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Chromatic Effects of Supplemental Light on the Fruit Quality of Strawberries

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Abstract: Supplemental light is widely applied in greenhouses to promote the production and flavor of strawberries in global markets. The present selections of colored lights are, however, quite empirical or qualitative, from the perspective of photometry or colorimetry, which lacks precision. The accurate control of chromatic parameters of supplemental light and their chromatic influences on fruit quality have been under-studied. In this study, color parameters including ten groups of correlated color temperatures (CCTs-2250 K, 2400 K, 2600 K, 2800 K, 3000 K, 3500 K, 4000 K, 4500 K, 5000 K, and 6000 K) and two groups of illuminances (600 lx and 1000 lx) of supplemental lights were precisely controlled using a digital color-coding method applied to LED supplemental lights, and the strawberry was irradiated with the LED supplemental light from December 2021 to March 2022 in facilities cultivation (greenhouse). Moreover, the irradiation time was 6 h per day (4:00 a.m.–7:00 a.m., 5:00 p.m.–8:00 p.m.). We systematically investigated the chromatic effects of supplemental light on five parameters of strawberries: plant height, single weight, fruit hardness, soluble solids, and titratable acids. The results showed that the supplemental light generally lowered the single weight by 14% and fruit hardness by 6%, and increased plant height by 21%, the contents of soluble solids by 7.4%, and titratable acids by 27%. The chromatic dependences of the five parameters were different and might be strengthened, weakened, or shifted by light illuminance. Our results demonstrated the beneficial roles of supplemental light in accelerating maturation and enhancing the flavor of strawberries in greenhouse cultivation. These results provided valuable guidance for the effective cultivation of strawberries. Moreover, the controlling method for accurate colors was ready for the implementation of supplemental lights in other fruits or plants.

Keywords: strawberry; supplemental lighting; digital color-coding method; light quality; light intensity; quality parameter

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1. Introduction

Known as "the queen of fruits", the strawberry (*Fragaria* × *ananassa*) is a photophilous and shade-tolerant herbaceous plant [1]. The strawberry is a widely grown hybrid species of the genus *Fragaria*, collectively known as strawberries [2]. The fruit is widely favored by consumers due to its attractive colors, sweet and sour tastes, and high nutritional value. With increasing demands for 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 [3,4]. As an essential environmental factor, light is indispensable for the photomorphogenesis and photosynthesis of plants under both natural and artificial conditions [5–9]. In addition to providing the energy for photosynthesis, light also dictates specific signals which regulate plant development, shaping, and metabolism, driven by light colors [7,10,11]. However, adverse weather conditions, like overcast, snow, rain, and fog in winter and spring, always lead to inadequate light exposure, resulting in a decline in the productivity of economic plants. Furthermore, because of the aging effect of plastic materials and accumulated layers of dust on the film in cultivation greenhouses, transmitted light levels are normally below the natural need for light for plants [12]. Hence, the introduction of artificial supplemental lights to supply adequate illumination for the plants in agricultural facilities is clearly needed.

In recent years, various factors of supplemental light have been investigated to explore their influence on the quality of strawberries. For example, studies showed that luminous intensity affects the growth rate and nutrient content of strawberries [13–16]. Photoperiod can influence photosynthesis, flowering stage, and yield of strawberries [3,17,18]. To date, increasing attention has been paid to investigations of plant growth and the photomorphogenesis of strawberries affected by the color of light [19–22]. For example, Takeda found that a red light treatment could reduce flower falling, and a high ratio of distant far-red light to visible light reaching the crown plays a role in floral bud induction [23]. Xu found that the treatment using blue light is helpful in maintaining the flavors and nutrition of harvested strawberries [11]. Nhut found that a ratio of 7:3 between the red light and the blue light is optimal for the growth of plantlets [19]. Li reported that the strawberry plants greatly benefited from a color ratio of 3:2:1 between the orange, red, and blue lights [24]. Furthermore, in terms of the fruit quality, different proportions of colors were also used to find the optimal light conditions. For instance, Wu found that a ratio of 1:1:1 between red LEDs, blue LEDs, and white LEDs increased the average weight addition by 7% for single strawberries and led to an improvement in fruit flavor; in particular, the solid acid ratio increased by 15% [25].

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 the perspective 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 of the fruit quality and production of strawberries in greenhouses during the implementation of supplemental lights. In this study, we employed a digital color-coding method (DCCM) to precisely control the chromatic parameters of supplemental light in terms of chromaticity coordinates or correlated color temperatures (CCTs) [26,27]. We systematically investigated the influence of these chromatic parameters on the fruit quality of strawberries. The DCCM utilized in this study, 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 1a showed a photo of a ripe strawberry. The supplemental lighting utilized in the experiment consisted of LED luminaires provided by Zhejiang Light Cone Technology Co., Ltd. Hangzhou, China. Each luminaire consisted of 12 "warm" white LED chips and 12 "cold" white LED chips. The term "warm" and "cold" were used to represent colors with high and low CCTs, respectively. LEDs with the same color were connected in series, while LEDs with different colors were connected in parallel and driven independently. The rated power of the supplemental luminaire was 24 W, with a luminous efficiency of 62.33 lm/W. The spectral distribution of the supplemental luminaire was shown in Figure 1b. In the actual arrangement layout, five supplemental luminaires formed an illumination group. Figure 1c illustrated the intensity distribution of an illumination group, which was simulated using DIALux software, https://www.dialux.com/en-GB/, accessed on 5 November 2023. DIALux is a tool commonly used for simulating and planning lighting setups. The supplemental luminaires were positioned 1.7 m above the top plane of strawberry plants. This placement is crucial in determining how effectively the light reaches the plants. Figure 1d provided a visual representment of the experimental greenhouse illuminated by supplemental luminaires with CCTs of 2250 K, 3000 K, and 6000 K, respectively.

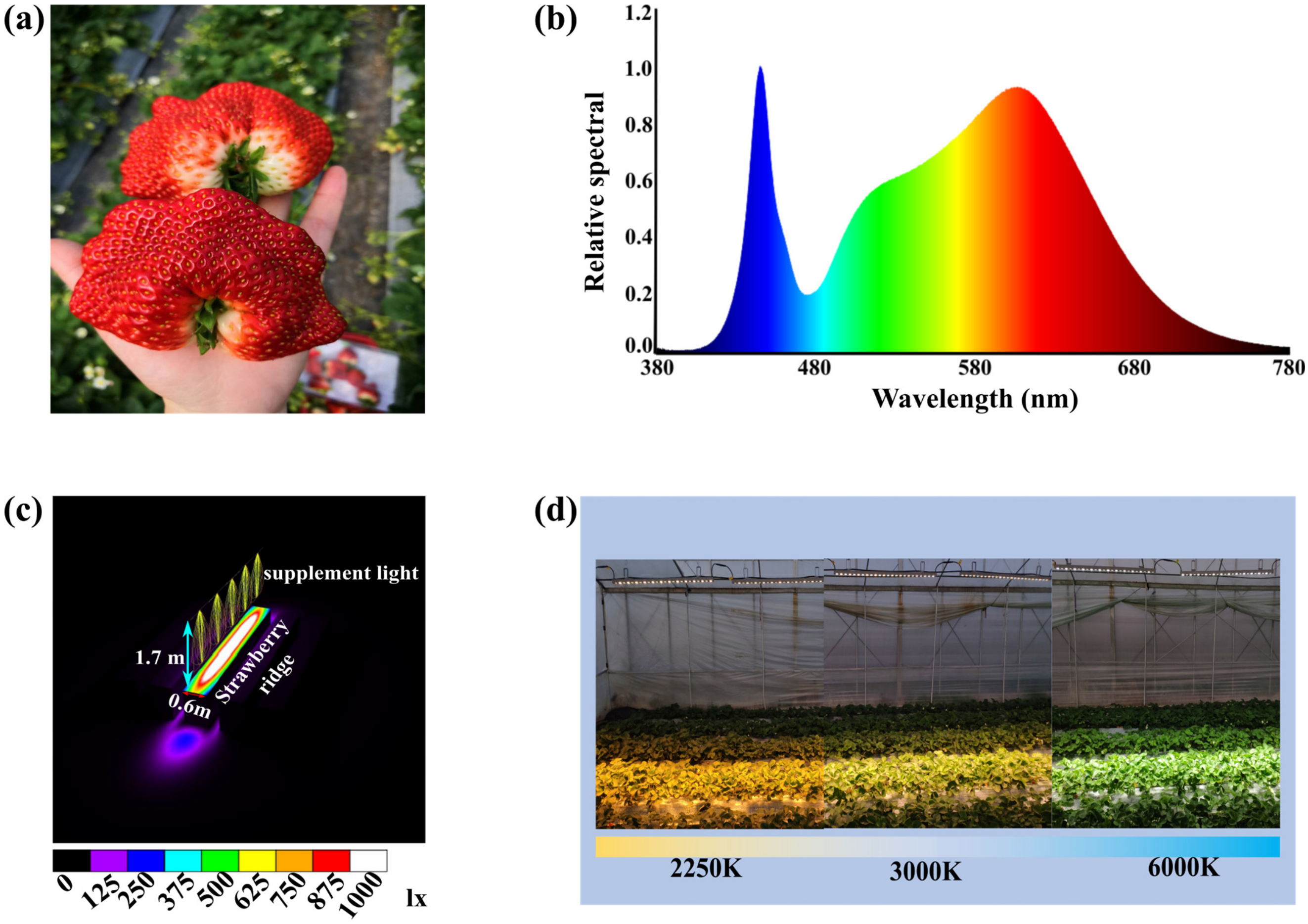

Figure 1. Experimental condition and materials. (**a**) A real photo of Jiandehong strawberry; (**b**) spectral distribution of the supplemental luminaire; (**c**) the intensity distribution of our illumination scheme, which is simulated by using the software of DIALux; (**d**) experimental greenhouse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

2.2. Methods

2.2.1. The Color Mixing Algorithm

In this study, we implemented the digital color-coding method (DCCM), an accurate color mixing algorithm that allows precise manipulation of light chromaticity and luminosity within color spaces defined by the Commission Internationale de l'éclairage (CIE) [26,27]. Both "cold" white LEDs and "warm" white LEDs, driven by pulsed modulation signals, were utilized. The algorithm used maps driven pulses with a specific duty cycle of each primary light to each color component of mixed light, facilitating independent manipulation of chromaticity and luminosity. Figure 2a,b illustrated the principles and effectiveness of our DCCM. Figure 2a depicted the dimming principle, where chromaticity remains constant while luminosity increased linearly in tandem with the duty cycle of individual color LEDs. Figure 2b demonstrated precise manipulations of chromaticity (as correlated color temperatures, or CCT) and luminosity (illuminance) that are achievable via the biprimary color mixing technique of the DCCM. The supplemental luminaire test comprised both "warm" and "cold" white LEDs. Within this demonstration, the illuminance of the supplemental luminaire was maintained at 1000 lx, while the CCT altered from 2250 K to 6000 K through a series of designed steps. The yellow area represented the accessible space, denoting the total gamut achievable using the DCCM [26,27]. Comparison between the experimental results (illustrated by red crosses) and the theoretical predictions (blue circles) affirms the efficacy and precision of our digital color-coding method.

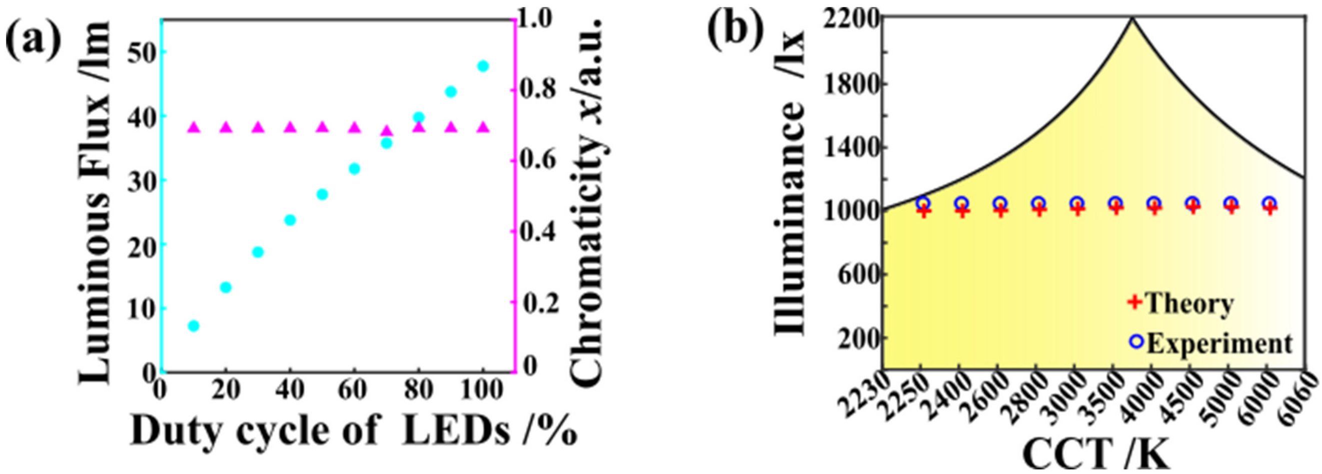

Figure 2. The working principle and experimental demonstrations of precise manipulations of the color of supplemental light using a digital color-coding method (DCCM). (**a**) The chromaticity x (pink triangles) and luminous flux (cyan dots) change with the duty cycle of single-color LEDs. (**b**) Theoretical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

2.2.2. The Experimental Method

Strawberries were cultivated in a pair of rows, with supplemental luminaires hung at a height of 1.7 m above the middle of a strawberry ridge. The spacing between adjacent strawberry ridges was 0.6 m. The lenses of the supplemental luminaire were specifically designed to uniformly project light to the current ridge without interfering with adjacent ones. An illumination group comprised of five supplemental luminaires with a total length of 5 m. Ten 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. The CCTs of five luminaires within an experimental ridge were kept the same. Two identical experimental ridges were used. One ridge maintained a constant illuminance of 1000 lx, while the other was set at 600 lx. Selected from the middle of the greenhouse, sufficiently far away from experimental ridges to avoid artificial light interference. Standard shed cultivation techniques were employed for watering, topdressing, and general management of the strawberry plants. Both reference and experimental ridges were exposed to natural sunlight. An additional 3 h of supplemental light was applied automatically by a programmed controller before sunrise (4:00 a.m.–7:00 a.m.) and after sunset (5:00 p.m.–8:00 p.m.) to the experimental ridges. In case of inclement weather conditions, such as cloudy, rainy, or snowy days, the supplemental luminaires for experimental ridges were manually opened from 7:00 a.m. to 5:00 p.m. These operations were performed from the flowing stages to the second crop of strawberries. Strawberries from both the experimental and reference ridges were harvested and immediately measured for various parameters, including plant height, single weight, hardness, soluble solids, and titratable acid.

The parameters were measured after 30 days of supplemental light exposure, corresponding to the first harvest stage in January 2022. The height of the strawberry plants was measured in centimeters using a tape measure. Five plants from each experimental and reference group were measured three times for each. The single weight was measured in grams using an electronic balance with an accuracy of 0.1 g. Ten strawberries from each group were measured. The hardness of strawberries was measured in kg/cm^2 using a GY- 4 digital fruit hardnessmeter. Ten strawberries, the same one measured for weight, were used for this measurement. The sugar content of strawberries, indicated by soluble solid content, was measured in percentage using a digital sugar meter based on prism optical sensing [28]. The same ten strawberries measured for their hardness were used for this measurement. The titratable acidity of the strawberries was assessed through sodium hydroxide solution titration [29]. One gram of the tested juice was obtained by grinding and dissolving it in 20 milliliters of pure water. The titratable acidity was determined by titrating 20 mL of the juice with 0.1 mol/L NaOH to a pH of 8.2. The titratable acidity was evaluated by millimoles (mmol) of citric acid per 100 g of juice. The titratable acidity content of each group was determined by measuring five strawberries for each group.

2.2.3. Statistical Analysis

Experiments were performed using a completely randomized design. Statistical analysis was performed using the Excell and Matlab R2022b software. All data are expressed as the mean ± standard error (SE).

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 was evaluated when the first crop ripened, 30 days after introducing supplemental light. The relationship between the height of the strawberry plant and the CCT and illuminances of supplemental light was illustrated in Figure 3. As seen in Figure 3a, in the presence of 1000 lx illuminance, the height of strawberry plants was significantly higher compared to the reference group (without supplemental light). The average height reached approximately 16.6 cm, which was approximately 21% higher than the reference group. Fluctuations in CCTs showed minor effects, with variations around 2.67 cm. When the illuminance was reduced to 600 lx, as displayed in Figure 3b, the average plant height was 15.0 cm, approximately 14% higher than the reference group. The impact of varying CCTs was more pronounced under this lower illuminance level compared to 1000 lx, though still consider minor. These results indicated that while CCTs had some influence, the primary driver of increased plant height under supplemental lighting conditions is the intensity of the light (illuminance).

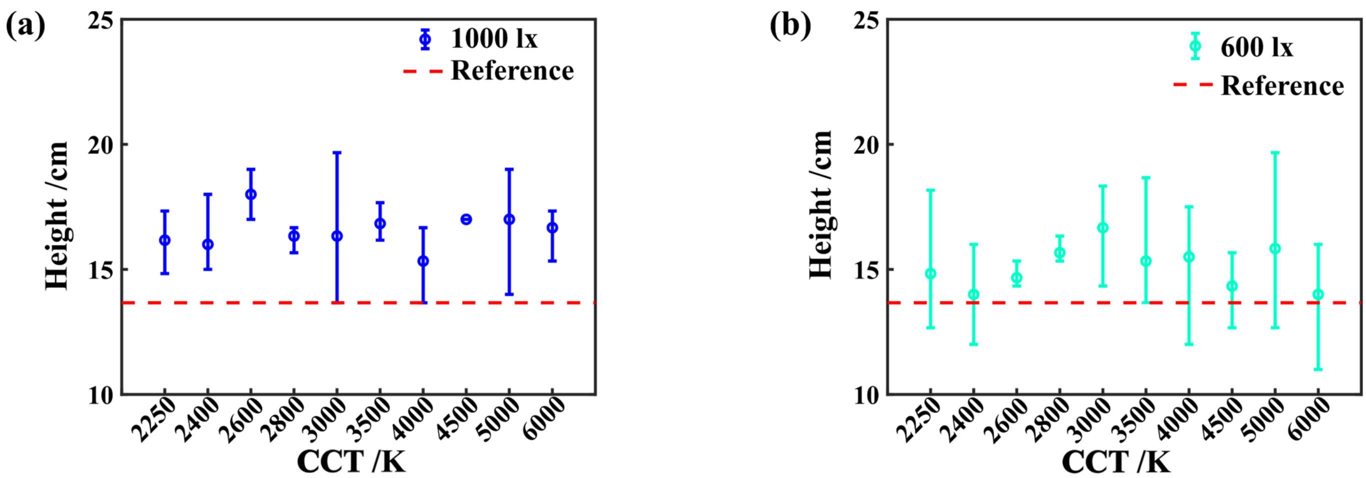

Figure 3. Effect of different CCT treatments on the height of the strawberry plant under different illuminances. Values are the means ± SE. Vertical bars represent the standard errors of the means. (**a**) Measured height as a function of CCT at an illuminance of 1000 lx; (**b**) measured height as a function of CCT at an illuminance of 600 lx.

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. This study explored the relationship between the CCTs of supplemental light and the single weight of strawberries under different illuminance levels: 1000 lx (Figure 4a) and 600 lx (Figure 4b). As shown in Figure 4a, the average single weight of strawberries under 1000 lx was 43.6 g, which was approximately 14% lower than the reference group, which had an average single weight of 50.62 g. Moreover, the mean of single weight was notably lower than the reference at CCTs between 2250 K to 2800 K and 4500 K to 6000 K. For other CCT ranges, the single weight remained similar to that of the reference group. When the illuminance was reduced at 600 lx, as shown in Figure 4b, the average single weight was 46.5 g, approximately 8% lower than the reference group. The exception was at a CCT of 5000 K, where the weight did not significantly differ from the reference. The variation in single weight across different CCTs was more pronounced at this lower illuminance compared to 1000 lx. This result suggests that the illuminance level of the supplemental light had a significant impact on the single weight of strawberries, CCTs have a more nuanced or secondary effect on the single weight.

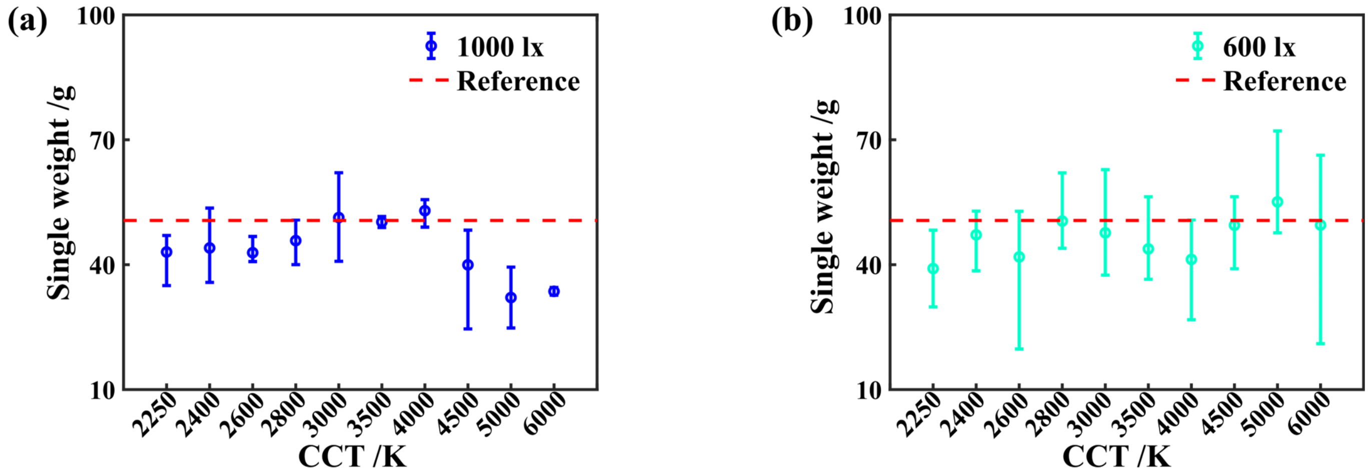

Figure 4. Effect of different CCT treatments on the single weight of strawberries under different illuminances. Values are the means ± SE. Vertical bars represent the standard errors of the means. (**a**) Measured single weight as a function of CCT at an illuminance of 1000 lx; (**b**) measured single weight as a function of CCT at an illuminance of 600 lx.

3.3. Chromatic Effect of Supplemental Light on the Fruit Hardness of Strawberries

Hardness is a vital parameter for assessing fruit quality, indicating the degree of maturation. Figure 5 showed 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 5a, the average hardness of strawberries under 1000 lx was 0.75 kg/cm^2. This was approximately 6% lower than the reference group, which had an average hardness of 0.80 kg/cm^2. The mean of hardness was significantly lower for CCTs ranging from 2400 K to 4500 K compared to the reference value. Interestingly, at CCTs below 2400 K or above 4500 K, the hardness tended to be higher than the reference, suggesting that these CCTs might delay the maturation process, resulting in firmer fruit. When the illuminance was reduced to 600 lx, as shown in Figure 5b, the average hardness was 0.77 kg/cm^2, which was 4% lower than the reference value. The variation in hardness across different CCTs was larger, but the overall deviation from the reference wan smaller. This implies that while lower illuminance affects hardness, the impact is not as pronounced as with higher illuminance.

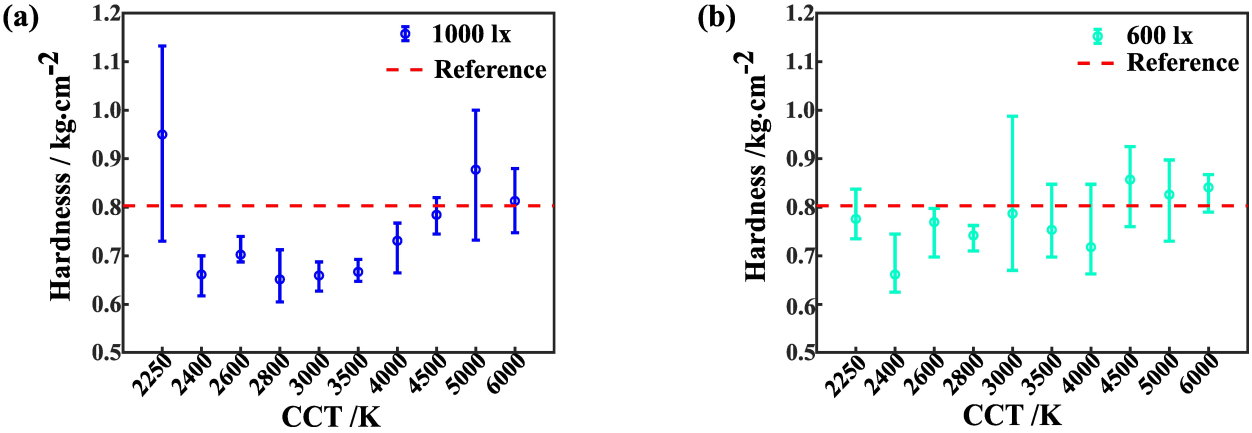

Figure 5. Effect of different CCT treatments on the hardness of strawberries under different illuminances. Values are the means ± SE. Vertical bars represent the standard errors of the means. (**a**) Measured hardness as a function of CCT at an illuminance of 1000 lx; (**b**) measured hardness as a function of CCT at an illuminance of 600 lx.

3.4. Chromatic Effect of Supplemental Light on Soluble Solids of Strawberries

Soluble solids primarily include sugars and other compounds that contribute to the sweetness and overall flavor profile of strawberries. Figure 6 demonstrated 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 6a) and 600 lx (Figure 6b). As illustrated in Figure 6a, under the influence of 1000 lx supplemental light, the average concentration of soluble solids in strawberries was 9.355%. This is a 7.4% increase compared to the reference group, which had an average concentration of 8.71%. Despite variations in CCT, the mean content fluctuation within soluble solids was only 0.37%, indicating that CCT did not significantly affect the concentration of soluble solids. These results suggest that supplemental light at 1000 lx effectively enhances the accumulation of soluble solids, thereby potentially improving sweetness and flavor. At 600 lx, as shown in Figure 6b, the average concentration of soluble solids was 9.284%; this represents a 6.6% increase over the reference group's 8.71%. The mean concentration range under different CCT conditions was broader, at 0.75%. This indicates a larger fluctuation in the soluble solids content at different CCTs under lower illuminance, suggesting that the impact of CCT on soluble solids concentration is more pronounced at lower light levels.

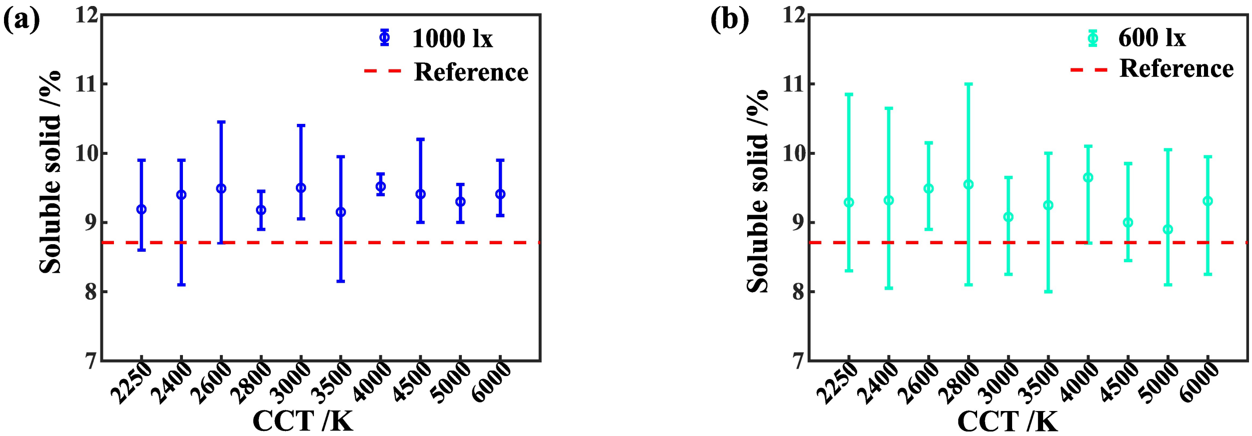

Figure 6. Effect of different CCT treatments on the soluble acids of strawberries under different illuminances. Values are the means ± SE. Vertical bars represent the standard errors of the means. (**a**) Measured soluble solids as a function of CCT at an illuminance of 1000 lx; (**b**) measured soluble solids as a function of CCT at an illuminance of 600 lx.

3.5. Chromatic Effect of Supplemental Light on Titratable Acids of Strawberries

Titratable acids in strawberries, such as citric acid, malic acid, and others, contribute significantly to their acidity and tartness. The tests for the titratable acids of strawberries as a function of CCT of supplemental light were shown in Figure 7. As can be seen from Figure 7a, with 1000 lx supplemental light, the average concentration of the titratable acids in strawberries was 8.87 mmol/100 g. This is a 27% increase compared to the reference group, which had an average concentration of 7.00 mmol/100 g. Moreover, it was also observed that chromatic influence is stronger on soluble solids. The CCT range of 2250 K to 2800 K and 3500 K to 4500 K notably influenced the increase in titratable acids concentration. The range of concentration variation across different CCTs was 2.61 mmol/100 g, indicating a significant effect of CCT on titratable acids at this illuminance level. When the illuminance was reduced to 600 lx, as shown in Figure 7b, the average concentration of the titratable acids was 8.36 mmol/100 g. This represents a 19% increase over the reference group's 7.00 mmol/100 g. Moreover, the mean concentration range under different CCT conditions was 1.78 mmol/100 g. This suggests a slightly smaller impact of CCT on titratable acids concentration at the lower illuminance level compared to 1000 lx.

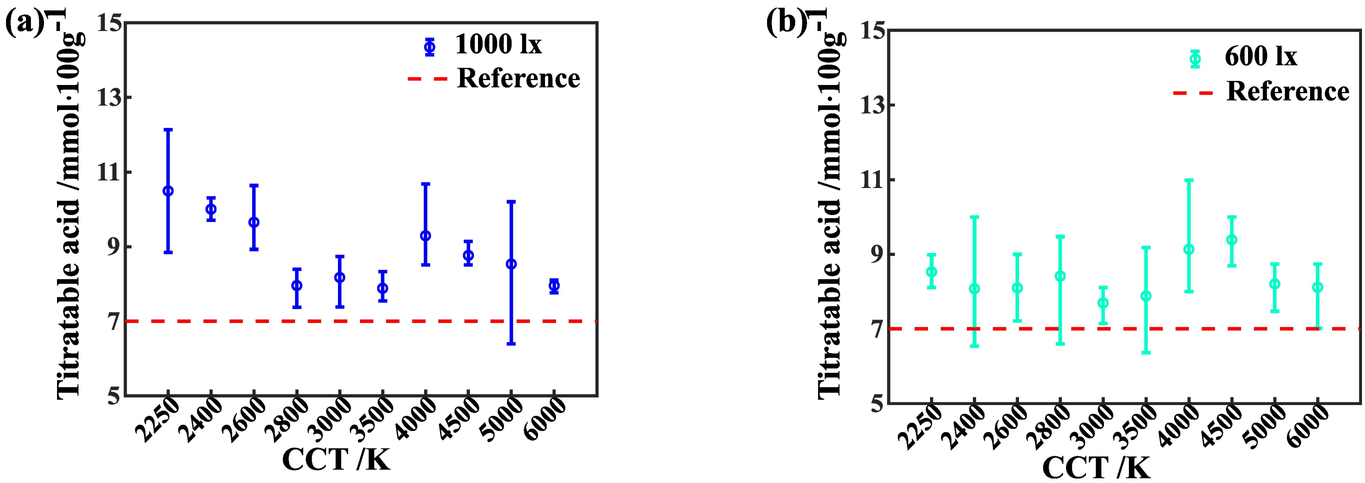

Figure 7. Effect of different CCT treatments on the titratable acids of strawberries under different illuminances. Values are the means ± SE. Vertical bars represent the standard errors of the means. (**a**) Measured titratable acids as a function of CCT at an illuminance of 1000 lx; (**b**) measured titratable acids as a function of CCT at an illuminance of 600 lx.

4. Discussion

Various light qualities and intensities exert a broad spectrum of consistent effects on the growth and development of plants. Specifically, the quality of light affects the balance of hormones in plants by acting on associated pigments. This, in turn, has significant implications for growth, development, and overall productivity [30]. Additionally, the intensity of light directly impacts crucial plant processes such as reproduction and the ripening of fruits [31,32].

The height of strawberry plants subjected to supplemental lights surpassed that the reference group. In particular, the height of strawberry plants exposed to supplemental lights at illuminances of 1000 lx and 600 lx exhibited an increase of approximately 22% and 10%, respectively, compared to the reference group (Figure 3). Notably, chromatic effects on plant height were not markedly significant. Noteworthy is the finding from other studies indicating that the impact of additional supplemental light on strawberry plant growth was notably superior to that of natural light [25]. The maximum plantlet height was observed at illuminances of 45 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 75 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [19]. Several experiments have been conducted to investigate the effects of different light qualities on plant height. For instance, the tallest plant height was recorded when plantlets were cultivated under 100% red light, while other combinations of red and blue light did not yield significant differences in height [19]. Plant height was evidently influenced by the rated power of the light source, where a larger rated power contributed to greater plant height when the same color mixing ratio was maintained [24]. Interestingly, when the rated power was hold constant, the addition of orange-color light to the red and blue color mix had been demonstrated to impact the plant height of strawberries [24]. Additionally, the tallest strawberry plants were obtained when cultivated under blue light [6]. Notably, a higher plant height was observed when the ratio of red LED to blue LED was 10:1, with no significant difference was noted when compared to a 19:1 red to blue light ratio [33]. In comparison to these findings, supplemental light was found to be beneficial for the growth of strawberry plants, but the optimal illuminance/intensity for Jiandehong strawberries was not found. Interestingly, the chromatic effect of supplemental light was not as pronounced as observed in previous studies, suggesting that the new variety Jiandehong strawberry might not be as sensitive to light quality. The results indicated that the supplemental light contributed to the plant growth of Jiandehong strawberry, but further investigation is needed to determine the best illuminance and chromatic quality for optimal results.

When comparing the single weight of strawberries under additional supplemental lights to these under normal natural lights, the weight remained nearly unchanged. Notably, a higher illuminance level (1000 lx) of supplemental light resulted in a smaller fluctuation in response to different colors. Additionally, chromatic effects on the single weight of strawberries showed that higher CCTs had a significantly lower impact compared to lower CCTs, as depicted in Figure 4. These findings aligned with prior research indicating that white LEDs did not increase the single weight of strawberries when compared to the reference group, maintaining a consistent value akin to the control treatment [6]. Furthermore, optimal single weight was found in the red LED treatment, while the lowest was found in the blue LED treatment [6]. A trend consistent with findings in some other studies as well [34,35]. In our present study, a similar trend was observed, but the chromatic effect of lower CCTs on the single weight was not as evident, suggesting the need for further investigation into this aspect.

The hardness of strawberries exhibited significant variation under different CCTs and illuminance treatments. Notably, hardness could be significantly reduced when using CCTs ranging from 2400 K to 4000 K, resulting in a decrease of 6.7%. Simultaneously, higher illuminance level could enhance these chromatic dependences, as illustrated in Figure 5. Previous studies have recommended a mixed ratio of 1:1:1 among red, blue, and white color supplemental lights to reduce strawberry hardness by 33%, although specific quantitative chromatic parameters were not provided [25]. Similarly, out present study maintained the lower hardness with a neutral CCTs range, aligning with the previous study's suggestion that neutral CCTs could be a potential method to accelerate strawberry ripening and maintain a high-quality postharvest strawberry fruit product.

The soluble solid content of strawberries exhibited significant improvements with the use of supplemental light treatments. In experimental groups, the soluble solid content was generally higher compared to the reference groups, showing an enhancement of 7.4%. Interestingly, the difference between illuminance level was not prominently noticeable, as depicted in Figure 6. These findings aligned with previous studies that have concluded that the quality of strawberry fruits can be significantly improved by supplemental light treatment, resulting in increased soluble solid content and soluble sugar content by 6.7% and 28%, respectively [25]. Furthermore, other research has indicated that variance in illuminance levels did not cause significant changes in soluble solid content [15]. Regarding the chromatic effect, our results aligned well with other studies [36], showing no significant differences in soluble solid content between different combinations of monochromatic LED lights (red, green, and blue) and polychromatic (W-R:G:B, 1:1:1) lights [36]. The similarity suggested that supplemental lighting can effectively improve the soluble solids of strawberries, while the illuminance and chromatic effect of the supplemental lights did not have a pronounced impact.

The titratable acid content of strawberries was significantly influenced by LED supplemental lights. The maximum titratable acid content was achieved when the CCT was within the range from 2250 K to 2600 K, and from 4000 K to 4500 K. Interestingly, the total titratable content was higher than that of reference group. Simultaneously, a higher illuminance level could enhance these chromatic dependences, as depicted in Figure 7. A similar study found that the titratable acid content could be enhanced by following a blue light treatment of supplemental light [11]. In our present study, both lower CCTs and higher CCTs significantly improved the concentration of titratable acid, consistent with the findings of the previous study.

In general, light intensity does not appear to be a significant concern for supplemental light, primarily because the dependences of five quality parameters on light intensity were much weaker than these on the CCTs. Even though intensity could slightly strengthen, weaken, or shift the corresponding chromatic dependences, it seems that other lighting factors, such as the lighting period, can compensate for the intensity effect to some extent.

5. Conclusions

In this work, we systematically studied the chromatic effect of supplemental light on the fruit quality of strawberries in artificial greenhouses. The supplemental light consisted of two-color white LEDs, and the color parameters of mixed light including CCTs and illuminance of supplemental lights were precisely controlled using a DCCM. We investigated the chromatic effects of supplemental light on five parameters of strawberries: plant height, single weight, fruit hardness, soluble solids, and titratable acids. The supplemental light led to an average increase in plant height by over 20% compared to the reference group. The fruit hardness was notably lower in the experimental group by 6.7% compared to the reference group. Specifically, the lowest hardness was observed within the CCTs ranging from 2400 K to 4000 K. The quality of strawberries showed enhancement, particularly in the contents of soluble solids and titratable acids. The content of soluble solids was notably higher by 7.4% in the experimental group compared to the reference group. However, differences in the soluble solids content among different CCTs were not found to be significant. The content of titratable acids was significantly higher in the experimental group, showing a 23% increase compared to the reference group. The identified optimal CCTs range for titratable acid growth was between 3500 K and 4500 K. Although the light intensity had some influence on titratable acids content, this study suggests that its impact was relatively weak compared to the more substantial influence of CCTs. This study outlines important directions for future research. Specifically, we plan to explore the saturation point of the supplemental light on the strawberry, add additional test parameters (both quality and growth-related), and investigate the effect of photoperiod and timing on strawbeery quality parameters. In conclusion, this study demonstrated the effective roles played by supplemental light in accelerating maturation and enhancing the flavor of strawberries in a greenhouse setting. These findings provided valuable insights that can guide the effective cultivation of strawberries, offering practical implications for growers and researchers alike.

Author Contributions: J.W. and M.Q. supervised the research. J.W. developed the methods for accurate color control of supplemental light. N.T., B.Z. and H.C. conducted the experiments. N.T. and J.W. analyzed the data. J.W., N.T. and M.Q. discussed the results and corrected the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. Giampieri, F.; Tulipani, S.; Alvarez-Suarez, J.M.; Quiles, J.L.; Mezzetti, B.; Battino, M. The strawberry: Composition, nutritional quality, and impact on human health. *Nutrition* **2012**, *28*, 9–19. [CrossRef] [PubMed]
2. Manganaris, G.A.; Goulas, V.; Vicente, A.R.; Terry, L.A. Berry antioxidants: Small fruits providing large benefits. *J. Sci. Food Agric.* **2014**, *94*, 825–833. [CrossRef] [PubMed]
3. Hidaka, K.; Dan, K.; Imamura, H.; Takayama, T.; Sameshima, K.; Okimura, M. Variety comparison of effect of supplemental lighting with LED on growth and yield in forcing culture of strawberry. *Environ. Control Biol.* **2015**, *53*, 135–143. [CrossRef]
4. Hidaka, K.; Dan, K.; Imamura, H.; Miyoshi, Y.; Takayama, T.; Sameshima, K.; Okimura, M.; Kitano, M. Investigation of supplemental lighting with Different light source for high yield of strawberry. *IFAC Proc. Vol.* **2013**, *46*, 115–119. [CrossRef]
5. Avercheva, O.V.; Berkovich, Y.A.; Erokhin, A.N.; Zhigalova, T.V.; Pogosyan, S.I.; Smolyanina, S.O. Growth and photosynthesis of Chinese cabbage plants grown under a light-emitting diode-based light source. *Russ. J. Plant Physiol.* **2009**, *56*, 14–21. [CrossRef]
6. Jamal Uddin, A.F.M.; Hoq, M.Y.; Rini, S.N.; Urme, F.B.R.; Ahmad, H. Influence of supplement LED spectrum on growth and yield of Strawberry. *J. Biosci. Agric. Res.* **2018**, *16*, 1348–1355. [CrossRef]
7. Rehman, M.; Ullah, S.; Bao, Y.; Wang, B.; Peng, D.X.; Liu, L.J. Light-emitting diodes: Whether an efficient source of light for indoor plants? *Environ. Sci. Pollut. Res.* **2017**, *24*, 24743–24752. [CrossRef]
8. Xu, F.; Cao, S.F.; Shi, L.Y.; Chen, W.; Su, X.G.; Yang, Z.F. Blue light irradiation affects anthocyanin content and enzyme activities involved in postharvest strawberry fruit. *J. Agric. Food Chem.* **2014**, *62*, 4778–4783. [CrossRef]
9. Nascimento, L.B.S.; Leal-Costa, M.V.; Coutinho, M.A.S.; Moreira, N.D.S.; Lage, C.L.S.; Barbi, N.D.S.; Costa, S.S.; Tavares, E.S. Increased antioxidant activity and changes in the phenolic profile of *Kalanchoe pinnata* (Lamarck) Persoon (Crassulaceae) specimens grown under supplemental blue light. *Photochem. Photobiol.* **2013**, *89*, 391–399. [CrossRef]
10. Samuolienė, G.; Sirtautas, R.; Brazaitytė, A.; Pavelas, D. LED lighting and seasonality effects antioxidant properties of baby leaf lettuce. *Food Chem.* **2012**, *134*, 1494–1499. [CrossRef]
11. Xu, F.; Shi, L.Y.; Chen, W.; Cao, S.F.; Su, X.G.; Yang, Z.F. Effect of blue light treatment on fruit quality, antioxidant enzymes and radical-scavenging activity in strawberry fruit. *Sci. Hortic.* **2014**, *175*, 181–186. [CrossRef]
12. Warner, R.; Wu, B.S.; MacPherson, S.; Lefsrud, M. A review of strawberry photobiology and fruit flavonoids in controlled environments. *Front. Plant Sci.* **2021**, *12*, 611893. [CrossRef]
13. Zheng, J.F.; He, D.X.; Ji, F. Effects of light intensity and photoperiod on runner plant propagation of hydroponic strawberry transplants under LED lighting. *Int. J. Agric. Biol. Eng.* **2019**, *12*, 26–31. [CrossRef]
14. Zheng, J.F.; Ji, F.; He, D.X.; Niu, G.H. Effect of light intensity on rooting and growth of hydroponic strawberry runner plants in a LED plant factory. *Agronomy* **2019**, *9*, 875. [CrossRef]
15. Zhong, P.L.; Yang, S.P.; Qiao, R.; Wang, T.W. Effect of light intensity on main quality of strawberry. *Southwest China J. Agric. Sci.* **2011**, *24*, 1219–1221.
16. Xu, X.N.; Hernandez, R. The effect of light intensity on vegetative propagation efficacy, growth, and morphology of "Albion" strawberry plants in a precision indoor propagation system. *Appl. Sci.* **2020**, *10*, 1044. [CrossRef]
17. Hidaka, K.; Okamoto, A.; Araki, T.; Miyoshi, Y.; Dan, K.; Imamura, H.; Kitano, M.; Sameshima, K.; Okimura, M. Effect of photoperiod of supplemental lighting with light-emitting diodes on growth and yield of strawberry. *Environ. Control Biol.* **2014**, *52*, 63–71. [CrossRef]
18. Yue, G.F. Influences of different light supplemental time on flowering, yield and quality of strawberry. *Jiangsu Agric. Sci.* **2020**, *48*, 14–144.
19. Nhut, D.T.; Takamura, T.; Watanabe, H.; Okamoto, K.; Tanaka, M. Responses of strawberry plantlets cultured in vitro under superbright red and blue light-emitting diodes (LEDs). *Plant Cell Tissue Organ Cult.* **2003**, *73*, 43–52. [CrossRef]
20. Lin, K.H.; Huang, M.Y.; Huang, W.D.; Hsu, M.H.; Yang, Z.W.; Yang, C.M. The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. capitata). *Sci. Hortic.* **2013**, *150*, 86–91. [CrossRef]
21. Paradiso, R.; Proietti, S. Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. *J. Plant Growth Regul.* **2022**, *41*, 742–778. [CrossRef]
22. Ouzounis, T.; Rosenqvist, E.; Ottosen, C.O. Spectral effects of artificial light on plant physiology and secondary metabolism: A review. *HortScience* **2015**, *50*, 1128–1135. [CrossRef]
23. Takeda, F.; Glenn, D.M.; Stutte, G.W. Red light affects flowering under long days in a short-day strawberry cultivar. *HortScience* **2008**, *43*, 2245–2247. [CrossRef]
24. Li, Y.P.; Chen, H.C.; Ji, H.H.; Wang, S.B.; Zhu, Z.H.; Wang, X.X. Effect of led supplemental illumination on the growth of strawberry plants. In Proceedings of the 2012 Symposium on Photonics and Optoelectronics, Shanghai, China, 21–23 May 2012.
25. Wu, P.F.; Wang, L.J.; Liu, Z.; Yoshikazu, K. Effect of LED Supplemental Lighting Treatment on Protected Strawberry Growth and Fruit Quality. *N. Hortic.* **2016**, *21*, 48–50.

26. Tang, N.; Zhang, L.; Zhou, J.B.; Yu, J.D.; Chen, B.Q.; Peng, Y.X.; Tian, X.Q.; Yan, W.; Wang, J.Y.; Qiu, M. Nonlinear color space coded by additive digital pulses. *Optica* **2021**, *8*, 977–983. [CrossRef]
27. Wang, J.Y.; Mou, T.S.; Wang, J.P.; Tian, X.Q. A quantitative dimming method for LED based on PWM. In Proceedings of the Twelfth International Conference on Solid State Lighting and Fourth International Conference on White LEDs and Solid-State Lighting (International Society for Optics and Photonics (SPIE)), San Diego, CA, USA, 15 October 2012.
28. Magwaza, L.S.; Opara, U.L. Analytical methods for determination of sugars and sweetness of horticultural products—A review. *Sci. Hortic.* **2015**, *184*, 179–192. [CrossRef]
29. International Organization for Standardization. *Fruit and Vegetable Products: Determination of Titratable Acidit*; International Organization for Standardization: Geneva, Switzerland, 1998.
30. Xing, Z.N.; Zhang, D.; Li, W.; Zhang, X.; Zhang, L.L.; Cui, J. Effects of light quality on the growth and quality of Helianthus annuus sprouts. *J. Nanjing Agric. Univ.* **2012**, *35*, 47–51.
31. Zhang, W.D.; Qi, L.W.; Yang, X.L.; Lu, Y.W.; Ping, L.; Yang, Z.L. Determination of tectorigenin in rat plasma: Application to a pharmacokinetic study after oral administration of tectorigenin or its prodrug tectoridin. *Chromatographia* **2008**, *68*, 1021–1025. [CrossRef]
32. Kang, J.H.; Krishnakumar, S.; Atulba, S.; Jeong, B.R.; Hwang, S.J. Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system. *Hortic. Environ. Biotechnol.* **2013**, *54*, 501–509. [CrossRef]
33. Naznin, M.T.; Lefsrud, M.; Gravel, V.; Hao, X. Using different ratios of red and blue LEDs to improve the growth of strawberry plants. *VIII Int. Symp. Light Hortic.* **2016**, *1134*, 125–130. [CrossRef]
34. Hidaka, K.; Dan, K.; Imamura, H.; Miyoshi, Y.; Takayama, T.; Sameshima, K.; Kitano, M.; Okimura, M. Effect of supplemental lighting from different light sources on growth and yield of strawberry. *Environ. Control Biol.* **2013**, *51*, 41–47. [CrossRef]
35. Ni, J.H.; Mao, H.P.; Chen, C.H.; Zuo, Z.Y.; Francis, K. Effects of different light-emitting diode (LEDs) on fruit yield of greenhouse cucumber. *Afr. J. Agric. Res.* **2013**, *8*, 4972–4974.
36. Lauria, G.; Lo Piccolo, E.; Ceccanti, C.; Guidi, L.; Bernardi, R.; Araniti, F.; Cotrozzi, L.; Pellegrini, E.; Moriconi, M.; Giordani, T.; et al. Supplemental red LED light promotes plant productivity, “photomodulates” fruit quality and increases Botrytis cinerea tolerance in strawberry. *Postharvest Biol. Technol.* **2023**, *198*, 112253. [CrossRef]