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Article

# Chromatic Effects of Supplemental Light on Fruit Quality of Strawberries

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**Abstract:** Supplemental light is widely applied in greenhouses for promotions of the product and flavors of strawberries in global markets. Present selections of colored lights are, however, quite empirical or qualitative, from the aspect of photometry or colorimetry. The accurate control of chromatic parameters of supplemental light and their chromatic influences on fruit quality has been under-studied. In this study, color parameters including correlated color temperatures (CCTs) and illuminance of supplement lights are precisely controlled using a digitally color-coding method. We systematically investigate the chromatic effect of supplemental light on five parameters of strawberries: plant height, single weight, fruit hardness, soluble solids, and titratable acids. Results show that the supplement light generally lowers down the single weight and the fruit hardness, increases the plant height, the contents of soluble solids and titratable acids. The chromatic dependences for the five parameters are different and might be strengthened, weakened, or shifted by light illuminance. We demonstrate the beneficial roles of supplemental light in accelerating the maturation and enhancing the flavor of strawberries in greenhouses cultivation. The results provide valuable guidance for the effective cultivation of strawberries. Moreover, the controlling method for accurate colors is ready for the implementation of supplemental lights in other fruits or plants.

**Keywords:** strawberries; supplemental light; color temperature; color coding

## 1. Introduction

Known as “the queen of fruits”, the strawberry is a photophilous, and shade-tolerant herbaceous plant [1]. It is widely favored by consumers due to its adorable colors, sweet, sour tastes, and high nutritional value. With increasing demands in both the quantity and quality of strawberries in the market, strawberry cultivations are shifting from natural surroundings to artificial greenhouses, due to the merits of environmental controllability and economic efficiency for the latter [2,3]. Being an essential environmental factor, light is indispensable to the photo-morphogenesis and photosynthesis of plants in both natural and artificial conditions [4–8]. More than providing the energy for photosynthesis, light also dictates specific signals which regulate plant development, shaping, and metabolism, driven by light colors [6,9,10]. However, adverse weather like overcast, snow, rain, and fog in winter and spring always leads to inadequate light exposure, resulting in declined productivity of economic plants. Furthermore, because of the aging effect of plastic material and accumulated layers of soil in cultivation greenhouses, transmitted light levels are normally below the natural need for light for plants [11]. Hence, the introduction of artificial supplemental lights to supply adequate illumination for the plants in facility agriculture is clearly needed.

In recent years, various factors of supplemental light are investigated to explore their influences on the quality of strawberries. For example, studies show that luminous intensity affects the growth speed and nutrient contents of strawberries [12–15]. Photoperiod could influence the photosynthesis,

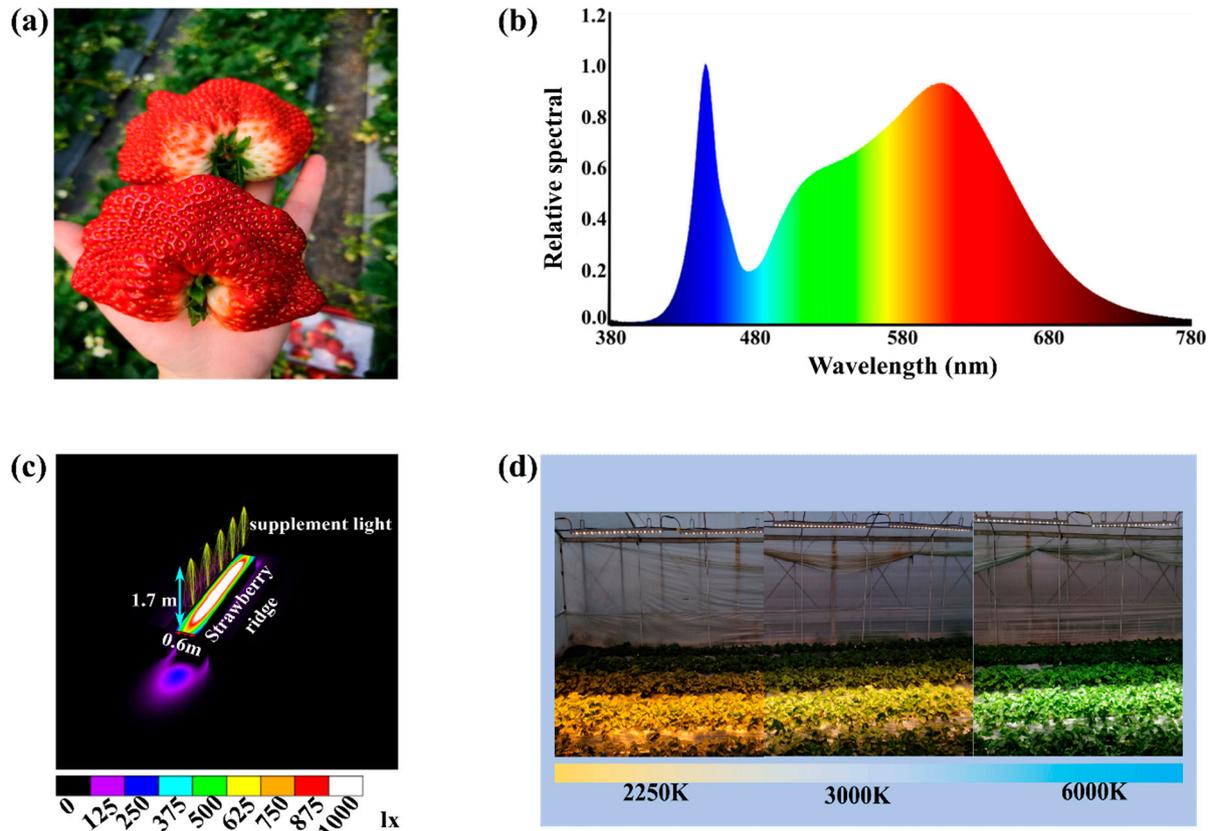
flowering stage, and yield of strawberries [2,16,17]. Up to date, more and more attention has been paid to investigations of plant growth and photomorphogenesis of strawberries affected by the color of light [18–21]. For example, Takeda found that a red-light treatment could reduce flower falling and a high ratio of far-red light to visible light reaching the crown plays a role in floral bud induction [22]. Xu found that the treatment using blue light is helpful to maintain the flavors and nutrition of harvested strawberries [10]. Nhut found that a ratio of 7:3 between the red light and the blue light is optimal for the growth of plantlets [18]. Li reported that the strawberry plants greatly benefited from a color ratio of 3:2:1 between the orange, red, and blue lights [23]. Furthermore, in terms of the fruit quality, different proportions of colors are also tried to find the optimal light condition. For instance, Wu found that a ratio of 1:1:1 between the red LEDs, blue LEDs, and white LEDs gave rise to an addition of average weight for single strawberries and an improvement in fruit flavor [24].

Although there are certain studies on the improvement of fruit quality and quantity of strawberries using supplemental light, selections of colored lights are more empirical or qualitative, from an aspect of photometry or colorimetry. Terms such as "red," "green," and "blue" commonly used in these studies cannot be precisely defined in the field of color or optics sciences. The lack of precision might cause poor repeatability and stability for the fruit quality and production of strawberries in greenhouses during implementations of supplemental lights. Here, we have employed a digitally col-or-coding method (DCCM) to precisely control chromatic parameters of supplemental light in terms of chromaticity coordinates or correlated color temperatures (CCTs) [25,26]. We have systematically investigated their influences of these chromatic parameters on the fruit quality of strawberries. The DCCM we have utilized, along with the results regarding the chromatic effects on strawberry fruit quality, can be widely applied to global greenhouses for artificial cultivation and mass production of high-quality strawberries and other fruits in markets.

## 2. Material and Method

### 2.1. Experimental Material

The experiment was conducted from December 2021 to March 2022 in a greenhouse in Jiande strawberry town, Zhejiang province, China. We selected a newly cultivated strawberry variety called "Jiandehong" for this study. Figure 1(a) shows one photo of ripe strawberry. The supplemental lighting utilized in the experiment consisted of LED luminaires provided by Zhejiang Light Cone Technology Co., Ltd. Each luminaire consists of 12 "warm" white LED chips and 12 "cold" white LED chips. The term "warm" and "cold" is routinely used to represent a color with high and low CCTs, respectively. The same color LED chips are connected in series, while LEDs with different colors are connected in parallel and driven independently. The rated power of the supplemental luminaire is 24 W, with a luminous efficiency of 62.33 lm/W. The spectral distribution of the supplemental luminaire is shown in Figure 1(b). In the actual arrangement layout, five supplemental luminaires compose an illumination group. Figure 1(c) illustrates the intensity distribution of such an illumination group, which is simulated by the software of DIALux. The supplemental luminaires are located 1.7 m above the top plane of strawberry plants. Figure 1(d) provides a visual representation of the experimental greenhouse illuminated by supplemental luminaires with CCTs of 2250 K, 3000 K, and 6000 K, respectively.

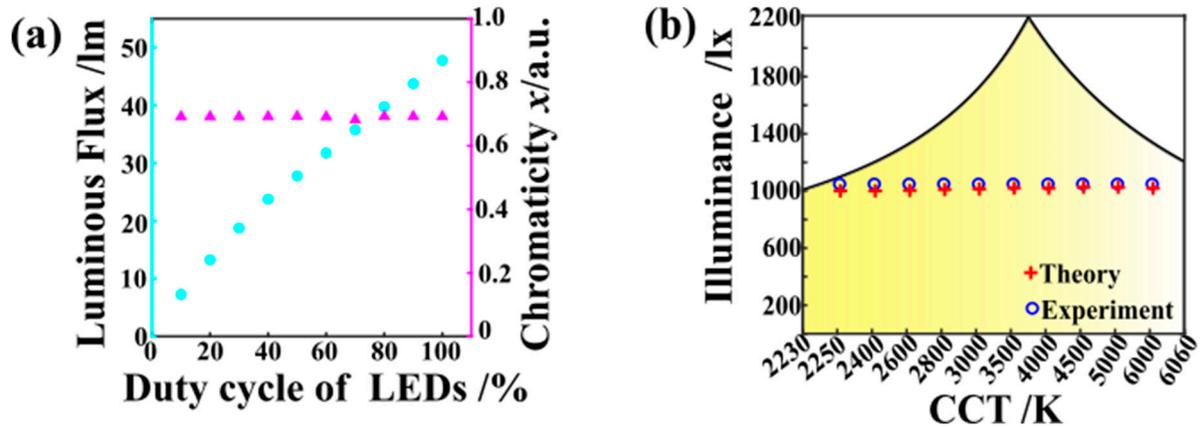


**Figure 1.** Experimental condition and materials. (a) A real photo of Jiandehong strawberry; (b) Spectral distribution of the supplemental luminaire; (c) The intensity distribution of our illumination scheme, which is simulated by using the software of DIALux; (d) Experimental greenhouse illuminated by the supplemental luminaire with CCTs of 2250 K, 3000 K, and 6000 K.

## 2.2. Methods

### 2.2.1. Color mixing algorithm

An accurate color mixing algorithm utilized in this study is DCCM, is used, which manipulates precise chromaticity and luminosity of light in the color spaces defined by the Commission Internationale de l'éclairage (CIE) [25,26]. The “cold” white LEDs and “warm” white LEDs are driven by pulsed modulation signals. The algorithm basically maps driven pulses with a specific duty cycle of each primary light to each color component of mixed light. The chromaticity and luminosity can be manipulated in-dependently. Figure 2(a) shows the dimming principle of such a DCCM, in which chromaticity remains constant while luminosity increases linearly with the duty cycle of single-color LEDs. Figure 2(b) demonstrates precise manipulations of chromaticity (CCT) and luminosity (illuminance) of colors by using the biprimary color mixing technique of DCCM. The supplemental luminaire tested consists of “warm” and “cold” white LEDs. In such a demonstration, the illuminance of the supplemental luminaire is expected to remain at 1000 lx and the CCT varies from 2250 K to 6000 K in the designed steps. The yellow region is the so-called accessible space, which represents the total gamut that such a DCCM can be achieved [25,26]. As can be clearly seen, the experimental results (red crosses) agree well with the theoretical ones (blue circles), demonstrating the validity and accuracy of our DCCM.



**Figure 2.** The working principle and experimental demonstrations of precise manipulations of the color of supplemental light using DCCM. (a) The chromaticity  $x$  (pink triangles) and luminous flux (cyan dots) change with the duty cycle of single-color LEDs. (b) Theoretical (blue circles) and experimental (red crosses) illuminance and CCTs of biprimary color-mixed LEDs mapped in a 2D accessible space (yellow region).

### 2.2.2. Experimental Method

Strawberries are cultivated in a pair of rows. Supplemental luminaires are hung at a height of 1.7 m above the middle of a strawberry ridge. The spacing between adjacent strawberry ridges is 0.6 m. The lenses of the supplemental luminaire are specifically designed so that the light is uniformly projected to the current ridge without interfering with others. An illumination group is composed of five supplemental luminaires, the total length of which is 5 m. The CCTs of five supplemental luminaires within an experimental ridge keep the same. An experimental ridge includes 10 groups of supplemental light with different CCTs: 2250 K, 2400 K, 2600 K, 2800 K, 3000 K, 3500 K, 4000 K, 4500 K, 5000 K, and 6000 K. Two identical experimental ridges are used in the current study, except that one ridge maintains a constant illuminance of 1000 lx, while the other ridge is set at 600 lx. A reference ridge is selected from the middle of the greenhouse, which is sufficiently far away from experimental ridges, avoiding any artificial light from supplemental luminaires. Standard shed cultivation techniques are employed for watering, topdressing, and general management of the strawberry plants. The reference ridge and experimental ridges are exposed to natural sunlight. However, an additional 3 hours is applied automatically by a programmed controller before sunrise (4:00 am - 7:00 am) and after sunset (5:00 pm - 8:00 pm) to the experimental ridges. In the case of inclement weather conditions, such as cloudy, rainy, or snowy days, the supplemental luminaires for experimental ridges are manually opened from 7:00 am to 5:00 pm. These operations are performed from the flowing stages to the second crop of strawberries. Strawberries from both the experimental ridges and reference ridges are harvested and immediately measured for various parameters. The parameters measured include plant height, single weight, hardness, soluble solids, and titratable acid.

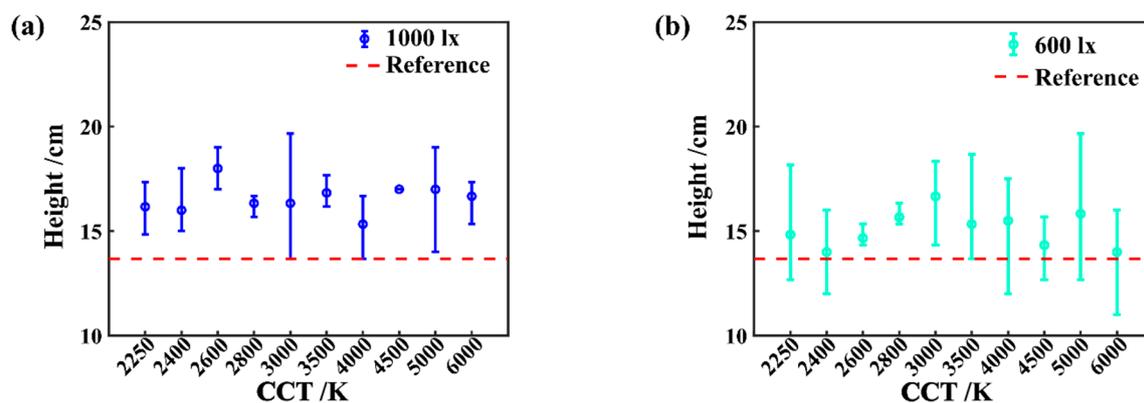
The parameters are measured after 30 days of supplemental light exposure, corresponding to the first harvest stage of strawberries. The height (cm) of the strawberry plants is measured using a tape measure. Five plants from each experimental and reference group are measured three times for each. The single weight (g) is measured using an electronic balance with an accuracy of 0.1 g. Ten strawberries are measured for each group. Ten strawberries from each group are measured for the hardness (kg/cm<sup>2</sup>) by using a GY-4 digital fruit hardnessmeter. The soluble solid content (%), which indicates the sugar content of the strawberries, is measured using a digital sugar meter. The same ten strawberries measured for their hardness are used for this measurement. The titratable acidity of the strawberries is assessed through sodium hydroxide solution titration. One gram of the tested juice is obtained by grinding and dissolving it in 20 milliliters of pure water. The titratable acidity is determined by titrating 20 ml of the juice with 0.1 mol/L NaOH to a pH of 8.2. The titratable acidity

is evaluated by millimoles (mmol) of citric acid per 100 grams (g) of juice. The titratable acidity content of each group is determined by measuring five strawberries for each group.

### 3. Results

#### 3.1. Chromatic effect of supplemental light on the height of the strawberry plant

The height of the strawberry plant is indeed the first parameter influenced by supplemental light. The effect of supplemental light on plant height is evaluated when the first strawberry crop is ripe, which occurs 30 days after the introduction of supplemental light. The relationship between the height of the strawberry plant and the CCT and illuminances of supplemental light is illustrated in Figure 3. As seen in Figure 3(a), after being treated with supplemental light at an illuminance of 1000 lx, the height of the strawberry plant is noticeably higher than that of the reference group, with the average height reaching approximately 16.6 cm. The chromatic effect, represented by different CCTs, shows minor fluctuations but does not have a significant impact on plant height. When the illuminance is reduced to 600 lx, as displayed in Figure 3(b), similar conclusions can be drawn. The average height of the strawberry plant in the experimental group being 15.0 cm. However, there is a larger fluctuation in CCTs when compared to the higher illuminance (1000 lx). This indicates that while supplemental light has an overall positive impact on plant height, the variations in CCTs have a small influence, with the primary factor determining plant height being the illuminance level. These results indicate that providing supplemental light at both 1000 lx and 600 lx can promote the growth and increase the height of strawberry plants. The specific CCT of the supplemental light has a minor effect on plant height compared to the illuminance level.

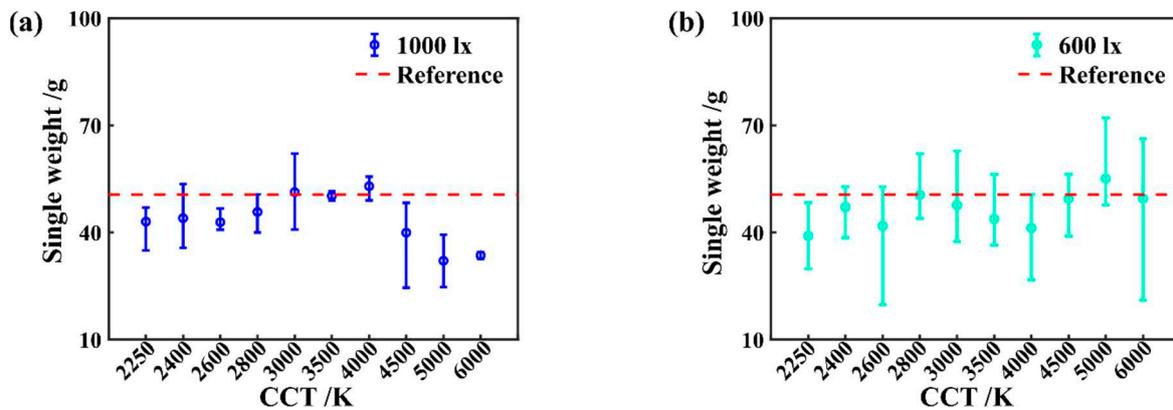


**Figure 3.** Influence of supplemental luminaire CCT on the height of the strawberry plant. The red dashed lines represent the reference levels. (a) Measured height as a function of CCT at an illuminance of 1000 lx. The blue circles represent the averaged experimental values at each measured CCT. The blue error bars indicate upper and lower errors; (b) Measured height as a function of CCT at an illuminance of 600 lx. The cyan circles represent the averaged experimental values at each measured CCT. The cyan error bars indicate upper and lower errors.

#### 3.2. Chromatic effect of supplemental light on the single weight of strawberries

The single weight of a strawberry is an important factor determining its economic value and contributes to the overall fruit yield. Figure 4 presents the relationship between the CCTs of supplemental light and the single weight of strawberries at illuminances of 1000 lx (Figure 4(a)) and 600 lx (Figure 4(b)). As shown in Figure 4(a), the single weight of strawberries is generally lower than that of the reference group for CCTs ranging from 2250 K to 2800 K and from 4500 K to 6000 K. However, other CCTs, the single weight remains similar to that of the reference group. When the illuminance is reduced to 600 lx, as shown in Figure 4(b), similar conclusions can be drawn that the single weight of strawberries is generally lower than that of the reference group, except for the CCT of 5000 K. When comparing the effect of higher illuminance (1000 lx) with lower illuminance (600 lx) in terms of the single weight of strawberries, it can be observed that the fluctuation range at the lower

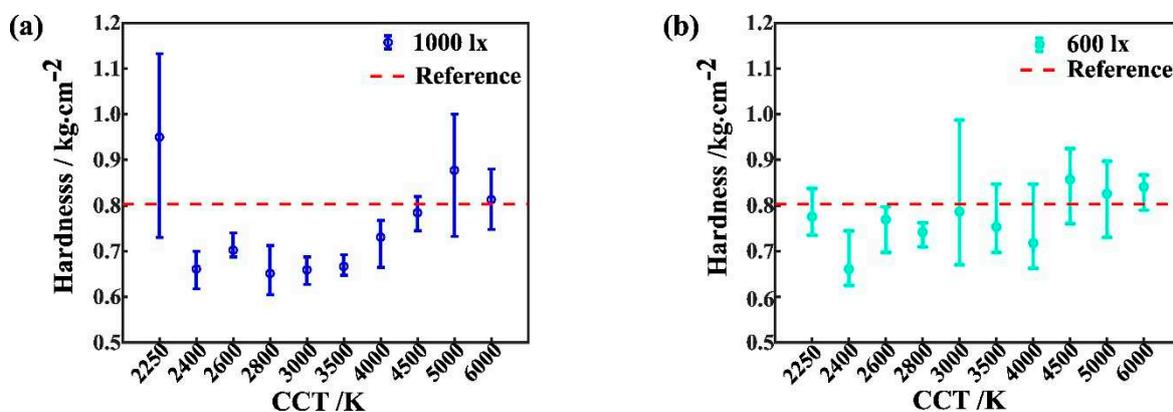
illuminance is larger than that influenced by higher illuminance. This suggests that the illuminance level of the supplemental light has a significant impact on the single weight of strawberries, while the specific CCTs play a more nuanced role in determining the single weight.



**Figure 4.** Influence of supplemental luminaire CCT on the single weight of strawberries. The red dashed lines represent the reference levels. (a) Measured single weight as a function of CCT at an illuminance of 1000 lx. The blue circles represent the averaged experimental values at each measured CCT. The blue error bars indicate upper and lower errors; (b) Measured single weight as a function of CCT at an illuminance of 600 lx. The cyan circles represent the averaged experimental values at each measured CCT. The cyan error bars indicate upper and lower errors.

### 3.3. Chromatic effect of supplemental light on the fruit hardness of strawberries

As one of the most important fruit quality parameters, hardness determines the degree of maturation. Figure 5 shows the measured hardness of strawberries as a function of CCTs at the illuminance of 1000 lx (a) and 600 lx (b). As shown in Figure 5 (a), the hardness of strawberries is generally lower than that of the reference group for CCTs ranging from 2400 K to 4500 K. This indicates that the supplemental light with such CCTs in this range could accelerate the maturation process of strawberries. However, for CCTs below 2400 K or beyond 4500 K, the hardness tends to be higher compared to the reference group. This suggests that light with CCTs outside the optimal range can delay maturation process, leading to higher hardness. When the illuminance is reduced to 600 lx, as shown in Figure 5(b), similar conclusions could be obtained, except for a larger varying range and a smaller derivation between different CCTs for the hardness. This implies that a higher illumination intensity of supplemental light has a more significant influence on the maturation of strawberries, as reflected by their hardness.

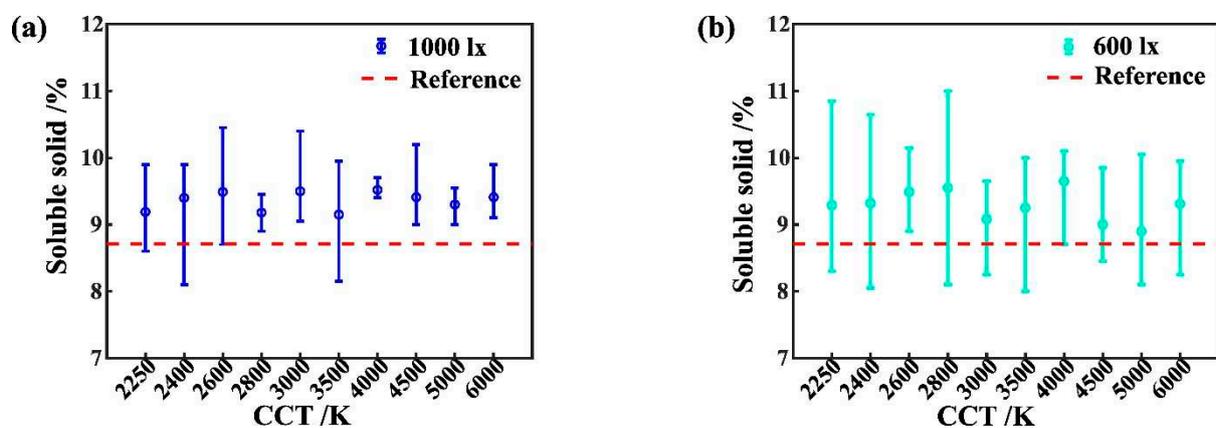


**Figure 5.** Influence of supplemental luminaire CCT on the hardness of strawberries. The red dashed lines represent the reference levels. (a) Measured hardness as a function of CCT at an illuminance of 1000 lx. The blue circles represent the averaged experimental values at each measured CCT. The blue

error bars indicate upper and lower errors; (b) Measured hardness as a function of CCT at an illuminance of 600 lx. The cyan circles represent the averaged experimental values at each measured CCT. The cyan error bars indicate upper and lower errors.

### 3.4. Chromatic effect of supplemental light on soluble solids of strawberries

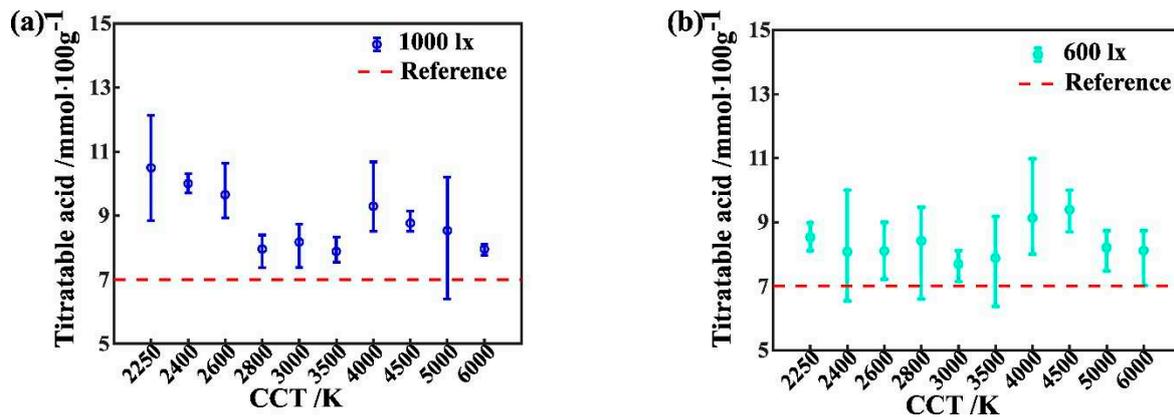
Soluble solids are an important parameter that determines the sweetness and flavor of the strawberries. Figure 6 demonstrates the results of tests conducted on the soluble solids in strawberries as a function of CCT of supplemental light at illuminances of 1000 lx (Figure 6(a)) and 600 lx (Figure 6(b)). As illustrated in Figure 6(a), after the treatment with supplemental light at an illuminance of 1000 lx, the concentrations of soluble solids are generally higher than the reference group. This indicates that the application of supplemental light effectively enhances the accumulation of soluble solids in strawberries, contributing to their sweetness and flavor. The chromatic effect, represented by the different CCTs, does not exhibit a significant influence on the concentration of soluble solids, although there are minor fluctuations observed with varying CCTs. When the illuminance is reduced to a lower level (600 lx), as shown in Figure 6(b), similar conclusions could be obtained, except for a larger fluctuation in CCTs and a larger derivation in soluble solids.



**Figure 6.** Influence of supplemental luminaire CCT on the soluble solids of strawberries. The red dashed lines represent the reference levels. (a) Measured soluble solids as a function of CCT at an illuminance of 1000 lx. The blue circles represent the averaged experimental values at each measured CCT. The blue error bars indicate upper and lower errors; (b) Measured soluble solids as a function of CCT at an illuminance of 600 lx. The cyan circles represent the averaged experimental values at each measured CCT. The cyan error bars indicate upper and lower errors.

### 3.5. Chromatic effect of supplemental light on titratable acids of strawberries

Titratable acids are an important parameter that determines the acidity and tartness of the strawberries. The tests for the titratable acids of strawberries as a function of CCT of supplemental light are shown in Figure 7. As can be seen from Figure 7(a), after the treatment with supplemental light with an illuminance of 1000 lx, the concentrations of the titratable acids are generally higher than the reference. Moreover, it is also observed that chromatic influence is stronger on soluble solids. The light with the CCTs ranging from 2250 K to 2800K, and from 3500 K to 4500 K has a noticeable effect in increasing the concentration of titratable acids. When the illuminance is reduced to 600 lx, as shown in Figure 7(b), similar conclusions could be obtained, except for a larger varying range and a smaller derivation between different CCTs for the titratable acids.



**Figure 7.** Influence of supplemental luminaire CCT on the titratable acids of strawberries. The red dashed lines represent the reference levels. (a) Measured titratable acids as a function of CCT at an illuminance of 1000 lx. The blue circles represent the averaged experimental values at each measured CCT. The blue error bars indicate upper and lower errors; (b) Measured titratable acids as a function of CCT at an illuminance of 600 lx. The cyan circles represent the averaged experimental values at each measured CCT. The cyan error bars indicate upper and lower errors.

#### 4. Discussion

Different light qualities and intensities have a wide range of regular effects on plant growth and development. Light quality affects hormone balance in plants through the action of related pigments, which in turn impacts growth, development, and production [27]. Light intensity directly influences plant reproduction and fruit ripening [28,29].

The height of strawberry plants under supplemental lights is higher than those in the reference group. Specifically, the height of strawberry plants with supplemental lights at illuminances of 1000 lx and 600 lx is about 22% and 10% higher than the reference group, respectively (Figure 3), while chromatic effects on plant height are not so significant. Other studies have found that additional supplemental light on strawberry plant growth is markedly better than natural light [24]. The maximum plantlet height was observed at illuminances of 45  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  and 75  $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$  [18]. Various experiments have been conducted to study the effects of different light qualities on plant height. For example, the tallest plant height was observed when plantlets were grown under 100% red light, while other combinations of red and blue light did not result in significant differences in height [18]. The plant height can be influenced by the rated power of the light source, with a larger rated power contributing to greater plant height when the same color mixing ratio was used [23]. When the rated power remains constant, adding orange-color light to the red and blue color mix has been shown to impact the plant height of strawberries [23]. Additionally, the tallest strawberry plants were obtained when grown under blue light [5]. A higher plant height was observed when the ratio of red LED to blue LED was 10:1, and no significant difference was observed compared to a 19:1 red to blue light ratio [30]. These findings indicate that the specific light quality and color mixing ratios can play a role in influencing plant height, although the overall impact of these factors may vary depending on the plant species and environmental conditions.

When comparing the single weight of strawberries with additional supplemental lights to normal natural lights, it nearly stays the same level. A higher illuminance (1000 lx) of supplemental light results in a smaller fluctuation in response to different colors. Furthermore, chromatic effects on the single weight of strawberries are not significant, as shown in Figure 4. These results agree with previous findings that white LEDs do not increase the single weight of strawberries compared to the reference group [5].

For the hardness of strawberries, significant variation can be observed under different CCTs and illuminance treatments. Hardness could be significantly reduced by using CCTs ranging from 2400 K to 4000 K. At the meantime, a higher illuminance could enhance such chromatic dependences, as illustrated in Figure 5. These results agree with previous study [14]. There are some studies

recommend a mixed ratio of 1:1:1 among red, blue and white color supplemental lights to reduce the hardness of strawberries, but their quantitative chromatic parameters are not provided [24].

The soluble solid content of strawberries shows significant improvements using the treatment of supplemental light. In experimental groups, the soluble solid content is generally higher than in reference groups, as depicted in Figure 6. These findings are consistent with previous studies, which concluded that the quality of strawberry fruits could be significantly improved by supplemental light treatment, including increased soluble solid content and soluble sugar content [24]. However, other research suggests that variance of illuminance levels doesn't cause significant changes in soluble solid content [14]. Regarding the chromatic effect, our results have a fair agreement with other studies [31], that is no significant differences in soluble solid content are found between different combinations of monochromatic LED lights (red, green, and blue) and polychromatic (W-R: G: B, 1:1:1) lights [31].

The titratable acid content of strawberries can be significantly influenced by LED supplemental lights. Maximum titratable acid content can be achieved if the CCT is within the range from 2250 K to 2600 K, and from 4000 K to 4500 K. At the meantime, a higher illuminance level could enhance such chromatic dependences, as shown in Figure 7. Similar study found that the titratable acid content could be enhanced by following a treatment of supplemental light but in an insignificant manner.

In general, the light intensity should not be a great concern for supplemental light. This is because the dependences of five quality parameters on the light intensity are much weaker than on the CCTs, even the intensity could slightly strengthen, weaken, or shift the corresponding chromatic dependences. Another reason is that the intensity effect can be compensated by other lighting factors, for example, lighting period, to some extent.

For future work, we plan to conduct more specific experiments from the following aspects:

- a) Change the CCT and illuminance of supplemental luminaires in smaller steps, so that more continuous chromatic and intensity dependences could be observed.
- b) Measure other important quality parameters like vitamins, soluble sugar, anthocyanidin, and so on.
- c) Record the total weight of the strawberries from different experimental group.
- d) Investigate the impact of supplemental light with varying parameters such as photoperiod and timing on quality parameters of the strawberries.
- e) Extend the related techniques to other kinds of fruits.

## 5. Conclusions

In this work, we systematically study the chromatic effect of supplemental light on the fruit quality of strawberries in artificial greenhouses. The supplemental light consists of two-colored white LEDs, and the color parameters of mixed light including CCTs, and illuminance of supplement lights are precisely controlled using a DCCM. We investigate the chromatic effects of supplemental light on five parameters of strawberries: plant height, single weight, fruit hardness, soluble solids, and titratable acids. It is found that the supplement light generally increases plant heights, with an average increase of over 20% compared to the reference group. The fruit hardness is lower than the reference group by 6.7%. Meanwhile, the lowest hardness appeared at CCTs from 2400 K to 4000 K. The quality of the strawberry is increased, including the contents of soluble solids and titratable acids. The content of soluble solids is found to be 7.4% higher in the experimental group compared to the reference group. However, the difference in soluble solids content between different CCTs is not significant. The content of titratable acids is 23% higher in the experimental group compared to the reference group. The optimal CCTs range for titratable acid growth is found between 3500 K and 4500 K. Although the light intensity had some influence on titratable acids content, its impact is relatively weak. In conclusion, the findings of this study demonstrate the effective roles played by supplemental light in accelerating maturation and enhancing the flavor of strawberries in greenhouse. These outcomes provide valuable insights and can serve as a useful guide for the effective cultivation of strawberries.

**Author Contributions:** J.Y. W. and M. Q. supervised the research. J.Y. W. developed the methods for accurate color controls of supplemental light. N. T, B. F. Z, and H. C conducted the experiments. N. T and J.Y. W. analyzed the data. J.Y. W., N. T., and M. Q. discussed the results and corrected the manuscript. All authors contributed to editing and preparing the manuscript.

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