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Experimental study on the effect of light quality on the quality of hydroponic *Cichorium endivia* L. in plant factory with artificial light

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In recent years, plant factories have developed rapidly and played an important role in modern agricultural production. Finding the best lighting formula has become the most basic and important research topic for the industrialization of the plant factory with artificial lighting (PFAL) hydroponic *Cichorium endivia* L. In this paper, the LED plant growth lamp with adjustable ratio of red, blue and white light intensity was used as the light source for the growth of *C. endivia* L., with 5R:8B:7W, 6R:7B:7W, 5.5R:8B:6.5W as the treatment group and white LED as the control group, the growth characteristics and nutritional quality of the grown plants of *C. endivia* L. were compared and analyzed through experiments. It was found that under the combined illumination of 5.5R:8B:6.5W, the leaves of *C. endivia* L. had the largest number, and the contents of VC (Vitamin C) and carotene were the highest. Under 6R:7B:7W illumination, the content of chlorophyll and soluble sugar was the highest. The combination illumination with the ratio of blue and white light slightly larger than that of red light was the most suitable illumination for hydroponic cultivation of *C. endivia* L. in PFAL.

Key words: Light formula, hydroponic cultivation, plant lighting, plant industrialized production, modern agriculture.

INTRODUCTION

With the development of LED plant-lighting technology, LED plant growth lamp has become the mainstream light source for plant growth in the plant factory with artificial light (PFAL), and the plant photosynthesis and light form construction under LED illumination has also become the heated research focus (Eva et al., 2014; Zakurin et al., 2020; Lee and Kim, 2021). Compared with traditional incandescent lamps, high-pressure sodium lamps and other artificial light sources, the new generation of LED artificial light sources has the advantages of small size, precise and controllable light quality and intensity, low heat energy consumption, energy saving and environmental protection (Yeh and Chung, 2009; Li et al., 2012; Sudthai and Sakhonwasee, 2022). It is found that

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the red light and blue light with the wavelength of 400 to 700 nm are closest to the efficiency curve of plant photosynthesis, and are the two main light sources for plant photosynthesis absorption (Niu et al., 2015; Miao et al., 2019; Paradiso and Proietti, 2021). Some scholars have studied pea seedlings, lettuce seedlings and strawberries under illumination, and found that red light can increase leaf area of pea seedlings, inhibit internode elongation of plants, promote tillering and increase the accumulation of chlorophyll, carotenoids, soluble sugar and other substances (Chen et al., 2017; Li et al., 2017; Díaz-Galián et al., 2020). Blue light is an important influencing factor of photosynthetic system activity and photosynthetic electron transfer capacity of plants, which can obviously shorten the vegetable internode spacing, promote lateral extension and reduce leaf area, and at the same time, blue light can also promote the accumulation of secondary metabolites of plants (Hitz et al., 2020; Díaz-Rueda et al., 2021). There are obvious species differences in the demand for light quality of plants. Zhang et al. (2021) studied the effects of continuous lighting with LED red and blue light before harvest and lighting with different light quality on the growth and nutrient absorption of nitrogen form hydroponic lettuce, and found that the aboveground fresh weight of lettuce increased significantly. Kim et al. (2018) studied the effects of different red and blue illumination time on the growth and development of ice plant, and analyzed its growth and development rules. It was found that when the ratio of red to blue light was 4:5 and the illumination time was 14 h, it was more beneficial to the growth of ice plant and improved their nutritional quality. Shao et al. (2020) studied the effects of different red and blue LED illumination intensity on the growth and nutritional quality of purple leaf lettuce. Their research results showed that appropriate higher intensity lighting significantly promoted the accumulation of total ascorbic acid (TA) in lettuce leaves, but reduced the ratio of ascorbic acid/TA. Lee et al. (2013) studied the effects of white-red and red-blue LED lighting environment on the growth, quality and energy utilization efficiency of two kinds of lettuce. At present, the influence conditions of light quality on the growth quality of various vegetables are mainly set as the mixed light quality composed of monochromatic light and light of different colors except white light, or different ratios of red and blue light. However, there has been little research on the lighting conditions of *Cichorium endivia* L. In this paper, the PFAL is used as the experimental condition, the *C. endivia* L. is used as the experimental material, the hydroponics is used as the cultivation method, the LED lamp is used to illuminate the plant growth, and the white light is added to the red, blue and white light, so as to study the influence of different proportions of LED red, blue and white light on the growth of *C. endivia* L., and provide theoretical reference for the high-quality cultivation of *C. endivia* L. in greenhouse and plant factory.

C. endivia L., which is native to Asia, India and southern Europe, is frequently fried, boiled or cold food with its young leaves. It is rich in nutrients such as VC, carotene, calcium and potassium, and has the functions of clearing away heat and relieving fever, inducing diuresis and relieving cough, etc., and has extremely high nutritional value and medicinal value. *C. endivia* L. has the characteristics of strong stress resistance, readily cultivated and not easy to produce diseases and insect pests, thus, it is widely selected by farmers (Amimoto et al., 1997). At present, it is also widely popular in China and has been planted in a large area (Zhao, 2020). Nevertheless, with the continuous improvement of people's living standards, the requirements for the quality of vegetables are getting higher and higher, and products with higher nutritional content are more likely to be favored. In order to meet the market demand for high-quality *C. endivia* L., it is of great economic significance to study the growth lighting conditions that make *C. endivia* L. produce better physiological indexes. Therefore, the purpose of this study was to explore the most suitable lighting formula for the industrial production of *C. endivia* L., so as to realize the accurate regulation of plant light environment, reduce the energy consumption of plant light, and promote the rapid development of PFAL.

MATERIALS AND METHODS

The test material was *C. endivia* L., and seeds were purchased in the market. The long LED lamp which composed of red, blue and white was used for plant lighting. The power was 200 W, and the light quality, light intensity and light period could be programmed. Hydroponics was adopted in the experiment and the preparation and recycling of nutrient solutions was automatically regulated by intelligent water and fertilizer integrated equipment. Environmental regulation and control between plants, such as temperature, humidity, fresh air, air flow in the plant canopy, etc., were centralized and comprehensively regulated by an intelligent comprehensive control system.

Experimental design

According to the purpose of the experiment, the LED lamps with different proportion of red (R), blue (B), and white (W) were divided into three treatment groups and one control group, in which the red light wavelength was 665 nm, the blue light wavelength was 445 nm, and the white light wavelength was 330~770 nm. Treatment group 1 (T1) was 5R: 8B: 7W, treatment group 2 (T2) was 6R: 7B: 7W, treatment group 3 (T3) was 5.5R: 8B: 6.5W, and control group (CK) was white light. The illumination intensity was 116±10 $\mu mol/m^2 \cdot s$, the illumination period is set as the ratio of illumination time to non-illumination time of 16 h: 8 h, and the distance between LED lamp and cultivation board was 23 cm (This data is calculated by experience combined with theory according to many factors such as light demand and growth height of *C. endivia* L). Under illumination, the growth environment temperature is constant at 22 ± 1°C and humidity was constant at 76±2%; under no illumination, the environment temperature was constant at 18 ± 1°C and humidity was constant at 76 ± 2%. Each process was

Table 1. Light quality composition of the experimental group.

Experimental group	Combined LED light of red, blue and white	Illumination intensity ($\mu mol/m^2.s$)
CK	White	116±10
T1	5R: 8B: 7W	116±10
T2	6R: 7B: 7W	116±10
T3	5.5R: 8B: 6.5W	116±10

CK Control group, T1 treatment group 1, T2 treatment group 2, T3 treatment group 3.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

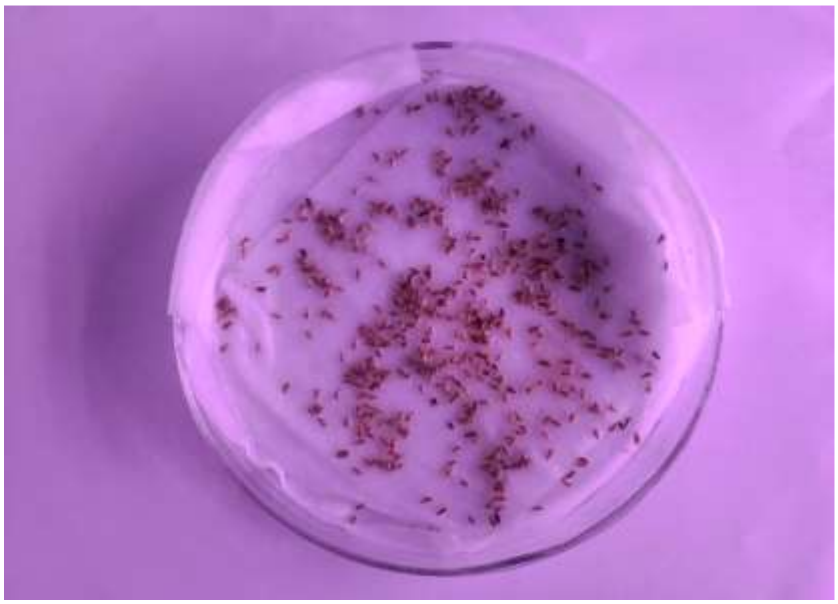

Figure 1. Seed germination of *Cichorium endivia* L.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

repeated five times (Table 1).

Experimental procedure

High-quality seeds of *C. endivia* L. were selected, soaked in warm boiled water at 50~60°C for 3 h, then wet and placed in a ventilated shade for 20 h, so as to relieve dormancy and promote the seeds to germinate, as shown in Figure 1. The seeds were selected with strong germination and transplanted into the planting sponge, add clean water and placed under the LED lamp for cultivation as shown in Figure 2. After about 7~10 days, when the seedlings grow to 2 leaves and 1 heart, robust seedlings were selected and transplanted to the planting tray for the growth and cultivation, as shown in Figure 3. According to the requirements of the experimental design, keep the growth environment, indoor air and CO_2 concentration in line with the experimental requirements, ensure the air flow in the canopy and the supply and flow of nutrient solution in the root zone, and precisely control the LED light quality ratio and illumination intensity. After about 30 days, when *C. endivia* L. grows to the level shown in Figure 4, the five largest plants from each group were selected to measure the indices such as leaf number, dry weight (g) and fresh weight (g) above ground, dry weight (g) and fresh weight (g) below ground, chlorophyll (mg/g), carotene (mg/g), soluble sugar (mg/g) and so on.

Index measurement and data processing

The determination method of aboveground and underground fresh weight and dry weight of *C. endivia* L. was as follows: in each treatment group, the largest 5 plants were selected, the water droplets on the leaves and roots were wiped, and allowed to dry for 20 min. Accurately weigh the fresh weight of the leaves and roots with an analytical balance, and then put them in an 80°C oven. After drying to constant weight, accurately weigh the corresponding dry weight with an analytical balance.

The chlorophyll content, VC and carotene content of *C. endivia* L. were measured by ultraviolet spectrophotometry, and the soluble sugar content was measured by anthrone colorimetry (Mu et al., 2010). Excel was used to collate the recorded data and SPSS 23 software was used to analyze the data variance ($P<0.05$), and the S-N-K method was used to test the hypothetical variance (Larrinaga, 2010). Make the chart with GraphPad Prism v5. The

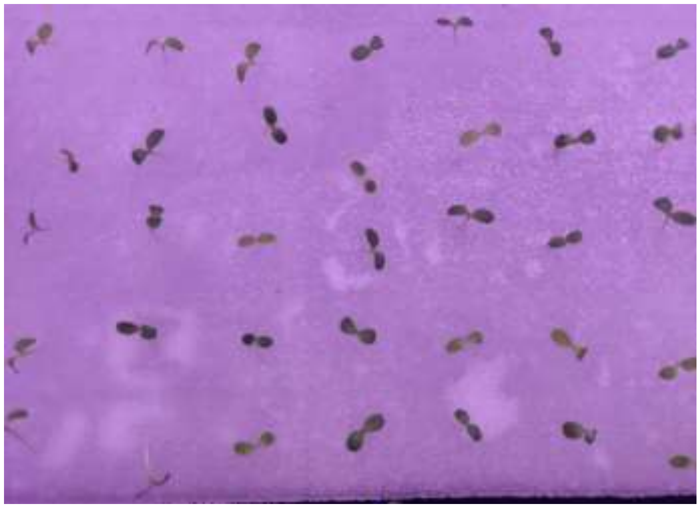

Figure 2. Seeding of *Cichorium endivia* L.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

Figure 3. Hydroponic *Cichorium endivia* L. growth.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

results were shown in the form of mean ± standard deviation.

RESULTS

Effects on the number of leaves and biomass

The statistical data of leaf number and biomass of *C. endivia* L. under different ratios of LED, blue and white light are shown in Table 2. For the number of leaves, T2 (78±7.63) and T3 (80.62±3.85) are higher than CK (63±6.38) in the control group, but because of the large standard deviation in CK group, the data improvement is not obvious when the average number in T1 group is the same. T2 and T3 are significantly improved. For aboveground fresh weight and aboveground dry weight, there is little difference in CK between T2 and control group, but there is no improvement in CK between T2 and T3. For underground fresh weight and underground dry weight, there is no significant difference between T2

Figure 4. A sample of hydroponics *Cichorium endivia* L. after harvest.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

Table 2. Effects of light quality of different proportions of LED red, blue and white on leaf number and biomass of *Cichorium endivia* L.

Light treatment	Number of leaves (pieces)	Aboveground fresh weight (g)	Aboveground dry weight (g)	Underground fresh weight (g)	Underground dry weight (g)
CK	63.00±6.38[b]	31.26±5.76[a]	2.39±0.72[a]	12.58±2.93[a]	1.06±0.29[a]
T1	63.00±3.26[b]	19.26±1.76[b]	1.36±0.16[ab]	9.76±1.65[b]	0.83±0.11[ab]
T2	78.00±7.63[a]	26.19±2.82[a]	1.91±0.23[a]	11.91±3.06[a]	0.91±0.09[a]
T3	80.62±3.85	18.96±2.69[b]	1.78±0.32[ab]	8.13±0.81[b]	0.63±0.12[b]

CK Control group, T1 treatment group 1, T2 treatment group 2, T3 treatment group 3.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

and CK in the control group, but CK in T2 is not improved compared with T3.

Effect on chlorophyll content

Figure 5 shows the influence of the light quality of different proportions of LED, blue and white on the chlorophyll content of *C. endivia* L. As can be seen from the figure, the T1 and T2 groups increased the chlorophyll content of *C. endivia* L., while the T3 group decreased the chlorophyll content of *C. endivia* L. Compared with CK group (0.796), T1(5R: 8B: 7W) and T2(6R: 7B: 7W) had higher mean value (1.089) than T2 group (1.023). Overall, 6R: 7B: 7W light irradiation on *C. endivia* L. had the most obvious effect on increasing soluble sugar content, and 5R: 8B: 7W chlorophyll content had the most obvious effect.

Effect on carotene content

Figure 6 shows the influence of the light quality of different proportions of LED, blue and white on the carotene content of *C. endivia* L. The variation of carotene content in *C. endivia* L. was similar to that of VC and shows a ladder-like upward trend. The mean value of T1 group (0.071) was slightly higher than that of CK group (0.058), and the maximum value of T1 group was 0.091. The mean value of T2 group (0.096) and the data of three samples were all 0.096, which was significantly higher than CK group. The mean value of T3 group (0.108) and the maximum value of samples reached 0.116, which was close to twice the mean value of CK

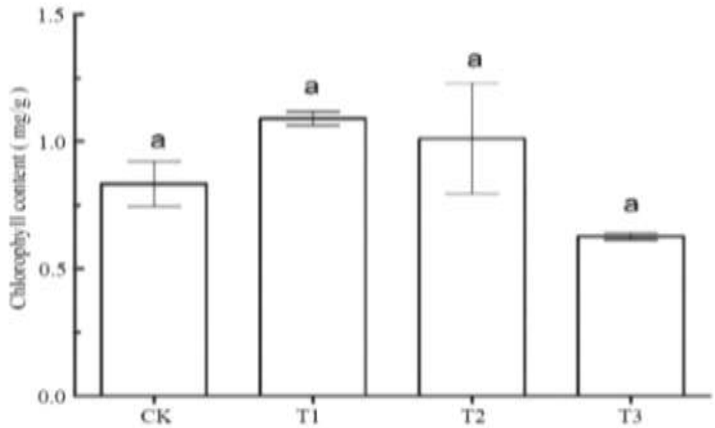

Figure 5. Effects of different proportions of LED red, blue and white light quality on chlorophyll content of *Cichorium endivia* L. CK Control group, T1 treatment group 1, T2 treatment group 2, T3 treatment group 3. Different lowercase letters indicate significant differences at the level of P<0.05.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

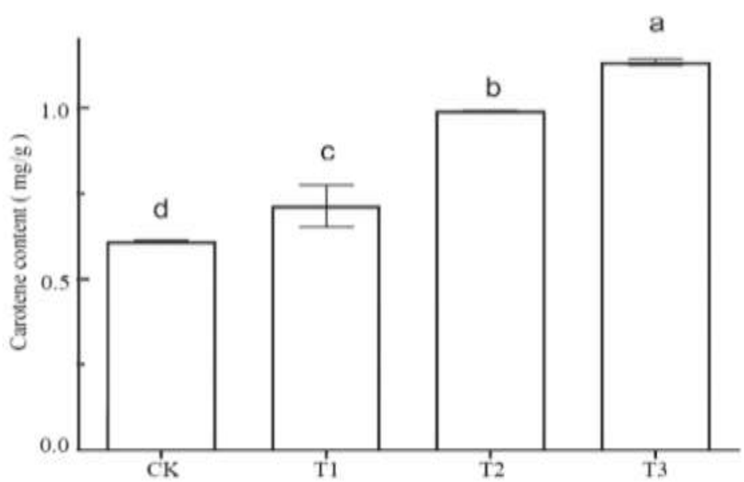

Figure 6. Effect of LED light with different ratios of red, blue and white on carotene content of *Cichorium endivia* L. CK Control group, T1 treatment group 1, T2 treatment group 2, T3 treatment group 3. Different lowercase letters indicate significant differences at the level of P<0.05.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

group, T1(5R: 8B: 7W), T2(6R: 7B: 7W) and T3(5.5R: 7W) can obviously promote the synthesis of *C. endivia* L., among which T3 group had the most significant promotion effect.

Effect on vitamin C content

Figure 7 shows the effect of light quality of different proportions of LED, blue and white on the vitamin C content of *C. endivia* L. Compared with the control group, the data of the three experimental groups were significantly improved. The mean value of group T1 (0.297) was about 2.6 times that of group CK (0.114), and the improvement was more significant. The mean value of T3 group reached (0.512), which was about 3.8 times that of CK group (0.131), greatly increasing the content of VC. The light combinations of T1 (5R: 8B: 7W), T2 (6R:

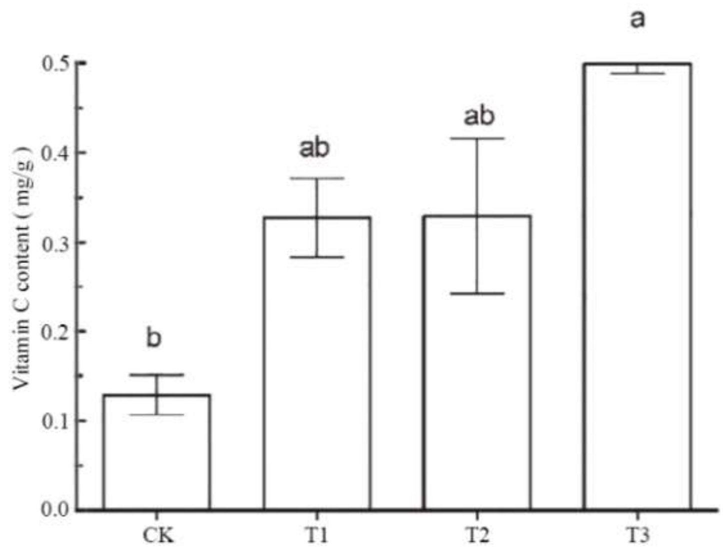

Figure 7. Effects of LED light with different ratios of red, blue and white on the vitamin C content of *Cichorium endivia* L. CK Control group, T1 treatment group 1, T2 treatment group 2, T3 treatment group 3. Different lowercase letters indicate significant differences at the level of P<0.05.
Source: Hydroponic *Cichorium endivia* L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

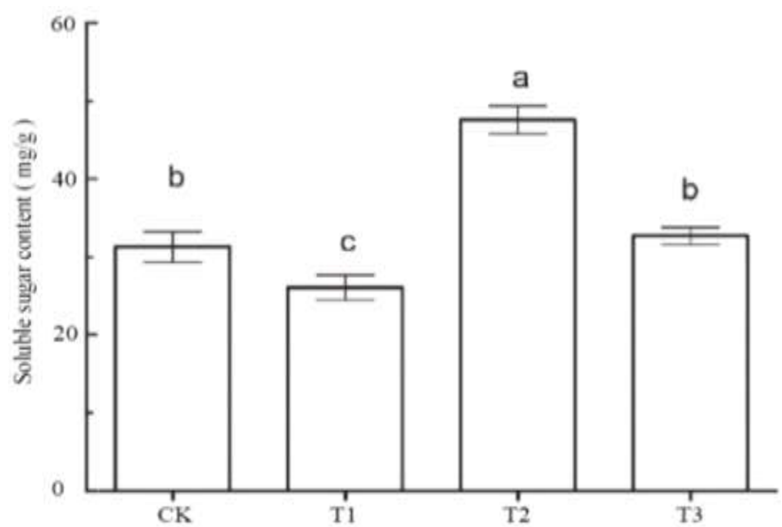

Figure 8. Effect of LED light with different ratios of red, blue and white on soluble sugar content of *Cichorium endivia* L. CK Control group, T1 treatment group 1, T2 treatment group 2, T3 treatment group 3. Different lowercase letters indicate significant differences at the level of P<0.05.
Source: Hydroponic Cichorium endivia L. experiment in the artificial light plant factory experiment of Henan Institute of Science and Technology in October 2021.

7B: 7W) and T3 (5.5R: 8B: 6.5W) can promote the synthesis of VC in *C. endivia* L., among which T3 group had a remarkable promotion effect.

Effect on soluble sugar content

Figure 8 shows the influence of the light quality of different proportions of LED, blue and white on the soluble sugar content of *C. endivia* L. There were significant differences among the three treatment groups, and the average content of the T1 group was lower than that of the CK group. Compared with the CK group, the T3 group had little difference, and the average value (2.806) was slightly higher than that of the control group (31.372). Compared with the CK group, the content of soluble sugar in the T2 group increased significantly. The T2 (6R: 7B: 7W) significantly promoted the synthesis of soluble sugar in *C. endivia* L., while T1 (5R: 8B: 7W) and T3 (5.5R: 8B: 6.5W) had no significant effect on the synthesis of soluble sugar in *C. endivia* L. On the whole, irradiation with 5.5R: 8B: 6.5W light quality had the most obvious effect on increasing the content of VC and carotene.

DISCUSSION

In the process of plant growth and development, light is one of the indispensable factors that affect plant physiology and morphology. Light quality is closely related to plant growth and development, and plays a key role in plant growth, light morphogenesis, photosynthetic pigment synthesis and nutrient accumulation (Gao et al., 2021). LED lamps with different light/mass ratios have different effects on the growth and nutritional quality indexes of *C. endivia* L. In the experiment, the light/mass ratio of 5.5R: 8B: 6.5W can promote the synthesis of vitamin C and carotene in *C. endivia* L.

The young leaves of *C. endivia* L. can be eaten, and vitamins and other nutrients are mainly contained in the leaves. The results showed that when the light/mass ratio was 6R: 7B: 7W and 5.5R: 8B: 6.5W, it was beneficial to increase the number of leaves of *C. endivia* L. When the light/mass ratio was 6R: 7B: 7W to 5R: 8B: 7W, it was beneficial to increase the chlorophyll content of *C. endivia* L., which indicates that increasing the proportion of blue light and decreasing the proportion of red light was more beneficial to the synthesis of chlorophyll. Li et al. (2020) also mentioned this point when studying the influence of different blue-red light combination LEDs on the growth of mung bean sprouts.

Soluble sugars in vegetables mainly include glucose, trehalose, sucrose and so on, which play an important role in maintaining the stability of plant protein (Saldivar et al., 2010). When the light/mass ratio was 6R: 7B: 7W, the soluble sugar content of *C. endivia* L. is significantly increased. Compared with 5R: 8B: 7W, it was speculated that red light is more beneficial to the synthesis of plant soluble sugar, which was consistent with the research results of Liu et al. (2014).

VC is an antioxidant substance in plants, and its content can basically reflect the active oxygen scavenging ability or antioxidant ability in plants, which has an important influence on the storage of vegetables. Experimental results show that the LED light quality of 5.5R: 8B: 6.5W was beneficial for increasing the VC content in *C. endivia* L. Liu and Iersel (2021) found that under the condition of red and blue light, the VC content increased with the increase of red light ratio. In this experiment, compared with 6R: 7B: 7W it was found that the increase of red light content, the decrease of blue light content and the increase of vitamin content were not significant.

Conclusion

In conclusion, compared with pure white light, the mixed light of red, white and blue could increase the number of adult leaves of borage, and the light quality of 5.5R: 8B: 6.5W was the most favorable for the increase of the number of leaves, VC content and carotenoid content of *C. endivia* L.. 6R: 7B: 7W light quality was the most favorable for increasing the soluble sugar content of *C. endivia* L., and 5R: 8B: 7W light quality is the most favorable for increasing the chlorophyll content. This showed that the quality of *C. endivia* L. could be improved by selecting a specific proportion of mixed light quality for supplementary lighting.

Through this experimental study, we have further verified that the quality of plant products can be improved through the precise regulation of light environment. However, the comparison of the effects of artificial light and natural light on plant quality and the needs of different varieties of plants for light regulation need more in-depth and extensive research.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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