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Research article

Effects of light quality on leaf growth and photosynthetic fluorescence of *Brasenia schreberi* seedlings

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ABSTRACT

Brasenia schreberi J. F. Gmel, a perennial floating-leaved macrophyte with high economic value as an aquatic vegetable, has been listed as first-class endangered species in China, mainly due to its habitat loss. Protected cultivation is a potential strategy to meet the demand of both plant conservation and vegetable market, whereas pre-experiments are still needed before series of parameters can be properly set for the large-scale growth of the plants indoor. Light quality is one of the major factors controlling the development of plants and consequently becomes an important factor when planting *B. schreberi* indoor. This experiment used three artificial light sources to investigate the response of *B. schreberi* seedlings to different light qualities, including the red-blue LED light (red: blue = 5:1, RB-LED), the white LED light (W-LED) and the white fluorescent (W-Fluo). Our results indicated that the responses of *B. schreberi* towards varied light qualities differed from those of most terrestrial plants. The total leaf number of the RB-LED treatment was the highest; the number of the submerged leaf and the rolled leaf of the RB-LED treatment was higher than that of the other two treatments, but the number of floating leaves was the lowest. Both the specific leaf weight and the pigment contents per unit leaf area were the lowest in the RB-LED treatment. Quantum yield of PSII (Φ_{PSII}), electron transport rate (ETR) and photochemical quenching (*qP*) measured through light induction curves followed the sequence from high to low as W-Fluo > W-LED > RB-LED, whereas the trend of non-photochemical quenching (NPQ) reversed. The maximum potential ETR (P_s) and maximum ETR (ETR_m) derived from ETR curves further verified the trends.

1. Introduction

Brasenia schreberi J. F. Gmel is a perennial floating-leaved macrophyte in the Nymphaeaceae family (also listed in the Cabombaceae family) (Yu, 1991), distributed in Southeast Asia, Europe, North America, Australia and some other regions (See Figure 1 for the natural habitat of *B. schreberi* and its floating, rolled and submerged leaves). It is an aquatic vegetable with high economic value in China. The underwater organs of the plant are wrapped by a thick mucilage mainly composed of polysaccharides, including galactose, mannose, trehalose, rhamnose, xylose, arabinose, etc (Kakuta and Misaki, 1979; Feng et al., 2019). The mucilage has strong antioxidant capacity which may enhance human immunity, reduce blood sugar and plasma cholesterol. Also, its zinc rich characteristic may prevent the occurrence of ADHD in children (Li et al., 2018). As a traditional aquatic vegetable in China, *B. schreberi* has a long history of cultivation in Suzhou of Jiangsu Province and Hangzhou of Zhejiang Province in east China, but the main cultivation areas have been transferred to Lichuan of Hubei Province and Shizhu of Chongqing Municipality in central China. The growth of *B. schreberi* requires good water quality and nutrient-enriched sediments (Xie et al., 2018a). With severe deterioration and degradation of wetlands, *B. schreberi* has been listed as an endangered species and its wild distribution area has shrunk sharply. In addition, recent studies have demonstrated that different *B. schreberi* populations in China have low levels of genetic diversity, which is unfavorable for its protection (Zhang and Gao, 2008; Liu et al., 2012; Li et al., 2018).

With rapid expansion of Chinese food market, indoor protected cultivation of vegetables has been considered as an efficient way in replacing the traditional outdoor cultivation, the latter is restricted due to farm land deficiency. We suppose that protected cultivation can be a potential strategy to meet the demands of *B. schreberi* for both the species conservation and the vegetable market. However, instead of the highly

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Figure 1. *Brasenia schreberi* growing in natural ponds (left) and different leaf forms of the plant (right).

developed indoor culture of terrestrial vegetables, that of aquatic vegetables has been scarcely attempted. Compared with the wild situation, the indoor growth of *B. schreberi* is quite different in morphological development, even unable to complete the life cycle.

Light is an important environmental regulator in protected cultivation. Light quality has effects on plant physiological metabolism, gene expression, photoperiod response, and photomorphogenesis, etc (Zheng et al., 2019a; De Keyser et al., 2019; Park et al., 2015). Plants can detect subtle changes in light and initiate changes in the physiological and morphological structures necessary for their survival (Hogewoning et al., 2010; Xu et al., 2015). Light-emitting diode (LED) has become a new light source in protected cultivation because of its advantages of energy saving, long service life and precise modulation of spectrum (Hernandez and Kubota, 2016; Tennessen et al., 1994). Researches on LED light quality was focused on crops in earlier stage (Zheng et al., 2019b; Goins et al., 1997), but have been switched to fruits, vegetables, flowers, etc. recently, such as pomegranates (Bantis et al., 2018), gabirobas (Centofante, 2019), hydroponic lettuces (Yan et al., 2019), and phalaenopsis (Ren et al., 2016), which are of higher economic value.

Red light can increase plant pigment contents, increase leaf area, and facilitate the accumulation of photosynthetic products (Xu et al., 2015); blue light can promote stomatal opening and increase photosynthetic rate (Sharkey and Raschke, 1981). However, in recent years, studies have shown that the response of plants to different light qualities varied among species, tissues and organs (Liu et al., 2018). In addition, although there are many reports on the cultivation of terrestrial plants and their response to light quality, few studies have been focused on aquatic plants. It is not clear whether the response of aquatic plants to different light qualities is the same as that of terrestrial plants.

We suspect that the responding mechanism of *B. schreberi* to varied light sources may be different to that of terrestrial plants, thus a proper light source becomes the first issue that need to be decided for its protected cultivation. Instead of the light intensity that has been well studied, we focused on the light quality in this paper. Three commonly used artificial light sources were explored for the indoor growth of the overwintering buds of *B. schreberi*. Through the analysis of leaf characteristics, pigment contents, chlorophyll fluorescence and relative photosynthetic indicators, the study is expected to provide a reference for the selection of light sources in the protected cultivation of *B. schreberi*.

2. Material and method

2.1. Experimental design

Three commonly used artificial light sources: red and blue LED (RB-LED, R: B = 5 : 1), white LED (W-LED) and white fluorescent (W-Fluo) were tested in the experiment. The light intensity was maintained as 120 ± 30 μmol m^{-2}•s^{-1}, which was a mean value of light intensity measured at the surface of both water and mud, with a photoperiod of 12 h/12 h, light/dark. Room temperature was set constantly at 25 ± 2 °C. Each of the light quality treatments had 36 cups of the plants as replication. To ensure the uniformity of light received by different plants, the location of each cup in the water tank was adjusted every 2 d between center and edge of the tank.

2.2. Plant materials

Overwinter buds of *B. schreberi* were collected at the end of March 2018 in Suzhou, Jiangsu Province. Healthy buds of similar size were selected and transplanted, as one bud per cup, into white translucent hard plastic culture cups (8 cm in diameter and 8 cm in depth) filled with fresh river mud. Then the culture cups with overwinter buds were moved into the bottom of water tanks with 500 × 380 × 250 mm (length × width × height) in size. During the experiment, the water level was maintained about 20 cm above the mud surface, and 5 mL of double strength Hoagland nutrient solution (Hoagland and Arnon, 1950) was injected into each cup every 7 d (3 cm in depth below mud surface) to make sure enough nutrients for growth.

2.3. Leaf characteristics and pigment measurements

After growth for 20 d, the numbers of floating leaves, submerged leaves and rolled leaves from each cup were counted. After 40 d, 7 largest floating leaves from each light treatment were harvest, weighed for the fresh weight of each leaf (M), scanned to obtain the single leaf area (S), and then the specific leaf weight was calculated as SLW = M/S (Mishanin et al. 2016). The pigments of the same leaf samples were extracted by 80% acetone after rapid homogenization, and the concentrations of chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*) and carotenoid (Cars) were measured by UV-2800A spectrophotometer (UNICO, USA), using the method of Lichtenthaler and Wellburn (1983).

2.4. Chlorophyll fluorescence measurements

Fully developed floating leaves were selected for chlorophyll fluorescence measurements. The F_m and F_o values were measured using MINI-PAM (WALZ, Germany) after 30 min of dark adaption. The selected leaves were then exposed to their original growing lights for more than 30 min to ensure fully light adaption, after which auto-light induction curves were maintained at the same site, with series of F_m', F_o' and F_t values being recorded. According to the formulas of Maxwell and Johnson (2000), the maximum photochemical efficiency of photosystem II (PSII) $F_v/F_m = (F_m\text{-}F_o)/F_m$ and the actual photochemical quantum yield of PSII under photoactivation conditions $\Phi_{PSII} = (F_m'\text{-}F_t)/F_m'$, electron transport rate ETR = Φ_{PSII}×PAR×0.5 × 0.84 (PAR is real-time light intensity in μmol•m^{-2}•s^{-1}), photochemical quenching $qP = (F_m'\text{-}F_t)/(F_m'\text{-}F_o')$ and non-photochemical quenching $NPQ = (F_m\text{–}F_m')/F_m'$ were calculated. The measurement of maximum photochemical efficiency after dark adaptation was repeated for 10 samples for each growth condition, while the rest parameters with induction curves were repeated for 7 samples.

Based on the Ralph and Gademann (2005) curve fitting model and the exponential decay equations of ETR = $P_s \times (1 - e^{-\alpha \times PAR/Ps}) \times e^{-\beta \times PAR/Ps}$, $ETR_m = P_s \times [\alpha/(\alpha+\beta)] \times [\beta/(\alpha+\beta)]^{\beta/\alpha}$, the initial slope ($\alpha$) and photoinhibition coefficient (β), maximum potential electron transfer rate (P_s), maximum electron transport rate (ETR_m), minimum saturating irradiance (E_k) and saturating irradiance (E_m) were further calculated. Here to unify the calculation process, we used the original ETR values ($ETR = \Phi_{PSII} \times PAR \times 0.5 \times 0.84$) directly to replace the rETR values ($rETR = \Phi_{PSII} \times PAR$) in the Ralph and Gademann equation (Xie et al., 2018b; Ye et al., 2013).

2.5. Statistical analyses

The data were statistically analyzed using SPSS 22. Among different treatment groups, the number of leaves, leaf area, specific leaf weight, maximum photochemical efficiency after dark adaptation, ETR curve fitting parameters and the leaf pigment contents were analyzed by one-way ANOVAs, and multiple comparisons were performed by LSD tests; Fluorescence-induced curves (Φ_{PSII}, ETR, qP and NPQ) were compared using paired data *T*-test. Effects were considered statistically significant at $P < 0.05$.

3. Results

3.1. Effects of different light qualities on leaf number of *B. schreberi* seedlings

After 20 d of cultivation, the number of floating leaves in RB-LED only accounted for 6% of the total number of leaves, and was significantly lower than that of the W-LED ($P < 0.05$, Figure 2 a), which accounted for 16% of the total number of leaves. Under all three light quality treatments, the proportion of submerged leaves in the total number of leaves is more than 75%. The number of submerged leaves in the RB-LED treatment was significantly higher than those in the W-LED and W-Fluo treatments ($P < 0.05$, Figure 2 b). The number of submerged leaves in W-LED was slightly lower than that in W-Fluo ($P > 0.05$, Figure 2 c). The number of rolled leaves in RB-LED and W-Fluo was similar ($P > 0.05$), accounting for 13% and 14% of the total number of leaves respectively. W-LED has the least amount of rolled leaves which accounted for 9% of the total number ($P > 0.05$). The total leaf number of RB-LED treated seedlings was significantly higher than those of W-LED and W-Fluo treatments ($P < 0.05$, Figure 2 d). The total leaf number of W-LED treatment was lower than that of the W-Fluo treatment ($P > 0.05$).

3.2. Effects of different light qualities on leaf area and specific leaf weight

After 40 d of cultivation, the single leaf area and SLW of the floating leaves in different light quality treatments also showed some differences (Table 1). The leaf area of the floating leaves in the white fluorescent treatment was significantly larger than that in the W-LED treatment ($P < 0.05$). The W-Fluo treatment had the largest SLW, the RB-LED treatment had the smallest, and the differences among the three light quality treatments were significant ($P < 0.05$).

3.3. Effects of different light qualities on photosynthetic pigment contents

It was found that the photosynthetic pigment contents of the three light quality treatments were different under the measurement of per unit leaf area and per unit fresh leaf weight (Figure 3). Under the fresh weight measurement mode, the total chlorophyll contents of the W-LED treatment were higher than those of the other two treatments, the difference was mainly reflected in Chl *a* ($P < 0.05$) instead of Chl *b* ($P > 0.05$). There was no difference in the total chlorophyll contents, Chl *a* and Chl *b* contents between RB-LED and W-Fluo under the fresh weight measurement mode ($P > 0.05$). However, under the leaf area measurement mode, the total chlorophyll contents and Chl *a* content of W-LED and W-Fluo were significantly higher than those of the RB-LED treatment ($P < 0.05$), and no difference was shown between the two white light sources ($P > 0.05$). The carotenoid contents under the three treatments also showed similar changes. The W-LED treatment was significantly higher than the other two treatments under the leaf weight measurement mode ($P < 0.05$). In comparison, two white light treatments were significantly

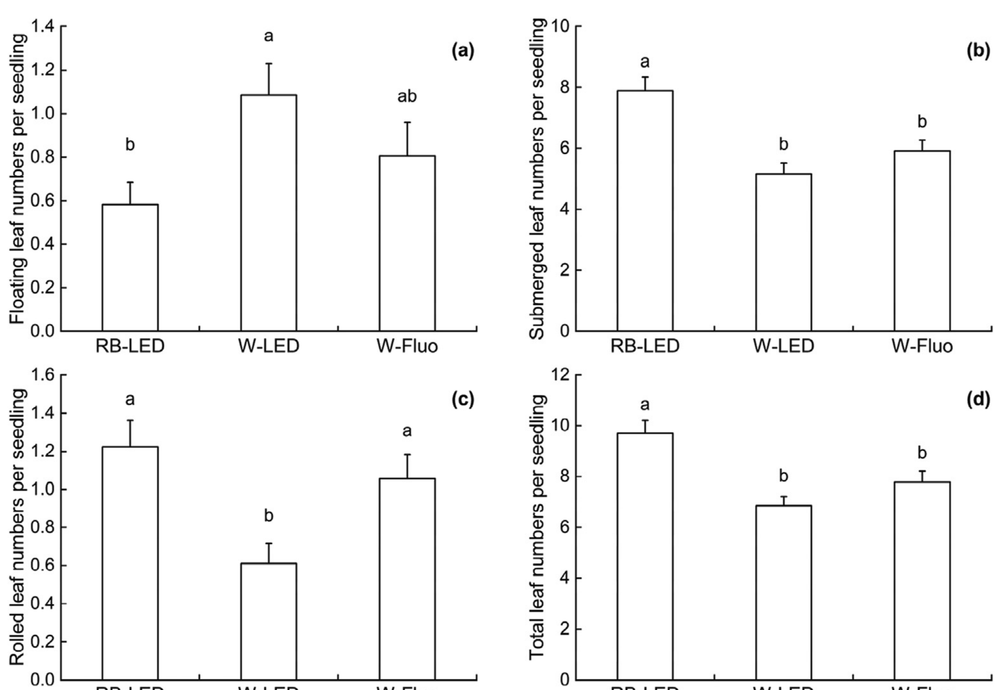

Figure 2. Leaf numbers of *Brasenia schreberi* seedlings under three light quality treatments. RB-LED: Red-Blue LED; W-LED: White LED; W-Fluo: White fluorescent. Mean ± SE, n = 36. Different lowercase letters indicate significant differences among three light quality treatment groups ($P < 0.05$).

Table 1. Leaf area and specific leaf weight of *Brasenia schreberi* under three light quality treatments.

Treatments	Leaf area (cm^2)	Specific leaf weight ($gFW\bullet m^{-2}$)
Red-blue LED	23.35 ± 1.53ab	126.36 ± 4.39c
White LED	19.59 ± 1.80b	136.87 ± 2.07b
White fluorescent	27.69 ± 2.17a	156.22 ± 3.26a

Mean ± SE, n = 7; Different lowercase letters indicate significant differences among three light quality treatment group ($P < 0.05$).

higher than the RB-LED treatment under the leaf area measurement mode ($P < 0.05$).

Regarding the relative proportions of different pigment compositions, the ratio of Chl *a/b* from high to low was RB-LED > W-LED > W-Fluo ($P > 0.05$, Figure 3 e). As for the ratio of chlorophylls to carotenoids, the RB-LED treatment was slightly higher than two white light treatments ($P > 0.05$ Figure 3 f).

3.4. Effects of different light qualities on chlorophyll fluorescence parameters

The maximum photochemical efficiency of *B. schreberi* floating leaves was measured after dark adaptation. It was found that the F_v/F_m values were higher than 0.8 under the three light quality treatments ($P > 0.05$, Figure 4), indicating all plants were relatively healthy and no obvious stress happened during cultivation.

Differences were shown on the light induction curves among the three different light quality treatments (Figure 5). Under the same measurement light intensity, the Φ_{PSII} value of the floating leaves was the highest under white fluorescent treatment, followed by W-LED and RB-LED and the differences among these three groups were significant ($P < 0.05$, Figure 5 a). The effect of different light qualities on ETR was more obvious than that of Φ_{PSII}. Under the medium and high measurement light intensity, the ETR values of the RB-LED treatment were only about 2/3 of that of the W-Fluo treatment ($P < 0.05$). The ETR values of the W-LED treatment were in the middle, and the difference was also significant ($P < 0.05$, Figure 5 b). The *q*P values under different light quality

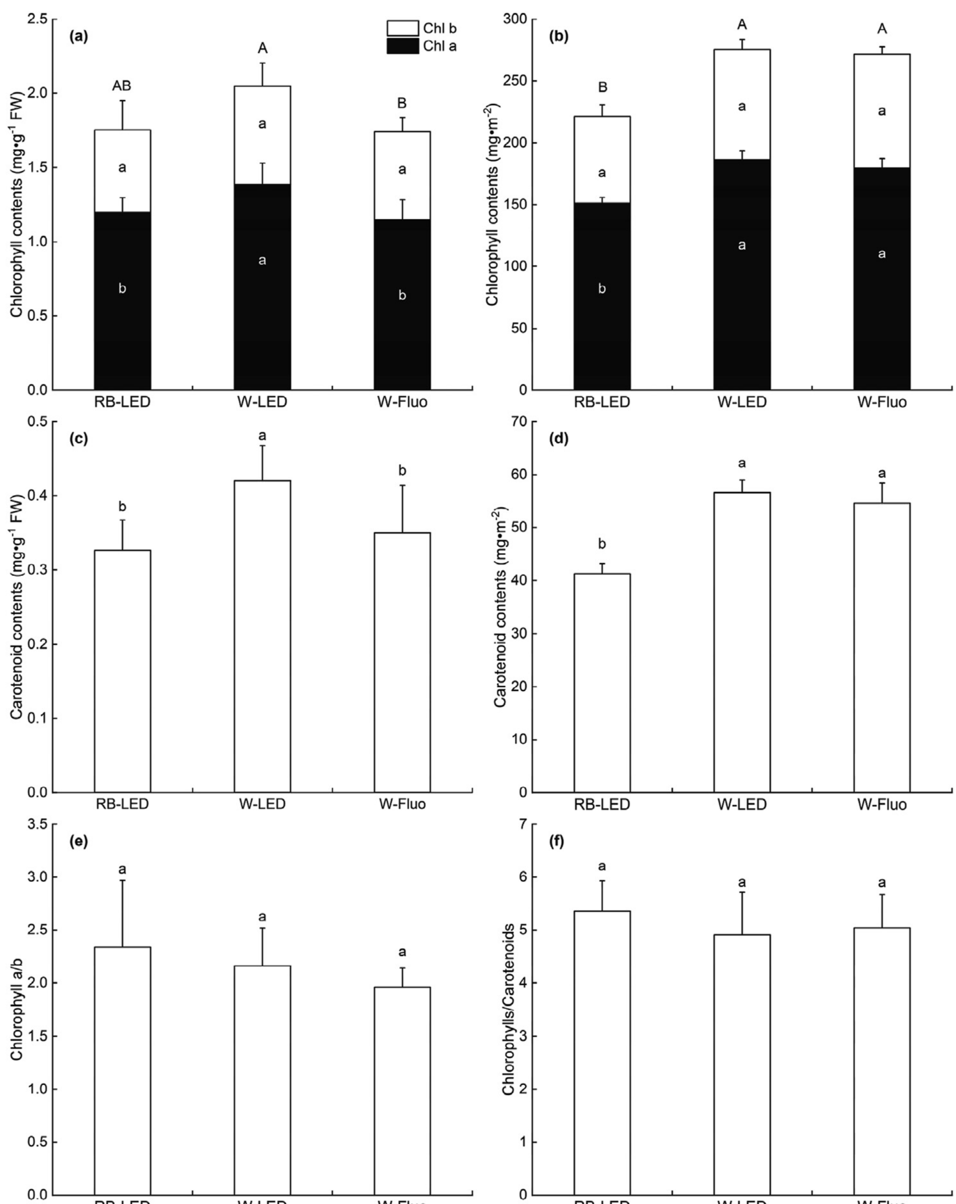

Figure 3. Photosynthetic pigment contents per unit leaf weight (a, c) or per unit leaf area (b, d) and their relative ratios (e, f) of *Brasenia schreberi* floating leaves under three light quality treatments. Mean ± SE, n = 7. RB-LED: Red-Blue LED; W-LED: White LED; W-Fluo: White fluorescent. Different lowercase letters indicate significant differences on specific parameters among three light quality treatment groups ($P < 0.05$). Different capital letters indicate significant differences in total chlorophyll contents among three light quality treatment groups ($P < 0.05$).

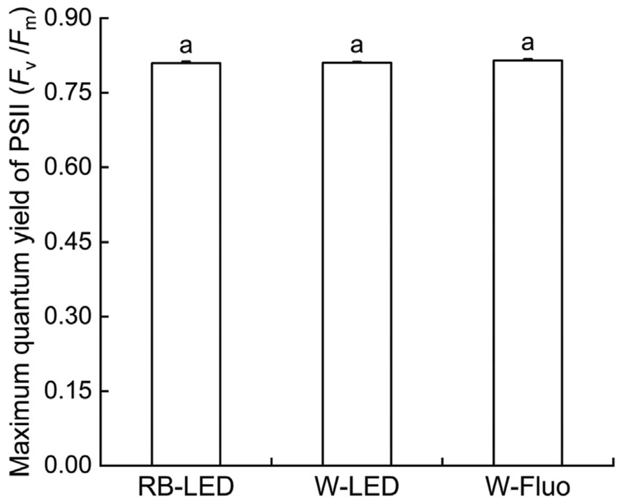

Figure 4. Maximum quantum yield of PSII (F_v/F_m) in *Brasenia schreberi* floating leaves under three light quality treatments. Mean ± SE, n = 10. RB-LED: Red-Blue LED; W-LED: White LED; W-Fluo: White fluorescent. The same lowercase letter indicates no significant differences among the three light quality treatment groups ($P > 0.05$).

treatments showed similar trends with Φ_{PSII}. It also showed that the qP values of the W-Fluo treatment were relatively high, followed by the W-LED treatment, and the RB-LED treatment was the lowest ($P < 0.05$, Figure 5 c). The trend of NPQ was reversed. Although the magnitude of the difference is relatively small, the NPQ values of the RB-LED treatment is obviously higher under medium and high measurement light intensity, followed by the W-LED and W-Fluo treatment. Statistical analysis showed that the NPQ values of the W-Fluo treatment were significantly different from the two LED treatments ($P < 0.05$, Figure 5 d), but the difference between the two LED treatments was not significant ($P > 0.05$).

3.5. ETR curve fitting analysis

The ETR curves of the *B. schreberi* floating leaves can be well fitted by the exponential decay equation ($R^2 > 0.989$). Although the α values, E_k values and E_m values of the three light quality treatments showed no significant difference ($P > 0.05$), it was still obvious that these three derived parameters followed the order of RB-LED < W-LED < W-Fluo (Table 2). The P_s and ETR_m shared the same trend and these values of the RB-LED treatment were 68% of the W-Fluo treatment ($P < 0.05$). The P_s value and ETR_m of the W-LED treatment were 90% and 88% of the W-Fluo treatment, respectively. The photoinhibition coefficient β of each light quality treatment was less than 0.01 ($P > 0.05$).

4. Discussion

Plants can sense subtle changes in light quality through photoreceptors, which in turn regulate growth and development of plants through exciting signaling pathways (Ward et al., 2005). Leaf chlorophylls are responsible for the absorption, transmission, and transformation of light energy, while carotenoids take functions on both light energy capture and light damage defense (Sun et al., 2010). Based on the consideration of indoor protected cultivation, low light treatment was designed in the early stage of the experiment. The average light intensity in this experiment was much lower than that of natural sun radiation in the field. The pigment contents of the floating leaves showed similar characteristics of shade plants (Lichtenthaler et al., 2007). We have also analyzed the floating leaves of *B. schreberi* grown under natural light in the field (Xie et al., 2018b). Under the low light treatment, SLW, chlorophyll contents per unit leaf area and carotenoid contents per unit leaf area of *B. schreberi* leaves were only about 60% of those in the field, and the ratio of Chl *a/b* was only about 50% of that in the field. Our results were similar with what Bartucca et al. (2020) found that einkorn had lower levels of chlorophylls and carotenoids contents under a high proportion of red-light treatment compared with that under wide wavelength treatment. However, the photosynthetic pigment contents per unit fresh weight and the ratio of chlorophylls to carotenoids were almost the same as those in the field. Therefore, on the one hand, we believe that this is a

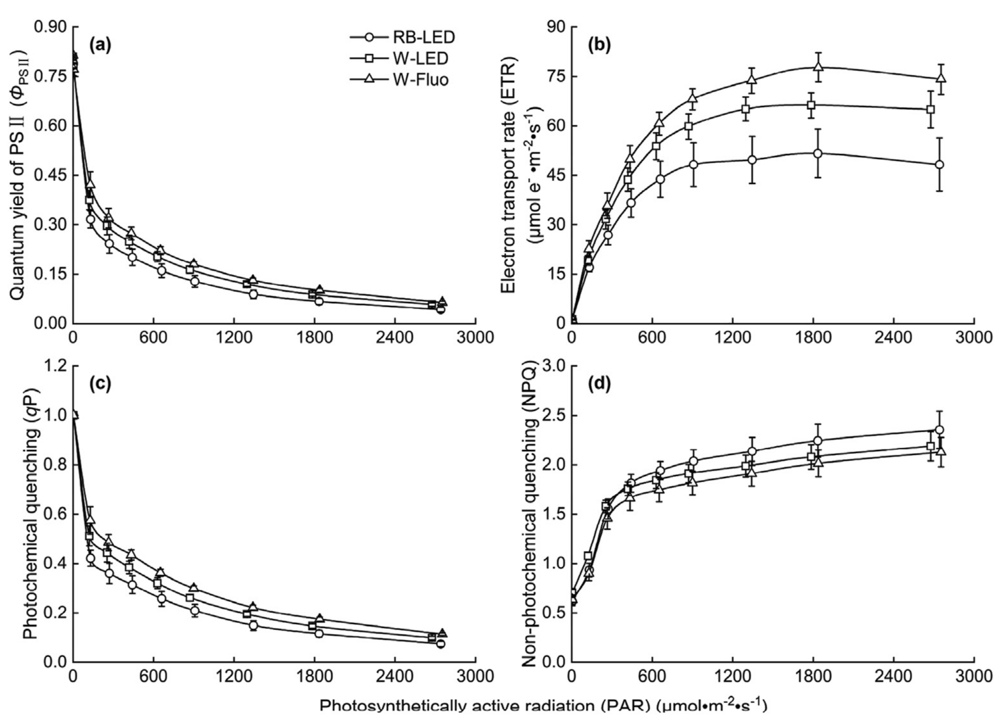

Figure 5. Chlorophyll fluorescence parameters of floating leaves of *Brasenia schreberi* under three light quality treatments. Mean ± SE, n = 7. RB-LED: Red-Blue LED; W-LED: White LED; W-Fluo: White fluorescent.

Table 2. Derived parameters from ETR curves of *Brasenia schreberi* floating leaves under three light quality treatments.

Treatment	α	β	P_s (μmol e^{-}•m^{-2}•s^{-1})	ETR_m (μmol e^{-}•m^{-2}•s^{-1})	E_k (μmol•m^{-2}•s^{-1})	E_m (μmol•m^{-2}•s^{-1})
Red-blue LED	0.150 ± 0.0151a	0.003 ± 0.0010a	58.9 ± 9.2b	52.9 ± 8.0b	344.1 ± 35.4a	1734.2 ± 262.9a
White LED	0.165 ± 0.0193a	0.006 ± 0.0019a	78.2 ± 4.8ab	67.9 ± 4.7ab	431.5 ± 40.1a	2082.5 ± 466.6a
White fluorescent	0.190 ± 0.0275a	0.005 ± 0.0020a	87.0 ± 5.0a	77.4 ± 3.9a	445.0 ± 46.4a	2159.9 ± 351.5a

α: Initial slope; β: Photoinhibition coefficient; P_s: Maximum potential electron transport rate; ETR_m: Maximum electron transport rate; E_k: Minimum saturating irradiance; E_m: Saturating irradiance. Different lowercase letters indicate significant differences among the three light quality treatment groups ($P < 0.05$).

certain self-regulation of *B. schreberi* leaves adapting to low light environment; on the other hand, due to the change of specific leaf weight with different light quality, which we used as an index of leaf thickness, we believe that the pigment contents per unit area may be more proper than that of the traditional unit per leaf mass for the analysis of leaf photosynthetic function.

Red and blue light sources are common in the current indoor protected cultivation. Our study showed that the contents of chlorophylls and carotenoids in the *B. schreberi* floating leaves under the treatment of 5:1 RB-LED were lower than that of the white light treatments. Red light is believed to increase anthocyanins, chlorophylls and carotenoids, but most evidence comes from terrestrial plants (Xu et al., 2015). In recent years, there have been reports of red light and white light that are not conducive to pigment accumulation and photosynthetic efficiency (Liu et al., 2018). We are not sure whether the phenomenon we observed is common in aquatic plants, but the specific response of different plants to different light qualities is obvious. In addition, studies on *Phalaenopsis* showed that red light is not conducive to the accumulation of chlorophylls, while blue light is conducive to the accumulation of chlorophylls (Ren et al., 2016). It is unknown whether increasing the proportion of the blue light in the RB-LED treatment can improve the pigment accumulation in the floating leaves of *B. schreberi*.

Chlorophyll fluorescence parameters are often used as effective probes for studying the photosynthetic physiological state of plants. The F_v/F_m values measured after dark adaptation can effectively reflect the intrinsic light energy conversion ability of PSII reaction center. Several studies showed that light quality has significant effects on chlorophyll fluorescence parameters in leaves of plantlets. *Cunninghamia lanceolate* had higher levels of F_v/F_m and ETR values under a composite light with red, blue, purple, and green (Xu et al. 2020). The F_v/F_m, qP and ETR of *Dendrobium candidum* plantlets under red and blue light were also found higher than under monochrome light (Wang et al., 2017). In our experiment, the F_v/F_m values of *B. schreberi* floating leaves under the three light quality treatments were all larger than 0.8, indicating that plants in this experiment were not under stress condition and hence generally healthy. However, the change of pigment ratio will affect the structure and stability of photosynthetic membrane of plant leaves, which will further affect other physiological processes related to photosynthesis in plants (Ramalho et al., 2002). Different light qualities can also affect the stomatal dynamic behaviour which will further affect the performance of photosynthesis in plants (Matthews et al., 2020). According to the light induction curve, the Φ_{PSII}, ETR, qP values and the P_s and ETR_m derived from ETR curves of the RB-LED treatment were lower than those of the white light treatments, but the NPQ increased slightly, indicating that the photochemical efficiency and ETR of the PSII reaction center are relatively weak under the red and blue light sources, which should be related to the decrease of chlorophyll contents (Chen et al., 2014). Based on the theory of Ralph and Gademann, E_k reflects the utilization of light energy by plants, which is related to fluorescence quenching. When PAR < E_k, photochemical quenching is dominant; when PAR > E_k, non-photochemical quenching is dominant. In the experiment, the E_k values of the three groups were higher than the light intensity received by the surface of the leaves, and the light energy was mainly utilized by fluorescence quenching (Ralph and Gademann, 2005). In the experiment, the NPQ value of the RB-LED treatment was slightly higher than those of the white light treatment groups, which should be a self-protection mechanism for the high light stress (Ruban, 2016). However, in view of the long-term cultivation in low light environment, we suppose that this NPQ-based protection mechanism has little contribution for the *B. schreberi* growth in the experiment.

Well planned LED lighting systems enables highly effective production and significantly extends production season (Sipos et al., 2020). Research was set up to assess the mechanisms engaged by plants to optimize light harvesting and utilization of different wavelengths during the early photomorphogenesis in tomato (Izzo et al., 2020). However, studies investigating the effect of monochromatic light during plant photomorphogenesis are still limited. In the field, leaves of *B. schreberi* will gradually unfold during development, and the petioles will elongate until the leaves float on the surface of the water. In this study, there were more submerged leaves in the RB-LED treatment, it seemed that the elongation of the petioles was limited and the leaves didn't reach the water surface in time. This may be related to the decrease of photosynthetic products and its distribution in the petiole. In addition, studies have indicated that red light can inhibit the translocation of photosynthetic products from leaves (Sæbø et al., 1995). Park and Runkle (2018) also found that *Petunia hybrida* seedlings grew longer under sole white lighting treatment. In our experiment, the total number of leaves was higher under red and blue light sources. Although the rolled leaf number of RB-LED has no statistically difference with the white fluorescent treatment, the number of submerged leaves was clearly larger than that of the two white light treatments. So, we speculate that the red and blue light is more conducive to the differentiation of young buds and leaves of *B. schreberi*. This aspect can further explain the reasons for the limited development of the petiole of the submerged leaf from the perspective of energy distribution; on the other hand, it is advantageous from the economic benefit of the cultivation, because the rolled leaf covered with mucilage is the edible portion, and we can harvest the *B. schreberi* product when the leaf is still folded.

Finally, compared with the white fluorescent light, the W-LED had the same contents of chlorophylls and carotenoids per unit area, but lower leaf area of the floating leaves, and the chlorophyll fluorescence parameters are also lower. This may be related to the difference in spectral characteristics between the LED source and the fluorescent source, both on wavelength range and relative abundance of specific wavelength.

5. Conclusion

Under artificial light conditions, the total leaf number of *B. schreberi* seedlings treated with the RB-LED was higher than that of the W-LED and W-Fluo treatments, but the development of petioles was limited, so that most leaves could not reach out of the water surface. The chlorophyll contents and carotenoid contents per unit leaf area of floating leaves treated with the RB- LED were lower than those of white light treatments. F_v/F_m under dark adaptation showed that the plants were still in a healthy state, but according to the light induction curves, Φ_{PSII}, ETR, qP and P_s, ETR_m derived from ETR curves of the RB-LED treatment were lower than those of the white light treatments, only NPQ was higher. This was not the same with the results of most terrestrial plants. However, red and blue light sources can be properly used to increase the yield of buds and rolled leaves, together with a white light source to ensure sufficient accumulation of photosynthetic products. In addition, the application of white fluorescent light source is recommended in the protected cultivation of *B. schreberi* which had better performance than white LED light source.

Declarations

Author contribution statement

Changfang Zhou: Conceived and designed the experiments; Wrote the paper.

Jiafeng Li: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Cuiyu Yi, Chenrong Zhang, Fan Pan, Chun Xie: Performed the experiments.

Wenzong Zhou: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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