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Effects of LED light quality on growth and development of pepper seedlings in a plant factory

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Abstract: Understanding the impacts of different light spectrums on the growth and development of pepper seedlings is vital for pepper cultivation in plant factories. In this paper, the effects of different light conditions on the growth and quality of pepper seedlings and their subsequent effects on the pepper plants after transplanting were explored. Based on the control light (white: red=3:2), pepper seedlings were cultivated under radiations of added different proportions of blue light, UV-A, and far-red light for 18 days. Compared with control, supplementary with UV-A and far-red light promoted the seedling height whereas blue light inhibited that. Blue and UV-A treatments increased seedlings' compactness and seedling indexes while far-red light treatments have obvious inhibitory effects. The chlorophyll content of the UV-A treatment was significantly increased, but far-red light reduced the carotenoid content. Far-red light increased the SOD and CAT activity and decreased the MDA content. After transplanting, there was no difference in the flowering time of pepper seedlings among all treatments. An increase in pepper yield was discovered when pepper seedlings was supplemented with blue and UVA light. Overall, our results exhibited that proper supplementation of UV-A and blue light at the seedling stage positively produce strong and healthy pepper seedlings, and could increase the yield of pepper after transplanting.

Keywords: light quality; growth; pepper seedlings

Citation: Lastname, F.; Lastname, F.; Lastname, F. Title. *Agronomy* **2022**, *12*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Firstname Lastname

Received: date
Accepted: date
Published: date

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1. Introduction

Being one of the important environmental factors, light is essential for all stages of plant growth and development [1]. Through the aspects of light intensity, light photoperiods, and light quality, the morphological and physiological traits of plants are affected. Light spectrum, from far-red to UV, has been widely investigated for its role in the growth and development of plants. For example, far-red light influences physiological processes such as seed germination, hypocotyl growth, induction of flowering, etc. [2]. It had been demonstrated that red light was beneficial to increasing the leaf area and promoting the photosynthates accumulation [3]. Blue light is mainly involved in the regulation of shade avoidance, stomatal movement, and photosynthetic performance [4-6]. Green light inhibited stem growth and chloroplast gene expression of plants, which were opposite to blue or red light [7]. In addition, UV-A had positive role in accumulating healthy compounds in different species [8,9].

Pepper（*Capsicum* spp.）is one of the worldwide grown vegetables whose growth and development are largely influenced by different light wavelengths. The anthocyanin content and the fruit ripening time of purple pepper were influenced by blue light [10]. Under the exposure to UV-B light, the peppers' vegetative growth was inhibited but increased the flavonoid accumulation in the leaves [11]. Taller pepper plants with greater dry weight and thicker stems were induced by green light [12]. Moreover, pepper plants radiated under distinct light spectrums showed different vulnerabilities to water deficit

[13]. Hence, altering the light environment according to the response of pepper to different light qualities could be used as an approach to cultivate pepper with desired traits.

Seedling growth is a critical developmental stage of vegetable growth which is the basis for high-quality vegetable production [14]. It has been reported that cultivating vegetable seedlings in plant factories has some advantages, such as short cultivation time and high energy efficiency [15,16]. For pepper seedling cultivation, much attention had focused on the effects of red and blue as well as far-red light quality on seedlings' development, but studies that described the flowering and fruiting traits of these pepper seedlings after transplanting were not comprehensive enough [17,18]. ~~Besides,~~ it was found that little research has reported the impacts of UV-A on the performance or characteristics of pepper seedlings until now. In this study, we studied the impacts of a different portion of blue, UV-A, and far-red light spectrum on the growth and development of pepper seedlings under the same total light intensity of 200 μmol·m^{-2}·s^{-1}, and the flowering and fruiting characteristics of these different quality pepper seedlings after transplanting, to select the favorable light quality for healthy and strong pepper seedlings production in a plant factory.

2. Materials and Methods

2.1. Plant Material and Growth Conditions

Seedlings were cultivated in an artificial plant factory of SCAU (in Guangzhou city, China) with a constant temperature (24±2 °C) and (humidity of 75±5% as well as air carbon dioxide concentration of about 565±10 PPM. The pepper seeds (cv Xiangyan No. 55, Hunan Xiangyan Seed Industry Co. LTD) were sown in sponge cubes (2 cm × 2 cm × 2 cm) and were planted in the hydroponic after germination. And, the white light (photosynthetic photon flux density, PPFD was 200 μmol·m^{-2}·s^{-1}) was used for 2 days. Then the seedlings were divided into 7 groups to grow under seven different light treatments CK: 3W2R(W:R=3:2); B30:3W2R1B(W:R:B=3:2:1); B60:3W2R2B(W:R:B=3:2:2); UVA2:3W2R+2μmol·m^{-2}·s^{-1}UV-A; UVA-6:3W2R+6μmol·m^{-2}·s−1UV-A; FR20:3W2R+20μmol·m^{-2}·s^{-1}FR; FR30: 3W2R+30 μmol·m^{-2}·s^{-1}FR. The photosynthetic photon flux density (PPFD) of all treatments was set as 200 μmol·m^{-2}·s^{-1} (Figure 1, Table S1), and the photoperiod was 12/12 h (day/night). The PPFD and light spectra were measured by a spectroradiometer (ALP-01, Asensetek, Taiwan), W: 400-700 nm，R: 660±10 nm，B: 450±10 nm，UV-A: 385±10 nm，FR: 735±10 nm. The hydroponic uses half-strength Hoagland nutrient solution (pH 5.5) with electrical conductivity (EC) of 1.3 mS·cm^{-2}.

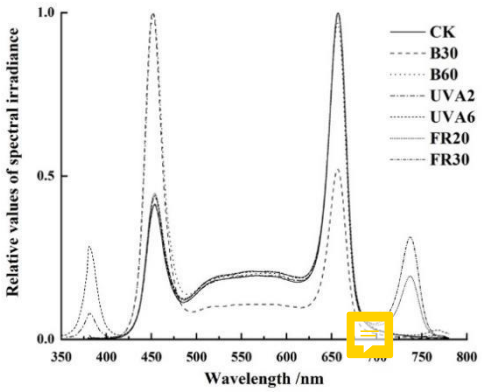


Figure 1. The spectral profile of all treatments delivered by different combinations of LEDs.

2.2. Determination of morphological traits and fresh and dry weight.

Fifteen uniform seedlings were selected to determine their growth indexes. For growth rate determination, measurements were taken 3 times every 6 days after the first day of light treatment. The plant height and hypocotyl length were measured by using a

measuring tape while the stem diameter was detected by using a vernier caliper, respectively. The growth rate of seedling height was obtained by the below formula:

Growth rate of seedling height= (The seedling height at 18 DAT - the seedling height before treatment)/ (Treatment days).

Hypocotyl and stem diameter growth rate were obtained in the same way as above. After 18 days' treatment, the true leaf area was measured by leaf area meter (LI-3000A). The amounts of seedlings leaves were counted. All the samples were dried at 105℃ for 30 minutes and dried at 75℃ to constant weight. The fresh and dry weight was measured by weighing with a thousandth electronic balance.

2.3. Calculation of seedling comprehensive index.

The comprehensive seedling index was calculated according to the following formula: specific leaf weight = leaf dry weight / leaf area; the plants compactness = shoot dry weight / plant height; root to shoot ratio = root dry weight / shoot dry weight; shoot dry matter content = shoot dry weight / shoot fresh weight; seedling index = (stem diameter/seedling height + root dry weight/shoot dry weight) * whole plant dry weight.

2.4. Measurement of chlorophyll content and chlorophyll fluorescence parameters.

Fresh leaves of pepper seedlings (0.5g) were taken for chlorophyll content determination, and the methods were described by He et al [8]. For the examination of chlorophyll fluorescence parameters, the chlorophyll fluorescence apparatus machine (MINI-PAM-II, Germany) was used. The parameters ~~including~~ F*v*/F*m*, Y(II), and ETR were measured by using the third true leaf after the whole seedling was dark adapted for 30 minutes.

2.5. Measurement of phytochemical substance and enzyme activities of seedlings.

The procedures used to determine the total soluble protein content in the experiment were with reference to [8]. A fresh leaf of 0.5 g was ground in 10 mL phosphate buffer (50 mM, pH 7.8), centrifuged at 10,000 rpm for 20 min, and then the supernatant was taken for enzyme activity determination. The SOD, POD, and CAT ~~activity was~~ estimated according to the described method of Giannopolitis and Ries [20], Kochba et al. [21], and Cakmak and Marschner[22], respectively.

The MDA contents were measured following the methods reported in Zhang et al. [23]. 0.5 g fresh sample was homogenized in a 10 mL 10% trichloroacetic acid (TCA) solution, centrifuged at 4000 rpm for 10 minutes, and the supernatant after centrifugation was taken as the sample extract. 2 mL of the supernatant after centrifugation was mixed with 2 mL of 0.6% TBA solution, then the mixture was reacted in boiling water for 15 min. After rapid cooling and centrifugation, the supernatant was measured at 532 nm, 600nm, and 450nm using a UV-spectrophotometer.

2.6. Data of flowering and fruit set after transplanting.

After 18 days of light treatment, 24 uniform pepper seedlings of each treatment were transplanted into a plastic greenhouse. The substrate was coconut bran, water and fertilizer were supplied by a drip irrigation system, and the nutrient solution was 1/2 Yamazaki pepper formula. At 30 days after transplanting, the first flowering time, the node of the first flower, fruits per plant at 15 and 30 DAT, number of harvested fruits, and total fruit weight were recorded. The number of fruits per plant was calculated by fruit length over 3 cm in 54 days after transplanting.

2.7. Statistical analysis.

All the experimental data were processed and analyzed by ~~the~~ SPSS 26.0 and Origin 2021 software. Duncan's method was used for the significance test ($P < 0.05$). All the pictures were obtained by ~~the~~ Origin 2021 software.

3. Results

3.1 Impacts of diverse LED light conditions on morphology and growth of pepper seedlings.

The morphological index of the pepper seedlings was significantly influenced after 18 days of treatment. The seedling height in FR30, FR20, UV-A2, and UV-A6 treatment were significantly 86%, 53.6%, 10.6%, and 8.6% higher than those in control, whereas B30 and B60 treated seedlings was 5.1% and 17.5% shorter than control seedlings (Figure 2B). The hypocotyl length of seedlings treated with FR30, UV-A2, UV-A6, and FR20 was significantly increased compared to those of B30, B60, and control, among which FR30 treated seedlings increased by 30.3% (Figure 2D). Compared with the control, FR20 treatment significantly increased the seedlings' stem diameter by 5.5%, while B60 treatment significantly decreased the stem diameter by 7.7% (Figure 2C). The amounts of true leaves under each treatment increased significantly compare to the control, with the increase of UV-A2 and UV-A6 treatments reaching 14.7% (Figure 2E).

The daily growth rate of pepper seedlings under various light conditions was examined. The seedling height growth rate of seedlings in UV-A6, FR20, and FR30 were higher, while those of B30 and B60 seedlings were lower than the control, respectively (Figure 2F). UV-A2, UV-A6, FR20 and FR30 treatment made the seedlings' hypocotyl growth rate 39.6%, 32.4%, 50.8% and 90.4% higher than the control, respectively (Figure 2F).

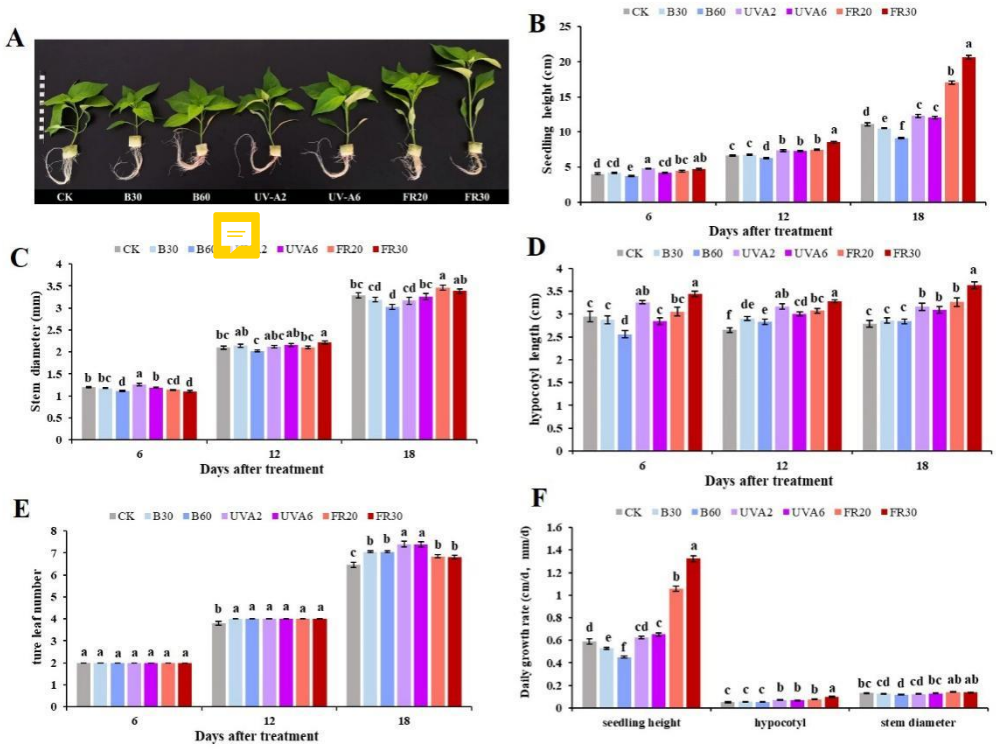


Figure 2. Effects of different light condition on the morphology and growth of pepper seedlings. (A) the typical morphology of pepper seedlings radiated under different light condition for 18 days. (B) seedling height, (C) stem diameter, (D) hypocotyl length, (E) true leaf number of pepper seedlings treated with distinct light environment. (F) The daily growth rate of pepper seedlings exposed to various light condition.

There were significant differences in biomass of pepper seedlings under different light quality treatments. The seedlings under UV-A2, UV-A6, FR20, and FR30 displayed elevated shoot fresh weight, with an increase of 12.8%, 16.1%, 19.1%, and 26.7%, respectively, compared with the control (Table 1). Both the plant fresh weight and the shoot dry weight of seedlings treated with UV-A6, FR20, and FR30 significantly increased (Table 1). FR20 and FR30 treatment led to a significant reduction in root dry weight than control

(Table 1). The plant dry weight of UV-A6 and FR30 was significantly 7.6% and 6.5% higher than the control. The percentage of dry matter in shoot under B60 and UV-A6 was significantly higher than those of the control by 6.0% and 5.8%, while those of FR treatment showed no comparable difference (Table 1).

In summary, the more the proportion of blue light (B30 and B60 treatments), the greater the inhibitory effect on the stem and hypocotyl elongation of pepper seedlings. Both UV-A2 and UV-A6 treatments increased the seedlings' biomass, the percentage of dry matter in shoot and seedlings' true leaf amount. Both FR20 and FR30 treatments were beneficial for increasing seedlings' hypocotyl growth, stem diameter, and biomass.

Table 1. Effects of different light quality treatments on biomass of pepper seedlings.

Treatment	Shoot fresh weight	Root fresh weight	Whole fresh weight	Shoot dry weight	Root dry weight	Whole dry weight	Percentage of shoot dry matter (%)
CK	4.62±0.18c	2.52±0.12ab	7.13±0.21cd	0.31±0.01cd	0.45±0.01a	0.75±0.02bc	6.53±0.13bc
B30	4.49±0.11c	2.28±0.07b	6.77±0.17d	0.29±0.01d	0.44±0.01ab	0.73±0.01c	6.67±0.05ab
B60	4.34±0.12c	2.27±0.05b	6.61±0.16d	0.29±0.01d	0.43±0.01abc	0.72±0.01c	6.89±0.09a
UVA2	5.21±0.21b	2.43±0.08ab	7.64±0.27bc	0.34±0.017bc	0.44±0.01ab	0.78±0.02ab	6.58±0.10bc
UVA6	5.37±0.19ab	2.46±0.07ab	7.82±0.25ab	0.36±0.01ab	0.45±0.01a	0.81±0.02a	6.88±0.06a
FR20	5.50±0.16ab	2.42±0.06ab	7.92±0.19ab	0.35±0.01ab	0.43±0.01bc	0.78±0.01ab	6.35±0.07c
FR30	5.86±0.21a	2.56±0.11a	8.42±0.28a	0.38±0.02a	0.42±0.01c	0.80±0.02a	6.43±0.07bc

Data represent mean ± SE, 20 pepper seedlings for each treatment were used for analysis. Different letters indicate significant differences between treatments at the $p < 0.05$, the same as all the tables below.

3.2 Influences of diverse LED light on the comprehensive index of pepper seedling growth.

Since distinct light conditions affected the morphology and biomass of pepper seedlings, then we studied the effects of different light conditions on comprehensive indexes of pepper seedling growth. The plant compactness increased in the B60 treatment but significantly reduced in FR treated seedlings (Table 2). Seedlings growing under FR20 and FR30 displayed a significantly decreased root-shoot ratio compared with the control (Table 2). The B60 seedlings showed obviously higher specific leaf weight, while seedlings of B30, FR20, and FR30 had apparently lower specific leaf weight in comparison with control (Table 2). Except for the FR20 and FR30 treatments showed a significantly lower seedling index, and other treatments' seedling index was significantly higher than those of the control (Table 2).

Table 2. The comprehensive index of pepper seedlings of all treatments.

Treatment	compactness	Root-shoot ratio	Specific leaf weight	Seedling index
CK	0.028±0.001b	0.272±0.024a	1.527±0.032b	0.210±0.014b
B30	0.028±0.001b	0.308±0.011a	1.325±0.022c	0.242±0.009a
B60	0.032±0.001a	0.315±0.025a	1.648±0.022a	0.248±0.007a
UVA2	0.027±0.001b	0.282±0.018a	1.477±0.034b	0.236±0.010a
UVA6	0.030±0.001ab	0.266±0.013a	1.495±0.030b	0.246±0.006a
FR20	0.021±0.001c	0.212±0.012b	1.219±0.019d	0.182±0.008c
FR30	0.018±0.001c	0.186±0.015b	1.184±0.019d	0.153±0.007d

Therefore, increasing proportion of blue light (B30 and B60 treatments) was conducive to cultivating healthy and strong pepper seedlings with compact phenotypes. The pepper seedlings radiated by UV-A2 and UV-A6 also showed compact seedlings, increased root-shoot ratio, and enhanced seedling index. The biomass of UV-A6 treated

seedlings was significantly elevated, suggesting that a certain dose of UV-A at the seedling stage could support the cultivation of healthy and strong seedlings. Supplementary FR (FR20 and FR30) treatment made the pepper seedling become slender, with almost all seedling growth indexes decreasing, implying that FR light was negative to the strong pepper seedling cultivation.

3.3 Effects of different LED light on photosynthetic pigment content and chlorophyll fluorescence parameters.

Wondering whether the photosynthetic traits of pepper seedlings were influenced, the content of photosynthetic pigment, including chlorophyll and carotenoids in pepper seedlings were examined. When exposed to UV-A2 and UV-A6 treatment, the contents of chlorophyll a and chlorophyll b were 8.3% higher than those in control, however only the seedlings in UV-A6 showed higher total chlorophyll content than the control (Table 3). The carotenoid content of FR20 treated seedlings was significantly lower than those of the control, while there was no significant difference between the other treatments and control seedlings (Table 3).

The chlorophyll fluorescence parameter, including Fv/Fm, Y(II) as well as ETR showed no comparable difference among all the treatments in pepper seedlings (Table 3). However, both the Y(II) and ETR of B60, UV-A6 pepper seedlings was slightly higher than that of FR20 pepper seedlings (Table 3). Which means that among all the treatments, blue and UV-A light were better in improving the actual photosynthetic efficiency and electron transport efficiency of PSII in pepper seedlings.

Table 3. Measurement of photosynthetic characteristics and pigment content of pepper seedlings under different treatments.

Treatment	chlorophyll a	chlorophyll b	Total chlorophyll	Carotenoid content	F*v*/F*m*	Y(Ⅱ)	ETR
CK	1.139±0.035cd	0.349±0.013b	1.505±0.049bc	0.226±0.004ab	0.754±0.003a	0.588±0.008ab	8.882±0.263ab
B30	1.192±0.008bc	0.379±0.003ab	1.588±0.011ab	0.231±0.001ab	0.749±0.002a	0.588±0.005ab	8.864±0.187ab
B60	1.127±0.016cd	0.348±0.006b	1.492±0.023bc	0.224±0.002ab	0.756±0.003a	0.603±0.016a	9.130±0.580a
UVA2	1.314±0.052a	0.407±0.025a	1.611±0.084ab	0.235±0.007a	0.751±0.002a	0.584±0.005ab	8.830±0.186ab
UVA6	1.234±0.020a	0.395±0.006a	1.648±0.026a	0.233±0.002ab	0.751±0.002a	0.596±0.007a	9.052±0.323a
FR20	1.058±0.036d	0.342±0.010b	1.417±0.047c	0.210±0.006c	0.754±0.002a	0.566±0.008b	8.516±0.290b
FR30	1.123±0.023cd	0.369±0.007ab	1.509±0.030bc	0.220±0.004bc	0.755±0.002a	0.581±0.007ab	8.812±0.273ab

3.4 The influence of different LED light on physiological characteristics and antioxidant enzyme activities of pepper seedlings.

The contents of soluble protein and MDA, as well as the activities of antioxidant enzymes (SOD, POD, CAT) were detected in pepper seedlings. Only the B60 seedlings displayed obviously higher soluble protein content than the control (Figure 3). The SOD activity of UV-A2 and UV-A6 pepper seedlings was significantly lower than that of the control, decreased by 23.9% and 23.3%, respectively (Figure 3), indicating that supplementary UV-A light quality could decrease SOD activity. The was no significant difference in POD activities among light quality treatment (Figure 3). The CAT activities increased in FR treatment compared to control, meanwhile, the MDA content in seedling leaves of FR20 and FR30 significantly decreased (Figure 3), implying that far-red light can improve the antioxidant capacity of leaves and alleviate the damage to the cell membrane.

3.5 The effect of different LED light on flowering and fruit setting of different seedlings after transplanting.

The growth status of the seedling stage often affects the flowering and fruiting of plants after transplanting [19]. In this study, the first flowering occurred within 14-16 days after transplanting (DAT) in all treatments (Table 4). However, the first flowering nodes of the FR20 seedlings were significantly higher than that of the control (Table 4). Although no significant difference in the fruit amount among the treatments was observed from the 15 to 30 DAT, the fruit amount was the highest in the UV-A2 whereas the lowest in the FR30 (Table 4). At the 53 DAT, the fruit yield per plant in B60 treatment was significantly 22.5% higher than that of the control, but there was no significant difference among other treatments (Table 4). In addition, the significant increase in the average fruit weight showed that UV-A6 treatment promoted pepper fruit growth (Table 4). Overall, in the early stage of pepper seedlings, the increasing proportion of blue light or adding a certain intensity of UV-A light had positive effects on the growth of flowers and fruits after transplantation.

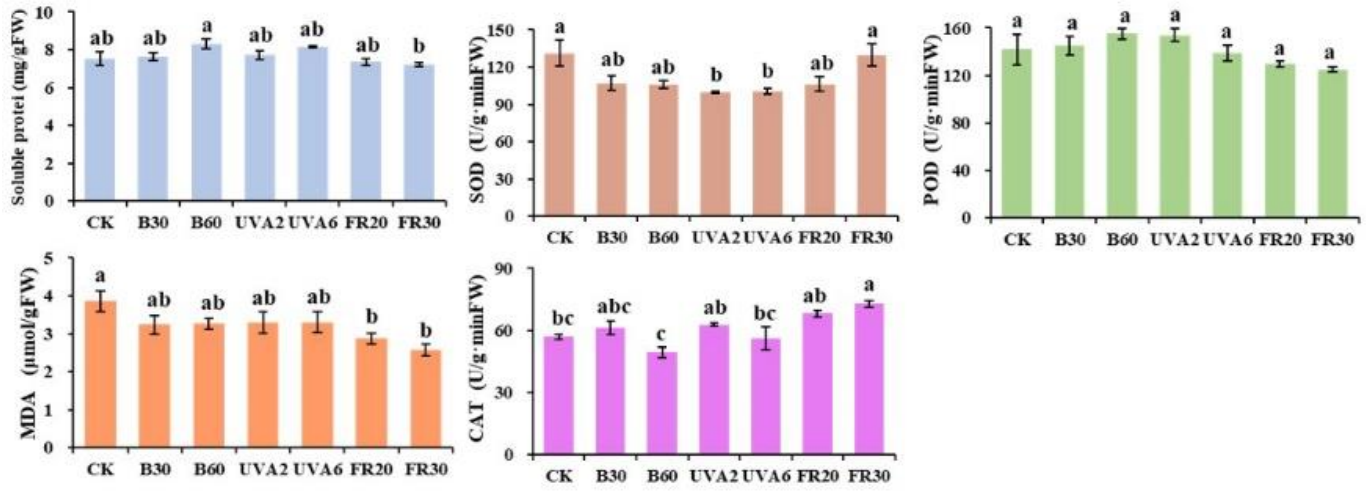


Figure 3. The soluble protein and antioxidant enzyme activities in pepper seedlings' leaves of different treatments in this study.

Table 4. The flowering and fruiting characteristics of all treated pepper seedlings after transplanting.

Treatment	Time of first flower	The node of first flower	Number of fruits on the 15th day	Number of fruits on the 30th day	Average number of fruits per plant	Average weight of fruits per plant
CK	15.3±0.3a	8.1±0.1bc	0.2±0.1ab	3.1±0.5ab	5.0±0.3b	13.8±0.6bc
B30	14.7±0.3a	7.8±0.1c	0.2±0.1ab	2.5±0.4ab	5.2±0.3b	16.5±1.9ab
B60	14.8±0.3a	8.0±0.2bc	0.2±0.1ab	3.2±0.5ab	6.1±0.2a	14.6±0.5abc
UVA2	14.8±0.3a	7.9±0.1c	0.3±0.1a	3.8±0.4a	5.4±0.3ab	15.0±0.7abc
UVA6	14.9±0.3a	8.1±0.1bc	0.2±0.1ab	2.7±0.3ab	5.6±0.3ab	17.3±1.2a
FR20	15.3±0.3a	8.6±0.1a	0.2±0.1ab	2.5±0.4ab	5.3±0.3ab	11.7±1.0c
FR30	15.5±0.3a	8.4±0.2ab	0.0±0.0b	2.1±0.4b	5.1±0.3b	11.9±1.2c

3.6 Correlation analysis and comprehensive evaluation.

To analyze the correlation between the examined indexes, and to make a comprehensive evaluation of pepper seedlings growing under different light conditions, the Pearson correlation and principal component analysis (PCA) were performed. The Pearson correlation analysis was used to analyze the correlation between growth and physiological indexes of pepper seedlings. There was a highly positive correlation between seedling index

with specific leaf weight, root-shoot ratio, plant compactness, chlorophyll a content, chlorophyll b content, total chlorophyll content, the carotenoids content, and POD activity. While the significantly negative correlation relation was found between seedling index with shoot dry weight, whole dry weight, shoot fresh weight, whole fresh weight, stem diameter, plant height, flowering time, SOD activity, and CAT activity (Figure 4A). In addition, no correlation was found between the seedling index and the percentage of shoot dry matter content, root dry weight, root fresh weight, true leaf number, hypocotyl length, single fruit weight, the number of fruits and flowers at 15 DAT and 30 DAT, the first flowering nodes, the MDA content, F*v*/F*m*, Y(II), and ETR (Figure 4A).

Principal component analysis (PCA) was used to determine the correlation between each index and treatment, with PC1 explained 24.20% and PC2 explained 18,71% of the total variance (Figure 4B). And the PCA results we obtained were similar to the Pearson correlation results. According to the result, the physiological growth characteristics of pepper seedlings were different under distinct light quality treatments, the seedling growth performance of B30, B60, UV-A2 and UV-A6 treatments were small, while that of FR20 and FR30 treatments were significantly different from other treatments (Figure 4B).

OriginPro 2021 software were used to simplify these evaluated indicators, then we constructed a comprehensive score model for evaluating the growth and development of pepper seedlings with different light quality as Y=25.43%×Y1+21.88%×Y2 (The meanings of Y1 and Y2 were listed in the SF1). Using this model, the comprehensive score value of growth and quality index of pepper seedlings was calculated. The higher the comprehensive score value, the better the performance under the treatment. Following the results, the optimal light quality treatment for the growth and quality of pepper seedlings was UV-A2 > UV-A6 > B60 > B30 > CK > FR30 > FR20.

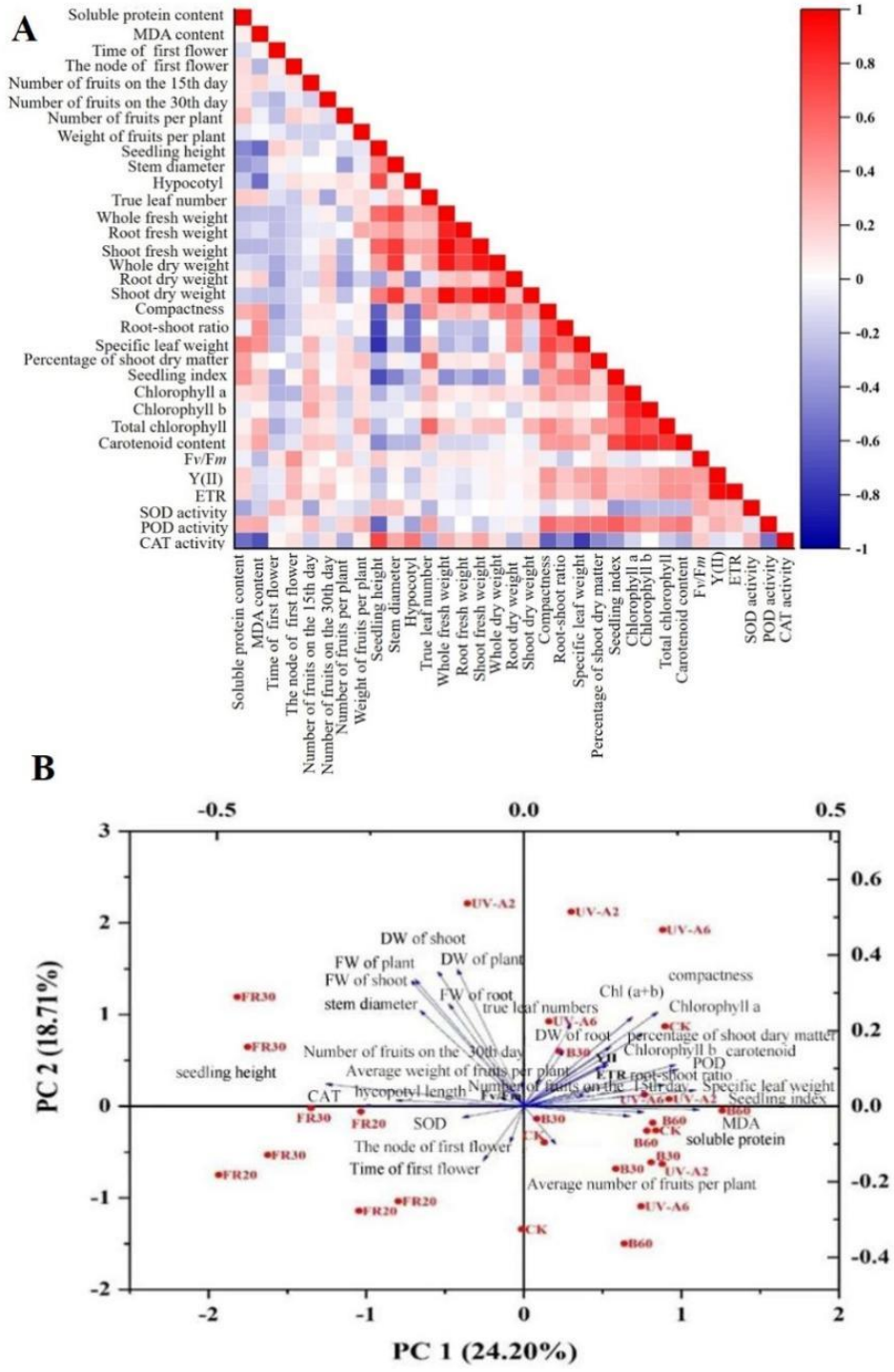


Figure 4. Correlation analysis in the examined index of pepper seedlings. (A) The Pearson correlation of pepper seedlings' growth and physiological indexes. (B) Principal component analysis of each seedling index and treatment.

4. Discussion

Supplementary with blue light resulted in the shorter height of cucumber seedlings [24], while supplementary far-red light consistently leads to stem elongation in plants [25]. ~~And, the~~ plant height and leaf area of tomato seedlings grown under appropriate UV-A radiation increased [26]. In this study, the seedling height and hypocotyl length of pepper seedlings were promoted by increase in UV-A (2 and 6 μmol·m^{-2}·s^{-1}) and far-red (20 and

30 μmol·m^{-2}·s^{-1}) light proportion, whereas inhibited in supplemental blue light treatment and this inhibitory effect was positively correlated with blue light proportion.

The seedling index could fully reflect the growth quality of pepper seedlings. Seedlings with higher compactness are short and denser, often have higher seedling index, and are more suitable for cultivating high-quality vegetables [27]. Similarly, our PCA results showed that the seedling index was positively correlated with the compactness, and negatively correlated with the seedling height. In this study, the plant compactness of B60 and UV-A6 seedlings increased but that of FR20 and FR30 treatment decreased. Besides, the seedlings grown under B30, B60, UV-A2, and UV-A6 treatment have higher seedling index than the control, whereas the plants of FR20 and FR30 treatment showed significantly lower seedling index. These results indicated that different light quality influence seedling quality by affecting plant type, in addition, UV-A and blue light are useful for cultivating healthy and strong pepper seedlings, while far-red light showed the opposite function.

Carotenoids and chlorophyll are mainly photosynthetic pigments, chlorophyll is mainly responsible for the absorption, transmission and transformation of light energy, while carotenoids function in the capture of light energy and light damage defense [28,29]. Our quantitative analysis displayed that UV-A treatment increased but FR treatment decreased carotenoid content, while blue light did not affect carotenoid content in pepper leaves. In terms of chlorophyll content, our results discovered that the total chlorophyll content showed increase in B30, UVA2 and UVA6 treatments, while those in FR20 treatment significantly decreased. Studies have proved that leaf pigment is critical for seedling photosynthesis and is a key parameter for seedling quality evaluation [30,31]. In our study, the PCA results also showed that the seedling index was positively correlated with chlorophyll content and carotenoid content. In accordance with this, UV-A treatment significantly increased photosynthetic pigment content in pepper seedlings, which might contribute to enhancing peppers' photosynthesis and seedling quality. The increase of photosynthetic pigment content pepper seedlings under blue light treatment was less than those under UV-A treatment, which was consistent with the conclusion calculated by the formula that the promoting effect of blue light treatment on seedling quality was less than those of UV-A treatment. Supplementary far-red light may reduce the seedlings quality by inhibiting the accumulation of photosynthetic pigments. Representing the utilization of light energy during leaf photosynthesis, chlorophyll fluorescence of plants is influenced by light quality [32,33]. However, we found that the chlorophyll fluorescence parameters, including F*v*/F*m*, Y(II), and ETR, exhibited no significant difference among all treatments.

When plants suffer from oxidative stress caused by a wide range of environmental factors, the increase of SOD, CAT, and POD activities in the antioxidant enzyme system of plants can effectively prevent active oxygen accumulation, reducing the MDA content and enabling the plants to grow normally [34]. Regarding light quality as an environmental factor, researchers have explored its effects on the plants' antioxidant enzymes system in recent years. For instance, with the supplementation of blue light, the antioxidant enzyme activities increased in onion plants [35]. Cotton plants exposed to the light exclusion of UV-B/A had a lower levels of antioxidant enzyme activities [36]. In the present study, examination analysis in pepper seedlings revealed that in comparison with control, blue light had little effect on the examined antioxidant enzymes activities and MDA content, UV-A light merely induced a decrease in the SOD activity, indicating that enhanced blue and UV-A light proportion did not cause oxidative stress on pepper seedlings. When adding far-red proportion to pepper seedlings, the CAT activity was significantly increased in the FR30 treatment, and significantly lower MDA content occurred in the FR20 and FR30 treatment relative to control, meaning that supplementary with far-red light improve the antioxidant capacity of pepper seedlings.

The flowering and fruiting performance after transplanting are largely influenced by the growth and development of seedlings [37,38]. In this study, the flowering time of pep-

per seedlings supplemented with blue, UV-A and far-red light was not significantly different from that of the control after transplanting. Concerning fruit development, although the average fruit weight per plant was not significantly altered by blue light, the average fruit amount per plant produced by pepper seedlings in B60 was the highest. The average number of fruits was not significantly affected by the lifted proportion of UV-A light, but UV-A led to an increase in the average weight of fruits, which was significantly elevated in UVA-6 treatment. These results suggested that the early yield of pepper plants was improved by supplemental UV-A and blue light during seedling stage, consistent with the results of Son et al., who observed significantly elevated fruit yield per plant after transplanting of tomato seedlings grown under appropriately increased blue light ratio [39].

5. Conclusions

In this study, we investigated the effects of LED light combined different light quality on the growth and development of pepper seedlings, and their subsequent flowering and fruiting performance of pepper seedlings after transplanting. Our results demonstrated that supplemental proportion of blue and UV-A light could be used as a strategy to enhance the quality of pepper seedlings in a plant factory and improve their performance after transplanting. Simply speaking, supplemental B or UV-A could increase pepper seedling indexes and pepper yield after transplanting, while supplemental FR light could decrease seedling indexes, and result in lower pepper yield.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: X.L., R.S, and M.G., performed the experiments and wrote the manuscript. R.H. and Y.L. performed the experiments and statistical analyses. H.L. conceived and designed the experiments. H.L. acquired of funding and contributed to revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by grant from the National Key Research and Development Program of China (2017YFE0131000) and Key Research and Development Program of Ningxia (2021BBF02024).

Data Availability Statement: The data that support the findings of this study are available from the online at https://www.mdpi.com/ethics.

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

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