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Wavelengths of LED light affect the growth and cannabidiol content in *Cannabis sativa* L

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A R T I C L E I N F O

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A B S T R A C T

Given the special pharmacological value of cannabidiol (CBD), industrial hemp (hemp) has become a real "hot" crop. Though indoor farming of hemp has been widely used, the effects of red and blue light-emitting diode (LED) acting as supplementary light on the CBD synthesis in hemp remains unclear. Herein, a pot experiment with six treatments [CK, high-pressure sodium as light source, (R:B (ratio of red light to blue light) 9.30:1, PPFD (photosynthetic photon flux density) 191); LED1 (R:B 9.20:1; PPFD 129); LED2 (R:B 1.61:1; PPFD 540); LED3 (R:B 6.47:1; PPFD 28.2); LED4 (R:B 7.15:1; PPFD 41.7); LED5 (R:B 16.8:1; PPFD 252)] was carried out to study the effects of LED light quality on the growth and cannabinoid synthesis of hemp. Results showed that LED2 and LED5 could well maintain hemp growth compared with CK in terms of plant height, stem diameter, and leaf numbers. Compared with CK, the treatment of LED1, LED4, and LED3 significantly decreased the aboveground biomass, while LED2 and LED5 notably improved the aboveground biomass with an increment of 15.2 % and 55.1 %; the biomass of hemp flowers for LED2 and LED5 was markedly increased compared with that for CK with increments of 238 % and 61.5 %, respectively, but the other LED light treatments significantly reduced the flowers yield; LED2 could significantly increase the CBD content of both leaves (1.81 %) and flowers (5.83 %) compared to CK (leaves 1.38 %, flowers 4.27 %) while LED5 only notably increased the CBD content of leaves; among the LED treatments, the theoretic CBD yield for a per plant of LED2 and LED5 was 26.8 % and 9.0 % higher than that of CK. In conclusion, different red and blue LED light intensity ratios would dramatically influence the growth and cannabinoid synthesis of hemp, LED2 and LED5 can be good choices for indoor farming of hemp targeted for higher CBD yield.

1. Introduction

Industrial hemp (*Cannabis sativa* L., hemp) is defined as a kind of cannabis with Δ-9- tetrahydrocannabinol (THC) less than 0.3 % and not usable as a drug. As a traditional versatile crop, it has been cultivated for over 10,000 years and applied to many fields, such as textile, paper, oil, food, medicine, and even the biocomposite, automotive, and aviation sectors (Abot et al., 2013; Guerriero et al., 2019; House et al., 2010; Huang et al., 2019; Zegada-Lizarazu et al., 2010). In recent years, hemp has become a real "hot" crop due to its special pharmacological values, especially for cannabidiol (CBD). Nowadays, CBD has attracted much more attention than ever before (Corroon and Kight, 2018), which is not addictive but effective in curing many difficult diseases, such as epilepsy, Alzheimer, anxiety, pain, and inflammation (Blessing et al., 2015; Corroon and Phillips, 2018; Devinsky et al., 2017; Franco and Perucca, 2019; Li et al., 2020; Poleg et al., 2019) and so on. Apart from these medical uses, CBD has also been applied to foods, drinks, cosmetics, and health products, which shows great profits in the markets. The above reasons have contributed to the increase of the planting area as well as the indoor farming for hemp. Indoor farming shows easy-management for light, nutrients, temperature, water and it can be modified and adjusted to improve crop yields. Besides, it does not compete for land with the main crop and uses space with high efficiency. Thus, indoor farming seems a good choice to obtain the target high-value products of hemp, such as CBD. However, only under suitable conditions can indoor farming obtain ideal yields, such as suitable light conditions.

It is well known that light plays an indispensable role in the higher plant because it is one of the necessary conditions for photosynthesis.

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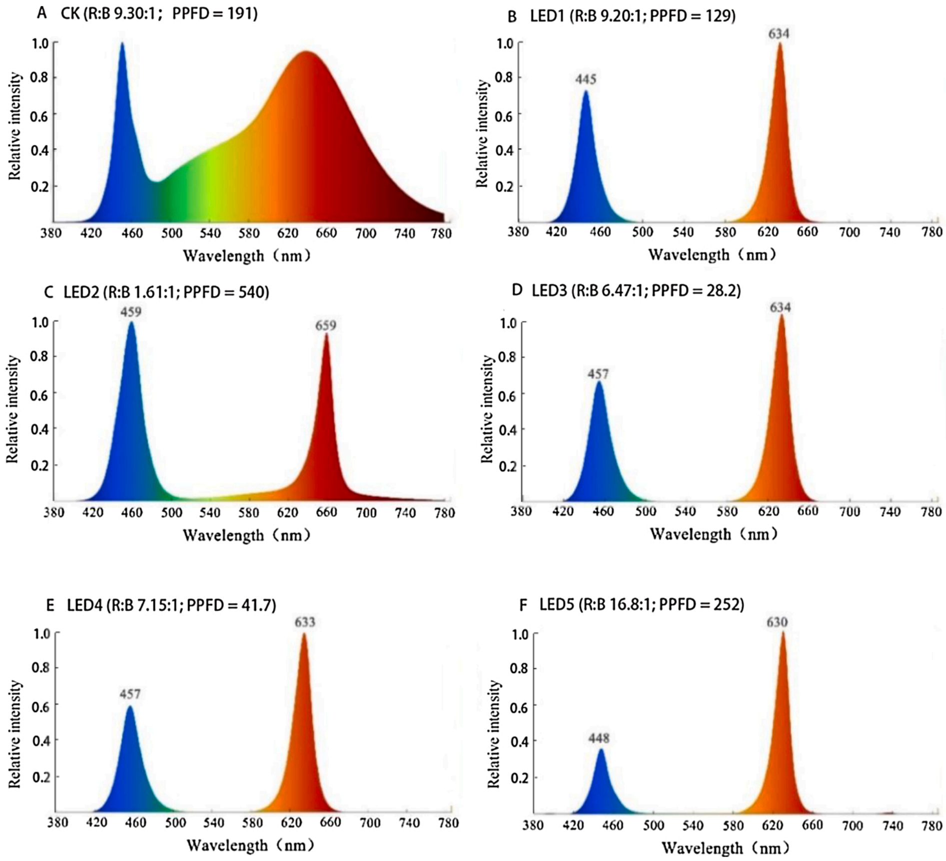

Fig. 1. The spectrum for different light treatments.
Note: CK refers to the treatment using the high-pressure sodium as light source; LED1-LED5 refer to the treatments with Light Emitting Diode lamps as light sources; R:B refers to the ratio of red light to blue light; PPFD refer to the photosynthetic photon flux density; Data above the peaks refer to the peak wavelength of lights; The powers for CK and LED1-LED5 are 50, 45, 120, 200, 240, 300 w, respectively.

Only obtains enough light, can plant grow and finish their life cycle. While, light can not only provide energy for photosynthesis, but also can act as sensory signals in modulating growth and development, altering physiological functions, and regulating biochemical pathways (Klem et al., 2019). Light conditions, such as light quality, light density, and photoperiod, can significantly affect plant growth and development, while light quality is the most complex one. The responses of the plant to different light conditions depend on the various photoreceptor, such as the phytochromes (perceiving red/far-red light), cryptochromes (perceiving blue light), and UVR8 (perceiving UV-light) (Lin, 2002; Ma and Dai, 2019). These photoreceptors can perceive the light quality or spectral composition and act as signaling cues to regulate the gene expression, and finally lead to the changes in morphology and development of plant (Kami et al., 2010).

The photosynthetic active spectrum for plants mainly concentrates in the visible part, especially in red (600–700 nm) and blue (400–500 nm) light (Spalholz et al., 2020). The spectrum can affect photosynthesis through plants of leaf structure, leaf size, leaf senescence rate, photosynthate transport, stomatal conductance, chlorophyll content, and composition directly and indirectly. Especially, the blue light can affect plant height, stomatal opening, circadian clock, photosynthate transport, photomorphogenesis, flowering time, and chlorophyll biosynthesis (Urbonavičiūtė et al., 2007; Heo et al., 2002; Yu et al., 2010). Compared with the blue light, red light has less confirmed and recognized effect, Barreiro et al. (1992) found that a low R/FR ratio led to the decreased photosynthetic capacity of kidney beans, which may be caused by the decrease of leaf area. However, Li and Kubota (2009) found that the promoting effect of FR supplementation on growth may be due to the increase of light absorption caused by the increase of leaf area (Li and Kubota, 2009).

As one of the most important factors influencing yields, the effects of light on crop yield in indoor farming have been investigated for a long time. Before the light-emitting diode (LED) appears, high-pressure sodium, incandescent lamps, fluorescent lamps, and metal halide lamps were widely used for indoor farming. Compared to these lamps, LED lamps feature flexible mobility, narrow spectrum range, low energy consumption, and longevity (Bourget, 2008; Gupta and Agarwal, 2017), besides, and these have made LED lamps more popular in indoor farming (De Keyser et al., 2019; Nakai et al., 2020; Poulet et al., 2014; Zabel et al., 2016). The above attributes also make it possible to mediate the spectrum for the specific crop by controlling each spectral range and manipulating spectral quality and light intensity precisely (Gupta and Agarwal, 2017; Pan, 2008). However, the best spectral ranges of LED lights and the ratios of different monochromatic LED lights usually vary among different crops for higher production. Studies showed that compared with the monochrome of red or blue light, the combination of red and blue light can more efficiently excite photoreceptors and increase both photosynthesis and plant growth (Sabzalian et al., 2014; Spalholz et al., 2020; Zhang et al., 2020). Li et al. (2018) found that LED lights can effectively promote peanut (*Arachis hypogaea* Linn.) growth and the ratio of red: blue 3:7 was best for pod growth and yield. But Poulet et al. (2014) proved red: blue 19:1 would give the best growth response for lettuce (*Lactuca sativa* L.) and He et al. (2017) demonstrated that the combination of red: blue 9:1 can obtain the highest shoot and root biomass and shoot/root ratio of *Mesembryanthemum crystallinum*. Thus, the ratios of red light to blue LED light should be considered for indoor farming.

In recent years, industrial hemp has attracted more attention than ever before, and the UN'decision of removing cannabis from the narcotics list in January 2021 would further promote the global hemp industry. As one of the most valuable products, CBD will be a "hot cake" for a long time. Thus, both farmers and researchers are interested in improving the CBD yield by trying different methods. Without a doubt, indoor farming combined with LED as a light source can be good access. Although some studies have investigated the effects of light quality on hemp, the studies mainly focused on the impacts of photoperiod, light

Fig. 2. The hemp grown in tents equipped with different LED-lamps.
Note: CK refers to the treatment using the high-pressure sodium as a light source; LED1-LED5 refers to the treatments with Light Emitting Diode lamps as light sources; R:B refers to the ratio of red light to blue light; PPFD refer to the photosynthetic photon flux density.

intensity, and monochromatic light on the THC content in hemp using non-LED light sources (Blessing et al., 2015; Chandra et al., 2008; Lydon et al., 1987; Valle et al., 1978). Previous studies have proved that light quality could affect the THC synthesis and accumulation in hemp. However, up to now, few studies have investigated the influence of different red and blue LED light ratios on the growth and CBD synthesis of hemp. Therefore, a hypothesis was raised that different red and blue LED light ratios can significantly impact the growth and CBD yield of hemp. Through this study, it was expected to obtain one or two suitable red and blue LED ratios for high CBD-yield hemp growing in indoor farming.

2. Materials and methods

2.1. Experimental design and procedures

The hemp seeds (“Xinma”) used in this study were provided by the Institute of Bast Fiber Crops, Chinese Academy of Agricultural Sciences. The experimental procedures were as follows: firstly, the hemp seeds were grown in seedling dishes containing nutritional soil (peat soil: perlite: vermiculite = 1:1:1) in a culture room (16 h light/8 h dark at 24 ± 1 °C and RH 60 %) and irrigated with distilled water every two days. Secondly, at the two-leaf stage, the seedlings were transplanted into plastic pots (30 cm × 20 cm) and placed in plant growing tents (1.2 m × 1.5 m) equipped with LED lamps for 110 days under the condition of 16/8 h (day/night) at 24℃, during this period, the male plant was removed for each treatment when it emerged.

Six treatments were set in the experiment: CK, using high-pressure sodium as light source, (R:B (ratio of red light to blue light) 9.30:1, PPFD (photosynthetic photon flux density) 191); LED1 (R:B 9.20:1; PPFD 129); LED2 (R:B 1.61:1; PPFD 540); LED3 (R:B 6.47:1; PPFD 28.2); LED4 (R:B 7.15:1; PPFD 41.7); LED5 (R:B 16.8:1; PPFD 252). Three pots were placed in each tent and there was one plant in each pot. Each treatment was replicated three times. The high-pressure sodium (220 V, 50 W) was brought from the Heming Co., Shanghai, China. The LED lamps (single LED band size, 2.8 mm × 3.5 mm) were supplied by the Weizaoye Co., in Guangzhou, China: LDE1 (45 W), LED2 (120 W), LED3 (200 W), LED4 (240 W), LED5 (300 W). And the parameters of the light measured using the Spectrograph OHSP-350 s (HopooColor Technology Co., Hangzhou, China) were shown in Fig. 1.

2.2. Measurements and methods

The growth parameters, such as plant height, stem diameter of hemp were measured. In details: plant height was measured with a straight steel ruler (from the base of the stem to the apex of the plant); stem diameter was measured with a vernier caliper; the number of leaves was directly counted at the end of the experiment; the leaf area was measured using the leaf area meter Yaxin-1241 (Yaxin Liyi Technology Co., Beijing, China). After that, the plants were harvested (16 weeks) and dried, and the dry weight of the stem and leaves, roots, and flowers were recorded.

Biomass samples taken from apical segments (flowering buds) of hemp were used for cannabinoids analysis following the procedure in the literature (Ambach et al., 2014; Hadener et al., 2019; Raharjo and Verpoorte, 2004). Briefly, the inflorescence samples of hemp were firstly separated into leaves and flowers, then were dried at 70 °C in an oven, respectively, and next were ground into power (≤0.425 mm). After that, the sample was extracted with a mixture of methanol/hexane 9:1 (v:v) by ultrasonication for 20 min (flowers:extractant (w:v) 5:1; leaves:

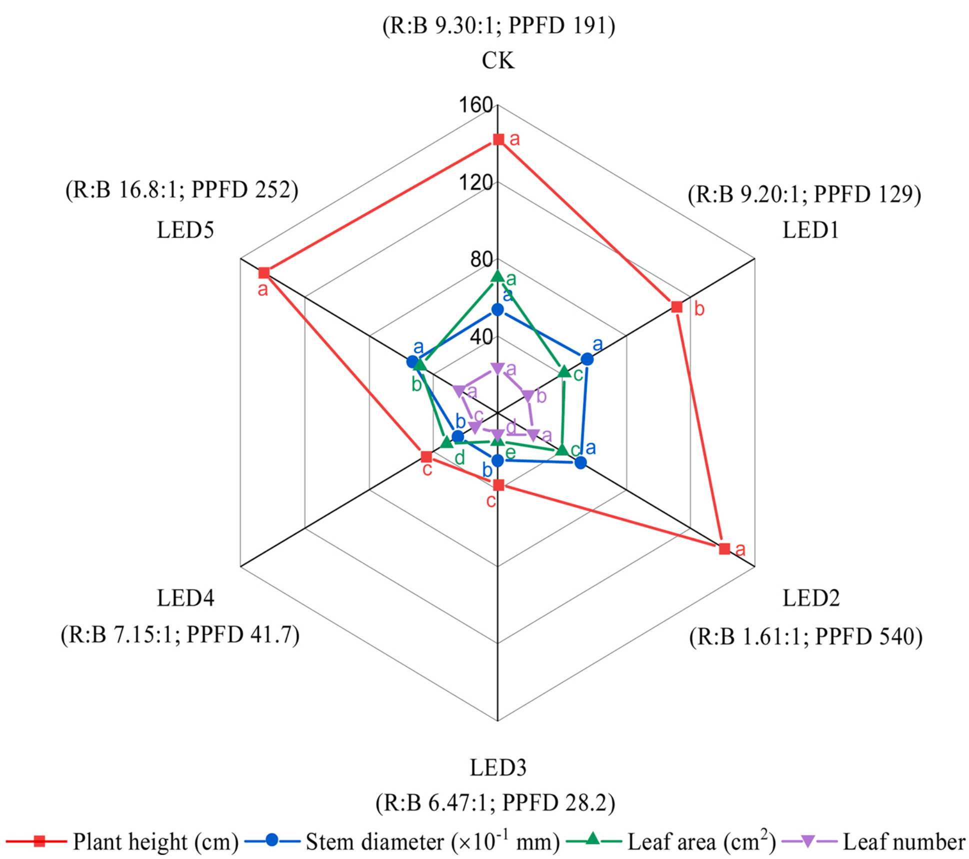

Fig. 3. The morphological indexes of industrial hemp as affected by different LED-lamps.
Note: CK refers to the treatment using high-pressure sodium as light source; LED1-LED5 refer to the treatments using Light Emitting Diode lamps as light source; R:B refers to the ratio of red light to blue light; PPFD refer to the photosynthetic photon flux density; Different letters near to the symbols in the same color mean significant differences between treatments ($P < 0.05$).

extractant 15:1). The extracts were diluted to 20-fold with the extractant for subsequent analysis of cannabinoids using an HPLC-DAD. The chromatographic conditions include Chromatographic column: Water Xbrige (250 mm × 4.6 mm i. d., 5 μm); Mobile phase: 0.1 % formic acid in water as mobile phase A and 0.1 % formic acid in acetonitrile as mobile phase B; Flow rate: 0.8 mL/min; Column temperature: 30 °C; Sample quantity: 10 μL ; Detection wavelength: 220 nm. The CBD and THC reference standards were purchased from Shanghai Yuanye Bio-Technology Co., Ltd.

2.3. Statistical analysis

The data were analyzed with one-way analysis of variance (ANOVA) via the SPSS 26.0 software (IBM, Armonk, NY, USA) and the figures were made using the software of Originpro 2019b (OriginLab, Massachusetts, USA). Significant differences between means were determined by Duncan's multiple range test at the $P < 0.05$ level.

3. Results

3.1. Morphological characteristics

Different light qualities can lead to visible morphological differences of hemp plants (Figs. 2 and 3). The plant height of hemp for LED5 (R:B 16.8:1; PPFD 252) (145.60 cm) and LED2 (R:B 1.61:1; PPFD 540) (140.20 cm) showed no significant difference compared with that for CK (142.03 cm), while LED3 (R:B 6.47:1; PPFD 28.2), LED4 (R:B 7.15:1; PPFD 41.7), notably decreased the plant height. The LED3 and LED4 notably decreased the hemp stem diameter by more than 50 % compared with that for CK, but other LED light treatments showed no marked difference relative to CK. As for the leaf area, it was significantly decreased by all LED light treatments compared with CK, while among the LED light treatments, LED5 and LED3 obtained the largest and smallest leaf area, respectively. The effects of light quality on the number of hemp leaves were similar to that on the plant height.

Table 1
The biomass of stem, roots, and flowers of industrial hemp as affected by light quality.

Treatments	Stem (with Leaves) (g)	Roots (g)	Flowers (g)
CK (R:B 9.30:1; PPFD 191)	14.91 ± 1.32c	0.19 ± 0.02c	1.30 ± 0.01c
LED1 (R:B 9.20:1; PPFD 129)	2.16 ± 0.16d	0.03 ± 0.003d	0.53 ± 0.04e
LED2 (R:B 1.61:1; PPFD 540)	17.17 ± 0.38b	0.71 ± 0.09a	4.40 ± 0.08a
LED3 (R:B 6.47:1; PPFD 28.2)	0.92 ± 0.07e	0.01 ± 0.01e	0.10 ± 0.01f
LED4 (R:B 7.15:1; PPFD 41.7)	1.79 ± 0.27de	0.02 ± 0.001d	0.70 ± 0.05d
LED5 (R:B 16.8:1; PPFD 252)	23.12 ± 0.19a	0.48 ± 0.02b	2.10 ± 0.52b

Note: CK refers to the treatment using high-pressure sodium as light source; LED1-LED5 refer to the treatments using Light Emitting Diode lamps as light source; R:B refers to the ratio of red light to blue light; PPFD refer to the photosynthetic photon flux density; Different letters near to the symbols in the same color mean significant differences between treatments (P < 0.05).

3.2. Biomass

The distribution of dry biomass to the stem (with leaves), roots and flowers were significantly affected by LED light treatments (Table 1). Compared with CK, the biomass of stem was notably increased by LED2 and LED5, with increments of 15.2 % and 55.1 %, respectively, while the other LED light treatments significantly decreased the stem biomass. Compared with CK, LED2 and LED5 significantly increased the root

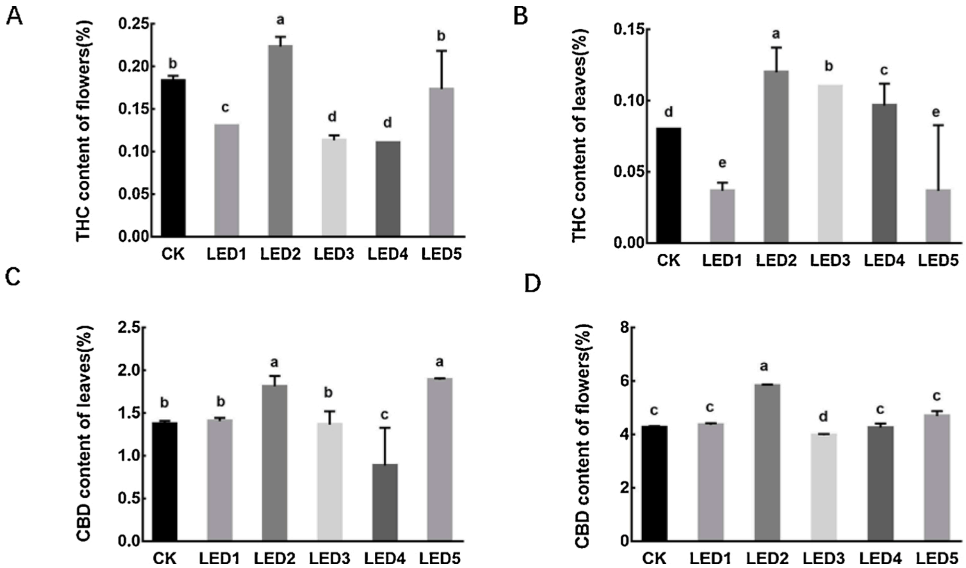

Fig. 4. The contents of THC and CBD in the different parts of the hemp plant as affected by light quality.
Note: CK, using high-pressure sodium as light source, (R:B (ratio of red light to blue light) 9.30:1, PPFD (photosynthetic photon flux density) 191); LED1 (R:B 9.20:1; PPFD 129); LED2 (R:B 1.61:1; PPFD 540); LED3 (R:B 6.47:1; PPFD 28.2); LED4 (R:B 7.15:1; PPFD 41.7); LED5 (R:B 16.8:1; PPFD 252). Different letters above the columns represent significant differences ($P < 0.05$).

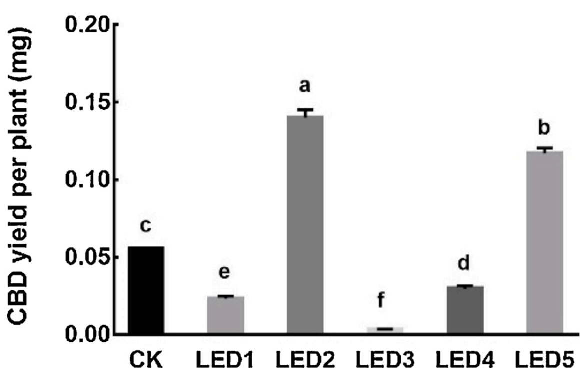

Fig. 5. The cannabidiol (CBD) yield of industrial hemp as affected by light quality.
Note: CK, using high-pressure sodium as light source, (R:B (ratio of red light to blue light) 9.30:1, PPFD (photosynthetic photon flux density) 191); LED1 (R:B 9.20:1; PPFD 129); LED2 (R:B 1.61:1; PPFD 540); LED3 (R:B 6.47:1; PPFD 28.2); LED4 (R:B 7.15:1; PPFD 41.7); LED5 (R:B 16.8:1; PPFD 252). Different letters above the columns represent significant differences ($P < 0.05$).

biomass by 273 % and 152 %, respectively, but LED1 (R: B 9.20:1; PPFD 129), LED4, and LED3 only obtained no more than 0.03 g biomass per plant. Similar to the root part, the biomass of flowers was also notably increased by LED2 and LED5 (with an increment of 238 % and 61.5 %, respectively) relative to CK.

3.3. Cannabinoids content and CBD yield

The LED light treatments markedly affected the cannabinoids content and yield of the hemp plant (Figs. 4 and 5). The CBD content for LED5 (1.89 w/w) and LED2 (5.83 w/w) were the highest among all the treatments with increments of 36.9 % and 36.5 % for leaves and flowers respectively, compared with that for CK (1.37 w/w, 4.27 w/w). There was also a notable increment of CBD in leaves for LED2 (1.81 w/w) relative to CK (1.37 w/w), but no comparable difference between the two treatments was found for the CBD content in flowers. Among other treatments, LED4 (0.89 w/w) markedly decreased the CBD content in leaves compared with CK, while LED3 (3.97 w/w) significantly reduced that in flowers. Whether the CBD content in hemp was increased or not, the THC contents in both organs for all treatments were still under the standard of 0.3 %.

Based on the dry biomass of flowers and CBD content, the theoretical CBD yield per plant of each treatment was calculated (Fig. 5). The CBD yield for six treatments differed from each other significantly. The highest CBD yield was found in LED2 (0.14 mg), followed by LED5 (0.12 mg), and the lowest CBD yield was found in LED3 (0.003 mg). The CBD yields of LED2 and LED5 were 26.8 % and 9.0 % higher than that of CK, respectively.

3.4. Correlations between different parameters

Pearson correlations between parameters obtained from both light and hemp were calculated (Fig. 6). Results showed that red light had a negative correlation with the CBD synthesis and accumulation, but blue light showed a positive correlation with that. The ratio of Red: Blue showed a notably negative correlation with THC in the leaf. While the ratio of Blue: Red showed a notably positive correlation with PPFD, flower biomass, as well as CBD in flower. PPFD was notably and positively correlated with flower biomass, CBD in flower, and THC in flower. The CBD yield per plant was significantly and positively related with PPFD, flower biomass, CBD/THC in flower. As the target product, the CBD yield was almost positively correlated with all the measured parameters except the red light and showed a significantly positive correlation with PPFD, flower biomass, total biomass, CBD in flower, and THC in flower.

4. Discussion

4.1. Effects of LED light qualities/wavelengths on hemp growth

Light is a necessary factor determining crop yield, the suitable spectral ranges and combinations can contribute to obtaining higher target products (Bian et al., 2018; Brown et al., 1995; Choi et al., 2015). Red and blue LED light ratios in the lighting spectrum were proved to be efficient enough for the normal growth and photosynthesis of various crops (Bian et al., 2018; Mitchell et al., 2015). In the present study, different red and blue LED light ratios showed distinct effects on hemp growth (Fig. 2), the hemp plant height, stem diameter, leaf area, and the number of leaves can be either slightly increased or significantly decreased by the supplied LED light compared with high-pressure sodium (CK). This result indicated that suitable red and blue LED light ratios can promote the growth of hemp.

For red light, its increasing proportion to total light hardly showed positive effects on hemp growth (Fig. 6). While the increment of the

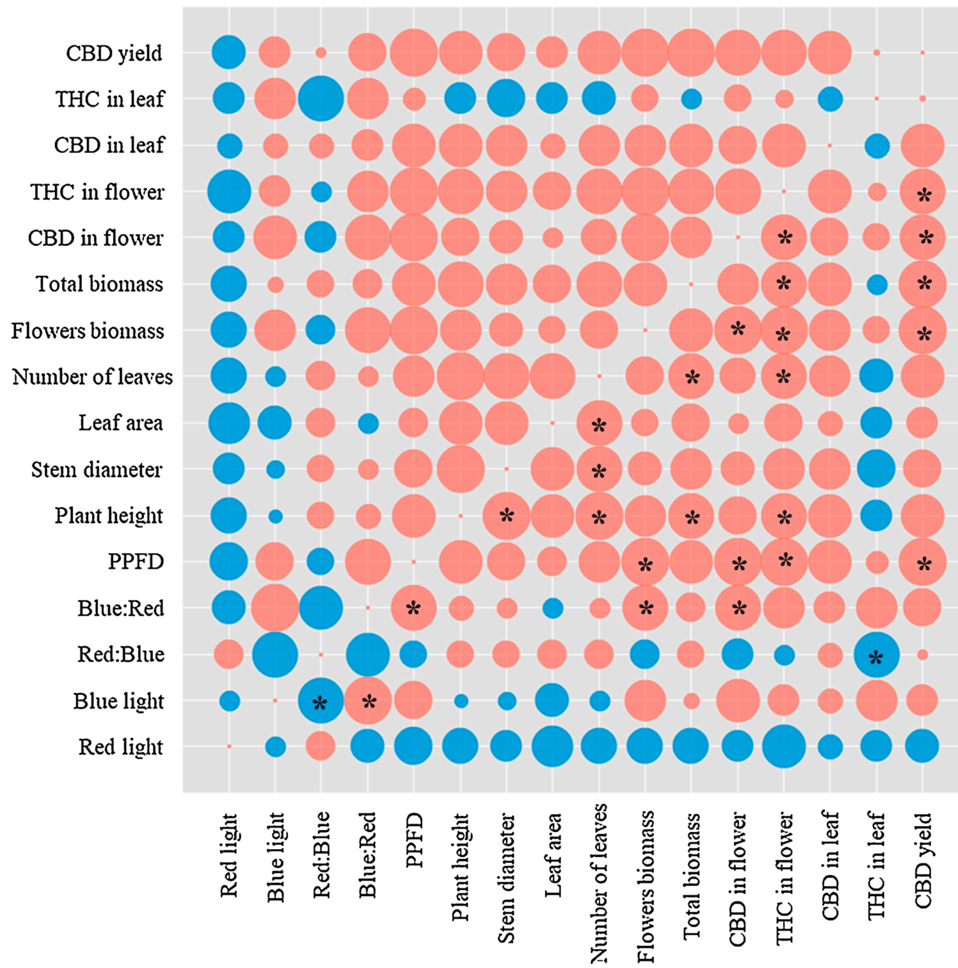

Fig. 6. Pearson correlations between parameters obtained from both light and hemp.
Note: Blue circle and red circle refer to negative correlation and positive correlation, respectively; The larger circles mean stronger correlations; Red:Blue refers to the ratio of red light to blue light; PPFD refer to the photosynthetic photon flux density; * means the correlation is significant at 0.05 level.

proportion of blue light to total light negatively correlated with the plant height, stem diameter, and so on, it can be positively correlated with the hemp flower biomass in hemp. Thus, the results of this study indicated that the higher proportion of blue light would increase the photosynthate accumulation in inflorescence and consequently restrain the vegetative growth of hemp. This was an important finding, especially for medical hemp cultivation, since most of the medicinal components were produced in the inflorescence of hemp (Fiorini et al., 2019). Especially, for the present study, both LED2 (R: B 1.61:1; PPFD 540) and LED5 (R: B 16.8:1; PPFD 252) can significantly increase the biomass of flowers, which suggested the LED2 and LED5 might be useful in promoting the CBD yield in hemp flowers. Similar results between light treatments were found in some species that focused on the effects of varying light intensities on the photosynthetic response (Bazzaz and Carlson, 1982; Hallik et al., 2012; Wahidin et al., 2013). On the other hand, interestingly, the combination of red and blue light can make up the disadvantages from either light, since the ratios of these two lights can significantly promote the growth of hemp (Table 1 and Fig. 3). As a result, it can be hypothesized some combinations of red light and blue LED light can contribute to the growth of hemp while increasing the target product yield.

4.2. Effects LED light qualities/wavelengths on the cannabinoid content

The increment in the proportion of red light to total light showed negative correlations with both CBD and THC content in hemp (Fig. 6), but the increasing proportion of blue light to total light showed contrary correlations. These findings indicated that the higher proportion of blue light would promote the synthesis and accumulation of cannabinoids in hemp. However, the combination of red and blue light could change the situation and different ratios of two lights can lead to varied effects on the cannabinoid distribution and accumulation (Figs. 4–5). CBD yield in hemp is not only determined by the relative content of CBD in plant organs but also depends on the biomass of the source organs. In this study, LED2 (R: B 1.61:1; PPFD 540) and LED5 (R: B 16.8:1; PPFD 252) can significantly increase the biomass of flowers, this also contributed to the CBD yield greatly.

The content of THC in hemp is also a focus for scientists since many countries are forbidden planting hemp with THC > 0.3 %, such as China. In this study, the LED light treatment can significantly improve or decrease the content of THC in the hemp organs, but the content of THC for all the harvested samples is below the permissible level. Thus the present study suggested that it is possible to increase CBD yield by combining indoor-farming and LED light in hemp.

4.3. The roles of LED light as signaling cues

Light can not only provide energy for photosynthesis, but also can act as sensory signals in modulating growth and development, altering physiological functions, and regulating biochemical pathways (Klem et al., 2019). For the present study, the increment of blue light proportion showed a positive correlation with flower biomass and CBD content in flower, these responses were mediated by the blue light receptors i.e. cryptochromes, which regulate various aspects of plant development (Liscum et al., 2003). In this study, when the cryptochromes in hemp perceive blue light, they are activated and produce signals to mediate the nuclear gene transcriptional through the modulation of transcription or interaction with the proteasome (Chaves et al., 2011), and finally lead to the accumulation of biomass and CBD.

5. Conclusion

From this study the following conclusions can be reached:

Firstly, wavelengths of LED light can significantly affect the growth and cannabinoid synthesis and accumulation in hemp; secondly, suitable ratios of red to blue LED light can greatly improve the target product yield of CBD either through increasing the biomass of inflorescence or the CBD concentration in inflorescence.

CRediT authorship contribution statement

Xiuye Wei: Experiment design, Software, Writing-original draft. **Xinlin Zhao:** Methodology, Validation, Investigation, Modification. **Songhua Long:** Conceptualization, Investigation. **Qingmei Xiao:** Data analysis. **Yuan Guo:** Data curation. Formal analysis. **Caisheng Qiu:** Resources. **Huajiao Qiu:** Conceptualization, Supervision. **Yufu Wang:** Funding acquisition, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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