases crop yield (Kim and Son 2022; Lee et al. 2023; Wojciechowska et al. 2015). Li et al. (2024) reported that LED lighting enhances photosynthesis in strawberry plants and improves fruit quality and yield by increasing their resistance to environmental stresses, such as low light and salinity, through abscisic acid and auxin. In the present study, supplemental blue lighting at the 1F and 2F phases did not inhibit flowering (Fig. 5). Therefore, supplemental lighting treatment at the 1F phase is appropriate for increasing fruit yield, grade, and income growth rate without hindering the flowering of 'Kuemsil' strawberry. To maximize the production of premium and high-grade fruits, blue supplemental lighting should be initiated from the 1F phase to achieve an improved yield of premium-grade and high-grade fruits. The findings of this study can be used to compensate for insufficient light during low-radiation periods in strawberry cultivation and are also expected to be applicable in indoor agriculture and space farming to manipulate plant growth or accelerate flowering or fruit production in restricted environments.

Conclusion

Strawberry plant growth and nutrient organ development were enhanced by supplemental blue lighting (Fig. 7). Supplemental blue lighting had a beneficial effect on the quality of fruit, commercial yield, and income

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