agronomy

Brief Report

Critical Photoperiod and Optimal Quality of Night Interruption Light for Runner Induction in June-Bearing Strawberries

Yali Li [1], Jie Xiao [1], Jiangtao Hu [1] and Byoung Ryong Jeong [1,2,3,*]

[1] Department of Horticulture, Division of Applied Life Science (BK21 Four), Graduate School of Gyeongsang National University, Jinju 52828, Korea; yalilee1001@gmail.com (Y.L.); xiaojsicau@163.com (J.X.); hujiangtao@caas.cn (J.H.)
[2] Institute of Agriculture and Life Science, Gyeongsang National University, Jinju 52828, Korea
[3] Research Institute of Life Science, Gyeongsang National University, Jinju 52828, Korea
* Correspondence: brjeong@gnu.ac.kr; Tel.: +82-55-772-1913

Abstract: The optimal photoperiod and light quality for runner induction in strawberries 'Sulhyang' and 'Maehyang' were investigated. Two experiments were carried out in a semi-closed walk-in growth chamber with 25/15 °C day/night temperatures and a light intensity of 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux density (PPFD) provided from white light-emitting diodes (LEDs). In the first experiment, plants were treated with a photoperiod of either 12, 14, 16, 18, 20, or 22 h In the second experiment, a total of 4 h of night interruption (NI) light at an intensity of 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$PPFD provided from either red, blue, green, white, or far-red LED in addition to 11 h short day (SD). The results showed that both 'Sulhyang' and 'Maehyang' produced runners when a photoperiod was longer than 16 h, and the number of runners induced positively correlated with the length of photoperiod. However, the plant growth, contents of chlorophyll, sugar and starch, and Fv/Fo decreased in a 22 h photoperiod. All qualities of the NI light, especially red light, significantly increased the number of runners and daughter plants induced per plant as compared with those in the SD treatment in both cultivars. In a conclusion, a photoperiod between 16 and 20 h and NI light, especially red NI light, can be used for quality runner induction in both 'Sulhyang' and 'Maehyang'.

Keywords: day length; night interruption light; propagation

Citation: Li, Y.; Xiao, J.; Hu, J.; Jeong, B.R. Critical Photoperiod and Optimal Quality of Night Interruption Light for Runner Induction in June-Bearing Strawberries. *Agronomy* **2021**, *11*, 1996. https://doi.org/10.3390/agronomy11101996

Academic Editors: Giovanni Caruso and Sara Serra

Received: 3 July 2021
Accepted: 28 September 2021
Published: 1 October 2021

1. Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is an herbaceous perennial crop species in the Rosaceae family. It is one of the most popular fruit crops all around the world for their beautiful appearance, flavor, and health benefits [1]. Strawberries, mostly a June-bearing type, were cultivated on 6,462 hectares and the annual yield was 234,225 tons (KOSIS, 2020) in Korea in 2020. The commercial success of this crop is due in part to its asexual propagation using runners because asexual production using daughter plants is faster in making quality transplants than seed propagation and daughter plants retain the characteristics of the mother plant [2]. Thus, commercially, almost all strawberry plants are propagated through runners instead of seeds.

In strawberries, runner development is intimately connected with flowering. They are oppositely influenced by the same environmental signal in most cases. Currently, most of our understanding relates to photoperiods, even though temperature is also known to play an important role. When strawberry plants were transferred from long day (LD) to short day (SD) conditions, the production of new runners ceased after 3 weeks [3]. When strawberries were treated with the same brief periods of SD, renewed runner formation happened when plants were transferred back to LD [4]. In June-bearing wild-type strawberries (*Fragaria vesca*), SD and low temperatures induce flowering and inhibit runners [5,6]. In contrast, LD and high temperatures inhibit flowering and induce runners. In the everbearing genotype, the number of induced runners increases in high-temperature conditions, while the photoperiodic condition gave various effects [7]. Everbearing genotypes produce fewer runners than June-bearing genotypes. Many everbearing genotypes of *F. vesca* do not produce runners in natural environmental conditions. However, Hawaii-4, an everbearing genotype that also forms runners, was enhanced to produce runners under SD treatment [8]. Some strawberry cultivars did not show any significant difference in runner induction between LD and SD [9]. Thus, photoperiod and temperature have different impacts on runner induction in various strawberry genotypes. The LD photoperiod was found to be the most influential factor for runner induction in strawberries according to our previous research [10]. However, the critical photoperiod for runner induction still remains unknown.

The effect of light quantity on branching, leaf area, and biomass production was intensively studied in recent years [11]. The growth and development of plants depend on both light intensity and quality. The 'Toyono' strawberry grown under 110 to 122 $\mu mol \cdot m^{-2} \cdot s^{-1}$photosynthetic photon flux density (PPFD) provided by white fluorescent lamps promoted plant growth and the formation of daughter plants when compared with plants under 50 to 55 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD [12]. Using filters to change the spectral distribution of natural sunlight directly influences photosynthesis [13]. Early studies of light quality on strawberry growth and flowering indicated that decreasing the ratio of far-red to red light promoted flowering while blue and far-red light delayed flowering and stimulated runner development [14,15]. Researchers also found that plants grown, by photon flux density, under light with 30% blue and 70% red produced the greatest number of runners whereas those grown under 20% blue, 10% green, and 70% red had the greatest number of daughter plants per runner [16].

Night interruption (NI) light breaks a long dark period during the night to deliver photoperiodic lighting to simulate modified LD conditions while saving in electrical energy consumption. The NI light is effective for accelerating the growth and development of plants [17]. The NI light was mostly used for flowering control, such as for preventing or delaying flowering of SD plants and for accelerating flowering of LD plants [18–20]. The NI effect on flowering promotion in LD plants and on flowering inhibition in SD plants varies depending on application timing and intensity of NI during the night [21]. Since flowering and runner initiation are mutually exclusive to each other [22,23], NI light may also affect the runner induction in strawberries.

Above all, the critical photoperiod and optimal quality of NI light for runner induction was investigated in the two most widely planted strawberries in Korea, 'Sulhyang' and 'Maehyang', to provide instructions for inducing runners in the large-scale commercial propagation of strawberries.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

In the first experiment, about 20 cm long runner plants with three fully expanded leaves of 'Sulhyang' and 'Maehyang' strawberries were purchased from a strawberry farm (Sugok-myeon, Jinju, Korea) and stuck in 21-cell zigzag trays (21-Zigpot/21 cell tray, Daeseung, Jeonju, Korea) filled with BVB Medium (Bas Van Buuren Substrates, EN-12580, De Lier, The Netherlands) on November 1, 2019. They were then put into a fogged tunnel for root development. Two weeks later, well-rooted daughter plants were taken out of the fogged tunnel and transferred to a bench in a glasshouse and were supplied with a nutrient solution (in $mg \cdot L^{-1}$) composed of 708.0 $(Ca(NO_3)_2 \cdot 4H_2O$, 246.0 $MgSO_4 \cdot 7H_2O$, 505.0 KNO_3, 230.0 $NH_4H_2PO_4$, 1.24 H_3BO_3, 0.124 $CuSO_4 \cdot 5H_2O$, 4.0 Fe-EDTA, 2.2 $MnSO_4 \cdot 4H_2O$, 0.08 H_2MoO_4, and 1.15 $ZnSO_4 \cdot 7H_2O$. The plants were transplanted into 10 cm pots on February 29, 2020 and moved into a semi-closed walk-in growth chamber with 25/15°C day/night and 70% relative humidity. They were grown there for one month under 12, 14, 16, 18, 20, or 22 h photoperiods with 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD provided from white LEDs (MEF50120, More Electronics Co., Ltd., Changwon, Korea). Each treatment contained three replicates of three plants.

In the second experiment, runnering of 'Sulhyang' and 'Maehyang' strawberries, as affected by the quality of NI light, was assessed. Runner plants of similar sizes were separated from the mother plants and planted in a 21-cell tray filled with the BVB (Bas Van Buuren Substrates, De Lier, The Netherlands) substrate on June 28, 2019 and then put into a fogged tunnel for rooting. Ten days later, well-rooted daughter plants were taken out of the fogged tunnel, cultivated in a glasshouse for one month, and then transplanted into 10 cm pots. The experiment was conducted in a semi-closed walk-in growth chamber with 25/15°C day/night and 70% relative humidity. The plants were grown under 250 μmol·m^{-2}·s^{-1} PPFD provided by white LEDs (MEF50120, More Electronics Co., Ltd., Changwon, Korea) under a light treatment regime of either LD (15 h light/9 h dark), SD (11 h light/13 h dark), or SD with a white, green, blue, red, or far-red NI lighting for a total of 4 h (Figure 1). The spectral distribution of the LEDs was measured with a portable spectroradiometer (Spectra Light ILT 950, International Light Technologies, Inc., Peabody, MA, USA). The peak wavelengths of blue, green, red, and far-red light were 470, 515, 660, and 740, respectively. The NI light intensity was 70 μmol·m^{-2}·s^{-1} PPFD, and a timing controller (SJP-CP16H, Seojun Ltd., Seoul, Korea) was used to control the entire circuit and to make sure that the LEDs were lit at 8:00 a.m. every day in all treatments. Each treatment contained three replicates of three plants. Data were collected one month later.

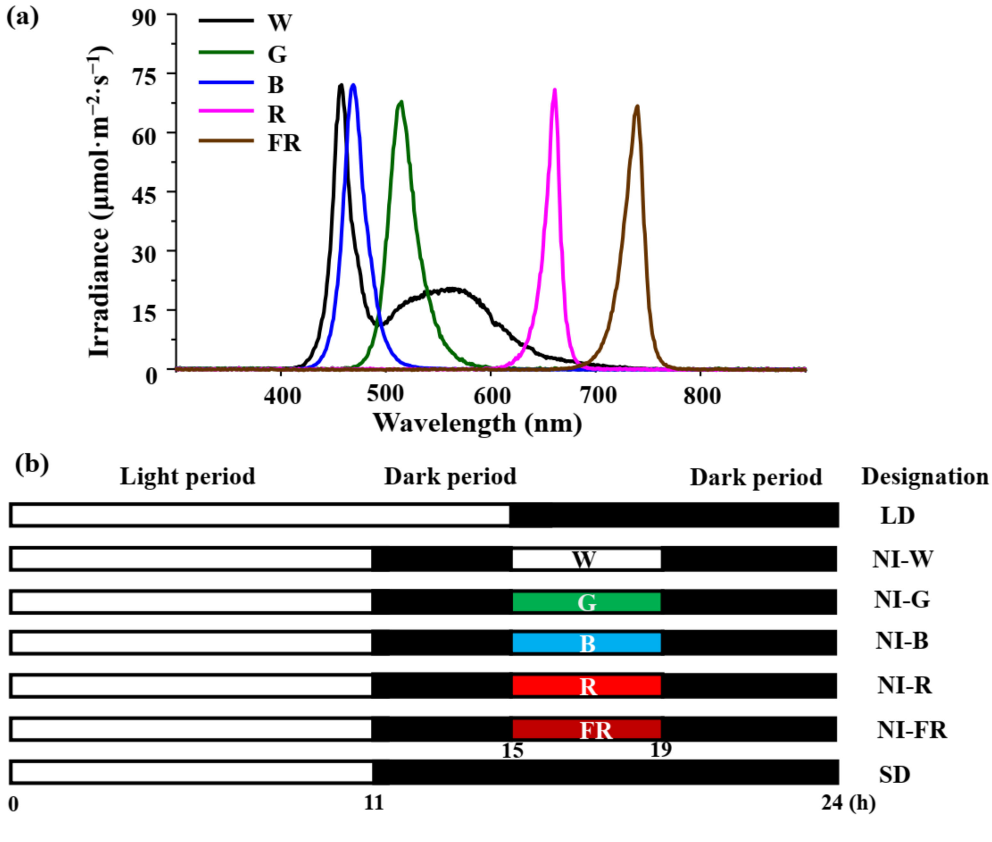

Figure 1. The light spectral distribution of the LEDs (**a**) and night interruption light (**b**) used in this study: W, white; G, green; B, blue; R, red; FR, far-red; LD, long day; NI, night interruption; and SD, short day.

2.2. *Measurement of Growth Parameters*

Growth parameters, such as the number of runners and daughter plants, runner length and diameter, plant height, leaf length and width, and petiole length and diameter were measured. The biggest young mature leaf was used to measure leaf and petiole size. The diameters of runners and petioles were measured using a Vernier caliper (CD-20CPX, Mitutoyo Korea Co., Gunpo, Korea).

2.3. Chlorophyll Contents

The contents of chlorophyll a and b in both experiments were estimated according to the method described by Wang et al. [24] with some modifications. To briefly describe, the fresh leaves were ground into fine powder in liquid nitrogen, and 0.03 g of the powder from each treatment was mixed with 2 mL extraction buffer (45% *v/v* ethanol, 45% *v/v* acetone, and 10% distilled water). The mixtures were covered with tin foil and put into a 4 °C refrigerator overnight. After centrifugation at 6000 rpm for 10 min, the supernatants were transferred to a colorimeter tube for determination of the absorbance at 645 and 663 nm. The contents of chlorophyll a and b were determined using the following formulae:

$$\text{Chlorophyll a} = \frac{(12.72 \times \text{OD } 663 - 2.59 \times \text{OD } 645) \times \text{V}}{\text{Sample fresh weight}} \quad \text{Chlorophyll b} = \frac{(22.88 \times \text{OD } 645 - 4.67 \times \text{OD } 663) \times \text{V}}{\text{Sample fresh weight}}$$

where OD is optical density and V is the volume of the extraction solution. The chlorophyll content was presented milligrams of chlorophyll per gram of fresh leaf weight.

2.4. Soluble Sugar and Starch Contents

The contents of soluble sugar and starch in both experiments were measured according to anthrone–sulfuric acid colorimetry as previously published [10].

2.5. Chlorophyll Fluorescence Parameters

The chlorophyll fluorescence parameter of Fv/Fm is the maximum/potential quantum efficiency of photosystem II (PS II), and Fv/Fo is the maximum primary yield of PS II photochemistry. These two parameters were measured in both experiments with a portable fluorometer after one month of cultivation (Fluorpen FP110, Photon Systems Instruments, Drásov, Czech Republic).

2.6. Statistical Analysis

Significant statistical differences among the treatments were determined by analysis of variance (ANOVA), followed by Duncan's multiple range test at a significance level of $p = 0.05$ with the Statistical Analysis System (SAS, V. 9.2, Cary, NC, USA).

3. Results

3.1. Runner Growth as Affected by Long Day Photoperiod

The strawberry plants were kept in the growth chamber for one month. The morphology of the strawberry plants at the end of the experiment is shown in Figure 2. Both strawberries 'Sulhyang' and 'Maehyang' produced runners when the photoperiod was longer than 16 h. Moreover, the number of runners was positively correlated with the length of the photoperiod in both cultivars (Figure 2). The strawberries produced daughter plants when photoperiod longer than 18 h in 'Sulhyang' and 20 h in 'Maehyang'. The runner length and diameter were significantly increased in 22 h photoperiod when compared with 16 h photoperiod.

3.2. Plant Growth as Affected by Long Day Photoperiod

Although runner growth was increased under longer photoperiods, plant height and petiole length were significantly decreased when the photoperiod was longer than 20 h (Table 1). The petiole diameter was not affected by photoperiod. Strawberry 'Maehyang' treated with 20-h photoperiods produced the biggest leaves.

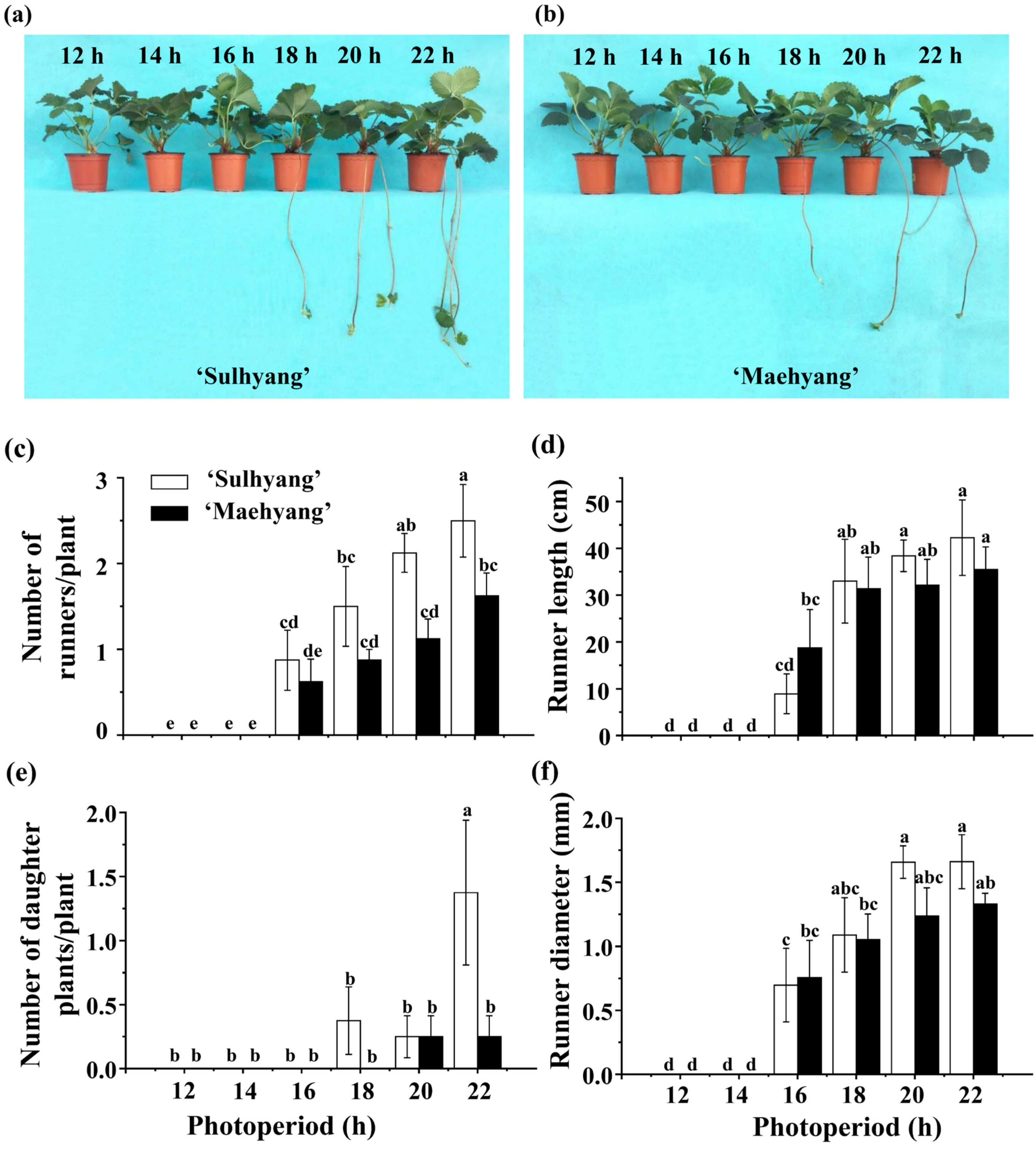

Figure 2. The morphology of strawberry plants (**a**,**b**) and runner-related parameters (**c**–**f**) as affected by the photoperiod. Lowercase letters indicate significant difference according to the Duncan's multiple range test at a 0.05 level. Vertical bars indicate standard errors.

Table 1. The growth parameters of strawberries as affected by the photoperiod.

Cultivar (A)	Photoperiod (B, h)	Plant Height (cm)	Petiole		Leaf	
			Length (cm)	Diameter (mm)	Length (cm)	Width (cm)
'Sulhyang'	12	20.4 cd[z]	12.5 b	2.0 bcd	7.4 de	6.3 bcd
	14	20.1 cd	11.7 bc	2.1 a-d	7.7 b-e	6.6 abcd
	16	18.6 de	10.3 cde	2.0 bcd	7.8 bcde	6.8 abc
	18	19.1 de	10.8 bcd	2.0 cd	7.9 bcd	6.9 ab
	20	17.9 ef	9.8 de	2.1 bcd	7.7 b-e	7.0 a
	22	17.3 f	9.2 e	1.9 d	7.1 e	6.8 a-d
'Maehyang'	12	23.2 a	13.5 a	2.1 abcd	8.2 bc	6.3 bcd
	14	22.4 abc	12.3 b	2.2 a-d	8.6 ab	6.2 cd
	16	22.7 abc	11.9 bc	2.4 a	8.1 bcd	6.4 abcd
	18	21.0 bc	11.6 bc	2.2 abcd	8.4 ab	6.7 a-d
	20	21.4 bc	11.4 bcd	2.3 ab	9.0 a	6.9 ab
	22	19.1 de	11.1 bcd	2.3 abc	7.6 cde	6.1 d
F-test[y]	A	***	***	***	***	*
	B	***	***	NS	**	*
	A×B	**	NS	NS	*	NS

[z] Significant statistical differences calculated by the Duncan's multiple range test at $p \leq 0.05$. [y] NS, *, **, and *** represent non-significant statistical difference or significant statistical difference by a two-way ANOVA F-test at $p \leq 0.05$, 0.01, and 0.001, respectively.

3.3. Runner and Plant Growth as Affected by NI Lights

The morphology of the strawberries treated with NI light at 70 μmol·m^{-2}·s^{-1} PPFD for one month is shown in Figure 3. Plants treated with LD were significantly promoted in runner induction compared with those in SD (Table 2). As the case with NI light, all light treatments significantly increased the number of runners per plant induced in both cultivars. Red NI light induced the largest number of runners in both cultivars. Far-red light significantly enhanced the runner length in both cultivars. However, runner diameter decreased by far-red NI light in both cultivars. Green, blue, and far-red NI lights increased plant height and petiole length in 'Sulhyang', whereas all qualities of NI lights, except for green light, increased plant height, petiole length, and leaf length in 'Maehyang' compared with LD. All qualities of NI lights promoted leaf length and width in 'Sulhyang'.

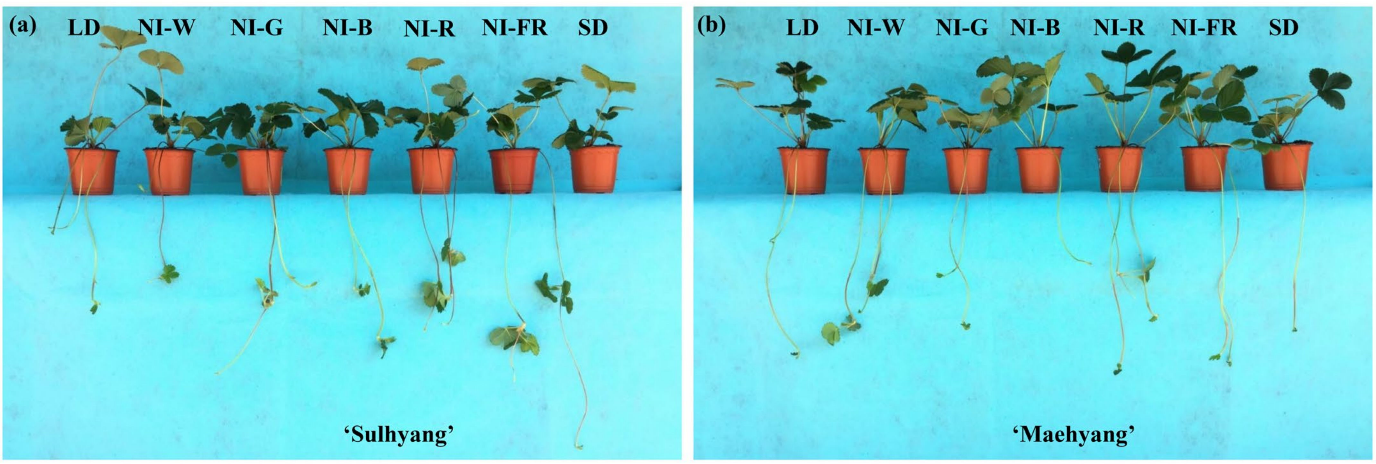

Figure 3. The morphology of 'Sulhyang' (**a**) and 'Maehyang' (**b**) strawberries as affected by night interruption (NI) light: LD, long day; SD, short day; W, white; G, green; B, blue; R, red; and FR, far-red.

Table 2. The growth of strawberries as affected by photoperiod and quality of night interruption light.

Cultivar (A)	Light Treatment (B)	Runner			Petiole		Leaf		Plant Height (cm)
		Number	Length (cm)	Diameter (mm)	Length (cm)	Diameter (mm)	Length (cm)	Width (cm)	
'Sulhyang'	LD	2.56 ab[z]	41.46 bcd	1.84 abc	3.63 e	2.36 e	5.08 d	4.82 ef	9.87 gh
	NI-W	1.44 cd	27.93 e	1.70 bcd	4.42 e	2.32 e	6.07 c	5.57 cd	11.35 fg
	NI-G	2.33 abc	43.83 bc	1.72 a–d	7.25 d	2.47 cde	7.20 ab	6.52 ab	15.42 cd
	NI-B	2.33 abc	36.51 cde	1.90 ab	7.58 cd	2.64 a–e	7.63 a	6.43 ab	16.00 cd
	NI-R	2.89 a	36.38 cde	1.90 ab	4.87 e	2.60 b–e	7.42 ab	6.72 a	12.93 ef
	NI-FR	2.00 a–d	53.48 a	1.53 d	7.20 d	2.54 b–e	7.22 ab	6.22 abc	15.07 de
	SD	0.67 f	35.50 cde	1.57 d	3.37 e	1.96 f	4.33 d	3.73 g	8.40 h
'Maehyang'	LD	2.11 abc	41.17 bcd	1.79 abc	6.63 d	2.86 ab	6.17 c	5.32 de	13.78 de
	NI-W	2.56 ab	35.33 cde	1.92 a	9.00 bc	2.80 abc	7.62 a	6.42 ab	17.53 bc
	NI-G	1.78 bcd	42.33 bcd	1.73 a–d	6.68 d	2.81 abc	6.68 bc	5.55 cd	13.95 de
	NI-B	1.32 cd	38.42 cd	1.84 abc	12.45 a	2.97 a	7.60 a	5.92 bcd	20.82 a
	NI-R	2.56 ab	43.20 bc	1.79 abc	10.27 b	2.77 a–d	7.80 a	5.98 bcd	18.77 ab
	NI-FR	2.33 abc	49.33 ab	1.66 cd	10.60 b	2.76 a–d	7.20 ab	5.60 cd	18.80 ab
	SD	0.89 ef	32.75 de	1.82 abc	4.62 e	2.42 de	4.88 d	4.37 f	10.55 gh
F-test [y]	A	NS	NS	NS	***	***	**	NS	***
	B	***	***	***	***	***	***	***	***
	A × B	***	***	***	***	***	***	***	***

, and * represent non-significant statistical difference or significant statistical difference by a two-way ANOVA F-test at $p \leq 0.01$, and 0.001, respectively.

3.4. Chlorophyll Contents

The contents of chlorophyll were the highest and lowest in 12 and 22 h photoperiods, respectively (Figure 4a,b). Blue, red, and far-red NI lights significantly increased the chlorophyll content in 'Sulhyang', and blue NI light increased the chlorophyll content in 'Maehyang' (Figure 4c,d). Green NI light significantly decreased the chlorophyll content in both cultivars.

3.5. Soluble Sugar and Starch Content

The sugar and starch contents increased with the increase in day length when the photoperiod was less than 20 h, and these carbohydrates decreased in 22-h photoperiods in both cultivars (Figure 5a,b). Red and far-red NI lights significantly promoted the sugar content in both cultivars, compared with that in SD (Figure 5c). All of the NI lights, except for Blue light, increased the starch content compared with SD in 'Maehyang' (Figure 5d).

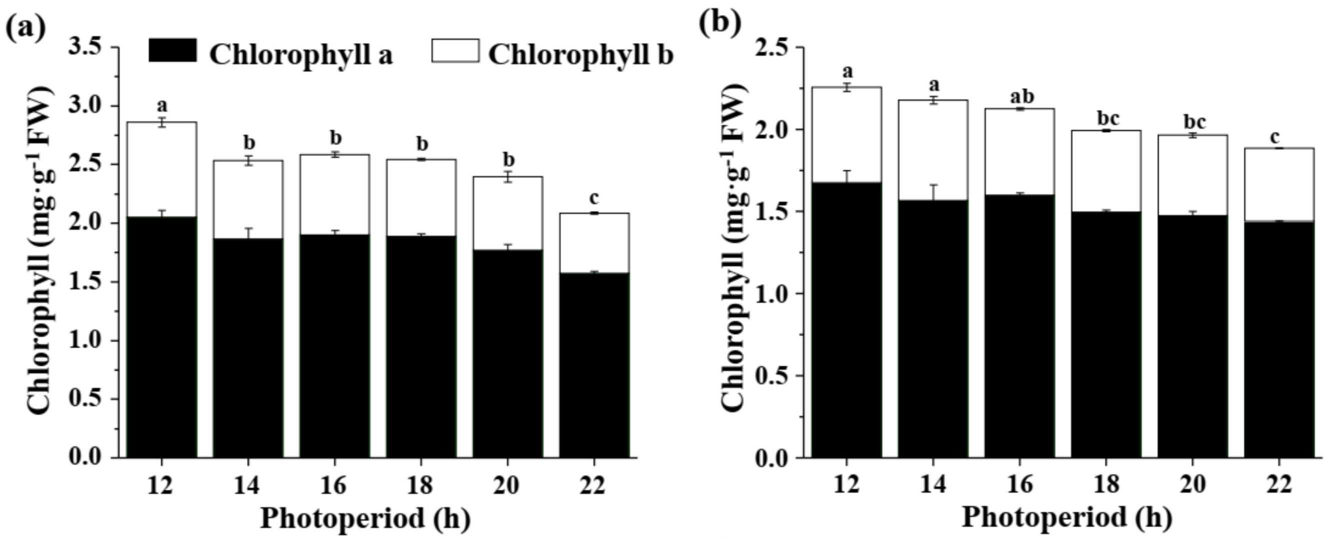

Figure 4. *Cont.*

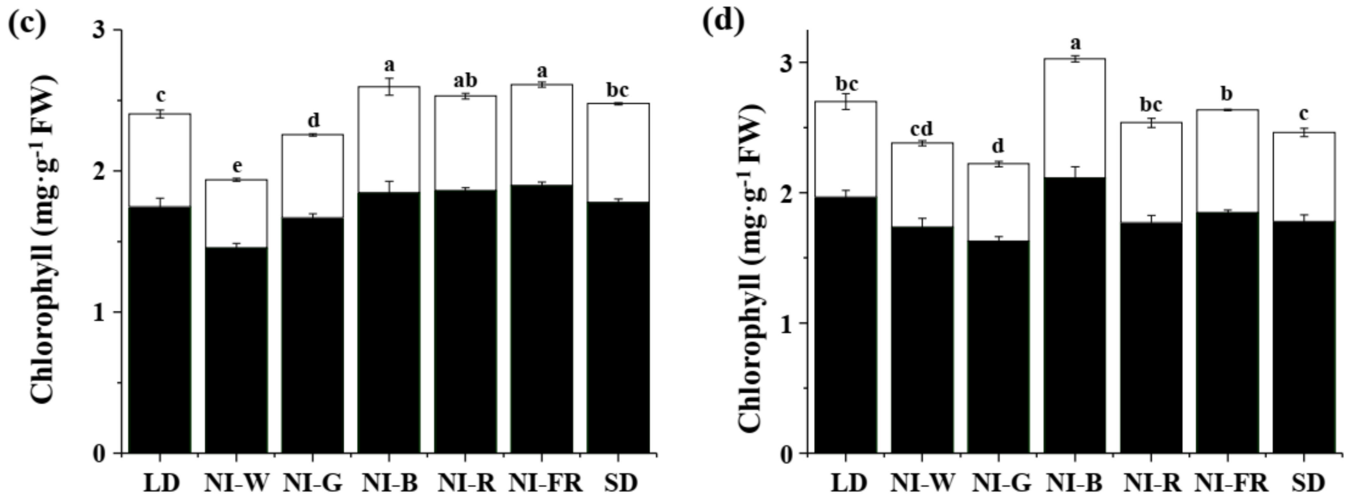

Figure 4. Chlorophyll contents as affected by photoperiod and quality of night interruption (NI) light: (**a**,**b**), the effect of photoperiod on chlorophyll contents in 'Sulhyang' and 'Maehyang', respectively; (**c**,**d**), the effect of NI light on chlorophyll contents in 'Sulhyang' and 'Maehyang', respectively: LD, long day; SD, short day; W, white; G, green; B, blue; R, red; and FR, far-red. Lowercase letters indicate significant difference according to the Duncan's multiple range test at a 0.05 level. Vertical bars indicate standard errors.

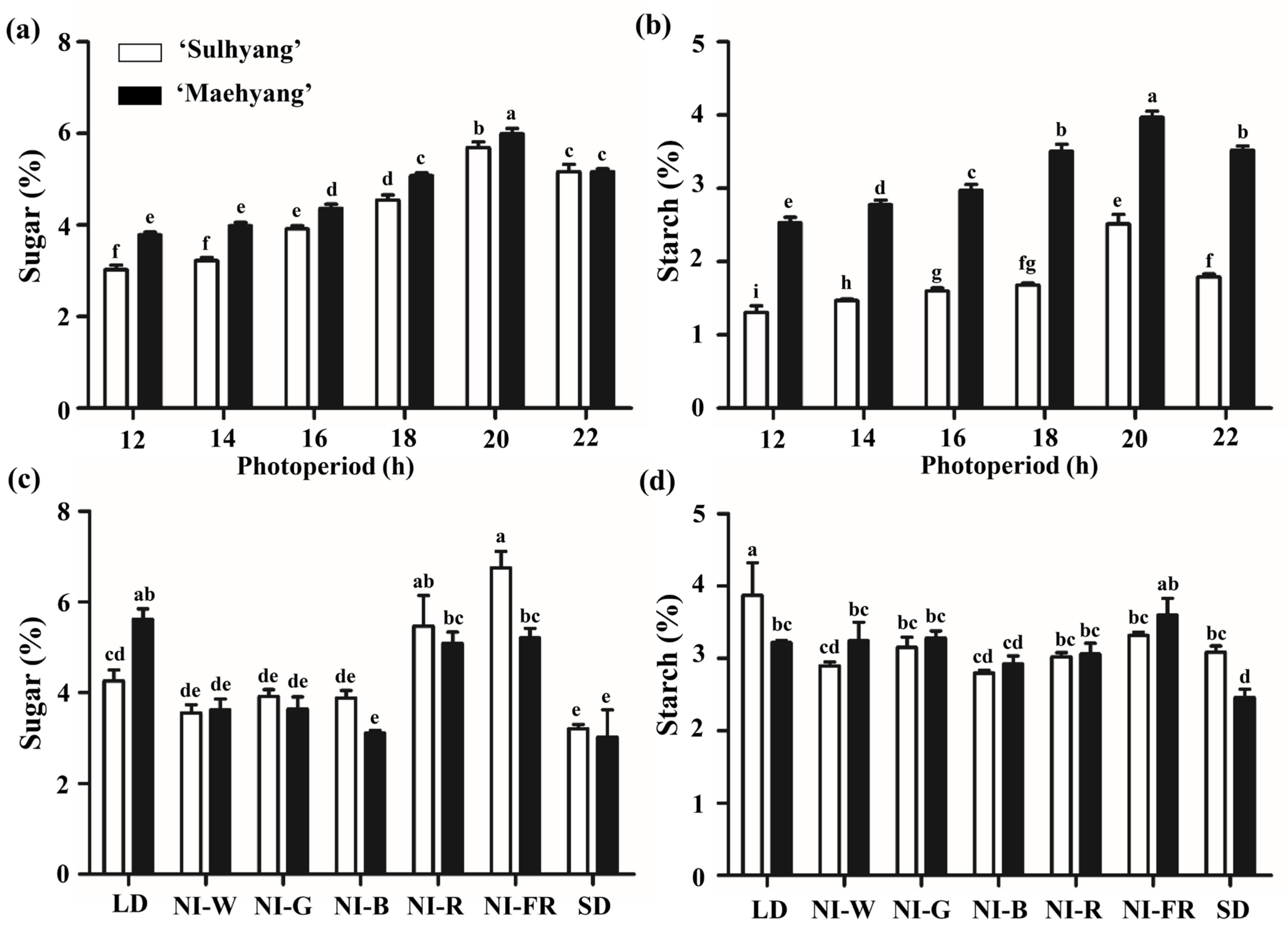

Figure 5. Contents of sugar and starch as affected by photoperiod (**a**,**b**) and quality of night interruption (NI) light (**c**,**d**): LD, long day; SD, short day; W, white; G, green; B, blue; R, red; and FR, far-red. Lowercase letters indicate significant difference according to the Duncan's multiple range test at a 0.05 level. Vertical bars indicate standard errors.

3.6. Chlorophyll Fluorescence Parameters

Although the value of Fv/Fm was not affected by photoperiod, the value of Fv/Fo decreased in 22-h photoperiods in both cultivars (Figure 6). The Fv/Fm and Fv/Fo did not show any significant difference in strawberries treated with different qualities of NI lights (data not shown).

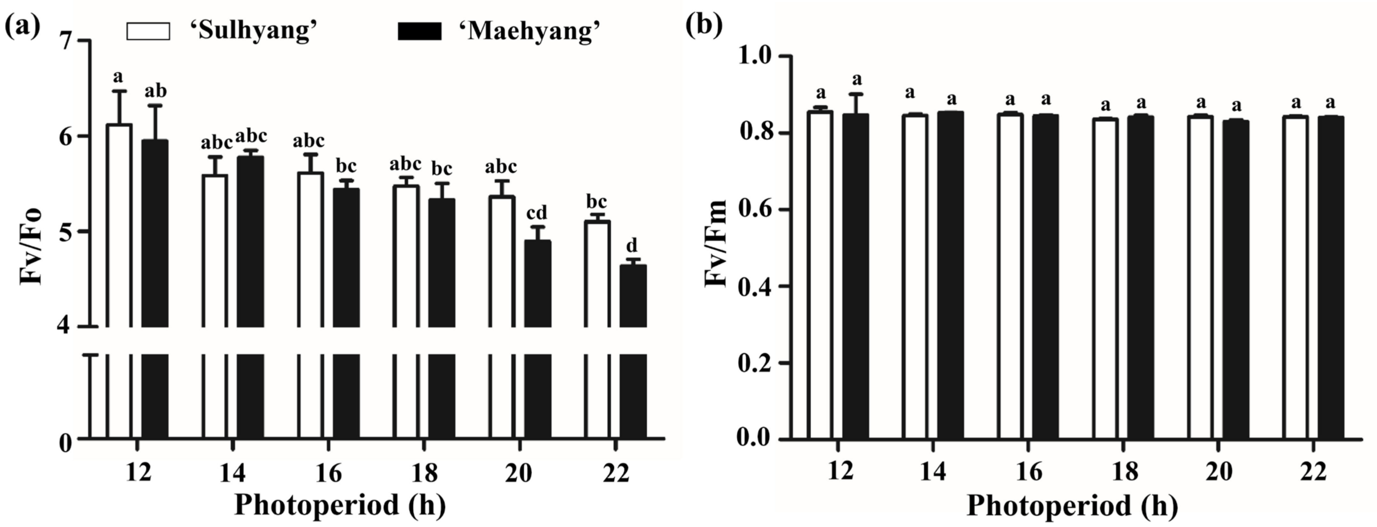

Figure 6. The Fv/Fo (**a**) and Fv/Fm (**b**) as affected by photoperiod. Lowercase letters indicate significant difference according to the Duncan's multiple range test at a 0.05 level. Vertical bars indicate standard errors.

4. Discussion

Light is essential for strawberry runner induction. The optimal light intensity for the vegetative growth of strawberries is 180–270 μmol·m^{-2}·s^{-1} [25]. Thus, the light intensity used in those two experiments was suitable for runner growth. The LD photoperiod is well known for inducing runners in strawberries [26–28]. Researchers found that the growth of runners was enhanced as the photoperiod increased from 10 to 16 h [29]. However, the photoperiod that increases vegetative growth varies with cultivar. Both 'Sulhyang' and 'Maehyang' started to produce runners at a photoperiod longer than 16 h in this study. The light intensity in the growth chamber was lower than that for natural light. Thus, strawberries may need longer photoperiods to produce enough photosynthate for runner initiation in growth chambers. The LD photoperiods were reported to be conducive of vegetative growth, including plant height, and fresh and dry weights in some plant species. However, the LD photoperiods used in those cases were generally even less than 18 h [30,31]. The growth of runners, which is also considered a vegetative growth, increased, while the growth of plants decreased when a photoperiod was longer than 20 h in this study. Thus, it was more conducive to the growth of runners than when the photoperiod was longer than 20 h.

The contents of chlorophyll, sugar, and starch were significantly decreased under 22-h photoperiods in both cultivars. The chlorophyll fluorescence parameters reflect the activity of the PS II reaction center. Both Fv/Fm and Fv/Fo are important parameters that reflect the activity of PS II [32,33]. Although the value of Fv/Fm did not show any difference among different photoperiods, the value of Fv/Fo was decreased in 22-h photoperiods. The Fv/Fm is a relatively inert ratio, while the ratio of Fv/Fo is more sensitive and a better indicator than Fv/Fm [34,35]. These data indicated that the photosynthesis decreased due to the low activity of the PS II. These results suggested that a photoperiod longer than 20 h was not suitable for runner induction.

NI lighting, which breaks the dark period, is useful to deliver photoperiodic lighting and to create LD-like conditions [36]. Vegetative growth increased by NI light through enhanced photosynthesis [37]. Some researchers found that NI light significantly increased the number of runners in everbearing strawberries [38]. The number of runners was also significantly increased by some NI light qualities in this study. Although the NI light used was only 70 μmol·m^{-2}·s^{-1} PPFD, a similar number of runners as strawberries treated with LD was found in those treatments, which means less electrical energy was spent to induce the same number of runners when compared with those in LD. Red NI light was found to be the best light for runner induction in both cultivars. Red and blue lights have great effects on plant growth because these lights contain the main light spectra for photosynthetic CO_2 fixation in plants [39]. Moreover, red light led to larger increases in the accumulation of photosynthate than blue light [40–42]. Red light also plays an important role in inducing starch degradation in many plants [43,44], which is very important for plant growth [45]. The soluble sugar content was increased by red NI light in this study. Thus, red light may have promoted runner induction by increasing photosynthesis and promoting starch degradation to provide more sugar and energy for growth of runners [10]. In addition, far-red NI light was found to increase plant height in some plants [46,47], since far-red light increases GA levels in plants [48,49], which may have been a reason for the elongated runners by far-red NI light in this study.

The genetic control of runner formation in cultivated strawberries is quite intricate due to their large number of chromosomes (2n = 8× = 56). Although several quantitative trait loci were reported to be related to runner formation in cultivated strawberries [50,51], the exact mechanism of runner induction still remains unknown. Previous work found the photoperiod to be the most influential factor for runner induction [10], and photosynthates such as sugar and starch are crucial for initiation of runners. However, the contents of sugar and starch were not always positively correlated with the number of runners in this study, indicating that the accumulation of photosynthates was not the only factor that affected the runner induction in cultivated strawberries. Some researchers also found that plant hormones are essential for the induction of axillary meristems and growth of runners. GA is widely recognized as playing an important role in runner induction in wild strawberries [52]. Moreover, recent research found that a high cytokinin to auxin ratio in the axillary bud triggers runner formation [53]. Thus, to help understand the mechanism of runner induction in cultivated strawberries, future work should focus on detecting the contents of hormones in different tissues of strawberry plants and on finding out the regulatory pathways involved.

5. Conclusions

'Sulhyang' and 'Maehyang' strawberries started to produce runners when a photoperiod longer than 16 h was provided, and the number of runners induced was positively correlated with the length of the photoperiod. However, plant growth and the contents of chlorophyll, sugar, and starch were significantly decreased in the 22-h photoperiod. Thus, a photoperiod between 16 and 20 h is suggested to induce runners in 'Sulhyang' and 'Maehyang'. Moreover, red NI light at an intensity of 70 μmol·m^{-2}·s^{-1} PPFD promoted more runner induction in both cultivars in this study.

Author Contributions: Conceptualization, B.R.J. and Y.L.; methodology, B.R.J. and Y.L.; software, Y.L.; validation, B.R.J.; investigation, Y.L., J.H. and J.X.; resources, B.R.J.; data curation, B.R.J., Y.L. and J.X.; writing—original draft preparation, Y.L.; writing—review and editing, B.R.J. and J.H.; supervision, B.R.J.; project administration, B.R.J. and Y.L.; funding acquisition, B.R.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries (Project No. 118078-2). Y.L. was supported by a scholarship from the China Scholarship Council, J.X. was supported by a scholarship from the BK21 Four, the Ministry of Education, Republic of Korea.

Data Availability Statement: The data presented in this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Li, D.; Zhang, X.; Qu, H.; Li, L.; Mao, B.; Xu, Y.; Lin, X.; Luo, Z. Delaying the biosynthesis of aromatic secondary metabolites in postharvest strawberry fruit exposed to elevated CO_2 atmosphere. *Food Chem.* **2020**, *306*, 125611. [CrossRef]
2. Caruana, J.C.; Sittmann, J.W.; Wang, W.; Liu, Z. Suppressor of runnerless encodes a della protein that controls runner formation for asexual reproduction in strawberry. *Mol. Plant* **2018**, *11*, 230–233. [CrossRef]
3. Heide, O.M. Photoperiod and temperature interactions in growth and flowering of strawberry. *Physiol. Plantarum* **1977**, *40*, 21–26. [CrossRef]
4. Heide, O.; Stavang, J.; Sønsteby, A. Physiology and genetics of flowering in cultivated and wild strawberries—A review. *J. Hortic. Sci. Biotechnol.* **2013**, *88*, 1–18. [CrossRef]
5. Hytönen, T.; Elomaa, P.; Moritz, T.; Junttila, O. Gibberellin mediates daylength-controlled differentiation of vegetative meristems in strawberry (*Fragaria× ananassa* duch). *BMC Plant Biol.* **2009**, *9*, 1–12. [CrossRef] [PubMed]
6. Mouhu, K.; Kurokura, T.; Koskela, E.A.; Albert, V.A.; Elomaa, P.; Hytönen, T. The *Fragaria vesca* homolog of suppressor of overexpression of constans1 represses flowering and promotes vegetative growth. *Plant Cell* **2013**, *25*, 3296–3310. [CrossRef] [PubMed]
7. Sønsteby, A.; Heide, O. Quantitative long-day flowering response in the perpetual-flowering F1 strawberry cultivar elan. *J. Hortic. Sci. Biotechnol.* **2007**, *82*, 266–274. [CrossRef]
8. Hytönen, T.; Elomaa, P. Genetic and environmental regulation of flowering and runnering in strawberry. *Genes Genom. Genom.* **2011**, *5*, 56–64.
9. Sonsteby, A.; Nes, A. Short days and temperature effects on growth and flowering in strawberry (*Fragaria× ananassa* duch.). *J. Hortic. Sci. Biotechnol.* **1998**, *73*, 730–736. [CrossRef]
10. Li, Y.; Hu, J.; Wei, H.; Jeong, B.R. A long-day photoperiod and 6-benzyladenine promote runner formation through upregulation of soluble sugar content in strawberry. *Int. J. Mol. Sci.* **2020**, *21*, 4917. [CrossRef]
11. Ohashi-Kaneko, K.; Takase, M.; Kon, N.; Fujiwara, K.; Kurata, K. Effect of light quality on growth and vegetable quality in leaf lettuce, spinach and komatsuna. *Environ. Control Biol.* **2007**, *45*, 189–198. [CrossRef]
12. Wu, C.; Hsu, S.; Chang, M.; Fang, W. Effect of light environment on runner plant propagation of strawberry. In Proceedings of the VI International Symposium on Light in Horticulture, Tsukuba, Japan, 15–19 November 2009; Volume 907, pp. 297–302.
13. Aubé, M.; Roby, J.; Kocifaj, M. Evaluating potential spectral impacts of various artificial lights on melatonin suppression, photosynthesis, and star visibility. *PLoS ONE* **2013**, *8*, e67798. [CrossRef]
14. Dufault, R.J.; Ward, B.K. Further attempts to enhance forced 'sweet charlie'strawberry yield through manipulation of light quality in high tunnels. *Int. J. Fruit Sci.* **2009**, *9*, 409–418. [CrossRef]
15. Uddin, A.J.; Hoq, M.; Rini, S.; Urme, F.; Ahmad, H. Influence of supplement led spectrum on growth and yield of strawberry. *J. Biosci. Agr. Res.* **2018**, *16*, 1348–1355. [CrossRef]
16. Kim, S.-K.; Jeong, M.-S.; Park, S.-W.; Kim, M.-J.; Na, H.-Y.; Chun, C.-H. Improvement of runner plant production by increasing photosynthetic photon flux during strawberry transplant propagation in a closed transplant production system. *Hortic. Sci. Technol.* **2010**, *28*, 535–539.
17. Kim, Y.J.; Lee, H.J.; Kim, K.S. Night interruption promotes vegetative growth and flowering of *Cymbidium*. *Sci. Hortic.* **2011**, *130*, 887–893. [CrossRef]
18. Kang, K.J.; Oh, W.; Shin, J.H.; Kim, K.S. Night interruption and cyclic lighting promote flowering of *Cyclamen persicum* under low temperature regime. *Hortic. Environ. Biotechnol.* **2008**, *49*, 72–77.
19. Blanchard, M.G.; Runkle, E.S. Use of a cyclic high-pressure sodium lamp to inhibit flowering of chrysanthemum and velvet sage. *Sci. Hortic.* **2009**, *122*, 448–454. [CrossRef]
20. Yamada, A.; Tanigawa, T.; Suyama, T.; Matsuno, T.; Kunitake, T. Red: Far-red light ratio and far-red light integral promote or retard growth and flowering in *Eustoma grandiflorum* (raf.) shinn. *Sci. Hortic.* **2009**, *120*, 101–106. [CrossRef]
21. Park, Y.J.; Kim, Y.J.; Kim, K.S. Vegetative growth and flowering of *Dianthus*, *Zinnia*, and *Pelargonium* as affected by night interruption at different timings. *Hortic. Environ. Biotechnol.* **2013**, *54*, 236–242. [CrossRef]
22. Koskela, E.A.; Hytönen, T. Control of flowering in strawberries. In *The Genomes of Rosaceous Berries and Their Wild Relatives*; Hytönen, T., Graham, J., Harrison, R., Eds.; Springer: Cham, Switzerland, 2018; pp. 35–48.
23. De Kort, H.; Panis, B.; Helsen, K.; Douzet, R.; Janssens, S.B.; Honnay, O. Pre-adaptation to climate change through topography-driven phenotypic plasticity. *J. Ecol.* **2020**, *108*, 1465–1474. [CrossRef]
24. Wang, M.; Xiao, J.; Wei, H.; Jeong, B.R. Supplementary light source affects growth and development of carnation 'dream-byul'cuttings. *Agronomy* **2020**, *10*, 1217. [CrossRef]
25. Zheng, J.; Ji, F.; He, D.; Niu, G. Effect of light intensity on rooting and growth of hydroponic strawberry runner plants in a LED plant factory. *Agronomy* **2019**, *9*, 875. [CrossRef]
26. Guttridge, C.; Thompson, P. The effect of gibberellins on growth and flowering of *Fragaria* and *Duchesnea*. *J. Exp. Bot.* **1964**, *15*, 631–646. [CrossRef]
27. Guo, L.; Plunkert, M.; Luo, X.; Liu, Z. Developmental regulation of stolon and rhizome. *Curr. Opin. Plant Biol.* **2021**, *59*, 101970. [CrossRef] [PubMed]
28. Li, W.; Wang, B.; Sun, H.; Zhang, Z. Transcriptome profiling of runner formation induced by exogenous gibberellin in *Fragaria vesca*. *Sci. Hortic.* **2021**, *281*, 109966. [CrossRef]

29. Butare, D. Effect of Temperature on Plant Growth and Yield in Everbearing Strawberry *Fragaria x ananassa*, cv. Florentina. A2E. Master Thesis, The Swedish University of Agricultural Sciences, Uppsala, Sweden, 29 August 2020.
30. Zhao, Y.; Wang, Z.; Wei, H.; Bao, Y.; Guo, P. Effect of prolonged photoperiod on morphology, biomass accumulation and nutrient utilization in post-transplant *Taxus cuspidata* seedlings. *Pak. J. Bot.* **2017**, *49*, 1285–1290.
31. Zha, L.; Liu, W. Effects of light quality, light intensity, and photoperiod on growth and yield of cherry radish grown under red plus blue leds. *Hortic. Environ. Biotechnol.* **2018**, *59*, 511–518. [CrossRef]
32. Roháček, K. Chlorophyll fluorescence parameters: The definitions, photosynthetic meaning, and mutual relationships. *Photosynthetica* **2002**, *40*, 13–29. [CrossRef]
33. Rascher, U.; Liebig, M.; Lüttge, U. Evaluation of instant light-response curves of chlorophyll fluorescence parameters obtained with a portable chlorophyll fluorometer on site in the field. *Plant Cell Environ.* **2000**, *23*, 1397–1405. [CrossRef]
34. Maxwell, K.; Johnson, G.N. Chlorophyll fluorescence—A practical guide. *J. Exp. Bot.* **2000**, *51*, 659–668. [CrossRef]
35. Zhu, X.-C.; Song, F.-B.; Xu, H.-W. Arbuscular mycorrhizae improves low temperature stress in maize via alterations in host water status and photosynthesis. *Plant Soil* **2010**, *331*, 129–137. [CrossRef]
36. Kim, Y.J.; Yu, D.J.; Rho, H.; Runkle, E.S.; Lee, H.J.; Kim, K.S. Photosynthetic changes in *Cymbidium* orchids grown under different intensities of night interruption lighting. *Sci. Hortic.* **2015**, *186*, 124–128. [CrossRef]
37. Torres, A.P.; Lopez, R.G. Photoperiod and temperature influence flowering responses and morphology of *Tecoma stans*. *HortScience* **2011**, *46*, 416–419. [CrossRef]
38. Sønsteby, A.; Heide, O. Long-day control of flowering in everbearing strawberries. *J. Hortic. Sci. Biotechnol.* **2007**, *82*, 875–884. [CrossRef]
39. Aliniaeifard, S.; Seif, M.; Arab, M.; Zare Mehrjerdi, M.; Li, T.; Lastochkina, O. Growth and photosynthetic performance of *Calendula officinalis* under monochromatic red light. *Int. J. Hortic. Sci. Technol.* **2018**, *5*, 123–132.
40. Kang, W.H.; Park, J.S.; Park, K.S.; Son, J.E. Leaf photosynthetic rate, growth, and morphology of lettuce under different fractions of red, blue, and green light from light-emitting diodes (leds). *Hortic. Environ. Biotechnol.* **2016**, *57*, 573–579. [CrossRef]
41. Rehman, M.; Ullah, S.; Bao, Y.; Wang, B.; Peng, D.; Liu, L. Light-emitting diodes: Whether an efficient source of light for indoor plants? *Environ. Sci. Pollut. Res.* **2017**, *24*, 24743–24752. [CrossRef] [PubMed]
42. Miao, Y.; Chen, Q.; Qu, M.; Gao, L.; Hou, L. Blue light alleviates 'red light syndrome'by regulating chloroplast ultrastructure, photosynthetic traits and nutrient accumulation in cucumber plants. *Sci. Hortic.* **2019**, *257*, 108680. [CrossRef]
43. Appenroth, K.J.; Gabrys, H. Light-induced starch degradation in non-dormant turions of *Spirodela polyrhiza*. *Photochem. Photobiol.* **2001**, *73*, 77–82. [CrossRef]
44. Appenroth, K.J.; Ziegler, P. Light-induced degradation of storage starch in turions of *Spirodela polyrhiza* depends on nitrate. *Plant Cell Environ.* **2008**, *31*, 1460–1469. [CrossRef] [PubMed]
45. Smith, A.M.; Zeeman, S.C.; Smith, S.M. Starch degradation. *Annu. Rev. Plant Biol.* **2005**, *56*, 73–98. [CrossRef] [PubMed]
46. Yang, F.; Huang, S.; Gao, R.; Liu, W.; Yong, T.; Wang, X.; Wu, X.; Yang, W. Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red: Far-red ratio. *Field Crop Res.* **2014**, *155*, 245–253. [CrossRef]
47. Park, Y.G.; Muneer, S.; Jeong, B.R. Morphogenesis, flowering, and gene expression of *Dendranthema grandiflorum* in response to shift in light quality of night interruption. *Int. J. Mol. Sci.* **2015**, *16*, 16497–16513. [CrossRef]
48. Martínez-García, J.F.; Santes, C.M.; García-Martínez, J.L. The end-of-day far-red irradiation increases gibberellin a1 content in cowpea (*vigna sinensis*) epicotyls by reducing its inactivation. *Physiol. Plant.* **2000**, *108*, 426–434. [CrossRef]
49. Liao, Y.; Suzuki, K.; Yu, W.; Zhuang, D.; Takai, Y.; Ogasawara, R.; Shimazu, T.; Fukui, H. Night-break effect of led light with different wavelengths on shoot elongation of *Chrysanthemum morifolium* ramat 'jimba'and 'iwa no hakusen'. *Environ. Control Biol.* **2014**, *52*, 51–55. [CrossRef]
50. Gaston, A.; Perrotte, J.; Lerceteau-Köhler, E.; Rousseau-Gueutin, M.; Petit, A.; Hernould, M.; Rothan, C.; Denoyes, B. PFRU, a single dominant locus regulates the balance between sexual and asexual plant reproduction in cultivated strawberry. *J. Exp. Bot.* **2013**, *64*, 1837–1848. [CrossRef]
51. Hossain, M.R.; Natarajan, S.; Kim, H.T.; Jesse, D.M.I.; Lee, C.G.; Park, J.I.; Nou, I.S. High density linkage map construction and QTL mapping for runner production in allo-octoploid strawberry *Fragaria× ananassa* based on ddRAD-seq derived SNPs. *Sci. Rep.* **2019**, *9*, 1–11. [CrossRef]
52. Martins, A.O.; Nunes-Nesi, A.; Araújo, W.L.; Fernie, A.R. To bring flowers or do a runner: Gibberellins make the decision. *Mol. Plant* **2018**, *11*, 4–6. [CrossRef]
53. Qiu, Y.; Guan, S.C.; Wen, C.; Li, P.; Gao, Z.; Chen, X. Auxin and cytokinin coordinate the dormancy and outgrowth of axillary bud in strawberry runner. *BMC Plant Biol.* **2019**, *19*, 1–16. [CrossRef]