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INFLUENCE OF LIGHT QUALITY ON PHOTOSYNTHESIS AND PLANT MORPHOLOGY OF *POLYGONATUM CYRTONEMA* HUA AND *POLYGONATUM SIBIRICUM* DELAR.EX REDOUTE

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Abstract

The subterranean tubers of *Polygonatum cyrtonema* Hua and *Polygonatum sibiricum* Delar.ex Redoute are the source of the traditional Chinese medicinal herb Huangjing. This study investigates the impact of light quality on the nursery cultivation of Huangjing herb. Seedlings of *P. cyrtonema* and *P. sibiricum* were exposed to treatments of white, red, and blue light. Gas exchange and chlorophyll fluorescence data were collected by Li-6400 photosynthesis meter, chlorophyll content was quantified through 95% ethanol extraction, and leaf morphology data were recorded. The results indicated that these two species of herb Huangjing exhibited the highest overall Pn-PAR curves and the maximum net photosynthetic rate (Pn) in the blue light group. The Pn exhibited a significant positive correlation with photosynthetically active radiation (PAR) and a negative correlation with intercellular carbon dioxide concentration (Ci). The total chlorophyll content of the plants was highest in the blue light group and lowest in the red light group. Two species of the herb Huangjing exhibited the greatest growth in underground tubers under blue light treatment, whereas plants displayed weakness and mortality under red light treatment. Chlorophyll content exhibited a highly significant positive correlation with electron transfer rate (ETR), PSII effective electron yield (Φ_{PSII}), and the growth of subterranean tubers. The blue light treatment significantly enhanced the chlorophyll content, electron transport rate (ETR), and subterranean tuber development of the herb Huangjing. Both species of the herb Huangjing exhibit a pronounced capacity to harness blue light. *P. cyrtonema* is particularly suited to blue light. Utilizing a substantial proportion of blue light is advisable for the cultivation of *P. cyrtonema* and *P. sibiricum* in facilities.

Key words: *Polygonatum cyrtonema* Hua, *Polygonatum sibiricum* Delar.ex Redoute, Light quality, Photosynthesis, Plant morphology.

Introduction

Polygonatum cyrtonema Hua and *Polygonatum sibiricum* Delar.ex Redoute are perennial herbaceous species within the genus *Polygonatum*. They are the origin of the traditional Chinese medicinal herb Huangjing, a prevalent source of nourishment and medicine. Their robust rhizomes constitute the primary edible and medicinal components. Certain researchers have discovered that the medicinal herb Huangjing is abundant in polysaccharides, steroid saponins, xanthones, and other compounds, which exhibit significant antioxidant, anti-tumor, and cognitive enhancement properties (Li *et al*., 2018). It possesses significant developmental potential in tonic diets, health products, cosmetics, food, ornamental horticulture, and feed additives. The implementation of facility seedling cultivation for the medicinal herb Huangjing is a trend driven by market demand. The choice and quality of the light source are essential for enhancing the yield and quality of the medicinal herb Huangjing.

Light significantly influences the growth and development of plants. Light quality pertains to light of varying wavelengths. Plants possess a comprehensive array of sophisticated light reception and signal transduction systems capable of detecting variations in light quality and executing adaptive responses, thereby influencing photomorphogenesis, physiological metabolism, photoperiodic responses, growth and development, and crop quality (Liu *et al*., 2020; Arantxa *et al*., 2020). Plant chloroplast pigments predominantly absorb light in the blue and red wavelengths of the visible spectrum. Chlorophyll is essential for the transformation of light energy, and an optimal increase in its concentration enhances the absorption of light quanta and promotes photosynthesis. Excessive chlorophyll content can generate surplus electrons, resulting in heightened non-photochemical quenching, which may harm the photosystem and induce photoinhibition (Song *et al*., 2017). The adaptability of PSI to photoinhibition varies considerably under different light conditions. Intense light can induce photoinhibition of plant PSI protection, and the increase in total chlorophyll content correlates with PSI's light sensitivity (Takagi *et al*., 2019). The quality of light influences the ratio and composition of chloroplast pigments, resulting in elevated chlorophyll a/b ratios in plant leaves exposed to blue light (Wang *et al*., 2016). Carotenoids serve as significant antioxidants, with their absorption spectra predominantly located in the blue light spectrum. Under white light irradiation, the accumulation of β-Carotene in plants is more substantial than under single blue or red light (Tuan *et al*., 2013). The quality of light influences the transcriptional level of β-Carotene hydroxylase 1. Red light enhances the transcription level of the antenna complex gene encoding photosystem II (Frede *et al*., 2019). Hamdani *et al*., (2019) discovered through transcriptome analysis that single red or blue light irradiation diminishes the abundance of catalase and ascorbic acid transcripts in rice tissues. That means monochromatic light irradiation can impair the antioxidant system, reduce the quantum yield of photosystem II, and elevate non-photochemical quenching. Plants exhibit elevated non-photochemical quenching (NPQ) under blue light irradiation with shorter wavelengths (Belgiol *et al*., 2017).

The wild medicinal herb Huangjing is commonly found in understory regions and forest margins, favouring shaded and moist habitats. Prior research indicates that the medicinal herb Huangjing exhibits intolerance to intense light exposure, necessitating the use of shade nets in artificial cultivation, with optimal photosynthetic rates achieved under a shading rate of 40-50% (Liang *et al.*, 2019; Tong *et al.*, 2020). Our prior research indicated that *P. cyrtonema* exhibits significant adaptability to varying light intensities, thriving in environments ranging from full sunlight to bamboo forests with a 90% reduction in light. It successfully completes its reproductive cycle, including flowering and fruiting (He *et al.*, 2021), which contradicts the previously reported optimal light transmittance of 40-50% by other researchers. The light quality in the understorey differs from that beneath the shade net, except for light intensity. The tree canopy absorbs the majority of red light and some blue light, resulting in the forest's undergrowth being predominantly illuminated by scattered light and short-wavelength blue-violet light. Our prior experiments revealed that, at equivalent light intensity, the biological yield and polysaccharide content of *P. cyrtonema* subjected to camphor tree (blue purple light) were markedly superior to those treated with shading net (white light). There were significant differences in the photosynthetic rate, chlorophyll fluorescence parameters, and chlorophyll content, along with notable alterations in the plant morphology of *P. cyrtonema* under two distinct light environments. Increased blue and purple light in the forest enhances the biological yield and polysaccharide accumulation of *P. cyrtonema* (He *et al.*, 2021). Red light fosters the development of aerial stems; thus, augmenting the ratio of blue light is more advantageous for cultivating crops aimed at subterranean stems. What is the capacity of these plants to harness blue light, and can assimilation products be efficiently transported to subterranean rhizomes? This article examines the physiological and morphological characteristics of *P. cyrtonema* and *P. sibiricum*, encompassing gas exchange, chlorophyll fluorescence metrics, and biological yield, under varying light quality conditions, which may offer significant theoretical and practical insights for the facility cultivation of the medicinal herb Huangjing.

Material and Methods

Planting and light quality treatment of experimental materials: In December 2021, we selected pest- and disease-free seed stems of *P. cyrtonema* and *P. sibiricum*, each weighing (15 ± 1) g, and planted them in flower pots with an upper diameter of 27 cm, a lower diameter of 25 cm, and a height of 27 cm. Each pot will contain a single stem planted. The potting substrate consisted of brown soil and nutrient soil in a ratio of 2:1, with a pH range of 6.0 to 6.5. 3 grammes of P_2O_5 and 3 grammes of K_2O were utilised as base fertilisers per pot, with the substrate volume constituting approximately 80% of the pot volume. In April 2022, prior to stem emergence, the potted materials were positioned in an artificial climate chamber for treatment. The experimental conditions included 100% white light, 100% red light, and 100% blue light, each at a light intensity of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$, with a duration of illumination of 12 hours per day. All environmental factors remained consistent, except for variations in light quality conditions. Consistently irrigated and weeded throughout the experiment, while maintaining records to guarantee uniform water and fertiliser conditions for each pot. Advance to the subsequent experimental assessment following a 30-day processing period.

A-Q curve measurement: In the morning, the incubator light should be activated, and the materials should be illuminated under white, red, and blue light at an intensity of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for a minimum duration of 30 minutes. Assessed the Pn-PAR curve of leaves utilising Li-6400 photosynthesis meter (Li-COR, USA). The airflow rate was established at 500 $\mu mol \cdot s^{-1}$, the blade chamber temperature at 25°C, and the atmospheric CO_2 concentration at 400 $\mu mol \cdot mol^{-1}$. The gradient of photosynthetically active radiation was established at 1,500, 1,300, 1,100, 900, 700, 500, 350, 200, 150, 100, 50, 25, and 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Gas exchange data were documented following a 2-minute interval for each light condition, with three replications conducted for each leaf at the specified light intensities of the various treatments. Five pots were selected for each treatment group, and two leaves from the upper and middle layers of the crown were measured for each pot. The Pn-PAR curve was plotted with photosynthetically active radiation (PAR) on the horizontal axis and net photosynthetic rate (Pn) on the vertical axis, employing a non-rectangular hyperbola model for curve equation fitting. Utilised light response curve fitting software (v1.0 green version) to derive parameters including dark respiration rate (Rd), light compensation point (LCP), leaf light saturation point (LSP), apparent quantum efficiency (AQY), and light-saturated net photosynthetic rate (A_{max}).

Chlorophyll content: Utilised healthy middle segment leaves, excised the primary veins, weighed 0.2 g, extracted with 95% ethanol, and diluted to 25 ml. Measured the absorbance values of the extraction solution at wavelengths of 470 nm, 649 nm, and 665 nm using a spectrophotometer, subsequently calculating the concentrations of chlorophyll a (Chl a), b (Chl b), total chlorophyll (Chl T) and carotenoids (Car) using the following formula: Chl a = $13.95A_{665}$ - $6.88A_{649}$; Chl b = $24.96A_{649}$ -$7.32A_{665}$; Chl T = Chl a + Chl b = $6.63A_{665}$ + $18.08A_{649}$; Car = ($1000A_{470}$ - 2.05Chl a - 114.8Chl b) / 245. The content of chloroplast pigments (mg/g·FW) is calculated using the formula: $(C \times V \times N) / m \times 1000$, where C denotes the pigment concentration (mg/L), V signifies the volume of the extraction solution (25 ml), N indicates the dilution ratio, and m represents the sample mass. Five pots were selected for each treatment, and two leaves from the upper and middle layers of the canopy were measured for each pot.

Chlorophyll fluorescence parameters: Enveloped the central portion of the leaf designated for testing with aluminum foil and permitted it to undergo dark adaptation for 30 minutes. Assessed the primary fluorescence (F_0), maximum fluorescence (Fm), potential activity of PSII (Fv/F_0), and maximal quantum yield of PSII photochemistry (Fv/Fm) in the dark using the fluorescence chamber (Li-COR, USA) of the Li-6400-40 portable photosynthesis apparatus. Opened the leaf chamber and illuminated the leaves with white, red, and blue light at intensities of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 30 minutes each. Quantified the steady-state fluorescence (Fs), maximum fluorescence (Fm′), and minimum fluorescence (F_0'). Parameters were computed using the following formulas: photochemical quenching coefficient (qP) = $(Fm'-Fs)/(Fm'-F_0')$, nonphotochemical quenching coefficient (qN) = $(Fm-Fm')/(Fm-F_0')$, effective quantum yield of PSII photochemistry (Φ_{PSII}) = (Fm'-Fs)/Fm', and electron transfer rate (ETR) = $\Phi_{PSII}\times0.5\times0.84\times1000$. Five pots were selected for each treatment, and two leaves from the upper and middle layers of the canopy were measured for each pot.

Plant leaf morphology and biomass: Utilized a ruler to measure plant height and employed a Li-3000C leaf area meter (Li-COR, USA) to assess the functional leaf area of an individual plant. Determined the weight and calculated the specific leaf weight of the leaves based on the weight-to-area ratio after desiccating the leaves to a constant weight. Documented the quantity of leaves per plant. The subterranean section was excavated and cleansed, and the freshly developed tubers were desiccated to ascertain the weight of the newly incorporated tubers post-processing.

Statistical analysis

All data were analyzed by Excel 2019 and SPSS 21.0 software. Single factor analysis of variance (ANOVA) was used to analyze the data of each light quality treatment group, and Tukey test was used to detect the significance of the differences between the mean values ($p<0.05$). The Origin 2021 (Origin Lab Inc., Hampton, MA, USA) and Excel 2016 software were used to plot the results.

Results

A-Q curves: The Pn-PAR curve of *P. cyrtonema* in the blue light group was the highest (Fig. 1), whereas the curve in the red light group was significantly lower than those of the other two groups. The Pn-PAR curve of *P. sibiricum* was highest in the blue light group; however, the disparity between the red and white light groups was minimal, resulting in nearly overlapping curves. The photosynthetic parameters derived from curve fitting indicated (Table 1) that the LCP of *P. cyrtonema* was merely 10 $\mu mol\cdot m^{-2}\cdot s^{-1}$ under blue light treatment, whereas the A_{max} reached 5.023 $\mu mol\cdot m^{-2}\cdot s^{-1}$, the highest across all treatment groups. A_{max} was significantly reduced under red light treatment, measuring only 1.233 $\mu mol\cdot m^{-2}\cdot s^{-1}$. For *P. sibiricum*, the LCP was the lowest and the LSP was the highest under blue light treatment. Additionally, there was no significant difference in the Pn between white and red light treatments, nor was there a significant difference in the Rd and AQY parameters derived from fitting.

A correlation analysis was performed on the gas exchange parameters of the Pn-PAR curves of leaves subjected to various light treatments, revealing a significant positive correlation between the transpiration rate (Tr) and stomatal conductance (Gs) of the two plant species. Tr exhibited a significant positive correlation with photosynthetically active radiation (PAR), with the exception of *P. cyrtonema* under blue light (Fig. 2). The relationship between Pn and its influencing factors differs across various light quality treatments. Pn exhibited a significant positive correlation with PAR, a positive correlation with Gs, and a negative correlation with intercellular carbon dioxide concentration (Ci). Nonetheless, the positive correlation between Pn and Gs of *P. cyrtonema* did not attain statistical significance in the white light group, whereas the negative correlation between Pn and Ci did not achieve statistical significance in the blue light group. As PAR increases, the stomata of the leaves progressively open, enhancing the capacity for carbon dioxide assimilation. The reduction in Ci under red light treatment was not statistically significant, suggesting that prolonged exposure to red light rendered the plant unhealthy (more evident in *P. cyrtonema*) and diminished its assimilation capacity.

Chlorophyll content: No significant difference in chlorophyll a/b ratios was observed between the two plants under varying light quality treatments (Fig. 3). The Chl T was highest in the blue light group, followed by the white light group, while the red light group exhibited the lowest levels. The Car was inferior to that of Chl T. Particularly under red light, the carotenoid content of *P. cyrtonema* was merely 0.027 $mg\cdot g^{-1}$. Under blue light, the Car content markedly increases, with *P. sibiricum* attaining 0.190 $mg\cdot g^{-1}$. *P. cyrtonema* and *P. sibiricum* exhibited divergent responses to light quality. The chlorophyll content of *P. cyrtonema* exhibited significant variation under different light qualities, whereas the difference in chlorophyll content of *P. sibiricum* under red and white light was not significant. The pigment concentration of *P. sibiricum* exceeded that of *P. cyrtonema* under blue and red light; however, *P. cyrtonema* exhibited a marginally higher pigment concentration under white light. This indicates the chlorophyll content of *P. cyrtonema* will markedly diminish under red light, rendering it highly inappropriate for red light exposure. The reaction of *P. sibiricum* to red light is not as pronounced.

Table 1. Photosynthetic parameters of *P. cyrtonema* and *P. sibiricum* leaves under different light quality.

Item	Rd ($\mu mol\cdot m^{-2}\cdot s^{-1}$) [z]	AQY ($\mu mol\cdot m^{-2}\cdot s^{-1}$) [z]	LCP ($\mu mol\cdot m^{-2}\cdot s^{-1}$) [z]	LSP ($\mu mol\cdot m^{-2}\cdot s^{-1}$) [z]	A_{max} ($\mu mol\cdot m^{-2}\cdot s^{-1}$) [z]
W-C	0.491 ± 0.098 c [y]	0.028 ± 0.004 b	17.33 ± 1.311 b	408.3 ± 43.92 c	4.703 ± 0.125 a
R-C	0.114 ± 0.024 e	0.007 ± 0.000 e	15.00 ± 1.301 c	406.5 ± 58.27 c	1.233 ± 0.095 d
B-C	0.158 ± 0.041 d	0.023 ± 0.010 c	10.00 ± 1.703 d	577.0 ± 47.05 b	5.023 ± 0.924 a
W-S	0.656 ± 0.083 b	0.014 ± 0.001 d	69.00 ± 5.196 a	1015 ± 97.96 a	3.360 ± 0.101 c
R-S	0.634 ± 0.068 b	0.016 ± 0.005 d	70.33 ± 9.291 a	1008 ± 54.58 a	3.387 ± 0.820 c
B-S	0.896 ± 0.022 a	0.050 ± 0.007 a	6.333 ± 0.577 e	1043 ± 24.56 a	4.114 ±0.623 b

[z] Values in table are obtained by Nonlinear Fitting by SPSS 21.0

[y] Means followed by the same letter do not differ based on the Duncan's New Multple Range Test at $p<0.05$

Rd – respiration rate; AQY – apparent quantum efficiency; LCP – light compensation point; LSP – light saturation point; A_{max} – maximum net photosynthetic rate

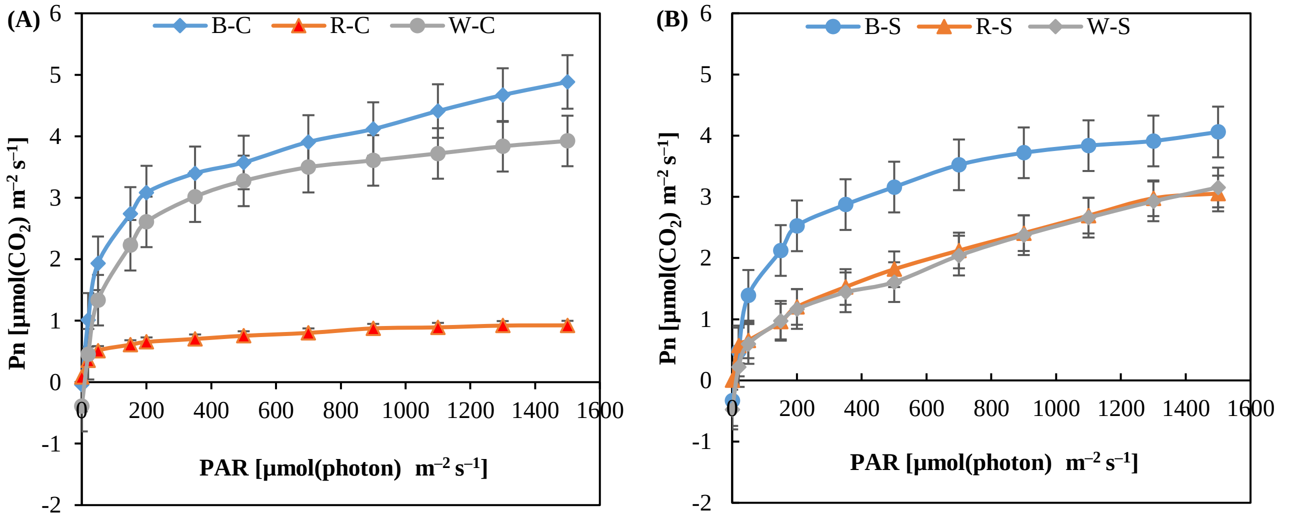

Fig. 1. The Pn-PAR curves of *Polygonatum cyrtonema* Hua and *Polygonatum sibiricum* Delar.ex Redoute leaves under different light quality treatment

Fig. 1(A) shows *P. cyrtonema* under different light quality treatments. Fig. 1(B) shows *P. sibiricum* under different light quality treatments.

Error bars reflect the standard deviation of biological duplicates (n=9).

B-C – *P. cyrtonema* under blue light treatments; R-C – *P. cyrtonema* under red light treatments; W-C – *P. cyrtonema* under white light treatments; B-S –*P. sibiricum* under blue light treatments; R-S – *P. sibiricum* under red light treatments; W-S –*P. sibiricum* under white light treatments; Pn – net photosynthetic rate; PAR – photosynthetically active radiation.

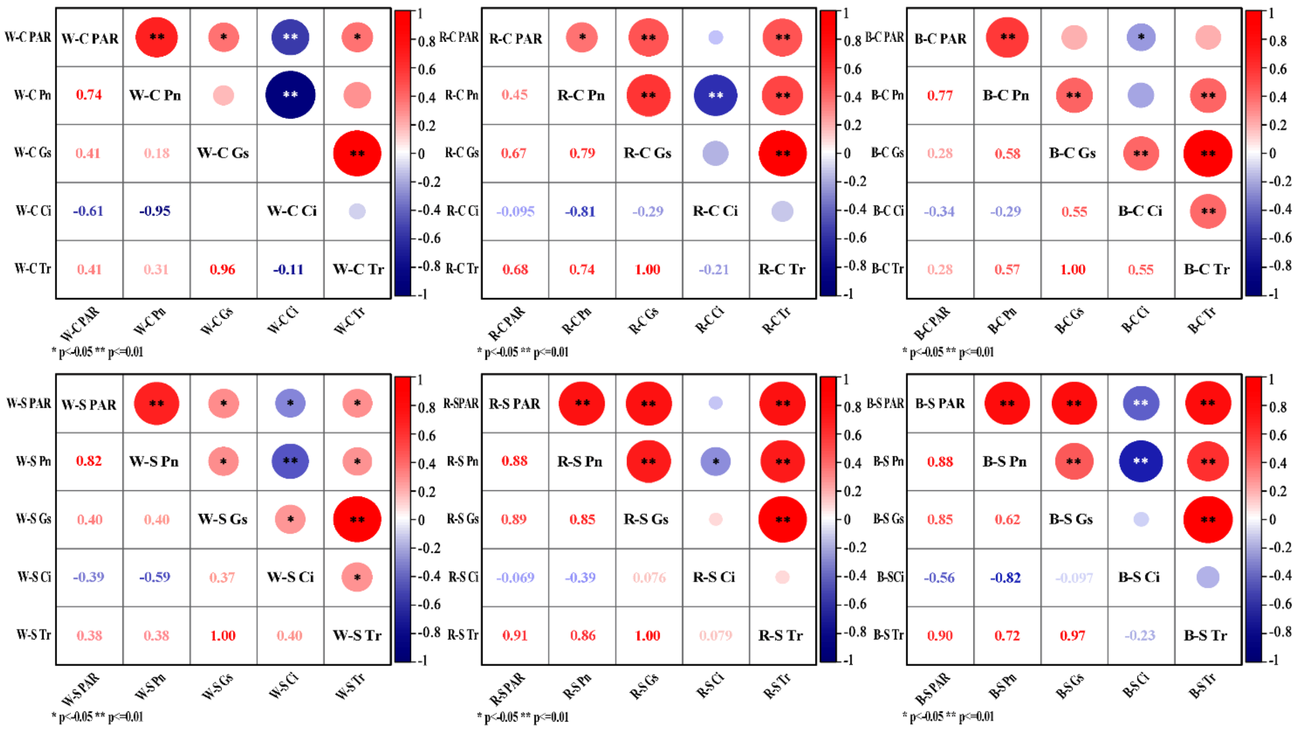

Fig. 2. Gas exchange parameters correlation coefficient diagram of *P. cyrtonema* and *P. sibiricum* leaves

* , ** Respectively represents the correlation at 0. 05, 0. 01 levels significantly.

PAR – photosynthetically active radiation; Pn – net photosynthetic rate; Gs – stomatal conductance; Ci – stomatal CO_2 concentration; Tr – transpiration rate.

Chlorophyll fluorescence parameters: The Fv/F_0, Fv/Fm, qP, Φ_{PSII} and ETR values were maximized in the blue light group according to the fluorescence parameters of the leaves (Table 2), with the Fv/Fm, Fv/F_0, ETR, and Φ_{PSII} of *P. cyrtonema* marginally exceeding those of *P. sibiricum*. The disparity between the two plants was negligible. The Fv/Fm value of *P. cyrtonema* in the red light group was the lowest at 0.641, indicating that *P. cyrtonema* experienced significant light stress at this time. *P. sibiricum* exhibited low Fv/Fm values under red light; however, no significant difference was observed when compared to the white light group. The qN of both material species was highest in the red light group, while qP, ETR, and Φ_{PSII} were lowest under red light, with a particularly significant decrease observed in *P. cyrtonema*.

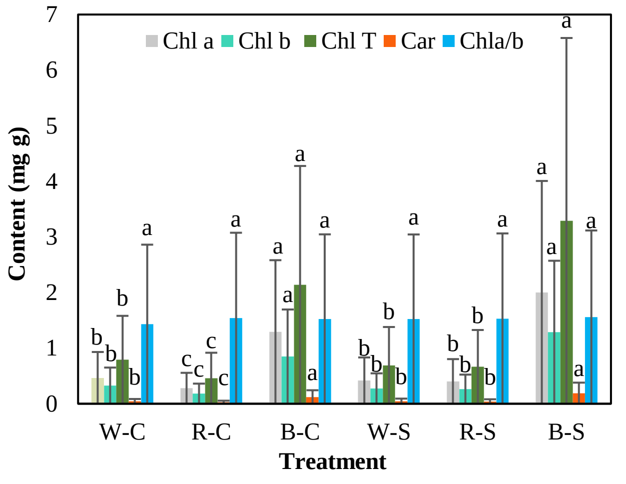

Fig. 3. Comparison of chlorophyll content [mg·g^{-1}(FM)] of *P. cyrtonema* and *P. sibiricum* leaves under different light quality

Error bars reflect the standard deviation of biological duplicates (n=9).

Lowercase letters means do not differ based on the Duncan's New Multple Range Test at p<0.05.

Chl a – chlorophyll a; Chl b –chlorophyll b; Chl T – total chlorophyll; Car – carotenoids; FM – fresh mass.

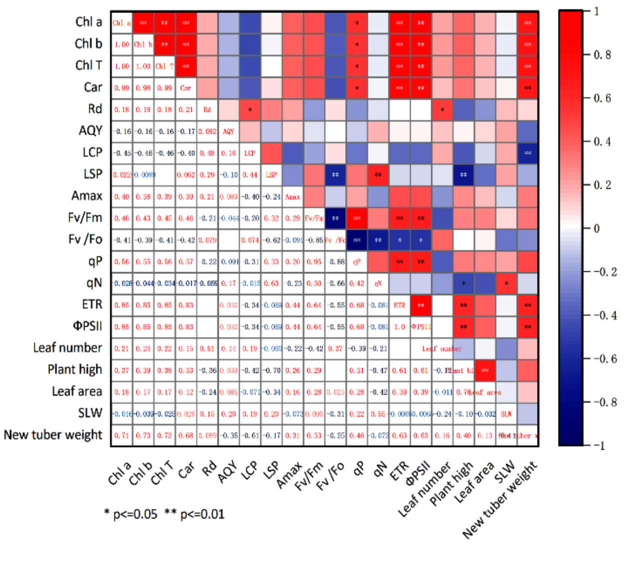

Fig. 4. Correlation analysis of photosynthetic parameters and leaf morphological factors of *P. cyrtonema* and *P. sibiricum* under different light quality

Chl a – chlorophyll a; Chl b –chlorophyll b; Chl T – total chlorophyll; Car – carotenoids; Rd – respiration rate; AQY – apparent quantum efficiency; LCP – light compensation point; LSP – leaf light saturation point; A_{max} – maximum net photosynthetic rate; F_v/F_m – maximal quantum yield of PSII photochemistry; F_v/F_0 – potential activity of PSII photochemistry; qP – photochemical quenching coefficient; qN – nonphotochemical quenching coefficient; ETR – electron transport rate; Φ_{PSII} – effective quantum yield of PSII photochemistry; SLW – specific leaf weight.

Plant morphology and newly added yield: The morphological traits of the two plants were also affected by light quality (Table 3). *P. cyrtonema* exhibited the highest leaf count under white light; however, its plant height, leaf area, specific leaf weight (SLW), and new tuber weight in the blue light group surpassed those in the other two light quality groups. The red light group of *P. cyrtonema* exhibited a reduced leaf count, diminished leaf area per plant, and attenuated plant growth. The biomass accumulation of the plants was minimal under red light, with the new tuber weight measuring only 0.29g, significantly lower than the other two light quality treatment groups. *P. sibiricum* exhibited enhanced growth under blue light, particularly in new tuber weight, which attained 1.07g, significantly surpassing other treatment groups. The leaf count and plant height of *P. sibiricum* in the red light group were inferior to those in the white light group. Nonetheless, the leaf area per plant, specific leaf weight, and newly formed underground tubers were marginally elevated in the white light treatment group.

Correlation analysis between photosynthetic parameters and morphological indicators: The correlation analysis of photosynthetic parameters and morphological indicators demonstrated a highly significant positive correlation between chlorophyll content and ETR, Φ_{PSII}, and new tuber weight (Fig. 4). During this period, the experimental plants were subjected to a low-light environment; however, their growth remained predominantly healthy. This condition notably enhanced the transfer efficiency of photosynthetic electron chains by elevating chlorophyll content, which also facilitated the development of subterranean tubers. The LSP in the gas exchange parameter exhibited a significant positive correlation with qN in the fluorescence parameter and a significant negative correlation with Fv/F_0. This suggests that prolonged exposure to low light conditions, followed by intense illumination on the leaves, can diminish the photochemical potential of PSII and enhance the thermal dissipation within the photosynthetic electron transport chain. The respiration rate of plants is a crucial reference point for energy metabolism. A respiration rate that is excessively low results in slow plant growth, whereas an excessively high rate may signify stress-related damage, including mechanical injury. Figure 4 demonstrated a substantial correlation between Rd, LCP and the leaf number. In the experiment, the respiratory rates of the plants in the six treatment groups were comparatively low. In this context, sustaining an elevated respiratory rate is advantageous for plant development.

Principal component analysis of photosynthesis parameters and morphological indicators: Figure 5 of the principal component analysis indicates that the proportions of the principal components were 40.3% and 17.9%, respectively. Chlorophyll content and chlorophyll fluorescence parameters significantly influenced the principal components, whereas new tuber weight, plant height, and leaf area substantially contributed to the indicators of plant leaf morphology. The values for the various light quality treatment groups were effectively clustered, exhibiting a significant concentration of data in the red light group, all of which fell within the confidence interval of the white light group. Conversely, the data in the blue light group exhibited significant divergence. The clustering outcomes of principal component analysis indicated that light quality can substantially alter the photosynthetic physiology and morphological traits of plants. The application of blue light treatment markedly enhances the chlorophyll content, electron transfer efficiency, and subterranean stem development of *P. cyrtonema* and *P. sibiricum*.

Table 2. Comparison of chlorophyll fluorescence parameters of *P. cyrtonema* and *P. sibiricum* leaves under different light quality.

Item	Fv/Fm [z]	F_v/F_0 [z]	qP [z]	qN [z]	ETR [z x]	Φ_{PSII} [z]
W-C	0.783 ± 0.008 a [y]	3.633 ± 0.174 bc	0.380 ± 0.005 c	0.318 ± 0.037 d	9.02 ± 0.642 d	0.215 ± 0.018 d
R-C	0.641 ± 0.062 c	1.880 ± 0.543 e	0.342 ± 0.018 d	0.752 ± 0.031 a	7.32 ± 0.117 e	0.174 ± 0.050 e
B-C	0.840 ± 0.040 a	4.271 ± 0.069 a	0.823 ± 0.038 a	0.412 ± 0.014 c	24.44 ± 1.460 a	0.582 ± 0.018 a
W-S	0.771 ± 0.007 ab	3.379 ± 0.143 c	0.550 ± 0.043 b	0.292 ± 0.036 e	12.04 ± 0.829 b	0.287 ± 0.095 b
R-S	0.724 ± 0.010 b	2.633 ± 0.144 d	0.386 ± 0.014 c	0.745 ± 0.048 a	10.43 ± 0.786 c	0.248 ± 0.016 c
B-S	0.796 ± 0.010 a	3.919 ± 0.242 ab	0.867 ± 0.027 a	0.574 ± 0.054 b	23.26 ± 1.152 a	0.562 ± 0.036 a

[z] Values in table are presented as mean ± standard deviation (n=9)
[y] Means followed by the same letter do not differ based on the Duncan's New Multple Range Test at p<0.05
[x] The photon flux density for actinic light (PPFD) is 100 μmol(photon)·m^{-2}· s^{-1}
F_v/F_m – maximal quantum yield of PSII photochemistry; F_v/F_0 – potential activity of PSII photochemistry; qP – photochemical quenching coefficient; qN – nonphotochemical quenching coefficient; ETR – electron transport rate; Φ_{PSII} – effective quantum yield of PSII photochemistry

Table 3. Comparison of plant and leaf morphology of *P. cyrtonema* and *P. sibiricum* under different light quality.

Item	Leaf number (piece) [z]	Plant high (cm) [z]	Leaf area (cm^2) [z]	SLW (mg mm^{-2}) [z]	New tuber weight (g) [z]
W-C	8.33 ± 0.31 a [y]	35.1 ± 3.17 a	35.0 ± 2.86 b	1.10 ± 0.10 c	0.74 ± 0.05 c
R-C	5.33 ± 0.52 c	19.23 ± 0.21 e	18.4 ± 1.68 d	1.20 ± 0.20 bc	0.29 ± 0.02 f
B-C	5.67 ± 0.15 c	37.1 ± 3.25 a	53.5 ± 3.54 a	1.23 ±0. 21 ab	0.84 ± 0.04 b
W-S	7.67 ± 0.58 ab	13.2 ± 1.37 c	26.6 ± 1.78 c	1.10 ±0.12 c	0.62 ± 0.04 d
R-S	7.33 ± 0.53 b	11.6 ± 1.32 d	27.3 ± 1.23 c	1.17 ± 0.15 bc	0.40 ± 0.03 e
B-S	8.33 ± 0.23 a	15.4 ± 1.32 b	34.6 ± 2.68 b	1.33 ± 0.15 a	1.07 ± 0.15 a

[z] Values in table are presented as mean ± standard deviation (n=9)
[y] Means followed by the same letter do not differ based on the Duncan's New Multple Range Test at p<0.05
SLW – specific leaf weight

Discussion

Effect of light quality on photosynthetic gas exchange in plant leaves: The quality of light significantly influences plant growth and development, with most studies indicating that plants exhibit superior growth under compound white light compared to monochromatic light exposure (Wu, *et al.*, 2020). In contemporary agricultural production facilities, red and blue light, which are more readily absorbed by chloroplast pigments, are frequently utilized to conserve light energy. The demand for red and blue light exhibited significant variation among various plant species (Dai *et al.*, 2021). The *P. cyrtonema* and *P. sibiricum* examined in this article exhibit elevated net photosynthetic rates (Pn) under blue light, especially the *P. cyrtonema* requiring merely 10μmol·m^{-2}·s^{-1} for the light compensation point (LCP) in this spectrum, and achieving a maximum net photosynthetic rate (A_{max}) of 5.023μmol·m^{-2}·s^{-1}. This contrasts with the conclusions of Brito C *et al.* (2023), who assert that water lilies (*Lolium perenne*) were more conducive to photosynthesis in white light. This may result from the varied experimental species. The photosynthetic rate of *P. cyrtonema* was marginally reduced in the white light treatment compared to the blue light treatment, while it was significantly diminished under the red light treatment. The distinction between *P. sibiricum* subjected to white and red light treatment was not statistically significant. This may also be associated with the diminished light intensity during the experimental procedure. All treatment groups utilized a weak light intensity of 100 μmol·m^{-2}·s^{-1}. Conversely, blue light produced higher energy photoelectrons, while *P. cyrtonema* and *P. sibiricum* exhibited enhanced absorption capacity for blue light, leading to elevated photosynthetic rates.

The quality of light influences the stomatal opening of leaves, thereby impacting the rate of photosynthesis. At a red to blue composite light ratio of 1:1, the stomatal conductance (Gs) of *Solanum melongena* reaches its peak, coinciding with the highest net photosynthetic rate (Pn) (Li, 2015). This article identified through correlation analysis of gas exchange parameters on the Pn-PAR curve of leaves that the transpiration rate (Tr) of *P. cyrtonema* and *P. sibiricum* exhibited a significant positive correlation with Gs, and Pn also demonstrated a positive correlation with Gs. This indicates that both Pn and Tr were constrained by stomatal factors across the three light quality treatments. Numerous studies indicate that monochromatic blue light irradiation is detrimental to plant photosynthesis; for instance, an increase in intercellular CO_2 concentration (Ci) signifies a reduction in the carbon dioxide assimilation capacity of *Allium tuberosum* under blue light exposure (Chen, 2012). In this article, the Pn and Ci of both plant species exhibited a negative correlation. Gs exhibited a significant positive correlation with Ci under blue light in *P. cyrtonema*, whereas a negative correlation was observed under red light, which slightly deviates from prior scholarly findings. This may be attributable to the low light intensity employed in this article. Plants exposed to weak blue light exhibit normal growth, and as photosynthetically active radiation (PAR) intensifies, their capacity to assimilate carbon dioxide progressively enhances, and the concentration of Ci diminishes gradually. Nevertheless, plants exposed to weak red light exhibit poor health, and an elevation in PAR fails to produce a notable reduction in Ci, particularly in the instance of *P. cyrtonema*. The gas exchange parameters suggest that *P. cyrtonema* can efficiently harness blue light, whereas the insufficient energy of red light severely impairs its growth. Conversely, *P. sibiricum* effectively utilized blue light; however, its capacity to utilize red and white light showed no significant difference.

Effect of light quality on chloroplast pigment content in plant leaves: The pigments within chloroplasts facilitate the absorption and transmission of light energy in the process of photosynthesis (Tong *et al*., 2000). The quality of light influences gene expression patterns that govern the synthesis pathway of photosynthetic pigments, thus modulating variations in pigment content levels. The oxidative decomposition of carotenoids serves as a pathway for the synthesis of abscisic acid (ABA). NCED functions as a rate-limiting enzyme in abscisic acid biosynthesis. The enhancement of carotenoid content and NCED under blue light treatment can bolster the resistance to photooxidation in *Lemna minor* and safeguard its photosynthetic system (Zhong *et al*., 2022). Studies indicate that blue light exposure can lead to an increase in carotene and chlorophyll levels in plants (Samuoleenė *et al*., 2021). The experiment revealed that blue light irradiation significantly enhanced the chloroplast pigment content in the leaves of *P. cyrtonema* and *P. sibiricum*, with the chlorophyll content in the blue light group markedly exceeding that of other light quality treatment groups. The carotenoid content was markedly elevated compared to the other two groups under blue light treatment. In contrast to red light, short wavelength blue light possesses greater energy even in low illumination conditions, prompting plants to mitigate light damage from excessive energy by augmenting carotenoid levels, thus enhancing blue light utilization efficiency. The content of Chl b increased more than that of Chl a under low light treatment, suggesting that plants enhance light absorption by elevating Chl b levels in low light conditions (Li *et al*., 2020). A reduction in light intensity within a specific range facilitates the synthesis of additional chlorophyll to absorb low light levels (He *et al*., 2017). This experiment revealed no significant difference in chlorophyll a/b levels between *P. cyrtonema* and *P. sibiricum*. The light intensity of each treatment group may have been insufficient, resulting in the quality of light having no impact on the chlorophyll a/b ratio. The photosynthetic pigment content of *P. cyrtonema* in the red light group was significantly lower than that of the other groups, whereas the difference in *P. sibiricum* under red and white light was not significant, indicating that *P. cyrtonema* possesses a diminished capacity to utilize weak red light compared to *P. sibiricum*.

Effect of light quality on chlorophyll fluorescence in plant leaves: Light emits photons that transmit energy, thereby activating chlorophyll and facilitating the photosynthetic electron transfer chain. Under typical physiological conditions, the maximal quantum yield of PSII photochemistry (Fv/Fm) remains relatively stable in most plants, approximately 0.8 (Xu *et al*., 2015). The Fv/Fm of *P. cyrtonema* in the blue light group was 0.840, significantly exceeding the 0.641 observed in the red light group. In various light quality treatments, the Fv/Fm of *P. sibiricum* exhibited a consistent pattern, with the highest values in the blue light group, followed by the white light group, and the lowest in the red light group. Nonetheless, no substantial difference in Fv/Fm was observed between the red light group and the white light group. Nonphotochemical quenching (qN) indicates a plant's capacity to utilize electrons within the photosynthetic chain. Excess photoelectrons can mitigate photosynthetic damage by utilizing heat dissipation energy (Gu *et al*., 2023). *P. cyrtonema* and *P. sibiricum* exhibited the highest qN values under red light treatment, signifying that during this period, the plants utilized the fewest electrons for photochemical reactions and demonstrated the lowest electron transfer efficiency. The photosynthetic apparatus of the plants was significantly impaired at this time, rendering them incapable of efficiently transferring electrons even in low light conditions. The effective quantum yield of PSII photochemistry (Φ_{PSII}) and electron transport rate (ETR) values for two plant species are maximized in blue light and minimized in red light, with *P. cyrtonema* exhibiting particularly pronounced performance. The chlorophyll fluorescence parameters reveal that under the light intensity treatment, both plant species experience varying degrees of weak light stress; however, *P. cyrtonema* effectively harnesses blue light, enhances electron transfer efficiency, and mitigates or completely alleviates this stress. Red light with low energy levels is insufficient to fulfill the growth requirements of *P. cyrtonema*. The response of *P. sibiricum* to red light is relatively weak.

Effect of light quality on plant morphology: There are notable disparities in the growth status and morphology of plants subjected to varying lighting conditions. White light facilitates the allocation of potato biomass from tubers to leaves, resulting in an increase in leaf specific weight and a decrease in tuber weight. Blue light enhances potato leaf area and anthocyanin concentration, thereby benefiting particular potato attributes (Xu *et al*., 2018). The height of *Sarcandra glabra* markedly increased under red light, while the stem diameter and leaf area diminished. The leaf area and plant height significantly diminished under blue light (Xie *et al*., 2020). This study demonstrates that white light enhances the leaf count of *P. cyrtonema*, whereas blue light irradiation promotes specific leaf weight, plant height, leaf area, and the development of underground tubers. *P. sibiricum* exhibited enhanced plant growth and increased subterranean tuber production under blue light. The inadequate red light treatment resulted in the plant exhibiting slender and frail growth, and the production of subterranean tubers was also minimal. Nonetheless, the two plants exhibited slight variations in their responses to red light. *P. sibiricum* exhibited a more pronounced utilization effect under red light compared to white light. However, *P. cyrtonema* could not withstand red light treatment; in the later stages of treatment, the leaves began to turn white, ultimately resulting in the plant's demise. The medicinal herb Huangjing is cultivated for its subterranean tubers. The blue light treatment was more advantageous for the enhancement of subterranean tubers under identical low light conditions.

Conclusion

Plant biomass derives from organic matter generated via photosynthesis. Regardless of the organ chosen for harvesting, photosynthesis directly affects the economic yield of plants. This article analyzes the correlation between photosynthetic parameters and morphological indicators, demonstrating a significant positive relationship between the growth of the medicinal herb Huangjing, cultivated for its subterranean tubers, and both chlorophyll content and electron transfer rate. Chlorophyll content and chlorophyll fluorescence parameters significantly influence the principal components of photosynthetic physiological factors. The morphological indicators of plants and leaves, namely new tuber weight, plant height, and leaf area, substantially influence the principal components. The application of blue light treatment markedly improves chlorophyll content, photoelectron conversion efficiency, and subterranean stem development in the medicinal herb Huangjing.

In summary, there are variations in the capacity of the medicinal herb Huangjing to utilize distinct light qualities. In indoor agricultural cultivation, the utilization of artificial light sources can enhance the ratio of blue light. *P. cyrtonema* is particularly ineffective at utilizing low energy red light, yet it demonstrates a robust capacity for blue light absorption. Under energy-efficient conditions, the application of pure blue light irradiation may be contemplated.

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