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Photosynthetic Daily Light Integral Has a Greater Impact on Basil Flowering than Photoperiod

Charlie Garcia and Roberto G. Lopez
Department of Horticulture, 1066 Bogue Street, Michigan State University, East Lansing, MI 48824-1325, USA

Christopher J. Currey
Department of Horticulture, 008 Horticulture Hall, Iowa State University, Ames, IA 50011-2030, USA

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Abstract. **Flower inhibition or induction of basil (*Ocimum* spp.) is desirable depending on its intended use, be it for culinary or ornamental purposes or the production of essential oils. However, limited controlled-environment studies have been conducted on common culinary herbs to determine how changes in day length and the photosynthetic daily light integral (DLI) influence flowering. Therefore, the objectives of this study were to: (1) quantify how photoperiod under a low DLI influenced flowering of Greek basil (*Ocimum minimum* 'Pluto'), holy basil (*Ocimum tenuiflorum*), lemon basil (*Ocimum ×citriodorum* 'Lime'), purple basil (*Ocimum basilicum* 'Red Rubin'), sweet basil (*O. basilicum* 'Cinnamon', 'Genovese', 'Nufar', and 'Sweet Dani Lemon'), and Thai basil (*O. basilicum* var. *thrysiflora* 'Sweet Thai') and (2) quantify how short-day (SD) and long-day (LD) photoperiods under a moderate and high DLI influenced flowering of holy, lemon, purple, sweet ('Genovese' and 'Nufar'), and Thai basil. In both experiments, seeds were germinated in plug trays, transplanted into larger containers, and grown at 25 °C. Photoperiods for Expt. 1 consisted of a 9-h SD; a 9-h photoperiod extended to 11, 12, 13, 14, 15, or 16 h; and a 4-h night interruption (200 to 0200 HR) using red + white + far-red light-emitting diode lamps providing a total photon flux density of ≈2 μmol·m^{-2}·s^{-1}. In Expt. 1, the low DLI was ≈7 mol·m^{-2}·d^{-1}. For Expt. 2, a 9-h SD and a 16-h LD were created under a moderate DLI of ≈13 mol·m^{-2}·d^{-1} and high DLI of ≈23 mol·m^{-2}·d^{-1}. All cultivars can be classified as day-neutral plants under a low DLI because there were no discernible flowering trends among treatments. Under moderate and high DLIs, purple, Thai, and sweet basil 'Nufar' exhibited a facultative LD response with a hastened time to first open flower under a 16-h photoperiod, while lemon basil was classified as a facultative LD plant only under a high DLI. In Expt. 2, time to first open flower and node number below the first open flower were reduced under the high DLI for all cultivars excluding lemon basil, thus indicating a facultative irradiance response. Our results indicate that photoperiod alone is not an effective method to manage the flowering responses of the basil cultivars evaluated.**

The genus *Ocimum*, composed of 30 (Simon et al. 1999) to 150 (Evans 2009) species, is collectively known as basil and is a member of the mint family (Lamiaceae). India, Asia, and Africa are the centers of basil diversity and presumed native origin (Putievsky and Galambosi 1999; Simon 1985), but its exact origin is uncertain. Basil has several uses, including as a medicinal herb, religious purposes, production of essential oils, landscape ornamental, or cut flower (Kalita and Khan 2013; Simon et al. 1990, 1999). However, sweet basil (*Ocimum basilicum*) is the most common species and is used as a culinary herb, either as a fresh-cut, container-grown, or dried product.

Basil is the most popular culinary herb commercially grown in greenhouses and indoor vertical farms, both hydroponically and in containers due to its high market value (Adam 2005; DeKalb et al. 2014). However, the US Department of Agriculture does not collect production statistics for individual commodities such as basil. Preventing flower initiation and development in culinary herbs is important (Davis 2024), as retailers often will reject fresh-cut herbs if buds or flowers are present. Retailers and consumers perceive flowering fresh-cut basil as old, off flavor, and bitter (Williamson 2019). In contrast, field producers of other basil species used for essential oils want their crops to flower quickly to maximize aromatic oil concentrations (Simon 1995), since the greatest concentrations of essential oils are primarily accumulated in the leaves of flowering plants and flowers (Nurzynska-Wierdak et al. 2013).

Flowering of many horticultural crops is influenced by day length (Erwin and Warner 2002; Mattson and Erwin 2005; Runkle and Heins 2003). Crops are classified into three primary photoperiodic classes: short-day plants (SDPs), long-day plants (LDPs), and day-neutral plants (DNPs) (Runkle et al. 2017; Thomas and Vince-Prue 1997). Both LDPs and SDPs can be further classified depending on whether the photoperiod is required for flowering (qualitative or obligate) or whether the photoperiod accelerates flowering but is not required (quantitative or facultative) (Blanchard and Runkle 2010). While photoperiodic flowering responses of ornamental flowering plants have been extensively studied, limited studies have examined how photoperiod influences growth and development of culinary herbs.

Burbott and Loomis (1967) reported that peppermint (*Mentha piperita*) grown under a 12-h day length remained vegetative, while Langston and Leopold (1954) indicated that flower induction of peppermint occurs when day length is extended to 14 or 18 h. When sweet basil was grown at day/night temperatures of 30/12, 24/12, and 18/12 °C and under 10- or 16-h photoperiods, plants flowered faster under long-days (LDs) and higher temperatures (Putievsky 1983). In a separate study, sweet basil grown under an 18-h photoperiod flowered 8, 5, and 3 d faster compared with plants grown under 9-, 12-, and 15-h photoperiods, respectively (Skrubis and Markakis 1976).

Herb production within greenhouses and other semicontrolled environments occurs year-round; however, during the winter months in northern latitudes ambient daily light integrals (DLIs) can be limitingly low. The only feasible way to appreciably increase the DLI is with the use of supplemental lighting (SL) (Currey et al. 2017). Walters and Currey (2018) reported fresh and dry weights, height, and number of nodes for sweet basil 'Nufar' increased by 144%, 178%, 20%, and 18%, respectively, as DLI increased from 7 to 15 mol·m^{-2}·d^{-1}. Similarly, Beaman et al. (2009) reported that sweet basil 'Genovese', 'Italian Large Leaf', and 'Nufar' had the greatest yield at a DLI of 29 mol·m^{-2}·d^{-1}. In a separate study, sweet basil 'Improved Genovese Compact' grown under sole-source lighting providing DLIs ranging from 9.3 to 17.8 mol·m^{-2}·d^{-1} resulted in larger and thicker leaves as DLI increased (Dou et al. 2018).

In addition to affecting vegetative biomass, increasing DLI may accelerate time to first open flower (OF) and reduce the number of nodes below the first OF (Erwin et al.

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R.G.L. is the corresponding author. E-mail: rglopez@msu.edu.

Table 1. Expt. 1 photoperiod, mean (±*SD*) canopy air daily temperature (ADT), and daily light integral (DLI) (±*SD*) during two experimental replications (Rep) for basil.

Photoperiod (h)	Rep 1 ADT [mean ± *SD* (°C)]	Rep 2 ADT [mean ± *SD* (°C)]	Rep 1 DLI ($mol{\cdot}m^{-2}{\cdot}d^{-1}$)	Rep 2 DLI ($mol{\cdot}m^{-2}{\cdot}d^{-1}$)
9	23.6 ± 1.3	24.4 ± 2.1	6.2 ± 2.5	—[i]
11	24.0 ± 1.2	24.7 ± 2.0	—	7.1 ± 3.6
12	24.5 ± 1.2	24.2 ± 1.9	—	6.8 ± 3.1
13	24.1 ± 1.6	24.9 ± 2.4	7.2 ± 4.4	—
14	23.9 ± 1.5	24.3 ± 2.0	—	6.2 ± 3.0
15	24.2 ± 1.4	24.3 ± 2.3	6.6 ± 4.5	—
16	24.0 ± 1.3	24.6 ± 2.2	—	6.7 ± 3.5
NI	23.1 ± 1.8	24.3 ± 1.8	7.5 ± 4.1	—

[i] A dash indicates that no data were collected.

Plants were grown under a truncated 9-h short day, and day length was extended with red + white + far-red light-emitting diode lamps to achieve 11-, 12-, 13-, 14-, 15-, or 16-h photoperiods or a 4-h night interruption (2200 to 0200 HR).

2017; Oh et al. 2010). A facultative irradiance (FI) response refers to a reduction in time to first OF and/or node number below the first OF from increasing DLI (Mattson and Erwin 2005) and can occur across all photoperiodic response groups (Erwin et al. 2017). Alternatively, an irradiance-indifferent response is where time to OF and node number are unaffected by increasing DLI. Plants exhibiting an FI response flower faster because the juvenile phase is shortened under high DLIs (Adams et al. 1999). For example, time to flower of cyclamen (*Cyclamen persicum* 'Metis Scarlet Red') decreased from 133 to 75 d as DLI increased from 1.4 to 17.3 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ (Oh et al. 2010). For sweet pea (*Lathyrus odoratus* 'Royal White'), leaf number below the first flower decreased from 16 to 11 leaves, and time to flower decreased from 78 to 57 d when grown under an 18-h photoperiod with a DLI of 9.7 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ provided by high-pressure sodium lamps in comparison with a 4-h night-interruption (NI); flowering did not occur under a 9-h short-day (SD), regardless of SL (Mattson and Erwin 2005).

Studies investigating how photoperiod and DLI interact to affect developmental parameters of popular basil species grown in controlled environments are needed, since previous studies have focused on growth (fresh and dry weight, height, leaf area) and not flowering parameters. Therefore, the objectives of this study were to: (1) quantify how photoperiod influences flowering of 10 basil species and cultivars and (2) determine whether photoperiod and DLI interact to influence flowering responses.

Materials and Methods

Plant material and culture

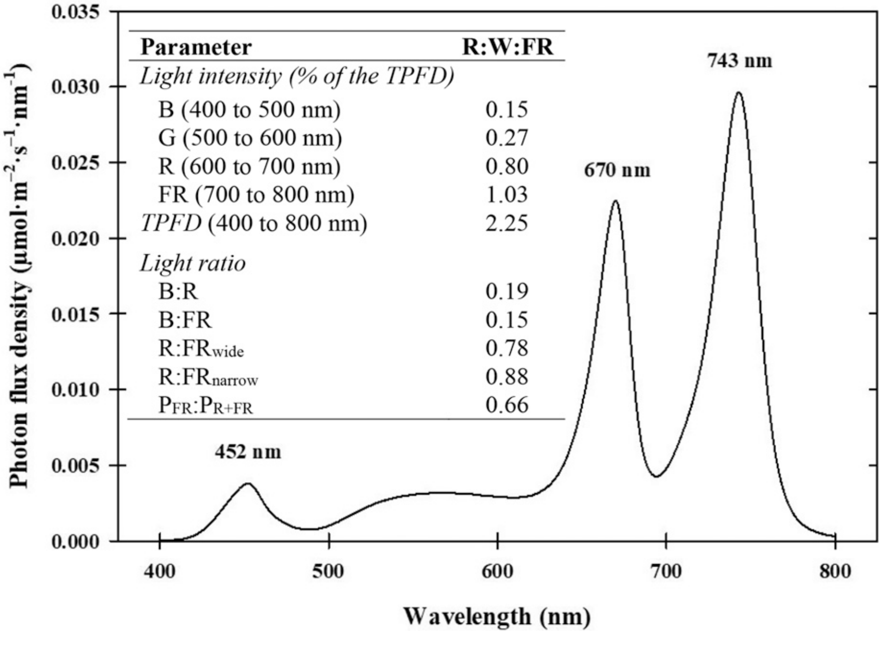
Expt. 1. Seeds of holy basil (*Ocimum tenuiflorum*), Greek basil (*Ocimum minimum* 'Pluto'), lemon basil (*Ocimum* ×*citriodorum* 'Lime'), purple basil (*O. basilicum* 'Red Rubin'), sweet basil ('Cinnamon', 'Genovese', 'Nufar', and 'Sweet Dani Lemon'), and Thai basil (*O. basilicum* var. *thyrsiflora* 'Sweet Thai') (Johnny's Selected Seeds, Winslow, ME, USA) were sown on 13 Oct and 20 Aug into 128-cell plug trays (2.7 × 2.7 cm; 12.0-mL cell volume). Each cell was filled with a soilless medium composed of (by vol.) 50% vermiculite (premium grade vermiculite; Sungro Horticulture, Agawam, MA, USA) and 50% soilless medium containing 70% peatmoss, 21% perlite, and 9% vermiculite (Suremix; Michigan Grower Products, Inc., Galesburg, MI, USA).

Trays of each cultivar were placed under each treatment on capillary mats. They were overhead irrigated as needed with reverse osmosis water supplemented with water-soluble fertilizer providing (in $mg{\cdot}L^{-1}$) 60 nitrogen, 23 phosphorus, 60 potassium, 28 calcium, 5 magnesium, 1 iron, 0.6 manganese, 0.6 zinc, 0.6 copper, 0.4 boron, and 0.1 molybdenum (MSU Plug Special; Blackmore Company, Kankakee, IL, USA). After cotyledon emergence, the seedlings were thinned to one plant/cell.

Once plugs were pullable (3 to 4 weeks), 10 randomly selected seedlings were transplanted into round 11-cm-diameter (600-mL) containers filled with the previously mentioned soilless medium (Suremix; Michigan Grower Products Inc., Galesburg, MI, USA). After transplant, the plants were irrigated as needed with reverse osmosis water supplemented with water-soluble fertilizer (in $mg{\cdot}L^{-1}$) 125 nitrogen, 12 phosphorus, 100 potassium, 65 calcium, 12 magnesium, 1.0 iron and copper, 0.5 manganese and zinc, 0.3 boron, and 0.1 molybdenum (MSU Orchid RO Water Special; Blackmore Company).

The plants were grown in a glass-glazed greenhouse with exhaust fans, evaporative-pad cooling, radiant steam heating, and SL controlled by an environmental control system (Priva Office version 725-3030; Priva North America, Vineland Station, ON, Canada). The greenhouse air mean daily temperature (MDT) set point was a constant 25 °C. Space heaters provided supplemental heat for each bench when the air temperature fell under 24 °C. The photoperiod was 9 h (0800 to 1700 HR), consisting of natural photoperiods (lat. 42°N) and SL from 200-W light-emitting diodes (LEDs) (Philips GP-TOPlight DRW-MB; Koninklijke Philips N.V., Eindhoven, The Netherlands), and provided a photosynthetic photon flux density (PPFD) (±*SD*) of 90.4 ± 14.2 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ when the outdoor light intensity was below ≈440 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ to achieve a DLI of <8 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, referred to as a low DLI (Table 1). The 100-nm waveband ratios (%) of the LED fixtures, defined by their blue [B (400 to 500 nm)], green [G (500 to 600 nm)], and red [R (600 to 700 nm)] PPFDs, were 10:5:85.

Opaque black cloths were pulled over each individual bench daily at 1700 HR and opened at 0800 HR to create a truncated 9-h SD for all treatments. Treatments consisted



Parameter	R:W:FR
Light intensity (% of the TPFD)	
B (400 to 500 nm)	0.15
G (500 to 600 nm)	0.27
R (600 to 700 nm)	0.80
FR (700 to 800 nm)	1.03
TPFD (400 to 800 nm)	2.25
Light ratio	
B:R	0.19
B:FR	0.15
$R{:}FR_{wide}$	0.78
$R{:}FR_{narrow}$	0.88
$P_{FR}{:}P_{R+FR}$	0.66

Fig. 1. Expt. 1 and 2 spectral distribution, intensity of blue [B (400 to 500 nm)], green [G (500 to 600 nm)], red [R (600 to 700 nm)], and far-red [FR (700 to 800 nm)] radiation, total photon flux density (TPFD), light ratio, and estimated phytochrome (P) photoequilibria [P_{FR}/P_{R+FR} (the proportion of FR-absorbing phytochromes in the pool of R- and FR-absorbing phytochromes; Sager et al. 1988)] of R+W+FR light-emitting diode (LED) lamps covered with multiple layers of wire mesh and used for day-extension lighting. $R{:}FR_{wide}$ was calculated as 600 to 700 nm:700 to 800 nm; $R{:}FR_{narrow}$ was calculated as 655 to 665 nm:725 to 735 nm. W = white light.

Table 2. Expt. 2 daily light integral (DLI) and photoperiod treatments, mean (±*SD*) canopy air mean daily temperature (ADT), and DLI delivered to basil.

DLI treatment	Photoperiod (h)	Rep 1 ADT [mean ± *SD* (°C)]	Rep 2 ADT [mean ± *SD* (°C)]	Rep 1 DLI ($mol·m^{-2}·d^{-1}$)	Rep 2 DLI ($mol·m^{-2}·d^{-1}$)
Moderate	9	25.7 ± 1.2	25.3 ± 0.5	12.8 ± 2.0	12.5 ± 4.5
	16	25.7 ± 1.2	25.4 ± 1.1	13.7 ± 3.4	13.4 ± 3.4
High	9	25.2 ± 2.4	25.1 ± 1.2	22.2 ± 4.9	23.3 ± 4.3
	16	25.2 ± 2.4	25.0 ± 1.0	23.2 ± 4.0	22.4 ± 3.9

Plants were grown under a truncated 9-h photoperiod or an extended 16-h photoperiod, with moderate or high photosynthetic DLIs. Day-extension photoperiodic lighting as delivered by light-emitting diode lamps (LED). LED lamps emitted red + white + far-red radiation and extended the photoperiod by 7 h [16 h total (1700 to 2400 HR)].

of the 9-h SD, 9-h SD extended by four R + white + far-red (R+W+FR) LED lamps (GreenPower LED flowering DR/W/FR 14 W, E26; Philips) on each bench to create 11-, 12-, 13-, 14-, 15-, or 16-h photoperiods, and a 4-h NI from 2200 to 0200 HR. Each LED lamp was covered with multiple layers of aluminum wire mesh to achieve a mean total photon flux density of ≈2 $\mu mol·m^{-2}·s^{-1}$ between 400 and 800 nm. The 100-nm waveband ratios (%) of the R+W+FR LED lamps, defined by their B, G, R, and FR radiation, were 7:12:35:46. The spectral distribution of the LED lamps was measured in five random locations throughout each bench by a spectroradiometer (PS-200; Stellar-Net, Tampa, FL, USA), and the phytochrome photo equilibrium was estimated according to Sager et al. (1988) (Fig. 1). A shielded and aspirated 0.13-mm type E thermocouple (Omega Engineering, Stamford, CT) at canopy height recorded the air temperatures on each bench, and a quantum sensor (LI-190R; LI-COR, Lincoln, NE, USA) placed at canopy height recorded the light intensity. A CR-1000 datalogger (Campbell Scientific, Logan, UT, USA) collected the environmental data every 30 s, and hourly means were recorded. Actual canopy air MDT and DLI are reported in Table 1.

The plants were assessed daily, and the date of first visible bud (VB) and first OF were recorded. At first OF, the number of nodes below the first OF and plant height were recorded (from the media surface to the plant apex). The plants that did not flower 105 d after sowing were considered nonflowering.

The experiment was replicated in time and a randomized complete block design with 10 plants of each cultivar was assigned to each treatment. Each replication was regarded as a blocking factor. Benches with different photoperiodic treatments were considered the experimental units, and the 10 pots randomly placed throughout the benches were considered subsamples. There was one factor (photoperiodic treatment) and eight levels

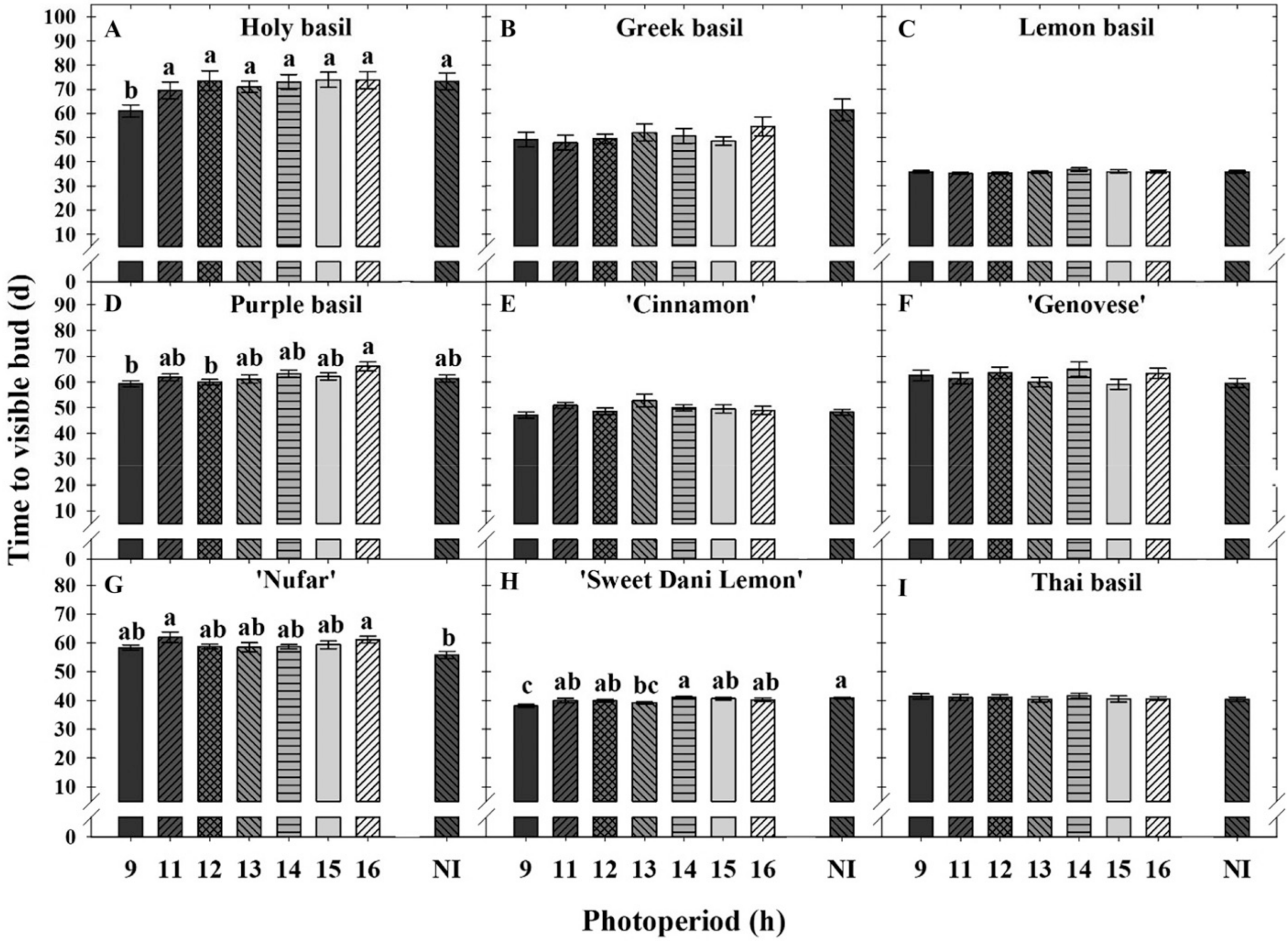


Fig. 2. Time to first visible bud of holy basil (*O. tenuiflorum*), Greek basil (*O. minimum* 'Pluto'), lemon basil (*Ocimum* ×*citriodorum* 'Lime'), purple basil (*O. basilicum* 'Red Rubin'), four cultivars of sweet basil (*O. basilicum* 'Cinnamon', 'Genovese', 'Nufar', and 'Sweet Dani Lemon'), or Thai basil (*O. basilicum* var. *thyrsiflora*) grown under a truncated 9-h photoperiod or under a 9-h photoperiod extended with red + white + far-red light-emitting diode lamps to achieve 11-, 12-, 13-, 14-, 15-, and 16-h photoperiods or a 4-h night interruption (NI; 2200 to 0200 HR) (Expt. 1). Data were pooled when there was no interaction between replication replications and treatment or if the response trends were similar between replications. Lowercase letters within each panel indicate mean separations across treatments using Tukey–Kramer difference test at $P \leq 0.05$. An absence of letters indicates no significant differences at $P \leq 0.05$. Error bars indicate standard error.

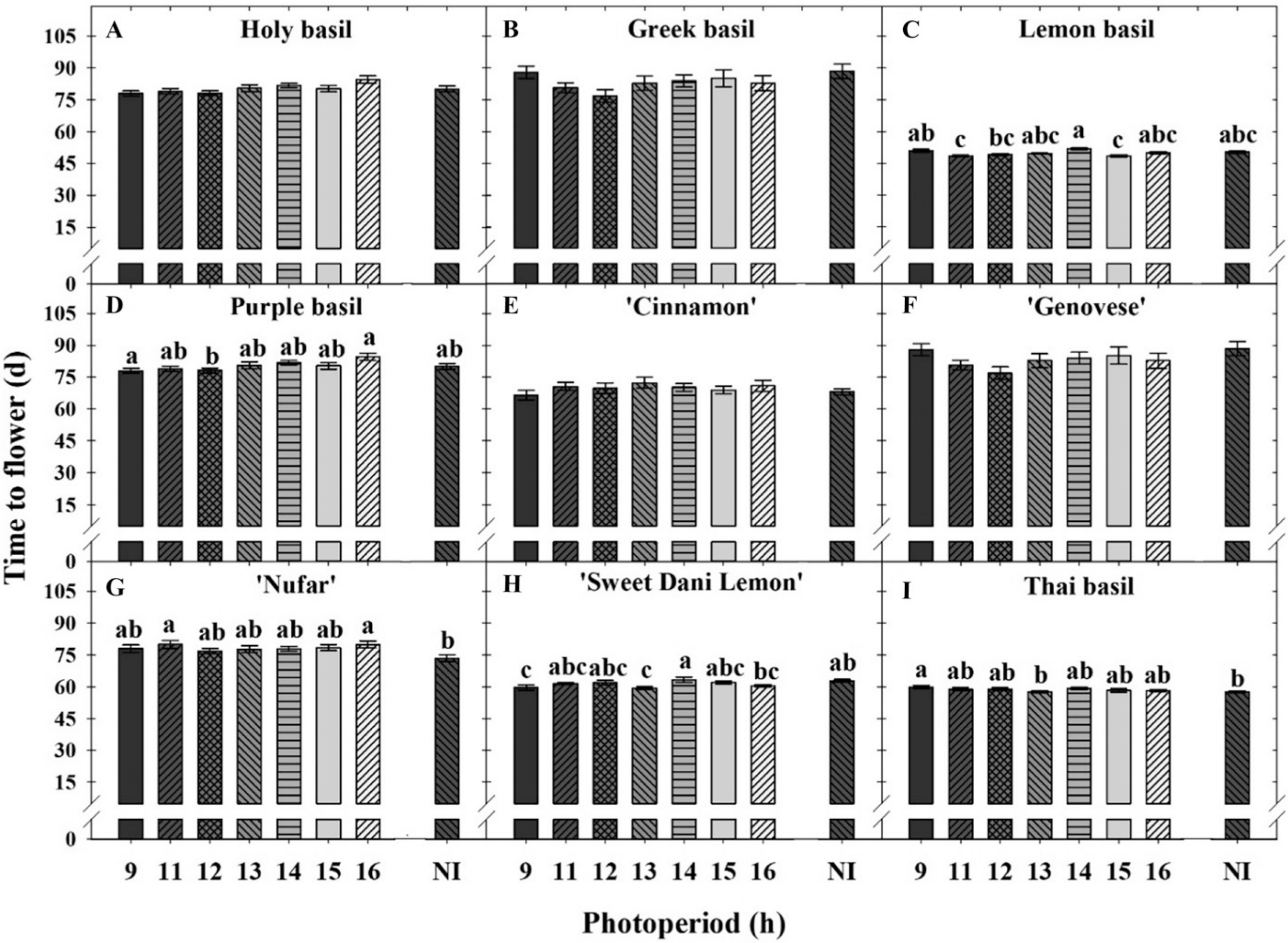


Fig. 3. Time to first open flower of holy basil (*O. tenuiflorum*), Greek basil (*O. minimum* 'Pluto'), lemon basil (*Ocimum ×citriodorum* 'Lime'), purple basil (*O. basilicum* 'Red Rubin'), four cultivars of sweet basil (*O. basilicum* 'Cinnamon', 'Genovese', 'Nufar', and 'Sweet Dani Lemon'), or Thai basil (*O. basilicum* var. *thyrsiflora*) grown under a truncated 9-h short-day (SD) or under a 9-h SD extended with red + white + far-red light-emitting diode lamps to achieve 11-, 12-, 13-, 14-, 15-, and 16-h photoperiods or a 4-h night interruption (NI; 2200 to 0200 HR) (Expt. 1). Data were pooled when there was no interaction between replications and treatment or if the response trends were similar between replications. Lowercase letters within each panel indicate mean separations across treatments using Tukey–Kramer difference test at $P \leq 0.05$. An absence of letters indicates no significant differences at $P \leq 0.05$. Error bars indicate standard error.

(9, 11, 12, 13, 14, 15, and 16 h and NI). The data were analyzed separately for each cultivar; therefore, species and cultivars were not considered another factor. The data were pooled if no interaction between replication and treatments was present or if similar response trends were observed between replications. The data were analyzed with the SAS version 9.4 (SAS Institute, Inc., Cary, NC, USA) using the PROC GLIMMIX procedure, and pairwise comparisons between treatments were performed using the Tukey–Kramer difference test ($P \leq 0.05$).

Expt. 2. Seeds of sweet 'Genovese' and 'Nufar', holy, lemon, purple, and Thai basil were sown on 10 Sep 2018 and 12 Mar 2019. Sowing, germination, thinning, and irrigation of seedlings and transplanting followed the same protocol as in Expt. 1. However, once plugs were pullable, 9 seedlings were randomly selected, and 1 seedling was transplanted into each round 15-cm-diameter (1,300-mL) container filled with the same soilless medium (Suremix; Michigan Grower Products Inc.).

The plants were grown in two separate glass-glazed greenhouse compartments. Environmental parameters such as heating, cooling, and SL were controlled by the same environmental control system previously mentioned in Expt. 1. The greenhouse air MDT was set at a constant 25 °C. Continuous SL was used in one of the greenhouse compartments for 9 h·d^{-1} (0800 to 1700 HR) consisting of six 200-W LED arrays (Philips GP-TOPlight DRW-MB) providing a supplemental PPFD (±*SD*) of ≈250.4 ± 1.7 μmol·m^{-2}·s^{-1}, resulting in a DLI of ≈23 mol·m^{-2}·d^{-1}, referred to as a high DLI (Table 2). The second greenhouse compartment did not receive any SL, and the mean DLI was ≈13 mol·m^{-2}·d^{-1}, referred to as a moderate DLI (Table 2).

There were two benches per greenhouse compartment, over which two photoperiodic lighting treatments were delivered. Treatments consisted of a truncated 9-h SD created by pulling an opaque black cloth over the plants as previously described. Day-extension lighting provided by R+W+FR LED lamps (as previously described) was used to create a 16-h (0800 to 2400 HR) photoperiod. Environmental data were measured as previously described, and actual canopy air MDT and DLI are reported in Table 2.

The data were collected as described for Expt. 1. The experiment was also a randomized complete block design in factorial arrangement with two factors: (1) photoperiod (two levels: 9- and 16-h photoperiods) and (2) light intensity (two levels: moderate or high DLI). The data were analyzed separately for each cultivar; therefore, species and cultivars were not considered another factor. There were nine individual plants per replication for each photoperiod and DLI combination, and the experiment was replicated twice over time. The data were analyzed using analyses of variance in SPSS 21.0 (IBM Corp., Armonk, NY, USA), and the cultivars and species were analyzed separately.

Results

Expt. 1. No differences in time to first VB were observed for Greek, lemon, 'Cinnamon' and 'Genovese' sweet, and Thai basil across photoperiod treatments under a low DLI (Fig. 2B, 2C, 2E, 2F, and 2I). Although there were some differences among photoperiodic treatments for purple and 'Nufar' and 'Sweet Dani Lemon' sweet basil, there were no discernable trends (Fig. 2D, 2G, and 2H). For holy basil, time to first VB occurred 9 d faster under a 9-h SD compared with plants under photoperiods ≥ 11 h or a 4-h NI (Fig. 2A).

Under a low DLI (<8 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), no differences for time to first OF were observed for holy, Greek, and 'Cinnamon' and 'Genovese' sweet basil (Fig. 3A, 3B, 3E, and 3F) under the photoperiods examined. Although there were differences, no discernable trend was evident for the effect of photoperiod on time to first OF for the remaining cultivars (Fig. 3C, 3D, and 3G–I).

There was no effect of photoperiod on the number of nodes below the first OF for Greek, lemon, and 'Genovese' and 'Sweet Dani Lemon' sweet basil under a low DLI (Fig. 4B, 4C, 4F, and 4H). For the remaining cultivars, there were differences in the node number below the first OF (Fig. 4A, 4D, 4E, 4G, and 4I), ranging from one to three nodes. For holy basil, plants grown under the 9-h SD had the lowest number of nodes compared with all other photoperiodic treatments, with the exception of plants grown under the 13-h photoperiod (Fig. 4A). Similarly, purple basil under the 9-h SD had one less node below the first OF compared with the 16-h LD (Fig. 4D).

Under a low DLI, photoperiod affected height of all other species and cultivars, excluding sweet basil 'Genovese' (Fig. 5A–I). Height at first OF was significantly shorter under the 9-h SD compared with all other photoperiodic treatments for holy basil, and 'Sweet Dani Lemon' (Fig. 5A and H). For example, under a 9-h SD, holy basil plants were 18 to 26% shorter in comparison with all other photoperiodic treatments (Fig. 5A). Furthermore, excluding the 4-h NI treatment, purple basil, sweet basil 'Nufar', and Thai basil were shortest under a 9-h SD compared with the remaining day-extension lighting treatments (Fig. 5D, 5G, and 5I).

Expt. 2. Time to VB for holy basil and sweet basil 'Nufar' was affected by the interaction of DLI and photoperiod (Fig. 6A and 6B). Time to VB for holy basil was hastened at the higher DLI within a 9- or 16-h photoperiod. However, while there was no difference in time to VB for holy basil between photoperiods under the higher DLI, time to VB was slower for plants grown under a 16-h photoperiod compared with the 9-h photoperiod under a moderate DLI (Fig. 6A). Similarly, increasing DLI hastened time to VB for sweet basil 'Nufar' within a 9- or 16-h photoperiod. Unlike holy basil under a high DLI, sweet basil 'Nufar' under a 9- and 16-h photoperiod reached visible bud at similar times, while plants grown under a moderate DLI reached VB faster when grown under a 16-h photoperiod compared with a 9-h photoperiod (Fig. 6B).

Time to VB for lemon basil, purple basil, sweet basil 'Genovese', and Thai basil

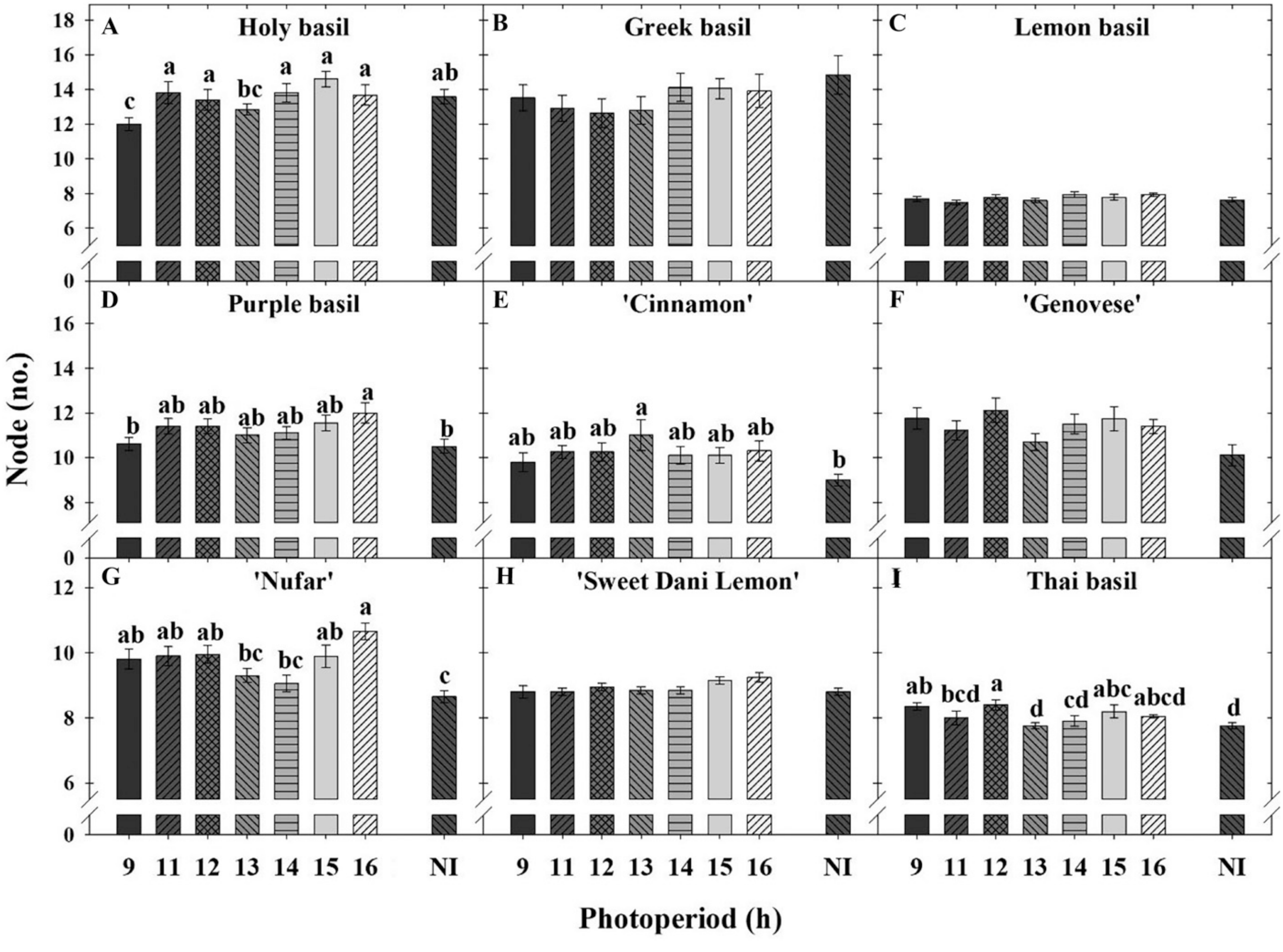


Fig. 4. Node number below the first open flower for holy basil (*O. tenuiflorum*), Greek basil (*O. minimum* 'Pluto'), lemon basil (*Ocimum ×citriodorum* 'Lime'), purple basil (*O. basilicum* 'Red Rubin'), four cultivars of sweet basil (*O. basilicum* 'Cinnamon', 'Genovese', 'Nufar', and 'Sweet Dani Lemon'), or Thai basil (*O. basilicum* var. *thrysiflora*) grown under a truncated 9-h short-day (SD) or under a 9-h SD extended with red + white + far-red light-emitting diode lamps to achieve 11-, 12-, 13-, 14-, 15-, and 16-h photoperiods or a 4-h night interruption (NI; 2200 to 0200 HR) (Expt. 1). Data were pooled when there was no interaction between replications and treatment or if the response trends were similar between replications. Lowercase letters within each panel indicate mean separations across treatments using Tukey–Kramer difference test at $P \leq 0.05$. An absence of letters indicates no significant differences at $P \leq 0.05$. Error bars indicate standard error.

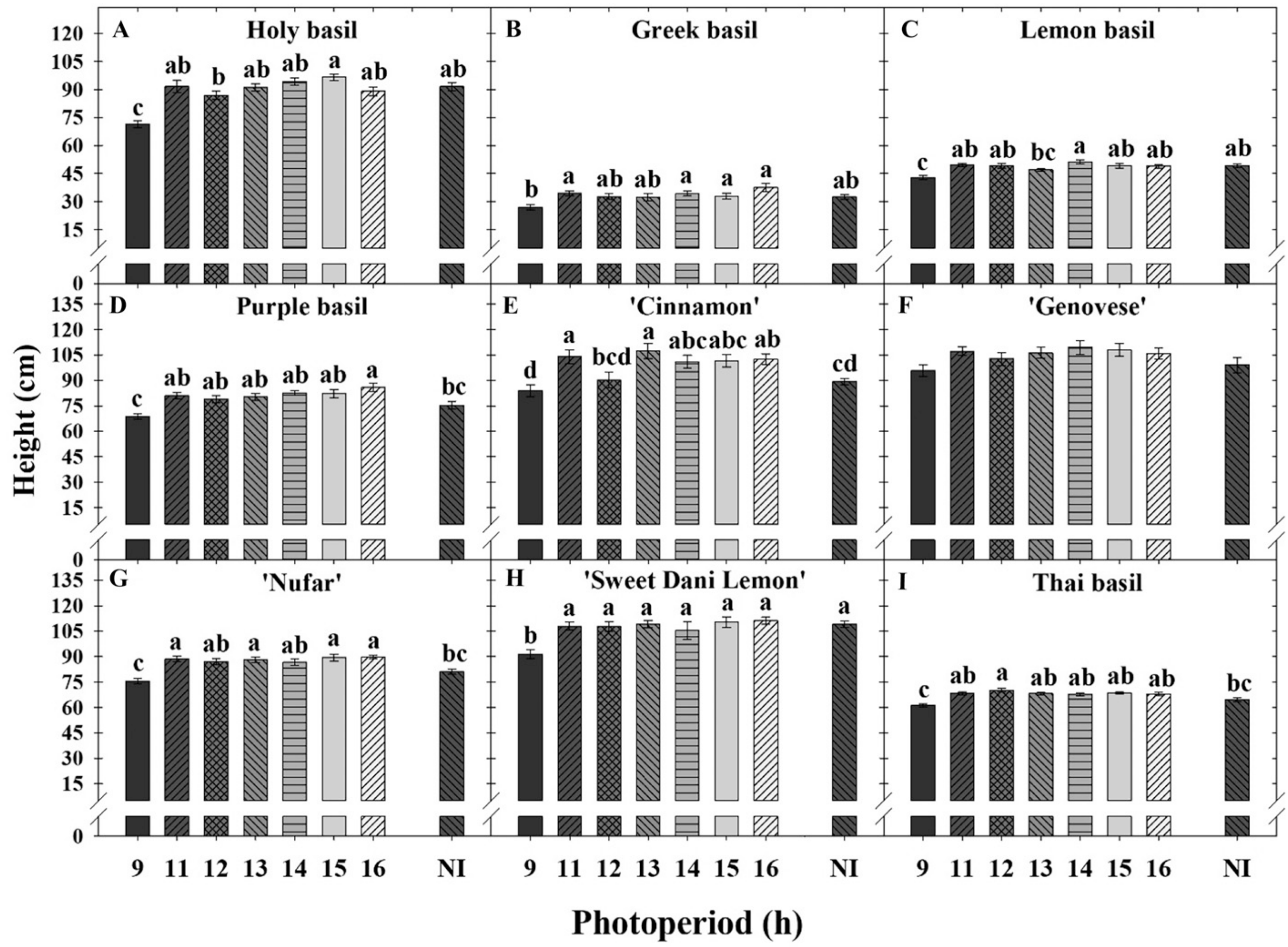


Fig. 5. Height at first open flower for holy basil (*O. tenuiflorum*), Greek basil (*O. minimum* ‘Pluto’), lemon basil (*Ocimum* ×*citriodorum* ‘Lime’), purple basil (*O. basilicum* ‘Red Rubin’), four cultivars of sweet basil (*O. basilicum* ‘Cinnamon’, ‘Genovese’, ‘Nufar’, and ‘Sweet Dani Lemon’), or Thai basil (*O. basilicum* var. *thrysiflora*) grown under a truncated 9-h short-day (SD) or under a 9-h SD extended with red + white + far-red light-emitting diode lamps to achieve 11-, 12-, 13-, 14-, 15-, and 16-h photoperiods or a 4-h night interruption (NI; 2200 to 0200 HR) (Expt. 1). Data were pooled when there was no interaction between replications and treatment or if the response trends were similar between replications. Lowercase letters within each panel indicate mean separations across treatments using Tukey–Kramer difference test at $P \leq 0.05$. An absence of letters indicates no significant differences at $P \leq 0.05$. Error bars indicate standard error.

decreased with increasing DLI (Tables 3 and 4), from 4.0 (lemon basil) to 11 (purple basil) d earlier under a high DLI compared with plants grown under a moderate DLI. Additionally, time to VB for purple basil, sweet basil ‘Genovese’, and Thai basil was 3 (purple basil) to 6 (sweet basil ‘Genovese’) d less for plants grown under a 16-h photoperiod than a 9-h photoperiod. Photoperiod had no effect on time to VB for lemon basil.

The DLI interacted with photoperiod to affect lemon basil time to OF (Table 3 and Fig. 7). Under a 9-h photoperiod, DLI did not affect time to OF, while under a 16-h photoperiod, a higher DLI hastened flowering (Fig. 7). Within a moderate DLI, plants under 9- and 16-h photoperiods flowered at similar times, whereas the longer day hastened time to OF under a high DLI (Fig. 7). Increasing the DLI reduced the time to OF for holy basil, purple basil, and Thai basil, with plants flowering 6 (Thai basil) to 21 d (holy basil) earlier as DLI increased from moderate to high (Table 4). The DLI did not affect time to OF for either sweet basil cultivars. Purple basil, sweet basil ‘Nufar’, and Thai basil flowered 6, 7, and 6 d earlier, respectively, when grown under 16-h photoperiod compared with a 9-h photoperiod. Photoperiod did not affect time to OF for holy basil or sweet basil ‘Genovese’ (Tables 3 and 4).

Node number beneath the first OF for purple basil was affected by the interaction of DLI and photoperiod (Table 3 and Fig. 8). Within a 9- or 16-h photoperiod, there were fewer nodes beneath the first OF as DLI increased from moderate to high. While purple basil node number beneath the first OF also decreased as the photoperiod increased from 9 to 16 h under a moderate DLI, there was no effect of photoperiod on node number under a high DLI (Fig. 8). Increasing DLI resulted in fewer nodes beneath the first OF for holy basil, lemon basil, sweet basil ‘Genovese’ and ‘Nufar’, and Thai basil by 1 (lemon basil) to 4 (holy basil) (Tables 3 and 4). While increasing the photoperiod from 9 to 16 h resulted in 0.5 fewer nodes for ‘Thai basil, photoperiod had no effect on node number for both sweet basil cultivars, holy basil, and lemon basil (Tables 3 and 5).

Under a high DLI, holy basil, purple basil, sweet basil ‘Genovese’, and Thai basil plants were 4.2 (Thai basil) to 24.1 (holy basil) cm shorter compared with a moderate DLI (Tables 3 and 4). The DLI had no effect on lemon basil or sweet basil ‘Nufar’ height (Tables 3 and 4). Additionally, increasing the photoperiod from 9 to 16 h resulted in purple basil plants being 4.1 cm taller but had no effect on holy basil, lemon basil, either sweet basil (‘Genovese’ and ‘Nufar’), or Thai basil height (Tables 3 and 4).

Discussion

An understanding of the environmental parameters influencing flowering is beneficial for growers who seek to induce flowering

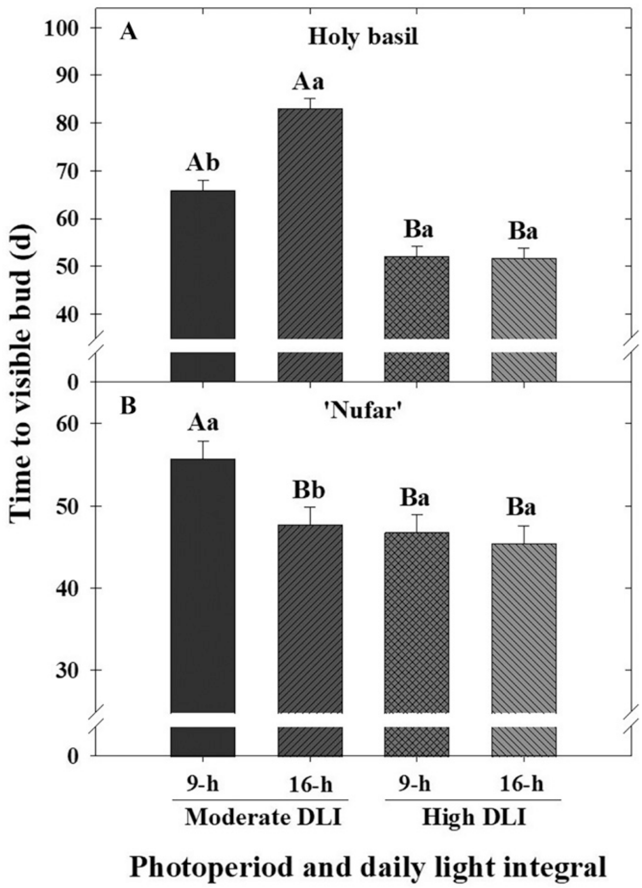


Fig. 6. Time to first visible bud for holy basil (*O. tenuiflorum*) and sweet basil (*O. basilicum*) ‘Nufar’ grown under moderate (≈13 $mol \cdot m^{-2} \cdot d^{-1}$) or high (≈23 $mol \cdot m^{-2} \cdot d^{-1}$) photosynthetic daily light integrals (DLIs) and a truncated 9-h photoperiod or day-extension lighting from low-intensity light-emitting diode lamps emitting red + white + far-red radiation for 7 h (1700 to 2400 HR) to achieve a 16-h photoperiod (Expt. 2). Uppercase letters indicate mean separations across DLI and photoperiod treatments, and lowercase letters indicate mean separations within DLI treatments using Tukey–Kramer difference test at $P \leq 0.05$. Error bars indicate standard error.

Table 3. Analyses of variance for time to visible bud (VB) and open flower (OF), nodes beneath the first OF, and height at OF for basil plants grown under a moderate or high daily light integral (DLI) with a 9- or 16-h photoperiod (P).

Parameter	DLI	P	DLI × P
Holy basil			
Time to VB	*[i]	NS	*
Time to OF	*	NS	NS
Nodes	*	NS	NS
Height	***	NS	NS
Lemon basil			
Time to VB	*	NS	NS
Time to OF	***	*	***
Nodes	*	NS	NS
Height	NS	NS	NS
Purple basil			
Time to VB	***	*	NS
Time to OF	***	**	NS
Nodes	**	NS	*
Height	*	*	NS
Sweet basil ‘Genovese’			
Time to VB	*	*	NS
Time to OF	NS	NS	NS
Nodes	*	NS	NS
Height	*	NS	NS
Sweet basil ‘Nufar’			
Time to VB	**	**	*
Time to OF	NS	*	NS
Nodes	*	NS	NS
Height	NS	NS	NS
Thai basil			
Time to VB	**	*	NS
Time to OF	***	***	NS
Nodes	***	*	NS
Height	*	NS	NS

[i] NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

when basil is used as an ornamental or for essential oil production. However, for culinary purposes, inhibition of flowering to maximize foliage production is desirable by fresh-cut or potted plant basil producers. Based on the results for time to first OF from Expt. 1, under a low DLI (<8 $mol \cdot m^{-2} \cdot d^{-1}$), all basil cultivars exhibited DNP responses (Fig. 3A–I). Generally, there were no significant differences in time to first OF, and when there were significant differences, no discernable trends were observed.

Results from Expt. 1 for sweet basil ‘Genovese’ and lemon basil agree with Erwin et al. (2017), who also described them as DNP; however, information regarding specific photoperiodic treatments were not provided. In contrast to our results, Skrubis and Markakis (1976) reported *O. basilicum* var. *citriodora* displayed a LD response, since flower development and subsequent anthesis occurred more rapidly under an 18-h photoperiod compared with 9-, 12-, and 15-h photoperiods, using cool-white fluorescent (CWF) lamps. However, plants in their study were grown under ambient sunlight for 9 h (0800 to 1700 HR) and then moved into a growth chamber where the CWF lamps provided day-extension (DE) lighting. The ambient DLI was not provided, and DE lighting did not increase the final DLI by more than ≈0.6 $mol \cdot m^{-2} \cdot d^{-1}$ for those treatments.

In addition to photoperiod, DLI also influences flowering (Mattson and Erwin 2005; Owen et al. 2018; Zhang et al. 1996). For instance, Zhang et al. (1996) reported time to flower of the facultative LDP yarrow (*Achillea millefolum* ‘Summer Pastels’) decreased from 57 to 37 d as DLI increased from 5.8 to 17.3 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, under a 16-h photoperiod. Similarly, increasing DLI from 5 to 20 $mol \cdot m^{-2} \cdot d^{-1}$ hastened flowering of the LDP petunia (*Petunia ×hybrida*) (Faust et al. 2005). In Expt. 2, time to first OF of lemon basil under a moderate DLI occurred similarly under a 9-h SD and a 16-h LD (Fig. 7). Under a high DLI, the time to first OF occurred 9 d faster under a 16-h LD compared with a 9-h SD. Therefore, under high DLIs, lemon basil exhibited a facultative LDP response (Fig. 7A). However, under moderate and high DLIs, purple basil, sweet basil ‘Nufar’, and Thai basil flowered faster under a 16-h photoperiod and can also be classified as facultative LDPs (Tables 3 and 4).

Increasing DLIs accelerates growth and development of numerous crops due to increased photosynthesis (Nemali and van Iersel 2004). Hastening of time to VB and OF in our study of basil under increased DLIs can be attributed to an increase in photosynthesis resulting from the additional irradiance that increased metabolic activity, thus accelerating plant growth and development and possibly reducing the juvenile phase (Adams et al. 1999). A FI response could further explain and validate this hypothesis. Warner (2010) described faster flowering and fewer nodes in petunia ‘Mitchell’, large white petunia (*Petunia axillaris*), Brazilian red petunia (*Petunia exserta*), and violetflower petunia (*Petunia integrifolia*) grown under 16-h LDs with a DLI of 16.5 $mol \cdot m^{-2} \cdot d^{-1}$ compared with 9-h SDs at 11.4 $mol \cdot m^{-2} \cdot d^{-1}$. For instance, node number below the first flower for large white petunia and Brazilian red petunia decreased by 18 and 13, respectively, while time to flower decreased by 25 and 11 d, respectively, as irradiance and day length increased. Therefore, sweet basil (‘Genovese’ and ‘Nufar’), holy basil, purple basil, and Thai basil exhibited an FI response, as time to first OF was hastened, and node number below the first OF was reduced, when the DLI was increased from a moderate to a high DLI (Table 4; Figs. 7 and 8).

Basil growth is promoted by increasing photosynthetic light (Beaman et al. 2009;

Table 4. Effect of a moderate (13 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) or high (23 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) daily light integral (DLI) on time to visible bud (VB) and open flower (OF), nodes beneath the first OF, and plant height at OF for different basil cultivars.

	DLI	
Parameter	Moderate	High
Holy basil		
Time to OF (d)	91.6	70.4
Nodes (no.)	14.9	10.6
Height (cm)	89.7	65.6
Lemon basil		
Time to VB (d)	35.1	31.8
Nodes (no.)	7.9	7.3
Purple basil		
Time to VB (d)	57.9	46.8
Time to OF (d)	73.2	65.0
Height (cm)	65.6	60.0
Sweet basil 'Genovese'		
Time to VB (d)	53.3	45.6
Nodes (no.)	10.8	8.7
Height (cm)	85.1	77.5
Sweet basil 'Nufar'		
Nodes (no.)	10.4	8.6
Thai basil		
Time to VB (d)	39.9	32.9
Time to OF (d)	54.9	49.0
Nodes (no.)	8.0	6.7
Height (cm)	53.7	49.5

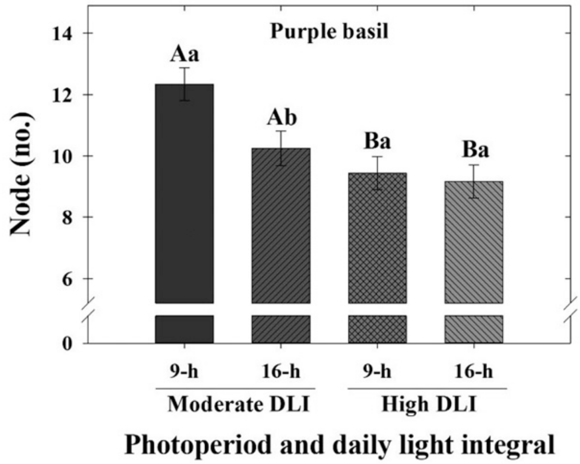


Fig. 8. Node number below the first open flower for purple basil (*O. basilicum* 'Red Rubin') grown under moderate (≈13 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) or high (≈23 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) photosynthetic daily light integrals (DLIs) and a truncated 9-h short-day or day-extension lighting from low-intensity light-emitting diode lamps emitting red + white + far-red radiation for 7 h (1700 to 2400 HR) to achieve a 16-h photoperiod (Expt. 2). Uppercase letters indicate mean separations across DLI and photoperiod treatments, and lowercase letters indicate mean separations within DLI treatments using Tukey–Kramer difference test at $P \leq 0.05$. Error bars indicate standard error.

Currey et al. 2017). The FI response of several basil cultivars in this study, when combined with the growth-enhancing effects of photosynthetic light, poses opportunities for some basil producers and challenges for others. For cut flower and/or essential oil producers, increasing DLI to promote growth and flowering is a positive development. Increasing the DLI to enhance basil growth may reduce crop time for cut flower producers. For essential oil producers, not only does enhancing DLI induce flowering and intensify flavor and aroma compounds from flower induction, the increased DLI will also increase biomass and, therefore, total yield of compounds of interest. Alternatively, fresh-cut and containerized herb growers who seek to maximize vegetative growth and minimize or inhibit flowering may need to seek alternative strategies to increase yield under increased light. For instance, under a high DLI, basil could be harvested earlier before flowering occurs, and the planting density could be increased to compensate for the earlier harvest.

From Expt. 1, the increase in plant height at flowering generally observed under DE lighting can be attributed to increased FR radiation from the R+W+FR LED lamps. Using FR radiation promotes stem elongation and suppresses lateral branching (Moe and Heins 1990) of crops such as watercress (Bleasdale 1964), pansy (*Viola* × *wittrockiana* 'Matrix Yellow'), and petunia 'Dreams Midnight' (Owen et al. 2018) when grown under incandescent lamps or R+W+FR LEDs. Similarly, in our study, all species and cultivars excluding sweet basil 'Genovese' were significantly taller when grown under a 16-h LD compared with a 9-h SD (Fig. 5A–I). Therefore, the increase in height was likely evoked by the shade avoidance response, mediated by the R and FR absorbing photoreceptor phytochrome. Plants in a greenhouse are generally exposed to nearly equal amounts of Y, G, R, and FR radiation from the sun. However, the R+W+FR LED lamps employed during our study had a low R:FR (R:FR ratio = 0.8), which created a FR-rich environment, resulting in taller plants.

Generally, photoperiod did not significantly affect plant height at first OF during Expt. 2 (Tables 3 and 4). However, under a higher DLI, the height of holy basil, purple basil, and sweet basil 'Genovese' was suppressed, regardless of photoperiod (Tables 3 and 4). Similar to our findings for these two

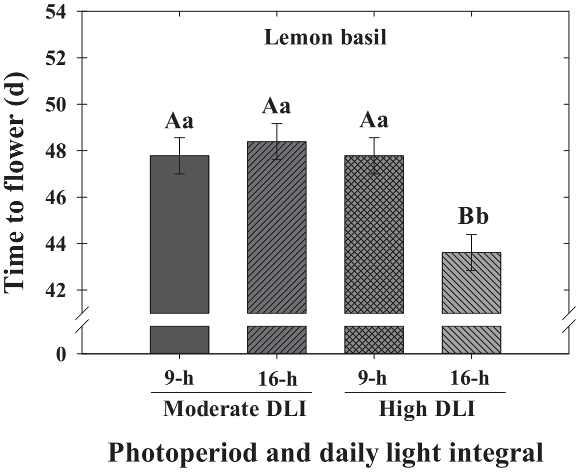


Fig. 7. Time to first open flower for lemon basil (*Ocimum* ×*citriodorum* 'Lime') grown under moderate (≈13 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) or high (≈23 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) photosynthetic daily light integrals (DLIs) and under a truncated 9-h short-day (SD) or day-extension lighting from low-intensity light-emitting diode lamps emitting red + white + far-red radiation for 7 h (1700 to 2400 HR) to achieve a 16-h photoperiod (Expt. 2). Uppercase letters indicate mean separations across DLI and photoperiod treatments, and lowercase letters indicate mean separations within DLI treatments using Tukey–Kramer difference test at $P \leq 0.05$. Error bars indicate standard error.

Table 5. Effect of a 9- or 16-h photoperiod on time to visible bud (VB) and open flower (OF), nodes beneath the first OF, and plant height at OF for different basil cultivars.

	Photoperiod	
Parameter	9 h	16 h
Purple basil		
Time to VB (d)	53.7	51.0
Time to OF (d)	71.9	66.4
Height (cm)	60.7	64.8
Sweet basil 'Genovese'		
Time to VB (d)	51.7	45.6
Sweet basil 'Nufar'		
Time to OF (d)	68.0	60.8
Thai basil		
Time to VB (d)	37.9	34.9
Time to OF (d)	54.9	49.0
Nodes (no.)	7.5	7.1

cultivars, Hurt et al. (2019) reported a decrease in stem length under SL in comparison with photoperiodic lighting and ambient light for impatiens (*Impatiens walleriana* 'Accent Premium Salmon') and petunia 'Ramblin Peach Glo' plants. A more compact plant resulting from an increase in DLI can be of great benefit to growers who struggle with canopy management, as chemical plant growth regulators are not labeled for use on culinary herbs.

Under a low DLI ($\leq$8 mol·m^{-2}·d^{-1}), we have classified sweet basil (*O. basilicum* 'Genovese', 'Cinnamon', 'Sweet Dani Lemon', and 'Nufar'), lemon basil, holy basil, purple, Thai, and Greek basil as DNPs since photoperiod either did not significantly affect time to first OF or no discernable trend was evident. Alternatively, under moderate to high DLIs ($\geq$13 mol·m^{-2}·d^{-1}), 'Genovese', 'Nufar', purple, and Thai basil exhibited facultative LDP responses. Furthermore, under a 9-h SD all cultivars excluding lemon basil exhibited an FI response, where higher DLIs induced faster flowering while reducing the number of nodes below the first OF. Our results indicate that photoperiod alone is not a feasible option for reproductive management of the basil cultivars evaluated. However, DLI generally had a greater impact on time to first VB and OF, node number, and height. Additionally, we have demonstrated that basil should not be grown under DLIs $\leq$ 13 mol·m^{-2}·d^{-1} to avoid excessive stem elongation, especially if growing under a FR-rich environment. Thus, DLI could be a more effective strategy for managing plant development of basil grown in controlled environments.

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