Photosynthetic Daily Light Integral Influences Flowering Time and Crop Characteristics of *Cyclamen persicum*

Wook Oh¹, In Hye Cheon², and Ki Sun Kim³

Department of Plant Science, and Research Institute for Agriculture and Life Sciences, Seoul National University, San 56-1, Seoul 151-921, Korea

Erik S. Runkle

Department of Horticulture, Michigan State University, East Lansing, MI 48824

Additional index words. dry weight, light intensity, photoperiod, photosynthesis, photosynthetic photon flux, rate of development

Abstract. This study was carried out to examine the effect of photosynthetic daily light integral (DLI) on the growth and flowering of cyclamen (*Cyclamen persicum* Mill. 'Metis Scarlet Red'). Plants with six fully unfolded leaves were grown at 24/16 °C (12 h/12 h) under an 8- or 16-h photoperiod at a photosynthetic photon flux of 50, 100, 150, 200, and 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, which provided seven DLIs: 1.4, 2.9, 4.3, 5.8, 8.6, 11.5, and 17.3 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Days to first flower decreased from 133 to 75 as DLI increased from 1.4 to 17.3 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, although the acceleration of flowering was less pronounced when the DLI was greater than 5.8 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Mean leaf and flower number increased from 8.7 to 28.0 and from 0 to 14.7, respectively, as DLI increased from 1.4 to 11.5 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, but there was no further increase under a DLI of 17.3 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Total dry weight and net photosynthetic rate showed a similar trend as leaf and flower number. We conclude that supplemental lighting can accelerate greenhouse production of potted cyclamen under a low ambient DLI (i.e., less than 12 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$).

Cyclamen (*Cyclamen persicum* L.) is commercially produced from fall until early spring in greenhouses for sales as common winter and spring flowering potted plants (Dole and Wilkins, 2005). In regions at high latitudes (e.g., greater than 35 °N, which includes Korea, the northern half of the United States, and Europe), the mean photosynthetic daily light integral (DLI) can be a limiting factor in the production of many greenhouse crops during the winter and early spring (Faust, 2003). The DLI delivered to greenhouse crops is typically reduced by 40% or more by greenhouse glazing and structure (Hanan, 1998). Therefore, some greenhouse crops are commercially grown under a mean DLI of less than 5 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (in December and January) to greater than 25

$\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (in April and May) (Korczynski et al., 2002). A common target minimum mean DLI for many greenhouse crops is 10 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ at plant canopy level (Faust, 2003).

Increasing DLI increases biomass accumulation, hastens development, and improves final plant quality in many floriculture crops. For example, increasing DLI decreased time to flower of eight species of bedding plants (Faust et al., 2005), in vinca [*Catharanthus roseus* (L.) G. Don.; Pietsch et al., 1995], and in petunia (*Petunia xhybrida* hort. Vilm.-Andr.; Kaczperski et al., 1991). Days to flower of petunia decreased from 67 to 56 d as DLI increased from 6.5 to 13.0 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ at 20 °C (Kaczperski et al., 1991). A higher DLI increased flower number and size in vinca (Pietsch et al., 1995) and petunia (Kaczperski et al., 1991). In impatiens (*Impatiens wallerana* L.), plants grown under a DLI of 12 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ had 2.9 more and 0.5 cm larger flowers compared with plants under 5 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Faust et al., 2005). Pansy (*Viola xwittrockiana* Gams.) had a shorter stem and flower peduncle under a high DLI than a lower one (Niu et al., 2000).

High DLI can increase growth rate by promoting photosynthesis (Nemali and van Iersel, 2004). Increasing DLI increased dry matter and flower and floral bud number in rose yarrow (*Achillea x millefolium* L.), gaura (*Gaura lindheimeri* Engelm. & Gray), lisianthus [*Eustoma grandiflorum* (Raf.) Shinn], red salvia (*Salvia splendens* Sell ex Roem. & Schult.), and French marigold (*Tagetes*

patula L.) (Fausey et al., 2005; Islam et al., 2005; Moccaldi and Runkle, 2007). Total dry weight of eight annuals increased, but generally at a decreasing rate, as DLI increased from 5 to 43 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Faust et al., 2005). These results suggest that plant developmental rate increases as DLI increases until some threshold beyond which a further increase has little or no effect on developmental rate.

Cyclamen has been classified as a day-neutral plant (Thomas and Vince-Prue, 1997), although some studies indicate that photoperiod, light quality, and light intensity can modify the flowering and subsequent growth of this plant (Erwin et al., 2004; Heo et al., 2003; Neuray, 1973; Widmer and Lyons, 1985). In particular, long days and a high irradiance promoted cyclamen growth and flowering (Cheon et al., 2006; Oh et al., 2008; Rhie et al., 2006). Supplemental lighting from high-pressure sodium lamps at 30 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 20 h per day shortened cultivation time and improved the quality of potted cyclamen (Verberkt et al., 2004).

Previous studies (Cheon et al., 2006; Rhie et al., 2006) showed that an increase in DLI, either by increasing the instantaneous photosynthetic photon flux (PPF) with the same photoperiod, or by extending the photoperiod at the same PPF, promoted growth and flowering of cyclamen. Subsequently, we found in preliminary research that flowering of cyclamen was accelerated by an increase in DLI within a narrow range (Oh et al., 2008). The objective of this study was to investigate the effect of DLI on growth and flowering of cyclamen to assist commercial growers manage light during cyclamen production.

Materials and Methods

Plugs of 12-week-old 'Metis Scarlet Red' cyclamen seedlings with five expanded leaves were received from a commercial propagator (Korea-America Plug Co., Ltd., Jincheon, Korea). Seedlings were transplanted into 7-cm round plastic pots filled with a commercial potting mixture (Sunshine Mix #2; Sun-Gro Horticulture, Bellevue, WA) and moved to plant growth modules [80 × 60 × 40 cm (L × W × H)] for 4 weeks. During this period, plants were grown at 24/16 °C (12 h/12 h) under a 12-h photoperiod with a PPF of 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ provided by cool-white fluorescent lamps (FL20EX-D; Wooree Lighting Co., Ltd., Seoul, Korea). Plants were then grown under an 8-h short day (SD, 1000–1800 HR) or a 16-h long day (LD, 0600–2200 HR) at a PPF of 50, 100, 150, 200, and 300 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for a total of 10 treatments. The resultant DLIs were 1.4, 2.9, 4.3, 5.8, 8.6, 11.5, and 17.3 $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, which were provided by the same type of cool-white fluorescent lamps. The module air temperatures were maintained at 24 °C from 0800 to 2000 HR and 16 °C during the remaining period. Air temperatures were measured using thermocouples connected to data loggers (WatchDog 200; Spectrum

Received for publication 28 Oct. 2008. Accepted for publication 18 Dec. 2008.

This study was supported by the Technology Development Program for Agriculture and Forestry, Ministry of Agriculture and Forestry, Republic of Korea.

We also thank the National Instrumentation Center for Environmental Management, Seoul National University, Korea, for the use of their photosynthesis systems.

¹Former graduate student. Currently Assistant Professor, Department of Horticulture, Yeungnam University, Gyeongsan, Korea.

²Former graduate student. Currently Researcher, Hankook Institute of Life Science, Seoul, Korea.

³To whom reprint requests should be addressed; e-mail kisun@snu.ac.kr.

Technologies, Inc., Plainfield, IL) and were consistently within 2 °C of set points. The PPF in each chamber was measured twice a week using an LI-250A light meter with an LI-210SA photometric sensor (LI-COR Inc., Lincoln, NE) and lamps were adjusted to maintain a constant irradiance. Plants were repositioned randomly in the modules every other week during the experiment.

Cyclamen plants were watered every day for 15 min using an ebb-and-flow automatic irrigation system with Sonneveld solution (Sonneveld and Starver, 1992) that contained macronutrients (mmol·L⁻¹) 11.7N–1.5P–5.5K–3.0Ca–0.8Mg–2.0S and micronutrients (μmol·L⁻¹) 20Fe–20B–10Mn–3Zn–0.5Mo–0.5Cu. The solution pH was maintained at 5.5 to 6.0 during the treatment period and the electrical conductivity (EC) was maintained at 1.2, 1.6, and 1.4 dS·m⁻¹ before flower bud initiation, from bud initiation to flowering, and after flowering, respectively. EC and pH were measured twice a week using an EC meter (CM-53; Takemura Electric Co., Tokyo, Japan) and a pH meter (HM-20P; TOA-DKK, Tokyo, Japan).

Days to first flower was calculated as the number of days from the start of treatment to when the first flower of each plant opened (petals were reflexed backward). At 16 weeks after treatment, the number of leaves (1 cm long or longer) and flowers (with fully reflexed petals) were counted from 20 plants per treatment. At this time, 10 plants per treatment were randomly collected, media was carefully rinsed off, and dry weight was measured after drying at 70 ± 2 °C for 3 d. The remaining plants were grown until first flowering.

Gas exchange in situ was measured with three recently fully expanded leaves on three plants randomly selected in each treatment from 1100 to 1500 HR at 10 weeks after treatment. Net CO₂ assimilation rate was measured using a portable photosynthesis system (Li-6400; LI-COR Inc.) equipped with an infrared gas analyzer. The leaf area enclosed by the chamber was 6 cm². The leaf chamber was maintained at 20 °C and a relative humidity of 40% during the measurements. Net CO₂ assimilation rate was determined at each leaf for 30 min. The concentration of applied CO₂ was maintained at 360 μmol·mol⁻¹.

Collected data were analyzed by analysis of variance and general linear models procedures using the SAS program (SAS Institute Inc., Cary, NC). Regression analysis and graph modules were analyzed using Sigma Plot software (SPSS, Inc., Chicago, IL).

Results

An increase in DLI promoted flowering of 'Metis Scarlet Red' cyclamen. Days to first flower decreased from 133 to 75 as DLI increased from 1.4 to 17.3 mol·m⁻²·d⁻¹ (Fig. 1). However, the effect of an increase in DLI was most notable when DLI increased from 1.4 to 5.8 mol·m⁻²·d⁻¹; a further increase had only a small effect on flowering time. Three

of the DLIs (2.9, 5.8, and 8.7 mol·m⁻²·d⁻¹) were delivered by both SD and LD. The only effect of photoperiod on flowering time occurred under the DLI of 2.9 mol·m⁻²·d⁻¹, when flowering was earlier under the 16-h LD (with a PPF of 50 μmol·m⁻²·s⁻¹) compared with the 8-h SD (with a PPF of 100 μmol·m⁻²·s⁻¹).

The number of leaves after 16 weeks of growth increased significantly as DLI increased within the range studied (Fig. 2A). Plants also developed more flowers as the DLI under which they were grown increased (Fig. 2B). Leaf and flower number were correlated with an R² of 0.92 (*P* = 0.0011; data not shown). However, flower number of plants under DLIs of 11.5 and 17.3 mol·m⁻²·d⁻¹ were similar. Plants had increased growth (dry matter accumulation) as DLI increased from 1.4 until ≈11 or 12 mol·m⁻²·d⁻¹ (Fig. 3). There was no statistical difference in dry weight of plants grown under a DLI of 11.5 and 17.3 mol·m⁻²·d⁻¹. Similarly, the photosynthetic rates in situ of 'Metis Scarlet Red' cyclamen increased with an increase in DLI (Fig. 4). There was little difference in instantaneous photosynthetic rate of plants grown under LD and SD at the same PPF.

Discussion

Flowering of 'Metis Scarlet Red' cyclamen was increasingly delayed as DLI decreased, especially when less than 5.8 mol·m⁻²·d⁻¹. Increasing DLI decreased time to flowering in many other floriculture crops, including ageratum (*Ageratum houstonianum* L.), celosia (*Celosia argentea* var. *plumose* L.), impatiens, geranium (*Pelargonium xhortorum* L.H. Bail.), French marigold, pansy, petunia, red salvia, snapdragon (*Antirrhinum majalis* L.), stock (*Matthiola incana* L.), vinca, and zinnia (*Zinnia elegans* L.) (Adams et al., 1998; Armitage et al., 1981; Dansereau et al., 1998; Erickson et al., 1980; Faust et al., 2005; Graper and Healy, 1991; Kaczperski et al., 1991; Moccaldi and Runkle, 2007; Niu et al., 2000; Pietsch et al., 1995; Pramuk and Runkle, 2005a, 2005b). Days to flowering in all of these plants, except for impatiens, decreased as DLI increased to more than 15 or 20 mol·m⁻²·d⁻¹. Similarly, increasing DLI to more than 10 mol·m⁻²·d⁻¹ did not promote the flowering of begonia (*Begonia xsemperflorens-cultorum* L.) and impatiens (Faust et al., 2005), similar to our results with cyclamen.

Loehrlein and Craig (2004) classified eight cultivars of Regal geranium (*Pelargonium xdomesticum* L.H. Bail.) into the following three categories according to floral initiation response to DLI: irradiance-responsive (IR), time-responsive (TR), and nonresponsive (NR) plants. The number of days to flowering of IR plants decreases with increasing DLI; TR plants initiate flowering in response to time and temperature rather than DLI or cumulative irradiance. Vogezang and Verberkt (1990) reported that supplemental lighting for 16 h at ≈30 μmol·m⁻²·s⁻¹ reduced

Fig. 1. The effect of photosynthetic daily light integral on time to first flower of cyclamen 'Metis Scarlet Red'. Plants were grown under an 8-h short day (SD) or 16-h long day (LD). Days to first flower was counted from the beginning of treatments to appearance of the first fully-reflexed flower for each plant. Error bars indicate SE.

cultivation time of cyclamen by 6 weeks when grown at a 16-h day/8-h night temperature of 14 to 16/12 to 14 °C. Therefore, at least this cultivar of cyclamen can be categorized as an IR plant from our results and that of Vogezang and Verberkt (1990).

Increasing DLI improved plant quality of 'Metis Scarlet Red' cyclamen by increasing the leaf number, flower number, and dry weight. Similarly, the total number of flowers and flower buds increased with increasing DLI in miniature rose (*Rosa* L.) (Mortensen and Moe, 1995), rose yarrow and gaura (Fausey et al., 2005), primula (*Primula vulgaris* Huds.; Karlsson, 2002), celosia and impatiens (Pramuk and Runkle, 2005a), salvia and marigold (Moccaldi and Runkle, 2007), geranium (White and Warrington, 1984), lisianthus (Islam et al., 2005), and vinca (Pietsch et al., 1995).

As DLI increased from 1.4 to 17.3 mol·m⁻²·d⁻¹, total dry weight of cyclamen increased. An increase in dry matter production with increasing DLI has been reported by Pramuk and Runkle (2005b) and Faust et al. (2005) in several floriculture crops. Similarly, dry weight of wax begonia increased linearly as DLI increased from 5.3 to 19.4 mol·m⁻²·d⁻¹ (Nemali and van Iersel, 2004). Similar responses have also been reported in petunia (Lieth et al., 1991), other studies with wax begonia (Graper and Healy, 1990; Kessler et al., 1990), lisianthus (Islam et al., 2005), geranium (White and Warrington, 1984), and rose yarrow (Fausey et al., 2005).

We also quantified how increasing DLI promoted cyclamen growth by increasing photosynthesis. As DLI increased from 1.4 to 17.3 mol·m⁻²·d⁻¹, photosynthetic rate in situ increased but at a decreasing rate. Nemali and van Iersel (2004) reported that high DLI increased whole plant photosynthesis and carbon use efficiency in wax begonia. Our regression analysis indicates that net photosynthetic rate of cyclamen was highest when grown under DLI of ≈17 mol·m⁻²·d⁻¹.

Moe (1994) divided the response of herbaceous ornamental species to DLI into

Fig. 2. The effect of photosynthetic daily light integral on the number of leaves (A) and flowers (B) in cyclamen 'Metis Scarlet Red' after 16 weeks in treatments. Plants were grown under an 8-h short day (SD) or 16-h long day (LD). Error bars indicate SE.

Fig. 3. The effect of photosynthetic daily light integral on plant dry weight in cyclamen 'Metis Scarlet Red' after 16 weeks in treatments. Plants were grown under an 8-h short day (SD) or 16-h long day (LD). Error bars indicate SE.

Fig. 4. The effect of photosynthetic daily light integral on in situ net CO_2 assimilation rate of cyclamen 'Metis Scarlet Red' after 10 weeks of treatments. Plants were grown under an 8-h short day (SD) or 16-h long day (LD). Error bars indicate SE.

four categories: low-light crops (5 to $10 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), medium-light crops (10 to $20 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), high-light crops (20 to $30 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), and very high-light crops (greater than $30 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). Faust et al. (2005) proposed three alternative DLI cate-

gories based on commercial acceptability and highest quality: low/medium DLI crops (i.e., a low DLI is acceptable, but a medium DLI is optimal), medium/high DLI crops, and high/very high DLI crops. From the data of this study, cyclamen can be categorized as a low/medium DLI plant similar to impatiens and wax begonia (Faust et al., 2005).

In this study, three DLI levels (2.9 , 5.8 , and $8.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) were provided by different daylengths. There were significant differences between SD and LD treatments in days to flower (at $2.9 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), number of leaves (at $8.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), and plant dry weight (at 2.9 and $8.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). The promotion of flowering, leaf unfolding, and dry matter accumulation in the LD treatments could at least partially be attributed to a slightly higher plant temperature from heat emitted from the lamps. In addition, the average daily temperature in the LD module was 0.7°C higher than that of the SD module (data not shown).

Many commercial growers strive to produce high-quality potted cyclamen rapidly and economically. Attributes of high-quality cyclamen include a moderately large mass, a large number of flowers and flower buds, and a compact and balanced shape. Rapid production of cyclamen through maximum leaf unfolding and flowering can be obtained by maintaining a greenhouse temperature at $\approx 20^\circ\text{C}$ (Karlsson and Werner, 2001a, 2001b) and by increasing DLI (Oh et al., 2008). However, increasing temperature or photoperiod can increase petiole length and thus deterioration of plant quality (Cheon et al., 2006; Karlsson and Werner, 2001a, 2001b; Oh, 2007). Low irradiance reduces plant dry weight and leaf and flower number and increases plant height and synergistically promotes shoot elongation when grown at high temperatures or under long days (Cheon et al., 2006; Oh, 2007). Unpublished data from Karlsson indicates that a moderate DLI ($12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) promotes development at any temperature and even a higher DLI accelerates flowering if temperature does not exceed 20°C (Dole and Wilkins, 2005).

Our data indicate that increasing DLI promotes flowering and improves plant quality by increasing dry matter and leaf and flower number. Therefore, supplemental lighting to increase DLI can be useful in greenhouse production of potted cyclamen in temperate climates from late fall until early spring, when the DLI delivered to crops is less than $10 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. 'Metis Scarlet Red' cyclamen is an irradiance-responsive plant in which days to flowering decreases as DLI increases, but there is little or no effect of increasing DLI above $\approx 12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Additional research performed in greenhouses exposed to natural sunlight, with supplemental lighting from a more common lamp type used in commercial greenhouses (e.g., high-pressure sodium lamps), is needed to compare our results in growth chambers with a more commercial environment.

Literature Cited

- Adams, S.R., P. Hadley, and S. Pearson. 1998. The effects of temperature, photoperiod, and photosynthetic photon flux on the time to flowering of *Petunia* 'Express Blush Pink'. J. Amer. Soc. Hort. Sci. 123:577-580.
- Armitage, A.M., W.H. Carlson, and J.A. Flore. 1981. The effect of temperature and quantum flux density on the morphology, physiology, and flowering of hybrid geraniums *Pelargonium xhortorum*. J. Amer. Soc. Hort. Sci. 106:643-647.
- Cheon, I.H., W. Oh, J.H. Park, and K.S. Kim. 2006. Long day and high photosynthetic photon flux promote the growth and flowering of *Cyclamen persicum*. Hort. Environ. Biotechnol. 47:353-358.
- Dansereau, B., Y. Zhang, and S. Gagnon. 1998. Stock and snapdragon as influenced by greenhouse covering materials and supplemental light. HortScience 33:668-671.
- Dole, J.M. and H.F. Wilkins. 2005. Floriculture: Principles and species. 2nd Ed. Pearson Education, Inc., Upper Saddle River, NJ.
- Erickson, V.A., A. Armitage, W.H. Carlson, and R.M. Miranda. 1980. The effect of cumulative photosynthetically active radiation on the growth and flowering of the seedling geranium, *Pelargonium xhortorum* Bailey. HortScience 15:815-817.
- Erwin, J., N. Mattson, and R. Warner. 2004. Light effects on annual bedding plants, p. 62-71. In: Fisher, P. and E. Runkle (eds.). Lighting up profits. Meister Media Worldwide, Willoughby, OH.
- Fausey, B.A., R.D. Heins, and A.C. Cameron. 2005. Daily light integral affects flowering and quality of greenhouse-grown *Achillea*, *Gaura*, and *Lavandula*. HortScience 40:114-118.
- Faust, J.E. 2003. Light, p. 71-84. In: Hamrick D. (ed.). Ball redbook: Crop production 17th Ed., Vol. 2. Ball Publishing, Batavia, IL.
- Faust, J.E., V. Holcombe, N.G. Rajapakse, and D.R. Layne. 2005. The effect of daily light integral on bedding plant growth and flowering. HortScience 41:114-119.
- Grafer, D.F. and W. Healy. 1990. Synergistic acceleration of *Begonia semperflorens* development using supplemental irradiance and soil heating. Acta Hort. 272:255-259.
- Grafer, D.F. and W. Healy. 1991. High pressure sodium irradiation and infrared radiation accelerate *Petunia* seedling growth. J. Amer. Soc. Hort. Sci. 116:435-438.

- Hanan, J. 1998. Greenhouses: Advanced technology for protected horticulture. CRC Press, Boca Raton, FL.
- Heo, J.W., C.W. Lee, H.N. Murthy, and K.Y. Paek. 2003. Influence of light quality and photoperiod on flowering of *Cyclamen persicum* Mill. cv. Dixie White. *Plant Growth Regulat.* 40:7–10.
- Islam, N., G.G. Patil, and H.R. Gislerød. 2005. Effect of photoperiod and light integral on flowering and growth of *Eustoma grandiflorum* (Raf.). *Shinn. Scientia Hort.* 103:441–451.
- Kaczperski, M.P., W.H. Carlson, and M.G. Karlsson. 1991. Growth and development of *Petunia ×hybrida* as a function of temperature and irradiance. *J. Amer. Soc. Hort. Sci.* 116:232–237.
- Karlsson, M.G. 2002. Flower formation in *Primula vulgaris* is affected by temperature, photoperiod and daily light integral. *Scientia Hort.* 95:99–110.
- Karlsson, M.G. and J.W. Werner. 2001a. Temperature affects leaf unfolding rate and flowering of cyclamen. *HortScience* 36:292–294.
- Karlsson, M.G. and J.W. Werner. 2001b. Temperature after flower initiation affects morphology and flowering of cyclamen. *Scientia Hort.* 91:357–363.
- Kessler, R., A.M. Armitage, and D. Koranski. 1990. Effect of supplemental light and duration of exposure on growth and flowering of *Begonia semperflorens*. *Acta Hort.* 272:137–144.
- Korczynski, P.M., J. Logan, and J.E. Faust. 2002. Mapping monthly distribution of daily light integrals across the contiguous United States. *HortTechnology* 12:12–16.
- Lieth, J.H., R.H. Merritt, and H.C. Kohl, Jr. 1991. Crop productivity of petunia in relation to photosynthetically active radiation and air temperature. *J. Amer. Soc. Hort. Sci.* 116:623–626.
- Loehrlein, M.M. and R. Craig. 2004. The effect of daily light integral on floral initiation of *Pelargonium ×domesticum* L.H. Bailey. *HortScience* 39:529–532.
- Moccaldi, L.A. and E.S. Runkle. 2007. Modeling the effects of temperature and photosynthetic daily light integral on growth and flowering of *Salvia splendens* and *Tagetes patula*. *J. Amer. Soc. Hort. Sci.* 132:283–288.
- Moe, R. 1994. Vekstfysiologiske aspekter med høje belysningsstyrker. *Gartneryrket* 84:8–13.
- Mortensen, L.M. and R. Moe. 1995. Effects of temperature, carbon dioxide concentration, daylength, and photon flux density on growth, morphogenesis, and flowering of miniature roses. *Acta Hort.* 378:63–70.
- Nemali, K.S. and M.W. van Iersel. 2004. Light effects on wax begonia: Photosynthesis, growth respiration, maintenance respiration, and carbon use efficiency. *J. Amer. Soc. Hort. Sci.* 129:416–424.
- Neuray, G. 1973. Bud formation in *Cyclamen persicum*. *Acta Hort.* 31:77–79.
- Niu, G., R.D. Heins, A.C. Cameron, and W.H. Carlson. 2000. Day and night temperatures, daily light integral, and CO₂ enrichment affect growth and flower development of pansy (*Viola ×wittrockiana*). *J. Amer. Soc. Hort. Sci.* 125: 436–441.
- Oh, W. 2007. Growth mechanism and its manipulation by temperature, light intensity, and plant growth regulators in *Cyclamen persicum*. PhD diss., Seoul Natl. Univ., Seoul, Korea.
- Oh, W., Y.H. Rhie, J.H. Park, E.S. Runkle, and K.S. Kim. 2008. Flowering of cyclamen is accelerated by an increase in temperature, photoperiod, and daily light integral. *J. Hort. Sci. Biotechnol.* 83:559–562.
- Pietsch, G.M., W.H. Carlson, R.D. Heins, and J.E. Faust. 1995. The effect of day and night temperature and irradiance on development of *Catharanthus roseus* (L.) ‘Grape Cooler’. *J. Amer. Soc. Hort. Sci.* 120:877–881.
- Pramuk, L.A. and E.S. Runkle. 2005a. Modeling growth and development of *Celosia* and *Impatiens* in response to temperature and photosynthetic daily light integral. *J. Amer. Soc. Hort. Sci.* 130:813–818.
- Pramuk, L.A. and E.S. Runkle. 2005b. Photosynthetic daily light integral during the seedling stage influences subsequent growth and flowering of *Celosia*, *Impatiens*, *Salvia*, *Tagetes*, and *Viola*. *HortScience* 40:1336–1339.
- Rhie, Y.H., W. Oh, J.H. Park, C. Chun, and K.S. Kim. 2006. Flowering response of ‘Metis Purple’ cyclamen to temperature and photoperiod according to growth stages. *Hort. Environ. Biotechnol.* 47:198–202.
- Sonneveld, C. and N. Starver. 1992. Nutrient solution for vegetables and flowers grown in water or substrates. *Serie Voedingsoplossingen Glastuinbouw*, No. 8, p. 42. Naaldwijk, The Netherlands.
- Thomas, B. and D. Vince-Prue. 1997. Photoperiodism in plants. 2nd Ed. Academic Press, London, UK.
- Verberkt, H., R.D. Heins, and T. Blom. 2004. Supplemental lighting on potted plants, p. 72–78. In: Fisher, P. and E. Runkle (eds.). *Lighting up profits*. Meister Media Worldwide, Wiloughby, OH.
- Vogelezang, J. and H. Verberkt. 1990. Supplementary lighting for pot plant cultures. *Acta Hort.* 272:159–162.
- White, J.W. and I.J. Warrington. 1984. Growth and development responses of geranium to temperature, light integral, CO₂, and chloromequat. *J. Amer. Soc. Hort. Sci.* 109:728–735.
- Widmer, R.E. and R.E. Lyons. 1985. *Cyclamen persicum*, p. 382–390. In: Halevy, A.H. (ed.). *Handbook of flowering II*. CRC Press, Boca Raton, FL.