

Bolting and Growth of *Spinacia oleracea* L. Can be Altered by Modifying the Photoperiod during Transplant Production

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Abstract. Spinach (*Spinacia oleracea* L. cv. Dimple) was chosen to determine whether bolting (i.e., elongation of flower stalks) could be controlled by manipulating the photoperiod during transplant production in a closed system using artificial light. Plants grown under various photoperiods during transplant production were transferred and cultured under natural short photoperiods and artificial long photoperiods. Vegetative growth at transplanting tended to be greater with the longer photoperiod because of the increased integrated photosynthetic photon flux. Bolting initiation reacted qualitatively to a long photoperiod, and the critical photoperiod for bolting initiation was longer than 13 h and shorter than 15 h. The plants grown under a longer photoperiod during transplant production had longer flower stalks at harvest. The long photoperiod and/or high temperature after transplanting therefore promoted flower stalk elongation. Growing plants under a photoperiod that was shorter than the critical photoperiod during transplant production reduced elongation of the flower stalks, thus there was no loss of market value even though the plants were cultured under a long photoperiod and high temperature for 2 weeks after transplanting.

Spinach cultured in spring and summer usually has a greater tendency to bolt (Singhal and Kulkarni, 1998). In general, a long photoperiod causes spinach plants to bolt and to flower (Garner and Allard, 1920; Hartmann et al., 1988). A solution to this problem is to grow cultivars that are less sensitive to photoperiod (Kagawa, 1997), but this limits the number of cultivars that can be supplied to markets during the spring and summer. Generally, oriental cultivars that Japanese and other Asian customers prefer bolt easily and therefore are available only in the winter season.

Manipulation of the photoperiod is commonly used in horticultural crop production

systems based on the flowering physiology of each crop. Supplementary lighting to extend the photoperiod is popular in flower production (Fredericq, 1964; Salisbury, 1965). Covering plants with an opaque curtain or other physical barrier is the only way to shorten the natural photoperiod. However, if artificial lighting is used for transplant production instead of natural light, the photoperiod can be easily manipulated. Recently, a closed transplant production system that uses only artificial light was introduced, and is expected to have many advantages over the conventional transplant production method with natural light (Kozai, 1998).

Chun et al. (2000) showed that bolting, a major problem for spinach production systems, can be prevented by manipulating the photoperiod and temperature during transplant production using artificial light. Kim et al. (2000) reported that spinach plants began to sense the photoperiod during transplant production, and that flower bud development during this period was enhanced under a longer photoperiod. In this study, the effects of photoperiod during transplant production on the growth and bolting of spinach plants cultured under a natural, short photoperiod and under an artificial, long photoperiod were investigated to determine whether bolting could be controlled.

Transplant production. Five spinach, cv. Dimple, seeds (Sakata Seed Co., Yokohama, Japan) were sown in each cell (2 cm in diameter) of transplant production trays (144 cells per tray, 30 × 60 cm; Taiyo Kogyo Co., Tokyo) that had been filled with 3 g (dry weight) of granules of rockwool (Nichias Co., Tokyo) on 10 Nov. 1998. The trays with seeds were wrapped with nontransparent plastic sheets and placed in a walk-in growth chamber for 3 d for germination.

The trays with germinated seeds were moved to three transplant production modules (0.51 m wide × 1.25 m long × 0.42 m high) in a growth chamber. Each module had eight cool-white fluorescent lamps (FPL55EX-N; Matsushita Electric Industrial Co., Osaka, Japan) and a time switch (TB15601; Matsushita Electric Works, Osaka, Japan). The photoperiods in the three modules were set at 11, 13, and 15 h, respectively, and the photosynthetic photon flux (PPF) measured on the trays was 310 ± 20 μmol·m⁻²·s⁻¹. Each module also had a ventilating fan (EG-35BSB; Mitsubishi Electric Co., Tokyo). Curtains were placed around each module to exclude light from neighboring modules.

During the transplant production period, the air temperature in each module was maintained at 21 ± 1 °C and 19 ± 1 °C during the photo- and dark periods, respectively. Irrigation was conducted once a day with commercial nutrient solution (High Tempo; Sumitomo Chemical Co., Tokyo). The solution contained 12.0 mmol·L⁻¹ NO₃-N, 0.8 mmol·L⁻¹ NH₄-N, 30.6 mmol·L⁻¹ P, 7.3 mmol·L⁻¹ K, 10.2 mmol·L⁻¹ Ca, and 4.2 mmol·L⁻¹ Mg. The pH and electrical conductivity (EC) of the nutrient solution were 6.0 and 140 mS·m⁻¹, respectively. At 14 d after sowing (DAS), the maximum leaf length, shoot fresh weight, and number of leaves of the 15 transplants from each replication were measured.

Culture after transplanting. At 14 DAS, the plants were transplanted to: 1) a plastic greenhouse under a short natural photoperiod (ca. 11 h) or 2) a growth chamber under a long artificial photoperiod (16 h). Six treatments were used as a result of combining each of the three photoperiods (11, 13, and 15 h) during transplant production (4–14 DAS) with the two photoperiods (ca. 11 and 16 h) from transplanting until harvest. The plants cultured under natural light in the greenhouse were harvested 28 d after transplanting (DAT), while those cultured under artificial light in the growth chamber were harvested 14 DAT.

Throughout the culture period in the greenhouse, the maximum air temperature was 30 °C, and the minimum was not allowed to drop below 13 °C. The air temperatures during photo- and dark periods in the growth chamber were 34 ± 1 and 30 ± 1 °C, respectively. Modified ebb and flow technique (EFT) (Buwalda et al., 1994) and nutrient film technique (NFT) (Cooper, 1973) hydroponic systems were installed in the greenhouse and the growth chamber, respectively. The plants were placed on planting panels (Taiyo Kogyo

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Co.) with a density of 63 cells/m² in both systems. In the EFT system, the supply and draining of the nutrient solution (280 mS·m⁻¹ of EC and pH 6.0) was repeated on a 20–40-min cycle, while in the NFT system, the nutrient solution was continuously circulated between the nutrient tank and the culture beds. At harvest, the maximum leaf length, shoot fresh weight, number of leaves, and flower-stalk length of 10 plants in each replication were measured. A completely random design was used with four replications. An analysis of variance (ANOVA) test and Duncan's multiple range test were used to compare means in each treatment.

Results

Maximum leaf length, average number of leaves per plant, and shoot fresh weight per plant at transplanting all increased significantly with increasing photoperiod during transplant production (Fig. 1).

Maximum leaf length at harvest was shortest when the photoperiod during transplant production was 15 h and the photoperiod after transplanting was 16 h (artificial light) (Fig. 2A). Maximum leaf length at harvest was greater in plants grown under natural light with an 11-h photoperiod after transplanting than those grown under artificial light with a 16-h photoperiod. Shoot fresh weight at harvest exhibited the same general trend as did the maximum leaf length at harvest, although the effect of photoperiod during transplant production was nonsignificant (Fig. 2B). Number of leaves per plant at harvest was greatest in the plants grown with the 15-h photoperiod during transplant production (Fig. 2C). Flower stalk length was zero in plants exposed to 11- or 13-h photoperiods during transplant production, then grown under natural light with 11-h photoperiod after transplanting. Flower stalk elongation was promoted by exposure to a 15-h photoperiod during transplant production, regardless of the photoperiod and light source after transplanting (Fig. 2D).

Discussion

Growth and bolting at transplanting. Since the transplants were normal in color and shape, fluorescent lighting was considered to be suitable for their production. The greater vegetative growth at transplanting with longer photoperiod was probably due to the greater integrated photosynthetic photon flux [IPPF (mol·m⁻²·d⁻¹), a product of photoperiod (s·d⁻¹) and PPF (μmol·m⁻²·s⁻¹)], as the PPF was identical in all treatments during transplant production. Kitaya et al. (1998) also reported that the growth of lettuce in a transplant production system using artificial light increased with increasing IPPF when various photoperiods and PPF combinations were used. Prediction and/or control of growth is essential for scheduling transplant production. Because elongation of flower stalks was observed only in plants initially exposed to a 15-h photoperiod, we conclude that bolting was initiated during transplant production.

However, it is not yet clear whether bolting resulted from exposure to a photoperiod that was longer than the critical photoperiod, or progressed regardless of photoperiod but was enhanced by the long photoperiod, as occurred in flower bud development (Eguchi and Ichikawa, 1940).

Growth at harvest. The spinach plants grown in the greenhouse after transplanting could be harvested at a marketable size (ca. 20 cm of the maximum leaf length) at 28 DAT in the winter season. Chun et al. (2000) harvested the same cultivar with a similar size at 14 DAT in a greenhouse experiment conducted in the summer season. Growth was retarded when plants were grown under artificial light, as air temperatures were high (ca. 34 and 30 °C during photo- and dark periods, respectively). The roots were brown when harvested.

Bolting at harvest. Spinach is a long-day plant (Boswell, 1935; Kagawa, 1997; Knott, 1932, 1934; Magruder and Allard, 1936; Metzger and Zeevaart, 1980; Zeevaart, 1971). However, the effect of photoperiod on the flowering process is not yet fully understood. Flowering in spinach occurs in several stages: flower bud start, flower bud development, the start of elongation of the flower stalk (bolting), and elongation of the flower stalk. Eguchi and Ichikawa (1940) reported that flower bud start in spinach occurred regardless of the photoperiod, and that a longer photoperiod promoted flower bud development. The longer flower stalk length in plants grown in a 15-h

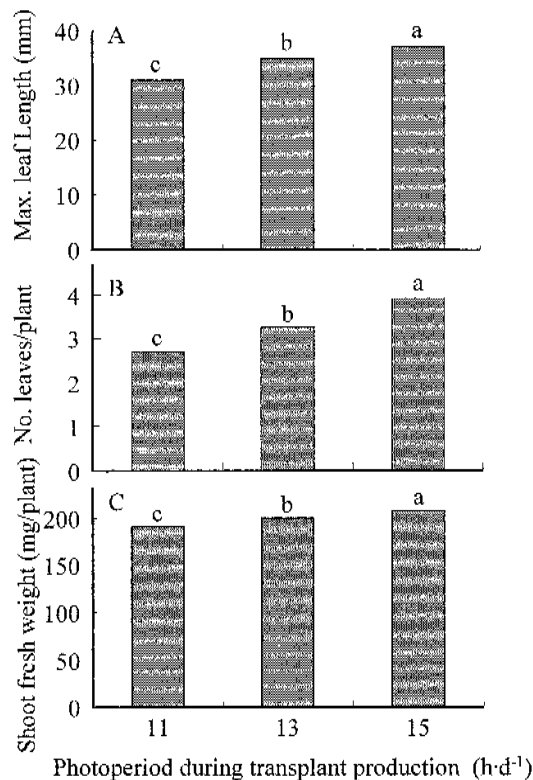


Fig. 1. Effects of photoperiod during transplant production (4–14 DAS) on (A) the maximum leaf length, (B) shoot fresh weight, and (C) number of leaves of spinach transplants at transplanting (14 DAS). Mean separation by Duncan's multiple range test, $P \leq 0.05$.

photoperiod prior to exposure to natural short photoperiods (11 h) indicates an effect of the long photoperiod during transplant production. The critical photoperiod for bolting in this cultivar was longer than 13 h and shorter than 15 h. Because plants that were exposed to a 15-h photoperiod during transplant production and then grown under an 11-h short photoperiod bolted, bolting, like flower bud development, is considered to be an irreversible process.

The significant effect of photoperiod prior to transplanting on flower stalk length in plants subsequently grown under artificial light presumably indicates that 15 h is longer than the critical photoperiod during transplant production, while 11 and 13 h are shorter than the critical photoperiod. Plants in the latter treatments were exposed to long photoperiod only after transplanting. Kim et al. (2000) reported that flower bud development was accelerated when spinach plants were grown under a long photoperiod. Since the flower stalk length was greater in plants grown in a 13-h than in an 11-h photoperiod prior to transfer to a 16-h photoperiod, the more advanced flower buds that developed in longer photoperiods produced longer flower stalks at harvest. However, more experiments are needed to clarify the relationship between the stages of flower bud development of the transplants and flower stalk length.

Flower stalk length was 70 mm in plants initially grown in a 15-h photoperiod, then exposed to artificial light with a 16-h photoperiod.

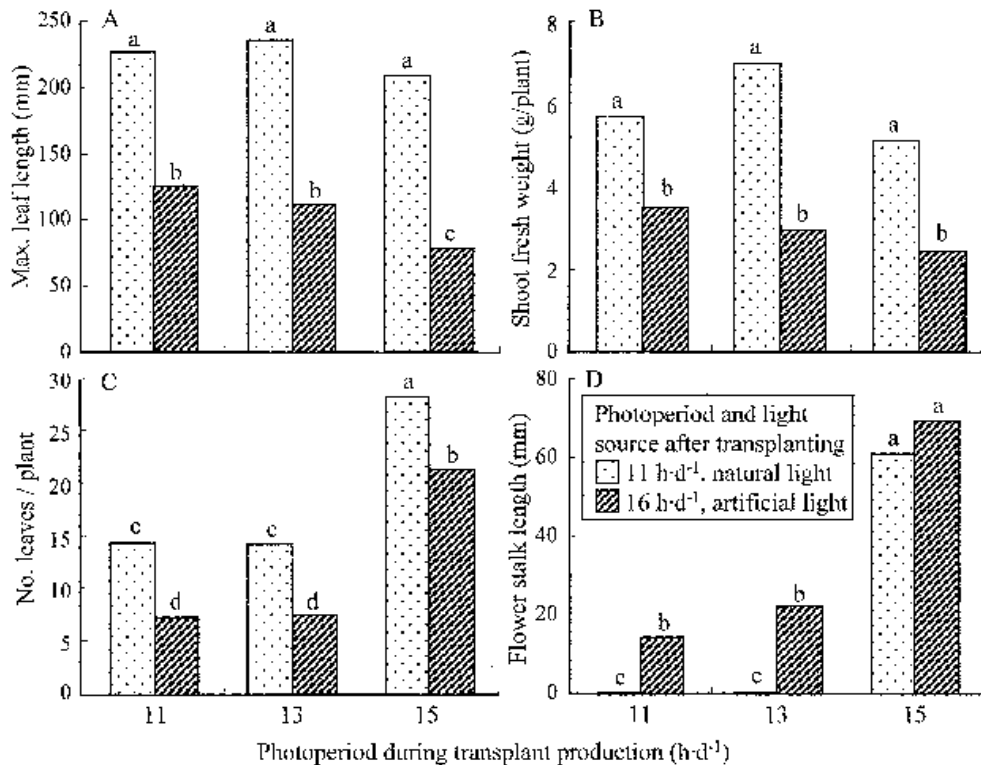


Fig. 2. Effects of photoperiod during leaf transplant production and photoperiod and light source after transplanting on (A) the maximum leaf length, (B) shoot fresh weight, (C) number of leaves, and (D) flower stalk length of spinach plants at harvest. Mean separation by Duncan's multiple range test, $P \leq 0.05$.

riod, vs. only 61 mm in similar plants grown in natural light with an 11-h photoperiod. Long photoperiod and/or high temperature after transplanting apparently promoted flower stalk elongation. However, the effects on flower stalk length of temperature and photoperiod after transplanting could not be separated in this experiment.

Spinach plants of many oriental cultivars tend to bolt and to lose their economic value at harvest when grown under a long photoperiod. The present results show that bolting can be prevented by using artificial lighting to shorten the photoperiod during transplant production. This manipulation of photoperiod has practical value in spinach production where transplants produced under artificial light are transferred to a greenhouse with natural light.

To better understand bolting and flowering physiology and to apply this knowledge to the production of value-added spinach transplants, further studies are needed on how bolting is affected by photo- and dark periods and air temperature during transplant production. The technique developed for spinach transplant production might be applied to similar systems producing transplants of lettuce (*Lactuca sativa* L.) and other leafy vegetables that are prone to bolt, and for other vegetables and ornamental plants in which bolting affects economic value.

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