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The effects of LEDs and duty ratio on the growth and physiological responses of *Silene capitata* Kom., endangered plant, in a plant factory

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Abstract

Background: In this study, we observed their growth and physiological responses using a variety of duty ratio under the mixed light using red, blue, and white lights. The red+blue mixed light was treated with 95%, 90%, 85%, 80%, and 75% duty ratios and red+blue+white mixed light with 85% and 70% duty ratios. We examined the width and length of leaves, total number of leaves, and number of shoots to examine their growth responses. The physiological responses were studied by measuring their photosynthetic rate, transpiration rate, stomatal conductance, water use efficiency, chlorophyll content, and fluorescence (F_o, F_m, and F_v/F_m).

Results: We found that lower duty ratio caused the length and width of the leaves to grow longer under red+blue mixed light but that it did not cause any difference in the red+blue+white mixed light condition. In addition, there was no difference in the number of leaves and shoots among all treatments. In the red+blue mixed light condition, the photosynthetic rate was no difference, but both transpiration rate and stomatal conductance were the highest at 95% duty ratio than in other ratios. Water use efficiency pattern was similar to that of photosynthetic rate; water use efficiency was no difference. Chlorophyll content was the highest at 95% duty ratios, and it was the least at 90%, 85%, and 75% duty ratio. F_o and F_m values were relatively high at 85% and 80% duty ratio and low at 90% duty ratio while F_v/F_m showed no difference.

Conclusions: Under the red+blue+white mixed light, all physiological items showed no difference between 70 and 85% treatments. But, photosynthetic rate, water use efficiency, chlorophyll content, and F_v/F_m were relatively greater in the red+blue+white mixed light than in the red+blue mixed light. Therefore, red+blue+white mixed light treated with 70% duty ratio could lessen the environmental stress and save more power when cultivating *Silene capitata* in a plant factory.

Keywords: Caryophyllaceae, Ecophysiological response, Environmental tolerance, Indoor plant, Light quality

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Background

Climate change, a global issue, increased the global annual temperature by 0.85 °C from 1880 to 2012 and the average global sea level by 19 cm from 1901 to 2010 (Ministry of Environment 2017). Moreover, it was reported that the area of Arctic Sea Ice is declining at a rate of 3.5–4.1% per decade (Ministry of Environment 2017). The increasing pattern of annual temperature and sea level is observed in Korea as well. The annual temperature in Korea increased by 0.23 °C per decade from 1954 to 1999, 0.41 °C per decade from 1981 to 2010, and 0.5 °C per decade from 2001 to 2010 (Ministry of Environment 2017). If the current trend follows the RCP 8.5 scenario, the domestic temperature between 2017 and 2100 is expected to rise by 5.3 °C compared to the present temperature (Ministry of Environment 2017). These environmental changes can lead to an extreme weather conditions (Houghton et al. 2001), and it is estimated that such change in the weather could reduce the biodiversity in Asia, including the Korean Peninsula, and cause a great deal of environmental impacts such as diseases and floods.

In order to overcome the adverse effects on agriculture caused by a recent change in weather, the plant factory, which is capable of cultivating crops in a closed space regardless of the season or temperature, was developed (Kim 2010). The plant factory can be categorized into partial control type that uses natural and artificial light and complete control one that only uses artificial light (Kim 2010).

Since the partial control type can use sunlight as a light source, the power consumed by lighting equipment can be saved more than the full control type, but the disadvantage is that it is difficult to control the environment as it is affected by the external environment. In addition, it is difficult to expect uniform plant growth when a multi-stage bed is installed (Kim 2010). The full control type can control the precise environment and can manage the growth state stably regardless of the season. However, an alternative power saving is required because of the high amount of electricity consumed by the lighting equipment (Kim 2010).

Light-emitting diodes (LEDs), the light source used in this study, were installed by selecting a specific wavelength effective for the development of plants and photosynthesis. LEDs generate relatively low heat compared with high-pressure sodium lamp, fluorescent lamp, and hybrid electrode fluorescent lamp (HEFL), and it reduces the damage to the plants and consumes less electricity (Kim 2010). For its advantage, much research on the productivity and physiological response of flowers and crop plants such as chrysanthemum, *Phalaenopsis*, *Petunia*, rocket salad, lamb's lettuce, lettuce, cucumber, wheat, spinach, radish, tomato, and rice cultivated in glasses, in greenhouses, or in plant factories has been reported (Goins et al. 1997; Yorio et al. 2001; Matsuda et al. 2004; Trouwborst et al. 2010; Lu et al. 2012; Im et al. 2013; Kim et al. 2013; Kobayashi et al. 2013; Wojciechowska et al. 2013; Phansurin et al. 2017; Lee et al. 2017; Kim et al. 2018).

Silene capitata Kom. is a perennial herb that belongs to Caryophyllaceae which grows naturally in Mt. Naejang in South Korea and in the central part of North Korea (NIBR 2011). Their habitat characteristics are shaded places with less light compared to open areas and rock slopes with less moisture and available soil nutrients (NIBR 2011). These features of the habitat environment are suitable to utilize the limited conditions—it can reduce power consumption when cultivating by using less light and can grow even with less water and soil nutrients—of a plant factory. Also, it is easy to manage in a plant factory because the shoot height is small, growing up to 30 cm (NIBR 2011).

S. capitata forms a rosette, and the leaf of the peduncle is smaller than the rosette leaf. The pink color of the flower is clear and impressive compared to the green leaves. Through observations in this study, we found that the flowers are formed on the leaf axil as well as on the tips of the peduncles. It can bloom more than hundreds per plant in a certain environment (Park et al. 2016). The flowering period is from October to November, and it flowers throughout the month (NIBR 2011). But their basic ecological and physiological information is not well known. Therefore, a basic ecophysiological study should be preceded in order to develop a cultivation method of *S. capitata* for conservational purposes.

In this study, the optimal light environment for the growth and physiological response of *S. capitata* was investigated by using an LED light source by applying different duty ratios in the plant factory. We used the red+blue mixed light and red+blue+white mixed light as a light quality because red light and blue light which are mainly absorbed by chlorophyll and are known to regulate photomorphogenesis and photosynthesis are commonly used in a plant factory (Hopkins and Huner 2008).

White light wavelength is not well absorbed by a chlorophyll; they are absorbed by pigments such as carotenoids and anthocyanins (Hopkins and Huner 2008). For cucumbers (*Cucumis sativus*), the growth rate, carbon assimilation rate, and photon yield of PSII were higher under white single light than in purple, red, blue, green, and yellow single light (Wang et al. 2009). The photon yield of PSII (F_v/F_m) of *S. capitata* was higher in R+B+W than in R+B (Park et al. 2016). For *Lactuca sativa* var. *capitata*, the biomass of aboveground and underground part, dry mass, and sugar content were higher in R+B+W than in R+B (Lin et al. 2013). Therefore, additional treatment of white light in red+blue mixed light may be more effective for plant growth and physiological responses.

Duty ratio (DR), which is used as a power-saving measure in this study, is defined as the fraction of light-on-time to the light on-and-off cycle (Kim et al. 2014). Several studies reported that crop growth and physiological responses were affected when DR feeds on crops were controlled (Cho et al. 2013; Mori et al. 2002). Therefore, controlling DR in plant factories could be utilized as an energy-saving technique.

In this study, we investigated that *S. capitata* is grown well in a plant factory that affected on proliferation and production of plants and not affected on the external environment. The collected information could be available of basic data on an optimal and stable indoor cultivation technique for *S. capitata*.

Methods

Cultivation and management

For the purpose of this study, the seeds of *S. capitata* were sown on March 20, 2014, in the greenhouse located within Kongju National University. The seeds were sown on a basal plate (60 × 30 × 3.5 cm) filled with Hanareum horticultural bed soil (Shinsung Mineral, Goesan, South Korea), and they were watered every 2–3 days until germination to prevent soil from drying out. The germinated seedlings were transplanted into round pots (diameter 12 cm, height 15 cm) also filled with Hanareum horticultural bed soil (Shinsung Mineral, Goesan, South Korea), and they were placed under seven light conditions (light chambers). Three plants were placed under each light condition. The plants were cultivated from June 2013 to March 2014. The transplanted seedlings were watered every 2–3 days to prevent the soil from drying out. Soil nutrients (Gold Soil, KGChemical, Ulsan, South Korea) containing organic matter (70%), nitrogen (4.3%), phosphoric acid (1.7%), and potassium (1%) were diluted in water and supplied at 7-day intervals.

During the cultivation period, the temperature inside the plant factory was maintained at 19.42 ± 5.10 °C on average using a hot air heater (SS-2000, Zero Engineering, Daejeon, South Korea), and the humidity was maintained at an average of 71.81 ± 9.22% using a humidifier (Fox-1H, Parus, Shanghai, China). Photosynthetic photon flux density (PPFD) in each chamber remained constant at an average of 150.89 ± 23.05 μmolm^{-2} s^{-1}, and the concentration of CO_2 was 401.59 ± 86.87 ppm. These environmental data were collected and managed every 10 min using a computer-based LCSEMS program (Parus, Shanghai, China). The day length was set at 16 h out of 24 h a day.

Light conditions in the plant factory

A total of seven light conditions were set inside the plant factory (Table 1) using "LED grow light system" developed by Parus (Shanghai, China). The size of the plant factory is 360 × 60 × 230 cm^3; it has three shelves in the container (582 × 334 × 260 cm^3). The power consumption of each light source was 200 W, and the size of the installed chamber (PGL-BOX, Parus, Shanghai, China) was 120x × 52 × 4.5 cm^3, installed in each shelves in the plant factory. Red light (R) and blue light (B) were selected to create red+blue mixed light (R+B) and red +blue+white mixed light (R+B+W) conditions. The spectral wavelength range of R and B is generally known as 640–700 nm for R and 425–490 nm for B (Hopkins and Huner 2008). In this experiment, R that showed the maximum peak at 630–660 nm range and B that showed the maximum peak at 440 nm in "LED grow light system" was used (Parus, Shanghai, China).

Table 1 LED sources and duty ratios (%) of seven treatments in the plant factory

LED source	Duty ratio (%)	Treatments
R+B	95	RB (95%)
	90	RB (90%)
	85	RB (85%)
	80	RB (80%)
	75	RB (75%)
R+B+W	85	RBW (85%)
	70	RBW (70%)

White light (W), which has the maximum peak at 450 nm and 540 nm, was used, and the wavelength range containing green wavelength (490–550 nm) and yellow wavelength (550–585 nm) was used in addition to R and B.

Measurement of growth responses

The total number of leaves per pot was counted in August 2013, and the length and width of three leaves per plant were measured in November to study the growth response of *S. capitata*. The leaves were selected in the upper, middle, and bottom part per plant. In March 2014, the number of shoots per plant which were budded at the roots was counted.

Measurement of physiological responses

To study the physiological response of *S. capitata*, photosynthetic rate (μmolCO_2m^{-2} s^{-1}), transpiration rate (mmolm^{-2} s^{-1}), stomatal conductance (mmolH_2Om^{-2} s^{-1}), and water use efficiency (μmolCO_2mmolH_2O^{-1}) were measured with "Lci Ultra Compact Photosynthesis System" (ADC, Hoddesdon, UK) between 10:00 a.m. and 12:00 p.m. throughout October 2013. Chlorophyll content was measured using chlorophyll content meter (CCM-200, ADC, Hoddesdon, UK), and it was represented with chlorophyll content index (CCI), a unit measure of chlorophyll content that shows the difference of light absorption rate when 660 nm and 940 nm light is irradiated on the leaves. Using this method, the chlorophyll content was measured nondestructively (Richardson et al. 2002; Van den Berg and Perkins 2004). The photosynthetic rate, transpiration rate, stomatal conductance, water use efficiency, and chlorophyll content were measured 9 times repeatedly. Chlorophyll fluorescence (F_o, F_m, and F_v/F_m) was measured with a chlorophyll fluorescence meter (OS30p, ADC, Hoddesdon, UK) to examine the environmental stress after dark adaptation for 20 min and was measured 18 times repeatedly. The leaves for measuring physiological responses were selected on the upper, middle, and bottom parts in each plant because the physiological responses can be different by the position of a leaf.

Statistical analysis

Statistical analysis of the growth and physiological responses of *S. capitata* was performed using statistical program Statistica 8 (Statsoft Inc., Tulsa, US). One-way ANOVA, which is a parametric statistical method, was used to analyze the data with normality and homoscedasticity. The data with no normality and homoscedasticity were tested using Kruskal-Wallis test, a nonparametric statistical method, with a 0.05 significance probability. The normality of each group was tested using the Shapiro-Wilk *W* test, and the homoscedasticity was tested using Levene's test with 0.05 significance probability as the criterion. The ANOVA, Kruskal-Wallis post-hoc tests, Fisher's least significant difference and Dunn's test for multiple comparisons, the post-hoc tests of the ANOVA and Kruskal-Wallis test were were analyzed in $p < 0.05$ (No and Jeong 2002).

Results

Growth responses

The leaf length was longest in RB (80%) ≥ RB (85%), with RB (75%), RBW (85%), and RBW (70%) ≥ RB (90%) ≥ RB (95%) following in descending order. In the R+B condition, the leaf length was longest at 80% DR and the shortest at 95% DR. In the R+B+W condition, no difference was observed with change in DR (Fig. 1a). The leaf width was widest in RB (85%), with ≥ RB (75%) ≥ RB (80%) ≥ RB (90%), RBW(85%) ≥ RB (95%), and RBW (70%) following in descending order. In the R+B condition, the leaf was widest at 85% DR and narrowest at 95% DR (Fig. 1a). There was no difference in the R+B+W condition (Fig. 1a) and in the number of leaves and shoots among all treatments (Fig. 1b, c).

Physiological responses

Photosynthetic rate was highest in RBW (85%), with RBW (70%) ≥ RB (95%), RB (90%), RB (80%), and RB (75%) ≥ RB (85%) following in descending order (Fig. 2a). In the R+B condition, the photosynthetic rate was lowest when DR was 85%, but no difference was observed in the R+B+W condition (Fig. 2a). Transpiration rate was highest in RB(95%) ≥ RB (90%), with RB (80%), RBW (85%) ≥ RB (85%), RB (75%), and RBW (70%) following in descending order. In the R+B condition, the transpiration rate was highest at 95% DR and lowest at 85% and 75% DR (Fig. 2b). There was no difference in the R+B+W condition with the change in DR (Fig. 2b). Stomatal conductance was highest in RB (95%) ≥ RB (90%), with RB (80%), RB (75%), RBW (85%) ≥ RB (85%), and RBW (70%) following in descending order. In the R+B condition, the stomatal conductance was highest at 95% and lowest at 85% DR (Fig. 2c). There was no difference in the R+B+W condition (Fig. 2c). Water use efficiency was highest in RBW (70%) ≥ RB (90%), with RB (80%), RB (75%), RBW (85%) ≥ RB (95%), and RB (85%) following in descending order. No difference was observed with the change in DR under the R+B and R+B+W conditions (Fig. 2d). Chlorophyll content was highest in RBW (85%) ≥ RB (95%), with RBW (70%) ≥ RB (80%) > RB (90%), RB (85%), and RB (75%) following in descending order. Chlorophyll content was highest at 95% and lowest at 90%, 85%, and 75% DR under the R+B condition (Fig. 2e). However, there was no difference in the R+B+W conditions (Fig. 2e).

F_o value was highest in RB (85%), with RB (80%) ≥ RB (95%), RB (75%) ≥ RB (90%) ≥ RBW (85%), and RBW (70%) following in descending order. In the R+B condition, F_o value was highest at 85% and 80% DR and lowest at 90% DR. But, there was no difference in R+B+W (Fig. 3a). F_m value was highest in RB (80%) ≥ RB (85%) ≥ RB (75%), with RBW (85%), RBW (70%) ≥ RB (95%), and ≥ RB (90%) following in descending order. In the R+B condition, F_m value was highest at 80% and lowest at 90% DR. There was no difference in the R+B+W condition (Fig. 3a). F_v/F_m value was highest in RBW (85%), with RBW (70%) > RB (95%), RB (90%), RB (85%), RB (80%), and RB (75%) following in descending order, showing that the value is higher when white light is added (Fig. 3b). No difference was observed with different DRs in DR in R+B and in R+B+W (Fig. 3b).

Discussions

The growth and physiological responses of *S. capitata* can be observed by subdividing the results into three conditions. The first is the response to the change in DR within the R+B and R+B+W group. The second is the response to the light quality when DR is kept constant. The third is the response to both DR and light quality.

Within the R+B group, leaf length and width are longest when DR was 80% and 85%, respectively. Leaves showed a tendency to grow longer under lower DR (Fig. 1a). The lower the DR, the longer the time that light is not irradiated. Thus, in general, the amount of far-red light is more abundant during the dark period

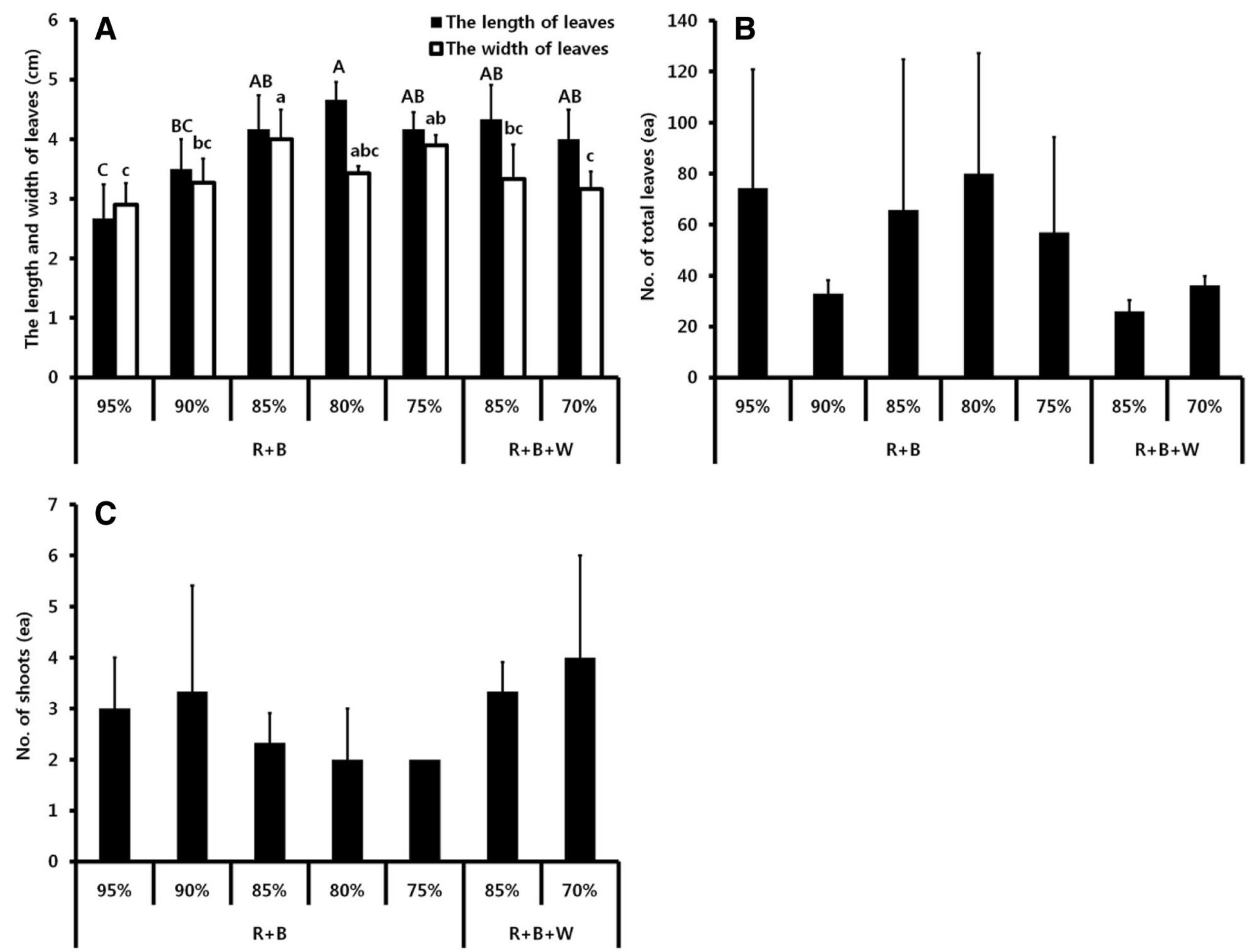

Fig. 1 Length and width of leaves (**a**; cm) of *S. capitata* was analyzed with one-way ANOVA (Fisher's least significant difference, $p > 0.05$) and the number of total leaves (**b**) and shoots (**c**) of *S. capitata* ($n = 3$) were analyzed with Kruskal-Wallis test (Dunn's test, $p > 0.05$). The bars are averages, and error bars show standard deviations of each group. Alphabets on each bar indicate the significant differences among the groups in the plant factory. The graphs without an alphabet on the bar mean there is no significant difference among the each bar

than in the red light, causing R:FR ratio to decrease and helping the stem, leaf, and petiole to grow better (Ballaré et al. 1990). Therefore, it seems that the length and width of the leaves of *S. capitata* grow longer with lower DR under R+B. Within the R+B+W group, there was no difference between 70 and 85% DR. When DR was constant at 85%, there was no difference in the leaf length between RB (85%) and RBW (85%) conditions, but the leaf width was shorter in RBW (85%) than in RB (85%).

Considering both light quality and DR, there was no difference in leaf length between R+B with 75–85% DR and R+B+W with 70–85% DR, but they were longer than R+B with 90–95% DR (Fig. 1a). In contrast, leaf width was greatest under R+B with 75–85% DR, and there was no difference between R+B with 90–95% DR and R+B+W with 70–85% DR (Fig. 1a). Considering that the environment treated with white light has 85% and 70% DR, there is no difference in the leaf length even when white light is additionally treated in a low DR environment, but it seems that the leaf width would be narrower.

The total number of leaves and the number of shoots of *S. capitata* were not different when treated with different DR under R+B or with additional treatment of white light at 85% DR (Fig. 1b, c). The results obtained in this study is the same as the result of the study conducted by Park et al. (2016) that show the total number of leaves of *S. capitata* under continuous light (100% DR) is not different in blue, red, white single light, red +far-red, red+blue, and red+blue+white mixed light conditions. Therefore, it is considered that the treatment of white light does not affect the total number of leaves and vegetative reproduction of *S. capitata*.

Similarly, the total biomass of *Chrysanthemum coronarium* var. *spatiosum* increased with higher DR towards 100% when they were cultivated in R+B with 100%, 99%, and 97% DR. But, the response to DR did

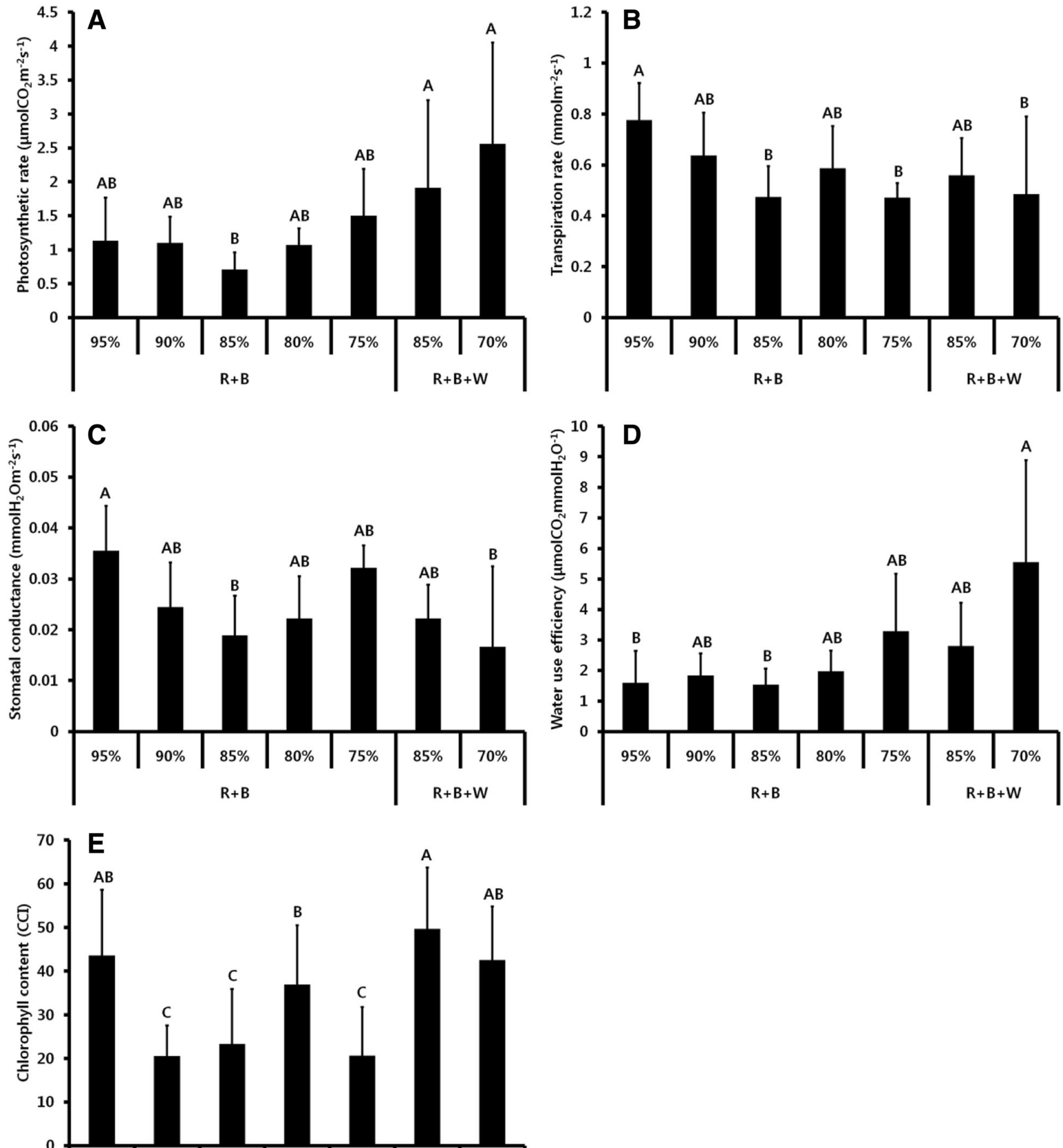

Fig. 2 Photosynthetic rate (**a**; $\mu molCO_2m^{-2}\ s^{-1}$), transpiration rate (**b**; $mmolm^{-2}\ s^{-1}$), stomatal conductance (**c**; $mmolH_2Om^{-2}\ s^{-1}$), and water use efficiency (**d**; $\mu molCO_2mmolH_2O^{-1}$) were analyzed with Kruskal-Wallis test ($n = 9$; Dunn's test, $p > 0.05$), and chlorophyll content (**e**; CCI) in the leaves of *S. capitata* was analyzed with one-way ANOVA ($n = 9$, Fisher's least significant difference, $p > 0.05$). The bars are averages, and error bars show standard deviations of each group. Alphabets on the each bar indicate the significant differences among the groups in the plant factory

not appear when the light quality was set to R+B+W (Kim et al. 2014). Under the same condition, the total biomass of *Brassica campestris* var. *chinensis* was not different in R+B environment unlike that of *C. coronarium* var. *spatiosum*. However, it was greater under R+B+W with 97% DR than R+B+W with 100% and 99% DR

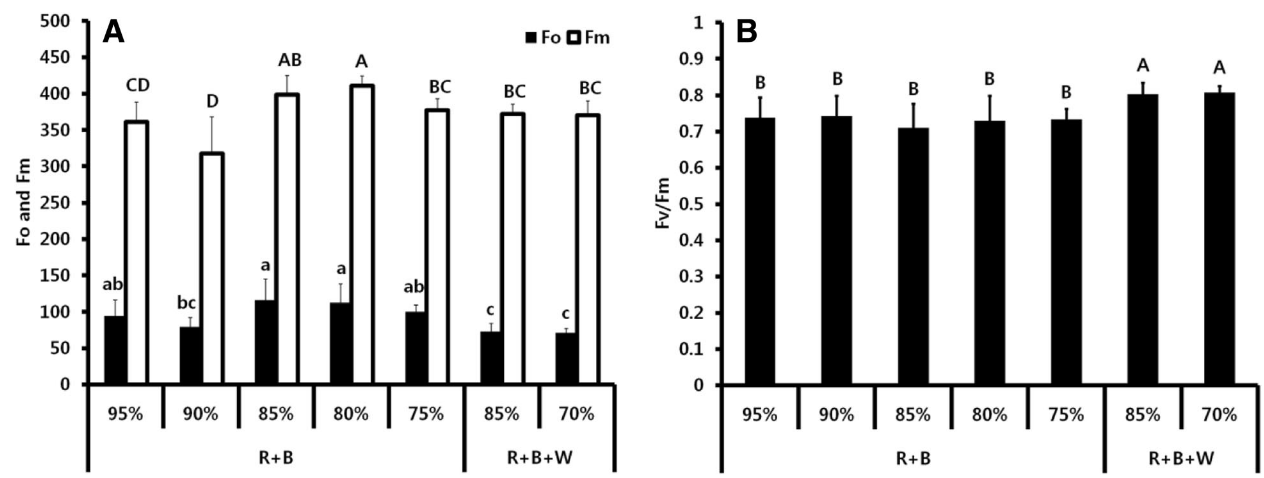

Fig. 3 F_o and F_m (**a**) and F_v/F_m (**b**) in the leaves of *S. capitata* were analyzed with Kruskal-Wallis test ($n = 18$; Dunn's test, $p > 0.05$). The bars are averages, and error bars show standard deviations of each group. Alphabets on each bar indicate the significant differences among the groups in the plant factory

(Kim et al. 2014). It seems that these species respond differently to the light environment because they uniquely adapted themselves to various environmental stresses to survive and to thrive in the wild (Middleton 2001).

In the R+B environment, the physiological response of *S. capitata* showed no difference in the photosynthetic rate and the water use efficiency with different DRs, but the stomatal conductance and the chlorophyll content were different (Fig. 2). These results suggest that, in the R+B environment, the photosynthetic rate of *S. capitata* is not affected with controlled DR. Although the transpiration rate was different, the water use efficiency was indifferent to the change in DR. This would mean that the carbon-fixing ability would not be affected by DR when the same amount of water is supplied.

F_v/F_m values were not affected with the change in DR, but F_o and F_m values were different (Fig. 3). F_o is the minimum fluorescence value when the photosynthetic active light is absent, and F_m is the maximum fluorescence value at maximum photochemical quenching (Maxwell and Johnson 2000). F_v/F_m value indicates the maximum quantum yield of PSII, and it is 0.832 in most plant species (Bjorkman and Demmig 1987). Increasing F_o value and decreasing F_v/F_m value also indicate the photo-inhibiting damage caused by environmental stress (Maxwell and Johnson 2000). F_o value was highest when DR was 85% and 80% although F_v/F_m value did not differ with the change in DR (Fig. 3a, b). This result demonstrates that these environments have relatively higher environmental stress. Yet, the environmental stress was relatively low at 90% DR (Fig. 3a).

Considering that *S. capitata* grows between rocks covered by canopy in the mountains, they are exposed to a stressful environment in which the plants have to photosynthesize using sunflecks, an irregular sunlight, caused by a developed forest crown. The crown reduces the amount of light quantity per day that reaches the forest floor. However, considering that the photosynthetic rate and water use efficiency did not differ with the change in DR (Fig. 2), the photosynthetic response would not be adversely affected if there is a stable water supply even though the light quantity reaching the forest floor is reduced. This is probably because *S. capitata* adapted to an irregular light quantity that reaches their habitat on the forest floor. But, in order to clarify this basic ecophysiology, it would be necessary to investigate their habitat environment in which they naturally grow and their physiological responses under various DR.

In R+B+W, there was no difference in all measured physiological responses with the change in DR (Figs. 2 and 3). This suggests that there is no significant change in physiological activity even if DR is changed. However, R+B+W was treated with only two conditions, 85% DR and 70% DR, in this experiment. Additional experiments should be conducted to determine whether there are differences under various DR conditions.

Photosynthetic rate and chlorophyll content of *S. capitata* were higher in RB (85%) than in RBW (85%) when DR was 85%, but there were no differences in transpiration rate, stomatal conductance, and water use efficiency (Fig. 2). In other studies, photosynthetic rate of *S. capitata* was higher in R+B+W than in R+B under continuous light (100% DR). But, the chlorophyll content did not differ between R+B and R+B+W treatments. It has been reported that chlorophyll content is produced more under the white single light than under the red and blue single light (Park et al. 2016). These results mean that lower DR would cause lower chlorophyll content if the environment lacks white light.

In addition, the result of Park et al. (2016) showed that transpiration rate, stomatal conductance, and water use efficiency of *S. capitata* under the continuous light did not differ between R+B and R+B+W, which is similar to the result of this study. Therefore, photosynthetic rate increases and more chlorophyll is synthesized with additional white light if DR remains constant, but this does not seem to have a significant effect on water use efficiency. However, F_o value is higher in RB (85%) than in RBW (85%), and F_v/F_m value is higher in RBW (85%) than in RB (85%) (Fig. 3). This result is similar to the study conducted by Park et al. (2016) that F_v/F_m was higher in R+B+W than in R+B under continuous light. The addition of white light seems to alleviate the environmental stresses on *S. capitata*.

When photosynthetic rate and DR were considered together, photosynthetic rate, water use efficiency, and chlorophyll content were greater in R+B+W than in R+B (Fig. 2). But, transpiration rate and stomatal conductance were highest in RB (95%) and relatively low in RBW (70%), showing a contrast (Fig. 2). It is thought that when white light is added, the amount of water released through pores is decreased and the photosynthetic rate is increased, resulting in higher water use efficiency. F_o and F_v/F_m values showed similar results. In both RBW (85%) and RBW (70%), F_o value was the lowest but F_v/F_m value was the highest (Fig. 3). This indicates that the environment treated with white light gives lesser environmental stress than those not treated with the white light irrespective of DR.

Considering the decrease in F_v/F_m caused by the photoinhibition that occurs under environmental stress (Maxwell and Johnson 2000), the difference in F_v/F_m value according to the light quality may be related to carotenoids which include the pigments of the xanthophyll cycle produced to protect the light-harvesting system from excessive light energy. Similarly, the seedlings of *Nicotiana tabacum* "Samsun" expressed more *psy* gene, which is a phytoene synthetase (precursor of carotenoids); *bhy* gene, which converts β-carotene to zeaxanthin; and *vde* gene, which converts violaxanthin to antheraxanthin and zeaxanthin, when the seedlings cultivated in the dark were irradiated with continuous red and white light than when they were irradiated with continuous blue light (Woitsch and Romer 2003). Therefore, if white light is treated in addition to red light and blue light, the environmental stress of *S. capitata* could be alleviated and water use efficiency could be improved.

Conclusion

These results suggest that the length of leaves would be longer in the low DR under R+B condition. But the number of shoots and leaves would not be affected by DR and additional white light. Physiologically, it could be possible for *S. capitata* to photosynthesize more efficiently in a plant factory with relatively low water supply if white light is treated together with red and blue mixed lights and if DR is treated at 70% because this improves water use efficiency. Also, the tendency of F_o value to decrease and F_v/F_m value to increase indicates that the photoinhibition could be reduced with lower environmental stress. The power could also be saved with lower DR. A study with a similar result was reported in the past showing that F_v/F_m value is highest in red+blue+white mixed light but relatively low in red+blue mixed light, red single light, and red+far-red mixed light when the DR was set at 100%. But, the number of flowers was greater in red single light and in red+far-red mixed light than in red +blue+white light (Park et al. 2016). Considering this report, additional white light could prevent light stress on the leaf, but red and far-red light waves could enhance its reproductive responses. Thus, the study on basic ecophysiological and reproductive responses to various light environments should be carried out to cultivate *S. capitata* stably in the plant factory for its species conservation.

Abbreviations

ANOVA: Analysis of variance; PPFD: Photosynthetic photon flux density

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Availability of data and materials

Not applicable

Authors' contributions

All authors conducted the survey together during the study period. PJH wrote the manuscript. YYH participated in the design of the study and examined the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

Publisher's Note

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