horticulturae

Article

Effects of Four Photo-Selective Colored Hail Nets on an Apple in Loess Plateau, China

Yutian Zhang [1,†], Baohua Chu [1,†], Dongdong Zhang [1], Qi Li [1], Qianjin Li [1], Xuewei Li [1], Zeyuan Liu [1], Fengwang Ma [1], Qingmei Guan [1], Dehui Zhang [2,*] and Yangjun Zou [1,*]

[1] State Key Laboratory of Crop Stress Biology for Arid Areas/Shaanxi Key Laboratory of Apple, College of Horticulture, Northwest A&F University, Yangling 712100, China; qguan@nwsuaf.edu.cn (Q.G.)
[2] College of Horticulture, Shanxi Agricultural University, Jinzhong 030801, China
[*] Correspondence: tsu.zhangdehui@163.com (D.Z.); yangjunzou@126.com (Y.Z.)
[†] These authors contributed equally to this work.

Abstract: Hail, known as an agricultural meteorological disaster, can substantially constrain the growth of the apple industry. Presently, apple orchards use a variety of colored (photo-selective) hail nets as a preventative measure. However, it is unclear which color proves most effective for apple orchards. This study provides a systematic investigation of the impact of four photo-selective colored hail nets (white, blue, black, and green; with white being the control) on the microenvironment of apple orchards, fruit tree development, fruit quality, and yield over a two-year period (2020–2021). Different photo-selective nets do not evidently alter the intensity of light, although the nets' shading effects decrease in the order from black to green to blue. Among them, blue nets increased the proportion of blue light, while green nets enhanced the proportion of green light. On the other hand, black, green, and blue nets diminished the proportion of red and far-red light. Such photo-selective nets effectively lowered soil temperature but did not have an impact on relative humidity and air temperature. Encasing apple trees with blue nets promoted growth, increasing shoot length, thickness, leaf area, and water content, while simultaneously decreasing leaf thickness. Black nets had comparable effects, although the impacts of green nets were inconsistent. Different photo-selective nets did not significantly influence the leaf shape index or overall chlorophyll content. However, black and green nets reduced the chlorophyll a/b ratio, while blue nets slightly boosted this ratio. Additionally, blue nets proved beneficial for apple trees' photosynthesis. With the employment of a principal component analysis and comprehensive evaluation, this study concludes that blue nets offer the most favorable environmental conditions for apple growth while protecting apple orchards against hail, compared to black, white, and green nets.

Keywords: photo-selective net; microenvironment; fruit tree growth; fruit quality; fruit production; apple

check for updates

Citation: Zhang, Y.; Chu, B.; Zhang, D.; Li, Q.; Li, Q.; Li, X.; Liu, Z.; Ma, F.; Guan, Q.; Zhang, D.; et al. Effects of Four Photo-Selective Colored Hail Nets on an Apple in Loess Plateau, China. *Horticulturae* **2023**, *9*, 1061. https://doi.org/10.3390/horticulturae9091061

Academic Editor: Jia-Long Yao

Received: 13 August 2023
Revised: 19 September 2023
Accepted: 19 September 2023
Published: 21 September 2023

1. Introduction

Apple is a globally important fruit crop, both economically and nutritionally. The Loess Plateau is the largest apple-growing area in the world, with apple cover and yield of 1.3 million ha and 23 million tons, respectively, accounting for 25.2% of global land cover and 26.3% of global apple production in 2016 [1]. However, the Loess Plateau is vulnerable to various environmental factors, including hailstorms, which can cause substantial damage to apple trees and their fruit. Hail damage not only impacts fruit production within the current season but also affects fruit yield in subsequent seasons by harming flower buds [2]. Traditional anti-hail measures, such as cloud seeding, anti-hail guns, nanocomposites, or expanding planting areas have proven to be expensive and ineffective [3]. Previous studies have indicated that hail nets can impact various environmental factors, including light, air flow, temperature, and humidity. Recently, photo-selective colored netting, a promising agro-technical approach, has emerged as an alternative solution that utilizes nets that not only offer vital protection against hail, wind, pests, and excessive solar radiation but also alter the quality of transmitted light [4,5]. By selectively manipulating light wavelengths, the photo-selective netting optimizes plant growth and enhances crop quality [2,5–9]. Therefore, it is crucial to understand the impact of photo-selective nets on apple tree physiology and fruit quality to effectively utilize anti-hail nets and maximize their benefits.

One of the primary advantages of photo-selective nets is their ability to reduce the amount of solar radiation reaching the orchard environment beneath them [2]. The subtle shading effect caused by photo-selective nets can decrease leaf temperature and evaporative demand, enhancing photosynthesis and subsequently promoting carbohydrate production, potentially resulting in improved yield quality [4,10,11]. Several studies have also emphasized the role of photo-selective nets in modifying the orchard environment, affecting factors such as light intensity, light quality, canopy temperature, air humidity, and soil temperature [7,9,12–14]. While photo-selective nets allow solar radiation to pass through, they also scatter it, mitigating its impact [5,11,13]. In a separate study conducted by Shahak et al., it was found that apple trees covered with red nets displayed a superior rate of leaf photosynthesis compared to those covered with blue, pearl, gray, and black nets [15]. Furthermore, an investigation comparing various protective netting colors discerned that the net photosynthesis rate in 'Fuji' apples showed notable elevation under blue and grey nets, as opposed to pearl-colored nets [16]. Variations in microclimatic conditions created by photo-selective nets have been found to significantly influence the physiological responses of fruit trees, which are closely linked to their growth, fruit production, and fruit quality [2,7,17,18]. In a comparative study on 'Mondial Gala' apples, Iglesias and Alegre reported that fruits grown under black nets exhibited significantly lower red coloration compared to those exposed to sunlight in three out of four growing seasons [19]. Similarly, Solomakhin and Blanke discovered that apple peels under photo-selective nets had higher chlorophyll levels but four to five times lower anthocyanin levels [20]. Furthermore, Blanke suggested the use of black nets specifically for monocolor green apple varieties and bicolor apple cultivars that require good coloration [21].

Over the past decade, numerous field studies have consistently demonstrated that photo-selective nets have varying effects on vegetative and reproductive growth in a wide range of cultivated species, with red and yellow nets promoting vegetative growth and blue nets inducing dwarfism [22,23]. Conversely, gray and pearl nets have been found to effectively enhance branching in ornamental crops [24–26]. In the context of apple cultivation, Solomakhin and Blanke observed that different types of photo-selective nets, particularly the green-black type, resulted in increased vegetative growth compared to uncovered trees [27]. In contrast, Bastías et al. found that blue nets stimulated a higher rate of apple shoot growth compared to red, gray, and white nets [28]. Additionally, Giaccone et al. reported an improvement in the vigor of nectarine trees when cultivated under red nets [29].

The importance of optimal internal fruit quality is increasingly recognized by consumers, and studies have shown that the use of photo-selective nets can affect the internal quality of fruits, particularly apples [2]. For instance, the use of black nets has been found to increase the total acidity of apples compared to those grown without any covering [19]. The firmness of apple fruits, such as 'Fuji' and 'Pinova', is subject to variation depending on the type of photo-selective netting employed for cultivation, with apples grown under green-black and red-black netting yielding softer fruits compared to those grown under red-white nets, while the firmest fruits are produced in the control group without any netting [20]. In a study by Do Amarante et al., it was observed that 'Gala' apples grown under white net exhibited a significant decrease in fruit flesh firmness at harvest, in contrast to 'Fuji' apples [30]. Additionally, fruits grown under white nets showed a decrease in total soluble solids content, which was attributed to shading and resulted in reduced carbohydrate reserves in the fruit, ultimately leading to lower levels of soluble sugar at commercial maturity [30].

This study aimed to assess the impact of four photo-selective nets (white, blue, black, and green nets) on apple orchards. As a result of the frequent hail storms in the Loess Plateau, it was impossible to utilize control plants that were exposed to direct sunlight.

To evaluate the photo-selective effect of the different colors, the white net, the most used locally, was considered the control net. The evaluation encompassed various aspects, including environmental factors, growth and development indices, fruit quality, and overall yield. To determine the most effective color for orchard hail net coverage, principal component analysis was employed for a comprehensive evaluation. The research findings have significant theoretical and practical implications, providing valuable insights for improving apple tree growth, fruit yield, and quality.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

The experiment was conducted at the Apple Research Center in Luochuan County, Shaanxi Province, China (109°32′40′′ E, 35°42′28′′ N). The experiment was conducted over a period of two years, from June 2019 to November 2021. The orchard area employed a dwarfing rootstock-mediated high-density planting system, with 4-year-old apple trees selected as the experimental materials. The rootstock used was M26, and the cultivar was Yanfu No.8. The row spacing and plant spacing were set at 3.5 × 1.5 m.

Based on the colors of photo-selective hail nets, four treatments were established: white, blue, black, and green. The hail nets were installed at a height of 5 m above the ground in a roof-shaped structure. The installation of the nets began in April and continued until the end of November each year. The nets were made with polyethylene material by adding UV stabilizers and anti-oxidants with hed quad crossover, 4 × 7 mm mesh, 25 mm mesh size, 480 denier, and 60 gsm (Dongshen Development Ltd., Xiamen, China).

The experimental layout employed a randomized block design. A single-colored net enveloped three rows of apple trees, encompassing no less than 60 trees. The measurements were conducted on nine trees per individual colored net (treatment) within the central row to mitigate any potential border effects.

2.2. Measurement of Air Humidity, Air Temperature, Light Intensity, and Light Quality

Temperature and illuminance measurements were conducted using a temperature and illuminance recorder (TPJ-22-G, Zhejiang topu yunnong Technology Co., Ltd., Hangzhou, China), as well as a spectroradiometer (HR-450, HiPoint, Taiwan, China), from 9:00 am to 5:00 pm in early August. The devices were placed at a distance of 20 cm from the outer edge of the canopy and at a height of 1.7 m above the ground, which roughly corresponded to the center of the canopy. To ensure precision and consistency, the measurements were repeated 10 times, and the obtained results were recorded for subsequent analysis.

2.3. Measurement of Soil Temperature

To measure soil temperature, a soil thermometer (TPJ-21-G, Zhejiang topu yunnong Technology Co., Ltd., Hangzhou, China) was inserted 5 cm deep and 20 cm away from the trunk. Each treatment had three biological replicates, and within each biological replicate, three trees were selected as the three basic replicates. Data changes were recorded between 9:00 am and 5:00 pm in early August.

2.4. Measurement of New Shoot Growth

The new shoot growth was calculated by measuring the shoot length and diameter at the end of the annual vegetative growth, specifically in early August. A minimum of fifteen non-fruiting bourse shoots were selected for each treatment.

2.5. Measurement of Leaf Relative Water Content

To determine the leaf relative water content, we followed a specific procedure described previously [31]. First, we collected fully expanded leaves and measured their weights while fresh. Next, we soaked the leaves in water for a period of 12 h and recorded their weight as saturated weight. Finally, we transferred the leaves to an oven and dried them until a constant weight (dry weight) was achieved. Fifty leaves were selected for each treatment. The relative water content was calculated using the following formula:

$$\text{Leaf relative water content} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Saturated weight} - \text{Dry weight}} \times 100$$

2.6. Measurement of Leaf Area

The leaves were scanned using a scanner (Epson, Suwa, Japan), and leaf auto compute software was employed for accurate calculation. Fifty leaves were selected for each treatment.

2.7. Measurement of Photosynthetic Parameters

The determination of leaf photosynthesis was conducted following the previously described methods [31]. During the new shoot growth period, photosynthetic parameters were measured under sunny conditions from 9:00 am to 5:00 pm. For each treatment, three branches with consistent tree vigor were selected from each biological replicate, and the sixth mature leaf from the top of each branch was used for measurement. The portable LI-6400 photosynthesis system (LI-COR, Lincoln, NE, USA) was used to measure the net photosynthetic rate, transpiration rate, intercellular carbon dioxide concentration, and stomatal conductance.

2.8. Determination of Relative Chlorophyll Content

The relative chlorophyll content of leaves in the top or mid-canopy was assessed by measuring the SPAD values of five selected leaves. The measurement of chlorophyll a and b was performed as described previously [32]. Simply, fresh leaves were collected, and the large veins were removed. The leaves were then cut into small pieces. Approximately 0.1 g of the leaf fragments was weighed and placed in a mortar. A small amount of 80% acetone was added to the mortar, along with a pinch of calcium carbonate and quartz sand. The mixture was thoroughly ground until it became a homogeneous paste. An additional 80% acetone was added to the paste, and the resulting mixture was transferred to a centrifuge tube. The volume was adjusted to 10 mL with 80% acetone. The extraction process was carried out at room temperature in a dark place for 24 h. After the extraction, the solution was collected, and the absorbance values at wavelengths of 663 nm (A_{663}) and 645 nm (A_{645}) were measured using 80% acetone as a reference. Chlorophyll a or b was calculated using the formula:

$$\text{Chlorophyll a content (mg/mL)} = 12.72A_{663} - 2.59A_{645}$$

$$\text{Chlorophyll b content (mg/mL)} = 22.88A_{645} - 4.67A_{663}$$

2.9. Determination of Fruit Quality

For the assessment of external quality, 15 similarly sized fruits were randomly chosen from each treatment for evaluation. Parameters such as fruit weight, shape, and skin color were measured. An electronic vernier caliper was used to measure the maximum longitudinal and transverse diameters of the fruit. A ratio of these diameters was then used to define the shape of the fruit. A portable Cr-100 colorimeter (X-Rite, Granville, MI, USA) was employed to measure skin color parameters. Variations in skin color were denoted using brightness (L*), red-greenness (a*), and yellow-blueness (b*) values. To compute the yield per plant, these fruits were harvested.

To evaluate internal quality, various parameters were measured, including flesh firmness, pericarp firmness, pericarp malleability, and flesh brittleness. These assessments were carried out at five distinct points on the fruit's equatorial surface using a fruit texture analyzer (TMS-Touch, FTC, Frederick, MD, USA). Subsequently, these individual measures were averaged to yield a single value for each parameter. Additional measurements included soluble solid content gauged using a PAL-1 digital refractometer (Atago, Tokyo, Japan). Lastly, the fruit's acidity level was determined with the use of a digital GMK-835F device (G-WON, Seongnam-si, Republic of Korea).

2.10. Principal Component Analysis

We conducted dimensionality reduction and principal component analysis on the data from 2020 and 2021 using IBM SPSS Statistics 20. The correspondence between factors and items was determined by analyzing the factor loading coefficient matrix table after rotation. A factor loading coefficient with an absolute value greater than 0.4 indicates a significant relationship between the item and the dimension (factor). In cases where a research item corresponds to multiple factors, professional knowledge is taken into account to determine its specific attribution to a particular factor.

2.11. Statistical Analysis

All statistical analyses were performed using Origin 2019b software. The significance of differences between treatments for the various measured parameters was evaluated through one-way ANOVA Tukey's test.

3. Results

3.1. The Impact of Photo-Selective Nets on the Orchard Environment

To examine the effects of photo-selective nets (black, blue, green, and white) on the microclimate of orchards (Figure 1A), we measured and analyzed the daily variations of four indicators: soil temperature, light intensity, relative air humidity, and relative air temperature. The results revealed that the colors of photo-selective nets had a noticeable influence on the orchard's microclimate, particularly in terms of the daily variations in soil temperature (Figure 1B). The findings demonstrated that covering orchards with black net effectively reduced soil temperature, with a maximum difference of up to 5 °C compared to white net and up to 3 °C compared to blue or green net (Figure 1B). Additionally, it was observed that the colorful nets reduced the daily amplitude of soil temperature variation, leading to a relatively stable daily variation pattern compared to the white net (Figure 1B). However, the photo-selective nets did not exhibit significant effects on the indicators of light intensity, relative air humidity, and relative air temperature (Figure 1C and Supplemental Table S1).

Furthermore, to examine the effects of various photo-selective nets on light quality, spectral measurements and analysis were conducted using a spectrometer during August and September of 2020 and 2021. The results indicated that the blue net had a substantial impact on altering the composition of light quality when compared to the white net. This effect was primarily achieved by increasing the proportion of blue light, while significantly reducing the proportions of red and far-red light. Additionally, the ratios of red and far-red light experienced a noteworthy decrease (Table 1). In comparison, the black net had a less pronounced influence on light quality compared to the blue net. However, they were still able to reduce the proportions of red and far-red light to some extent (Table 1). On the other hand, the green net significantly impacted the composition of light quality. They increased the proportion of green light while decreasing the proportions of red and far-red light. Furthermore, the green net exhibited a significant reduction in the ratio of red and far-red light (Table 1). All three colors of photo-selective nets (blue, black, and green) were found to substantially decrease the ratio of red and far-red light, with the green net having the most significant impact. However, the influence of photo-selective net colors on the proportion of ultraviolet light was relatively minor (Table 1). In addition to spectral analysis, the experiment also compared the light intensity. The results from four experiments demonstrated that photo-selective colored nets of the same specifications did not significantly alter the light intensity (Table 1). However, there was a slight trend of decreased light transmission as the color of the photo-selective net darkened. Specifically, the light transmission performance order was as follows: white net > green net > blue net > black net (Table 1).

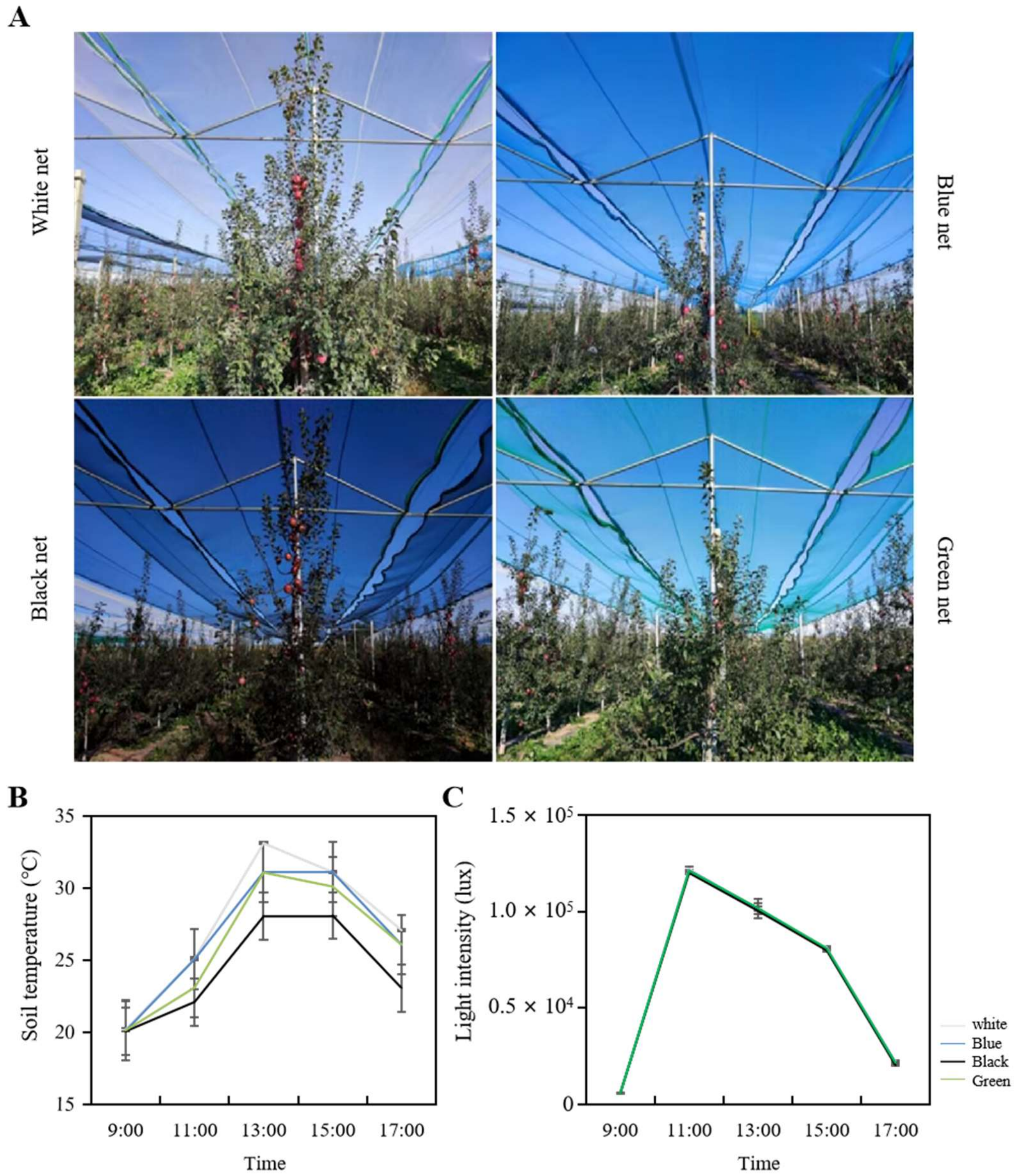

Figure 1. The effects of photo-selective colored nets on soil temperature and light intensity. (**A**) Apple orchards under photo-selective white, blue, black, and green nets. (**B**) Soil temperature variations at different hours of the day under photo-selective colored nets. (**C**) Light intensity at different hours of the day under photo-selective colored nets. Error bars indicate the standard deviation (n = 10).

Table 1. The effects of photo-selective colored nets on light quality in August and September 2020 and 2021.

Year.	Proportion	White Net	Blue Net	Black Net	Green Net
2020.08	Light intensity (lux)	51,149.84 ± 2274.53	50,897.65 ± 5722.07	50,723.53 ± 2159.15	50,996.85 ± 5591.69
	PFD-UV (380~400 nm)	0.02 ± 0.0001	0.02 ± 0.0004	0.02 ± 0.0004	0.02 ± 0.0005
	PFD-B (400~500 nm)	0.22 ± 0.0006	0.24 ± 0.0026 ***	0.22 ± 0.0032	0.2 ± 0.0043 ***
	PFD-G (500~600 nm)	0.27 ± 0.0004	0.28 ± 0.0012 *	0.27 ± 0.0021	0.28 ± 0.0024 ***
	PFD-R (600~700 nm)	0.27 ± 0.0009	0.26 ± 0.002 ***	0.27 ± 0.0003	0.26 ± 0.002 ***
	PFD-FR (700~780 nm)	0.21 ± 0.0011	0.2 ± 0.0045 *	0.22 ± 0.0058 ***	0.23 ± 0.0055 ***
	R/FR	1.29 ± 0.0102	1.28 ± 0.0344 ***	1.25 ± 0.0339 ***	1.22 ± 0.0233 ***

Table 1. *Cont.*

Year.	Proportion	White Net	Blue Net	Black Net	Green Net
2020.09	Light intensity (lux)	59,628.72 ± 4783.35	59,321.15 ± 1370.72	58,548.1 ± 4544.35	59,722.44 ± 3116.6
	PFD-UV (380~400 nm)	0.02 ± 0.0001	0.02 ± 0.0176	0.02 ± 0.0004	0.02 ± 0.0003
	PFD-B (400~500 nm)	0.21 ± 0.0011	0.22 ± 0.2189 ***	0.2 ± 0.0036 ***	0.21 ± 0.0023
	PFD-G (500~600 nm)	0.27 ± 0.0009	0.27 ± 0.2715	0.27 ± 0.0019	0.28 ± 0.0013 ***
	PFD-R (600~700 nm)	0.29 ± 0.0006	0.28 ± 0.2756 ***	0.29 ± 0.0005	0.27 ± 0.0016 ***
	PFD-FR (700~780 nm)	0.22 ± 0.0026	0.22 ± 0.2164	0.22 ± 0.006	0.22 ± 0.0042
	R/FR	1.3 ± 0.0179	1.27 ± 0.0185 ***	1.28 ± 0.0355 ***	1.25 ± 0.0271 ***
2021.08	Light intensity (lux)	31,373.76 ± 1139.86	30,458.75 ± 1722.69	29,091.76 ± 413.05	30,121.7 ± 499.27
	PFD-UV (380~400 nm)	0.02 ± 0.0002	0.02 ± 0.0002	0.02 ± 0.0002	0.02 ± 0.0001
	PFD-B (400~500 nm)	0.21 ± 0.002	0.23 ± 0.001 ***	0.22 ± 0.0009 ***	0.22 ± 0.001 ***
	PFD-G (500~600 nm)	0.27 ± 0.0006	0.27 ± 0.0005	0.27 ± 0.0003	0.28 ± 0.0004 ***
	PFD-R (600~700 nm)	0.28 ± 0.0003	0.26 ± 0.0012 ***	0.27 ± 0.0005 ***	0.26 ± 0.0003 ***
	PFD-FR (700~780 nm)	0.22 ± 0.0031	0.21 ± 0.0012 ***	0.22 ± 0.0013	0.22 ± 0.0016
	R/FR	1.26 ± 0.0191	1.25 ± 0.0115 *	1.25 ± 0.0084 *	1.16 ± 0.0088 ***
2021.09	Light intensity (lux)	88,583.17 ± 1393.4	87,457.55 ± 1754	85,664.3 ± 2284.84	87,542.17 ± 3022.61
	PFD-UV (380~400 nm)	0.02 ± 0.0002	0.02 ± 0.0003	0.02 ± 0.0001	0.02 ± 0.0004
	PFD-B (400~500 nm)	0.2 ± 0.001	0.21 ± 0.0026 ***	0.2 ± 0.0007	0.2 ± 0.0033
	PFD-G (500~600 nm)	0.27 ± 0.0006	0.27 ± 0.0009	0.27 ± 0.0003	0.27 ± 0.0016 ***
	PFD-R (600~700 nm)	0.29 ± 0.0003	0.28 ± 0.0004 ***	0.29 ± 0.0003	0.28 ± 0.0012 ***
	PFD-FR (700~780 nm)	0.23 ± 0.0024	0.22 ± 0.0069 ***	0.23 ± 0.0011	0.23 ± 0.0041
	R/FR	1.25 ± 0.0132	1.25 ± 0.0176	1.28 ± 0.0071 *	1.21 ± 0.0168 ***

PFD-UV: photon flux density-UV light; PFD-B: photon flux density-blue light; PFD-G: photon flux density-green light; PFD-R: photon flux density-red light; PFD-FR: photon flux density-far red light; R/FR: red/far-red light ratio. Error bars indicate standard deviation [n = 6]. Asterisks indicate significant differences (Tukey's test; * $p < 0.05$ and *** $p < 0.001$).

3.2. The Effect of Photo-Selective Nets on the New Shoots' Growth

The presence of photo-selective nets can influence various aspects of plant growth, including leaf health and shoot development, as they alter environmental factors [2]. This experiment aimed to assess the impact of photo-selective nets on shoot growth. Based on the measurements of the new shoot length in 2020, it was observed that blue, black, and green nets significantly increased shoot length compared to the white net. Among them, the blue net resulted in the greatest increase in shoot length, followed by the green, black, and white nets (Figure 2A). This trend of increased shoot length continued in 2021, although the overall significance was reduced compared to the white net (Figure 2B). Furthermore, the thickness of the new shoots in 2020 was significantly greater under the blue, black, and green nets compared to the white net. Specifically, the green net led to the greatest thickness of new shoots in 2020, followed by the blue, black, and white nets (Figure 2C). In 2021, the thickness of new shoots under the green net exhibited a significant decline, while the thickness under the blue net remained the greatest, followed by the black, white, and green nets (Figure 2D). Overall, there was an increase in the thickness of the new shoots in 2021 compared to 2020 (Figure 2C,D).

In summary, the blue net had a significant positive effect on both the length and thickness of the new shoots in both years, resulting in higher biomass accumulation. While the black net also promoted shoot elongation and thickening, its effect was not as pronounced as that of the blue net. On the other hand, the green net initially showed a remarkable increase in shoot length and thickness in the first year, but its growth exhibited a clear decline in the second year.

3.3. The Effect of Photo-Selective Nets on Relevant Leaf Indices

Leaves, the largest plant organs exposed to the external environment, are highly susceptible to changes in environmental conditions, which can greatly influence their morphological structure and physicochemical properties [33]. Based on the leaf-related data from 2020, it was observed that the utilization of blue, black, and green nets significantly increased the leaf area compared to the white net (Figure 3A). The largest leaf area was observed under the blue net, followed by the black, green, and white nets (Figure 3B). However, when considering the physiological indicator of leaf thickness, the leaves under the blue net were significantly thinner than those under the white net. Conversely, the leaves under the black and green nets exhibited increased thickness, with the greatest increase observed under the green net (Figure 3C). In terms of leaf biomass accumulation, both the green and blue nets had similar effects, resulting in a higher leaf biomass compared to the black net and significantly higher than the white net (Figure 3D,E). However, there was no significant effect of photo-selective colored nets on leaf indices (Figure 3F). Moreover, the relative leaf water content exhibited a moderate increase under the blue and green nets compared to the white net, whereas it experienced a slight decrease under the black net (Supplemental Figure S1A).

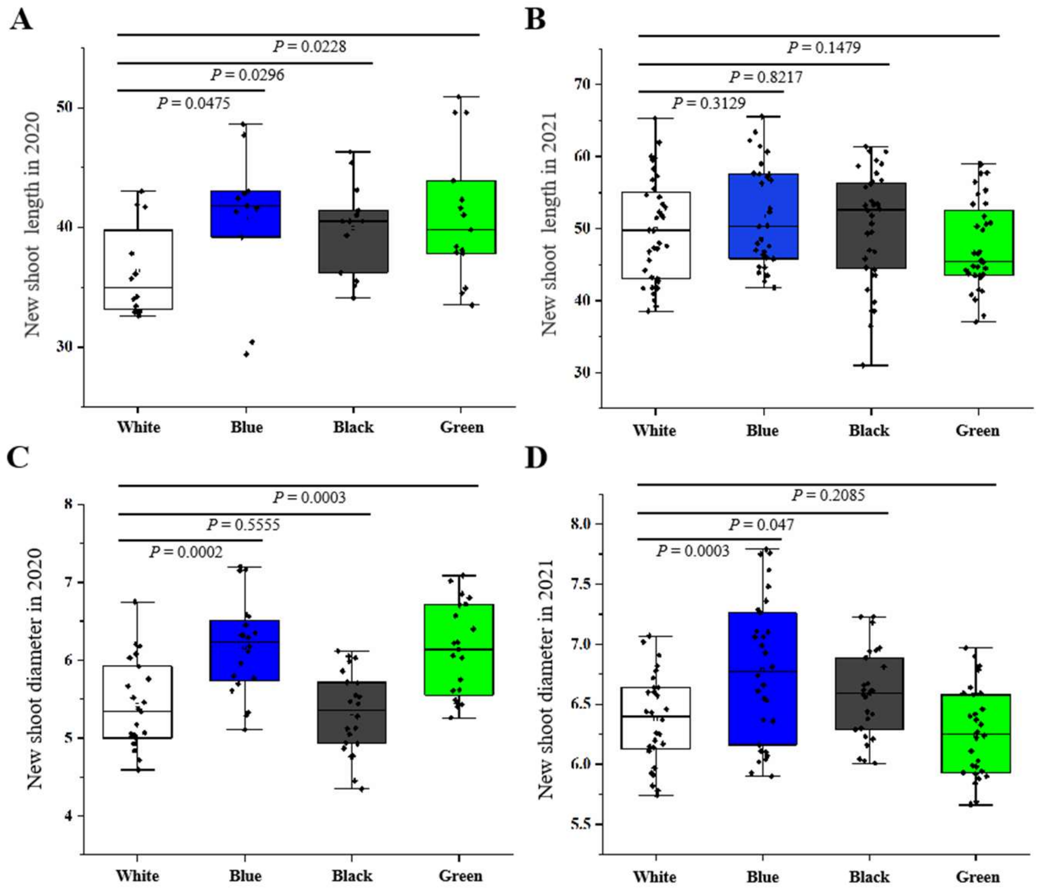

Figure 2. The effects of photo-selective colored nets on new shoot growth. (**A**) New shoot length in 2020. (**B**) New shoot length in 2021. (**C**) New shoot diameter in 2020. (**D**) New shoot diameter in 2021. Error bars indicate standard deviation [n = 15 in (**A**), n = 36 in (**B**), and n = 20 in (**C**,**D**)]. *p* values from Tukey's test.

In comparison to 2020′s data, the overall pattern in 2021 remained largely constant (Figure 3G–L). The use of the blue net led to a significant rise in leaf area and a minor decrease in leaf thickness (Figure 3H,I). Nonetheless, there was a minor increment in the total leaf biomass, with no alteration in the leaf index (Figure 3J–L). Furthermore, the blue net resulted in a slight increment in relative leaf water content (Supplemental Figure S1B). Conversely, the black net slightly boosted the leaf area and, to some degree, led to increases in leaf thickness and dry weight, while the leaf index remained unaffected (Figure 3H–L). Likewise, the green net not only augmented the leaf area but also facilitated an escalation in leaf thickness and relative water content. The leaf index, however, was unaltered (Figure 3H–L and Supplemental Figure S1B).

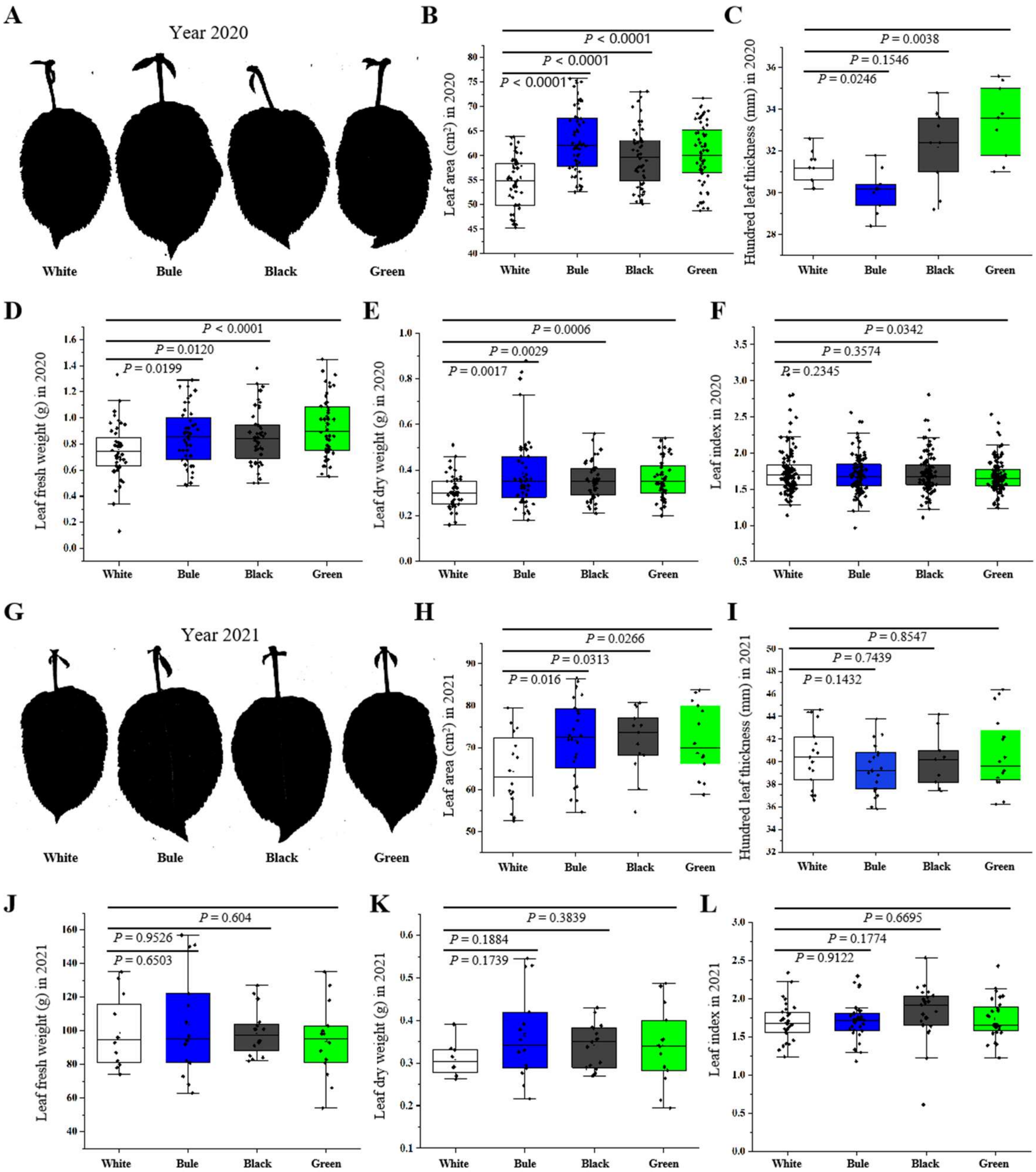

Figure 3. Response of leaves to different photo-selective colored nets. (**A**) Leaf scan images in 2020. (**B**–**F**) Determination of (**B**) leaf area, (**C**) hundred leaf thickness, (**D**) leaf fresh weight, (**E**) leaf dry weight, and (**F**) leaf index shown in (**A**) under different photo-selective colored nets. Error bars indicate standard deviation [n = 60 in (**B**), n = 9 in (**C**), and n = 46 in (**D**–**F**)]. (**G**) Leaf scan images in 2021. (**G**–**L**) Determination of (**H**) leaf area, (**I**) hundred leaf thickness, (**J**) leaf fresh weight, and (**K**) leaf dry weight, and (**L**) leaf index shown in (**G**) under different photo-selective colored nets. Error bars indicate standard deviation [n = 15 in (**H**), n = 16 in (**I**), n = 10 in (**J**), n = 14 in (**K**), and n = 24 in (**L**)]. *p* values from Tukey's test.

In general, the trend observed in 2021 paralleled that of 2020, albeit with diminished significance, potentially attributed to the cyclical fruit-bearing pattern of the tree. Of the various photo-selective nets, the blue net consistently demonstrated the most pronounced shading effect, precipitating a considerable increase in leaf area and fresh weight, a decrease in leaf thickness, and an elevation in both the leaf dry weight and relative water content when compared with the white net. The black and green nets similarly culminated in significant amplifications in leaf area and thickness along with leaf biomass accumulation.

Interestingly, the shading influence of photo-selective nets appeared to exert no discernible effect on the total leaf shape index of the apple tree.

3.4. The Effect of Photo-Selective Nets on Chlorophyll Content

Chlorophyll, existing in two forms (chlorophyll a and b), is the primary light-absorbing pigment in plants, directly influencing their light energy utilization and serving as an indicator of overall plant health [34]. In this study, we examined chlorophyll content as a means of assessing the impact of different photo-selective nets on tree growth. Based on the 2020 data shown in Figure 4A,B, the blue, black, and green nets did not cause significant changes in relative chlorophyll content at the top and middle of the tree canopy compared to the white net. However, the chlorophyll a/b ratios under the black and green nets decreased significantly (Figure 4C). On the other hand, the chlorophyll a/b ratio under the blue hail net slightly increased, but without any significant changes compared to the white net (Figure 4C).

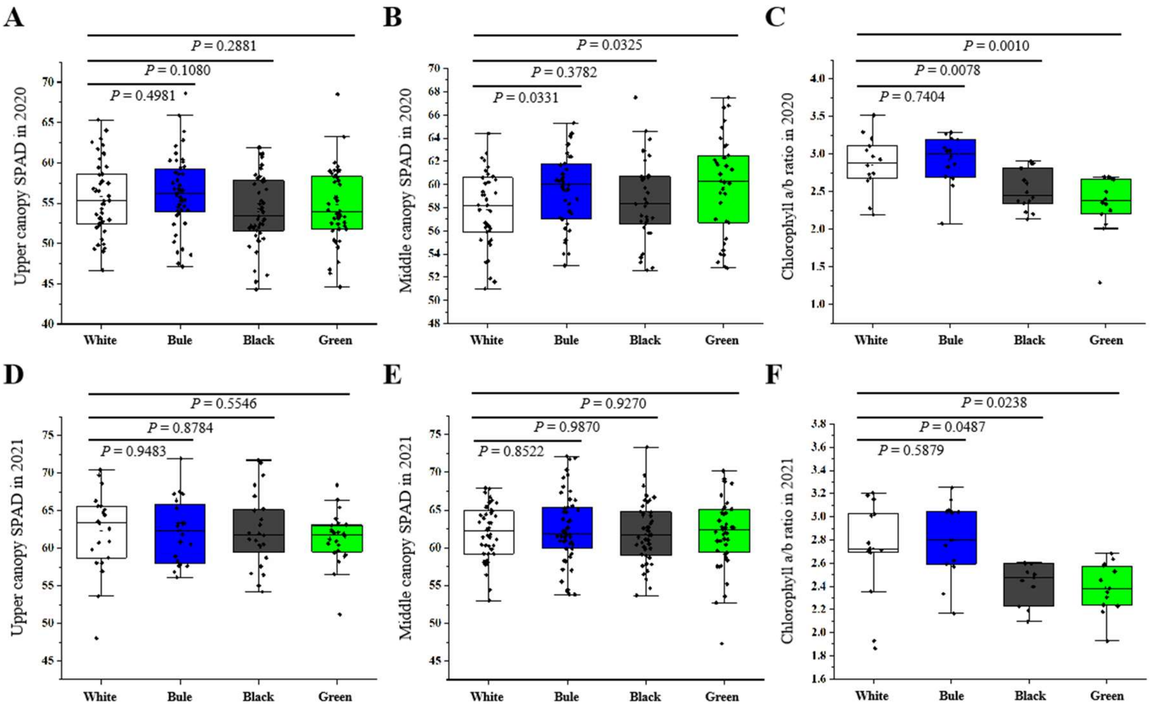

Figure 4. Chlorophyll content under different photo-selective colored nets. (**A**–**C**) Determination of (**A**) upper canopy SPAD, (**B**) middle canopy SPAD, and (**C**) chlorophyll a/b ratio under different photo-selective colored nets. (**D**–**F**) Determination of (**D**) upper canopy SPAD, (**E**) middle canopy SPAD, and (**F**) chlorophyll a/b ratio under different photo-selective colored nets. Error bars indicate standard deviation [n = 36 in (**A**,**B**), n = 15 in (**C**), n = 25 in (**D**,**E**), and n = 15 in (**F**)]. *p* values from Tukey's test.

The 2021 data, as depicted in Figure 4D–F, are consistent with the discoveries from 2020. No significant variations were observed in the SPAD values at the top and middle of the tree canopy among the different photo-selective nets (Figure 4D,E). Similarly, a considerable decrease in chlorophyll a/b ratios was noted under the black and green nets, whereas a minor increase was observed under the blue hail net when compared with the ratios under the white net (Figure 4F).

3.5. The Effect of Photo-Selective Nets on Photosynthetic Parameters

Given the significant influence of light quality and intensity on plant leaf photosynthesis [35], we endeavored to assess how differently colored hail nets affect plant growth through the lens of photosynthesis. As shown in Figure 5, photosynthesis under various photo-selective nets was compared on the grounds of photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and intercellular CO_2 (Ci). It was deduced that the blue net yielded the highest Pn, succeeded by black and green, with the white net resulting in the lowest. The data charted a bimodal curve for Pn, peaking at 11:00 and 15:00, and reaching its nadir at 13:00 or denoting a photosynthetic 'siesta'. Prior to 11:00, no significant differences in Pn were noted among plants under diverse nets. However, at 13:00, apple trees under the blue net demonstrated the fastest resumption of photosynthesis, followed by those under the green and black nets. In contrast, apple trees under the white net struggled with photosynthetic 'siesta' and intense midday light (Figure 5A). Trees under blue, black, and green nets recorded elevated Tr from 13:00 to 15:00, indicating a higher Pn (Figure 5B). Similarly, higher Gs during this time period suggested a more effective reduction of stomatal closure induced by the 'siesta', in comparison to the white net (Figure 5C). Ci was found to decrease under all nets, aligning with the CO_2 accumulation when stomata close at night and its optimal utilization within cells for photosynthesis during the day (Figure 5D).

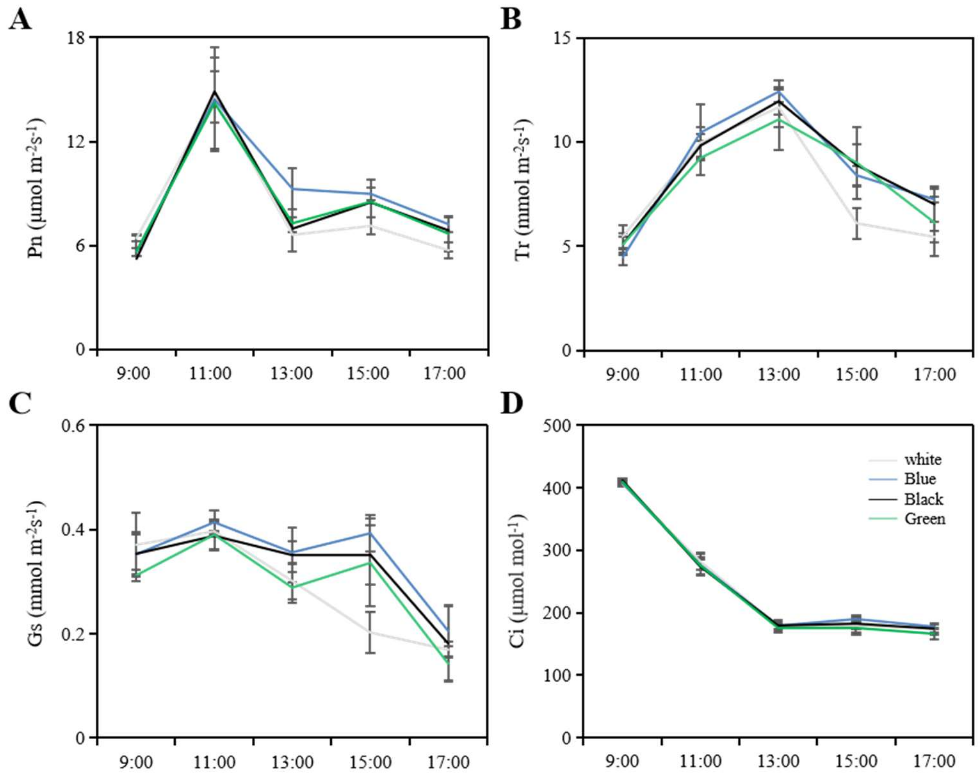

Figure 5. Photosynthetic parameters of the trees pretreated with different photo-selective colored nets (**A**–**D**). (**A**) The photosynthetic rate, (**B**) the transpiration rate, (**C**) the stomatal conductance, and (**D**) intercellular carbon dioxide concentration of the trees under different photo-selective colored nets. Error bars indicate the standard deviation [n = 3]. *p* values from Tukey's test.

3.6. The Effect of Photo-Selective Nets on Fruit Quality

Fruits exhibit many distinctive external traits, including color, shape, and size, and internal characteristics, Iing texture, taste, soluble solids, and titratable acidity [36]. To investigate the impact of photo-selective nets on the external and internal quality of fruit, we examined the firmness and malleability of the pericarp, the brittleness of the flesh, as well as the concentration of soluble solids and titratable acidity. The findings showed no significant impact of photo-selective nets on the external quality of fruits in 2020 and 2021 (Supplemental Figures S2 and S3).

For an in-depth understanding of the effect of these nets on internal fruit quality, the analysis was continued using data from 2020 and 2021 (Figure 6). The data analysis of 2020 revealed that blue and green nets considerably enhanced pericarp malleability while reducing flesh firmness and brittleness in comparison to the usage of white net. Interestingly, a minor decrease in pericarp firmness, soluble solids, and titratable acidity was observed, but these variations were not statistically significant (Figure 6A–F). The black net, however, showed a significant reduction in soluble solids and a moderate increase in pericarp firmness relative to the white net, while displaying similar trends to blue and green nets for the other parameters (Figure 6A–F).

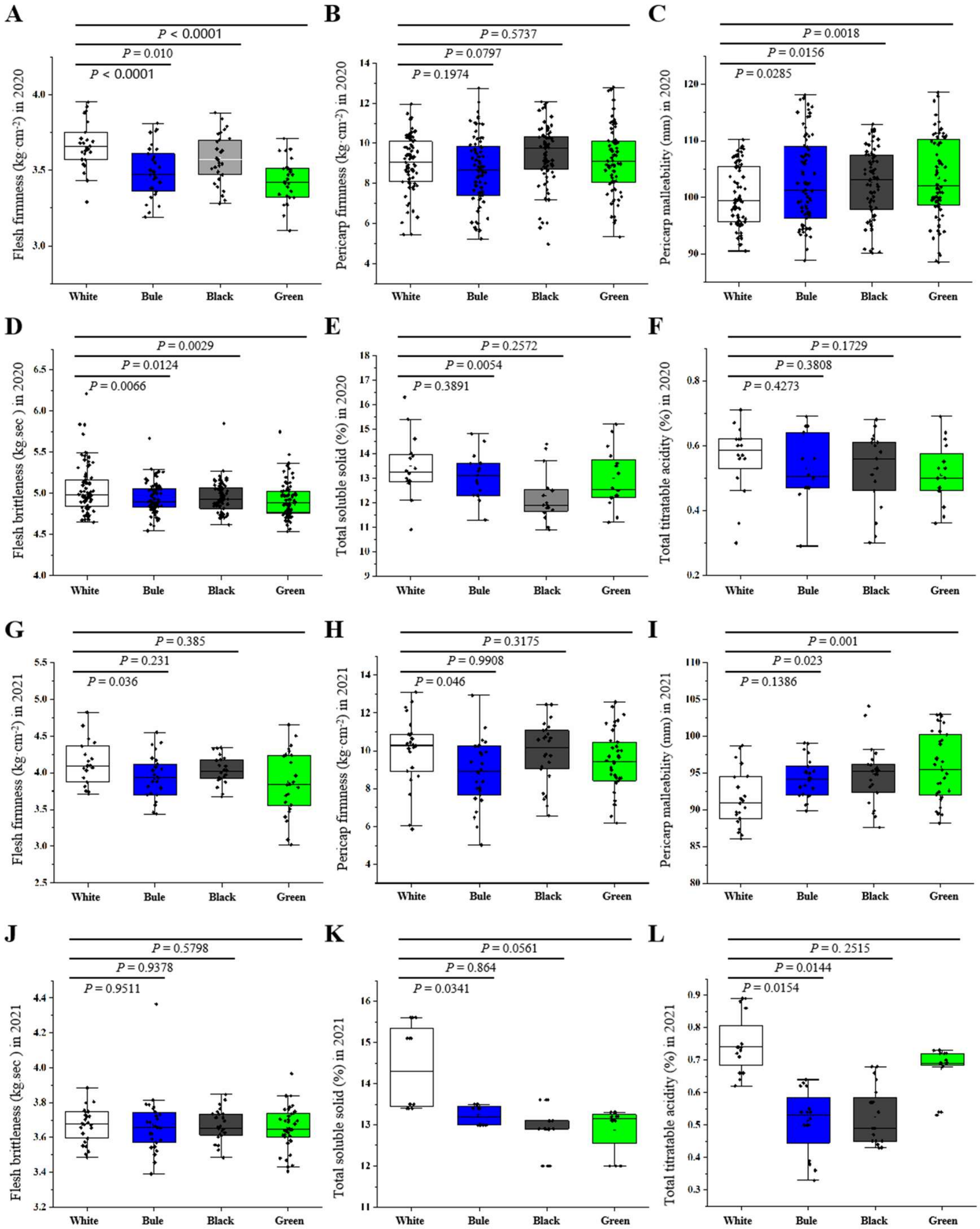

Figure 6. The combined effects of photo-selective colored nets on the internal qualities of apple fruits at harvest. (**A**–**F**) Measurement of (**A**) flesh firmness, (**B**) pericarp firmness, (**C**) pericarp malleability, (**D**) flesh brittleness, (**E**) total soluble solid, (**F**) total titratable acidity of fruits under different photo-selective colored nets in 2020. (**G**–**L**) Measurement of (**G**) flesh firmness, (**H**) pericarp firmness, (**I**) pericarp malleability, (**J**) flesh brittleness, (**K**) total soluble solid, (**L**) total titratable acidity of fruits under different photo-selective colored nets in 2021. Error bars indicate standard deviation [n = 30 in (**A**), n = 50 in (**B**–**D**), n = 16 in (**E**,**F**), n = 25 in (**G**–**J**), n = 12 in (**K**), and n = 15 in (**L**)]. *p* values from Tukey's test.

The analysis from 2021 confirmed that the blue, black, and green photo-selective nets significantly increased pericarp malleability compared to the white net, while mildly reducing other factors such as flesh firmness and brittleness, pericarp firmness, soluble solids, and titratable acidity (Figure 6G–L). All these observations suggest that the use of photo-selective colored nets has a significant effect on the internal quality of fruits, while the external quality is not substantially altered when compared to white nets.

3.7. The Effect of Photo-Selective Nets on Tree Productivity

According to the 2020 data presented in Figure 7A, significant disparities in the individual weights of fruits were observed across the various photo-selective nets employed. The blue net was associated with the highest increase in individual fruit weight, followed closely by the black net. In contrast, when covered by the green net, the weight of individual fruits was found to be less than that observed under the white net (Figure 7A). This trend also held true for the yield per tree, with blue and black net-covered trees yielding the most fruit, and green net-covered trees yielding the least (Figure 7C). This significant yield reduction under the green net contrasted starkly with the impressive increase under the blue net, followed consecutively by the black net. These trends suggest that both the weight of individual fruits and their quantity per plant were significantly improved under blue and black nets, while green net led to a considerable decline when compared to white nets (Figure 7A–C).

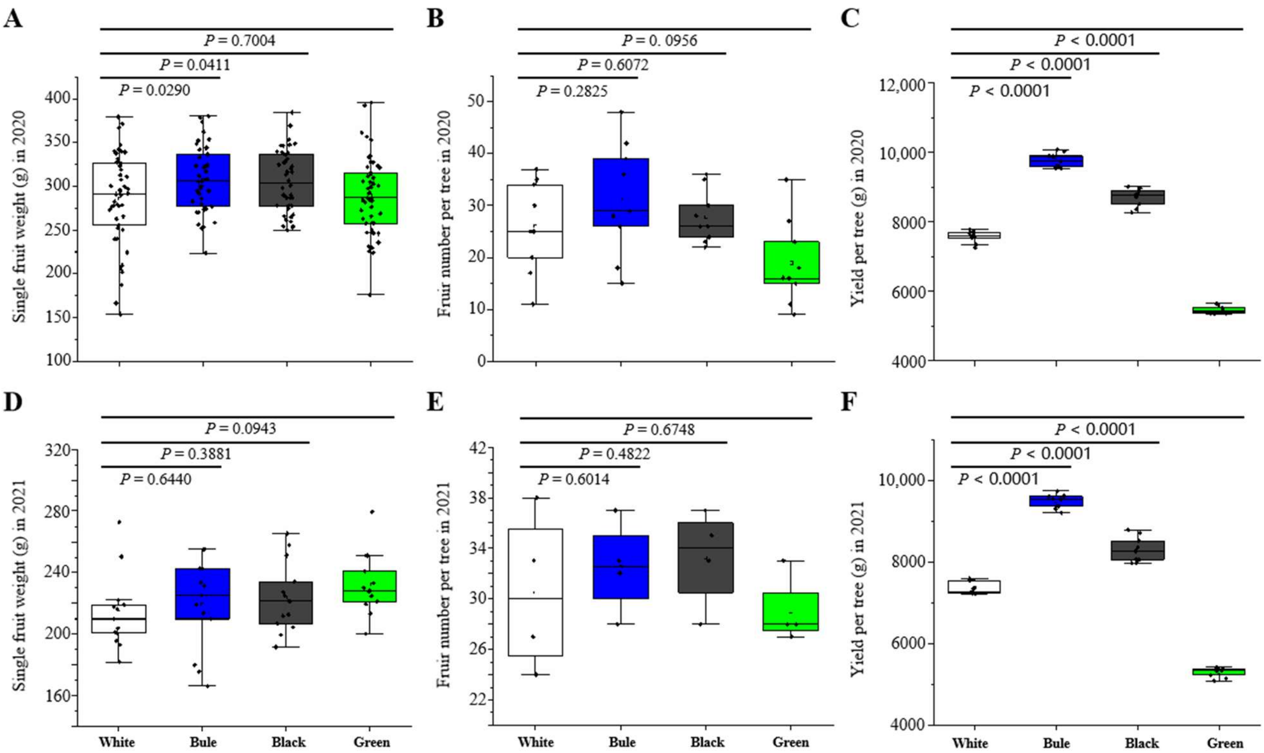

Figure 7. The impact of photo-selective colored nets on yield per tree. (**A**) Single fruit weight, (**B**) Fruir number, and (**C**) Yield of trees covered with different photo-selective colored nets in 2020. (**D**) Single fruit weight, (**E**) Fruit number, and (**F**) Yield of trees covered with different photo-selective colored nets in 2021. Error bars indicate standard deviation [n = 50 in (**A**), n = 9 in (**B**–**F**)] *p* values from Tukey's test.

In the follow-up experiments conducted in 2021, apples cultivated under blue, black, and green nets resulted in a superior weight per fruit than those grown under white net. The use of blue and green nets led to the most substantial increase in individual fruit weight, with black nets following suit (Figure 7D). Furthermore, the blue net resulted in the highest overall yield per tree, with the black net close behind. Interestingly, the yields associated with green nets in the follow-up experiments showed a marked improvement when compared to the results of the previous year (Figure 7D–F). In conclusion, a consistent pattern in data from both 2020 and 2021 conclusively demonstrated that the blue net had a substantial positive effect on both the weight of individual fruits and the yield per tree for apple cultivation. The black net also showed promising results. In contrast, the use of green nets yielded inconsistent results in terms of overall tree yield.

3.8. Comprehensive Evaluation of Photo-Selective Nets on Apple Trees

In 2020, we meticulously evaluated the impact of various photo-selective nets, including white, blue, black, and green nets, on apple trees by conducting a principal component analysis using the SPSS 20 software's dimension reduction module on parameters such as new shoot length and diameter, leaf area, leaf thickness, leaf weight, flesh firmness and brittleness, soluble solids, and titratable acidity, or others. Disclosed in Table 2 are the component matrices, serving as graphical illustrations of the relationship between the three key principal components extracted and the raw variables. The findings proposed that principal component 1 (PC1) registered strong correlations with parameters like new shoot length, shoot thickness, relative water content of leaves, chlorophyll a, chlorophyll b, and fruit firmness; principal component 2 (PC2) had strong links with leaf area, soluble solids content, and fruit flesh crispness; and principal component 3 (PC3) bore a strong connection exclusively with the primary parameter of the leaf shape index (Table 2). The contribution rates of the three principal components, displayed in Table 3, collectively concluded the influence of photo-selective nets on apple trees, accounting for 100% of the total contribution rate. Explicitly, PC1 contributed 56.978%, PC2 contributed 23.994%, and PC3 contributed 19.028% (Table 3). Using the ratios of the eigenvalues of each principal component to total eigenvalues as weights, we aggregated comprehensive scores (F_total = 0.571F1 + 0.239F2 + 0.190F3) for each treatment, as exhibited in Tables 3 and 4. The exhaustive study demonstrated that the blue net offered the most optimal coverage, trailed by the black net, white net, and finally the green net (Table 4).

Table 2. Factor loading matrix of principal components on different traits in 2020.

Table	**Principal Component**		
	PC1	**PC2**	**PC3**
New shoots length	0.999	0.044	−0.006
New shoot diameter	0.637	0.343	−0.691
Leaf area	0.481	0.791	−0.378
Relative water content	0.397	−0.024	−0.918
Leaf index	−0.964	0.104	0.245
Chlorophyll a	0.771	−0.491	0.406
Chlorophyll b	0.976	−0.109	0.186
Total soluble soild	−0.994	0.101	−0.042
Flesh brittleness	−0.231	0.851	0.472
Fruit number per tree	0.836	−0.458	0.302

Table 3. Eigenvalues and variance contribution rates of principal component in 2020.

Component	**Eigenvalue**	**Variance Contributionrate (%)**	**Total Contributionrate (%)**
PC1	13.675	56.978	56.978
PC2	5.759	23.994	80.972
PC3	4.567	19.028	100.000

Table 4. Comprehensive evaluation of different photo-selective colored nets in 2020.

	F1	F2	F3	F_Total	Ranking
White net	0.93059	−0.87748	−0.7836	0.171059	3
Blue net	0.28827	1.43869	−0.31158	0.449385	1
Black net	0.1993	−0.24361	1.46661	0.334303	2
Green net	−1.41816	−0.31759	−0.37142	−0.95474	4

In the subsequent year of 2021, we executed a parallel comprehensive assessment. The component matrix contained in Table 5 projects the correlation between the extracted seven principal components and the raw variables. The variance contribution rates are showcased in Table 6. The experimental results disclosed that the contribution rates of these seven principal components amounted to 88.976%. As a result, the comprehensive influence of diverse photo-selective nets on apple trees can be represented by these seven principal components. By leveraging the proportions of the eigenvalues of each principal component to total eigenvalues as weights, we devised the principal component scoring model: $F\_total = 0.210F1 + 0.193F2 + 0.150F3 + 0.143F4 + 0.120F5 + 0.094F6 + 0.088F7$ (Tables 6 and 7). The comprehensive scores for each treatment are presented in Table 7. The comprehensive analysis inferred that the blue net delivers the prime coverage, succeeded by the black net, green net, and, lastly, the white net.

Table 5. Factor loading matrix of principal components on different traits in 2021.

Traits	Principal Component						
	PC1	PC2	PC3	PC4	PC5	PC6	PC7
New shoots length	0.808	−0.271	0.424	−0.004	0.087	−0.066	0.017
New shoot diameter	0.492	−0.297	−0.582	0.463	0.053	0.139	−0.083
Leaf area	0.494	−0.367	−0.168	0.350	−0.408	−0.097	0.359
Relative water content	0.646	−0.298	0.210	−0.302	0.441	−0.219	0.080
Leaf index	0.132	0.179	0.735	0.388	−0.330	−0.040	0.186
Chlorophyll A	0.681	0.436	−0.347	0.282	0.197	0.031	0.163
Chlorophyll B	−0.214	0.033	0.720	−0.073	−0.185	0.429	0.111
Total soluble soild	0.657	−0.017	−0.194	0.315	−0.094	0.503	−0.135

Table 6. Eigenvalues and variance contribution rates of principal component in 2021.

Component	Eigenvalue	Variance Contribution Rate (%)	Total Contribution Rate (%)
PC1	4.490	18.708	18.708
PC2	4.130	17.208	35.916
PC3	3.205	13.352	49.268
PC4	3.060	12.749	62.017
PC5	2.571	10.711	72.728
PC6	2.018	8.407	81.136
PC7	1.882	7.841	88.976

Table 7. Comprehensive evaluation of different photo-selective colored nets in 2021.

	F1	F2	F3	F4	F5	F6	F7	F_Total	Ranking
White net	0.22	−1.02	2.74	−1.31	3.29	−0.84	0.64	0.45	3
Blue net	1.74	0.93	2.19	0.24	0.78	−0.82	−0.85	0.85	1
Black net	0.84	−1.36	4.23	1.56	−1.25	1.49	−0.94	0.68	2
Green net	−1.73	−2.06	0.84	−1.12	−0.70	−2.34	0.14	−1.09	4

4. Discussion

Apple crops are increasingly being cultivated under protective netting systems, providing protection against extreme weather events [6]. Technological advancements have facilitated the development of colored nets equipped with photo-selective plastic filters. These nets not only offer differential filtration of solar radiation and physical protection but also drastically alter the light conditions, notably the spectral light composition [37]. Plant perception of light is affected by both its intensity and spectral characteristics. [2]. According to our research findings, these photo-selective nets do not noticeably influence light intensity indicators, a result that is consistent with the findings by Bastías et al. that red and blue nets curtailed the photosynthetically active radiation equivalently as compared to the white net [28]. In a related study, Serra et al. found that apple trees cultivated under photo-selective nets intercepted more light than their uncovered counterparts. Nevertheless, the net's color had no significant effect on the tree's light interception over the course of two years [38]. In addition, several studies have demonstrated the direct impact of photo-selective nets on the transmission spectra of sunlight. Specifically, the blue net was found to reduce transmission in the 600–720 nm range, while increasing transmission in the blue and blue-green wavelengths, particularly within the 440–520 nm range [39,40]. Consistent with these findings, our research revealed that the blue net increased the proportion of blue light while significantly decreasing the proportion of red and far-red light, and the red to far-red light ratio. Similarly, the black and green nets in our study partially reduced the proportion of red and far-red light. In conclusion, it appears that photo-selective nets modify the spectrum of light that reaches the orchard.

Photo-selective nets have been found to alter the microenvironment of orchards, leading to changes in soil temperature [2,14,19]. The decrease in soil temperature is largely due to the decreased amount of light that penetrates the ground as a result of the shade net [12,41]. In our study, we found the black net to be especially efficient in reducing soil temperature when compared with other colors, such as white, blue, and green. These results are consistent with findings by Kalcsits et al., where soil temperatures under pearl and blue nets were significantly lower than those under uncovered control and red nets [14]. Although there is no documented evidence regarding the varying impact of photo-selective netting on soil temperature in the prevalent literature, we speculate that there may be other characteristics of the net's transmittance spectrum that influence soil temperature. However, further research is required to explore this possibility.

Multiple studies have proposed that photo-selective nets not only partially transmit solar radiation but also diffuse it, which is essential for the photosynthesis of leaves in the lower part of the canopy [8,11]. A comparison has shown that the net photosynthesis in 'Fuji' apples was considerably higher under blue and grey nets than those grown under pearl net [16]. Similar patterns have also been observed in ornamental plants as well [42]. Our research supports these findings and further reveals that photosynthesis was most effective under the blue net, followed by the black and green nets, with the white net demonstrating the lowest efficiency. We also noted a slight increase in SPAD values when measurements were taken under the blue net in comparison to the white net. This could potentially be attributed to the enhanced absorption capacity of the primary photosynthetic pigments (chlorophylls a/b) in the blue spectrum. Moreover, our study uncovered a positive correlation between the blue net and higher stomatal conductance, leading to an increase in photosynthesis. This observation aligns with evidence obtained from research on ornamental plants, which states that blue light wavelength is more effective in triggering stomatal opening and inhibiting stomatal closure [43]. Thus, the elevated stomatal conductance observed in leaves grown under the blue net in our research can be attributed to the effect of blue light on the stomatal aperture.

One crucial organ for analyzing crop growth is the leaf, as it helps us comprehend the crop's ability to convert radiation into dry matter via photosynthesis [44]. Microscopy analysis has shown that under blue net, both the palisade thickness and the ratio of palisade to spongy mesophyll decreased by 19% compared to leaves under white net [45]. It is important to note that earlier studies have underlined the importance of a low red to far-red (R/FR) ratio in governing plant growth. This not only stimulates an enlargement of the cell wall, leading to an increase in leaf area, but also improves leaf photosynthetic capacity, dry matter accumulation, and overall plant growth [46–48]. Our research affirms these findings, as it revealed an increase in leaf area and a reduction in leaf thickness under blue net, suggesting that these are adaptive responses for shaded leaves to maximize light transmission to the chloroplasts. Moreover, our results are in line with the significantly lower R/FR ratios observed under blue netting, reinforcing the role of the R/FR ratio in facilitating these responses. Adjusting the R/FR ratio has been recommended as a strategy for managing shoot extension, particularly to encourage greater shoot length under low R/FR ratios [13]. Previous investigations have consistently demonstrated that a reduction in the R/FR ratio leads to shoot elongation across various plant species, such as kiwifruit [49], grapevines [50], peach [29], and ornamental plants [51]. Similarly, our study found that trees grown under blue net with a low R/FR ratio exhibited significantly greater total shoot length and roughness compared to those grown under white net. These effects may be the result of responses induced by the phytochrome, which are triggered by the lowered R/FR ratio and the consequent decrease in phytochrome photo-equilibrium as observed under blue net.

Fruit color is a critical aspect that influences consumers' fruit consumption decisions [52]. Our study revealed that diversely colored nets have no significant impact on fruit color or fruit shape index. These observations align with most previous studies, which reported minimal or no effects of netting on apple fruit color and shape [5,39,53]. However, it is important to note that the influence of netting can differ based on various factors, including the type of net and apple variety.

Consumer preference for apples hinges heavily on their sweetness, which is generally determined by the total soluble solids (TSS) content [54]. In three growing seasons, the use of a black shade net significantly reduced TSS in 'Mondial Gala' apples compared to both a crystal shade net and a control group without any shade. However, these differences were not apparent in another growing season [19]. Similarly, for 'Elstar' apples, both white and black shade nets resulted in a reduction of TSS compared to the control group [55]. Do Amarante et al. also reported a significant reduction in TSS for 'Gala' apples grown under a white shade net, a phenomenon not observed in 'Fuji' apples during harvest [30]. Our study found that apples grown under blue nets presented a decrease in TSS accompanying a significant decrease in titratable acidity compared to white nets. These observations indicate the influence of net color on soluble solids and titratable acidity, potentially due to the modulation of light diffusion. This further emphasizes the importance of integrating photo-selective nets in apple cultivation practices, as they markedly affect the levels of soluble solids and titratable acidity in apples.

While consumers initially judge a product by its appearance, their ultimate decision to repurchase it is based on its edible quality [56]. High initial firmness values at harvest can extend the duration of flesh firmness retention [57]. Prior research suggests that consumers favor firmer apples [58]. Compared to those cultivated under red-white nets, "Fuji" and "Pinova" apples grown under green-black and red-black netting were found to have a softer texture. Fruit from the control group, not covered by any netting, displayed the highest firmness [20]. Even though limited research has been conducted on pericarp malleability, pericarp firmness, and flesh brittleness, these factors are closely associated with postharvest storage quality. They are critical for the long-term storage of fruits. However, the impact of photo-selective netting on pericarp firmness, malleability, and flesh brittleness at both pre- and post-harvest stages remains largely unexplored. In this study, the use of colored nets resulted in a reduction in flesh firmness, suggesting a potentially negative effect of photo-selective netting on either postharvest fruit storage or consumer purchasing behavior.

The illumination conditions created by photo-selective nets can influence plant physiology, thereby affecting both the average fruit weight and plant yield [59]. Previous studies found that the use of blue or grey netting significantly increased the weight of 'Fuji' apples compared to a control group using white netting [28]. Likewise, cucumbers grew heavier when under aluminized, pearl, blue, or red nets [60]. Consistent with these results, our study showed that blue nets yielded heavier individual fruits compared to white nets. Additionally, research has indicated that prolonged exposure to blue light may improve photosystem II, stomatal conductance, and dry matter production [61,62]. Therefore, adjusting the combination of blue, red, and far-red light using photo-selective nets could manipulate the processes controlling carbohydrate availability, which is crucial for apple growth and yield. Our study also observed a significant rise in apple yield when using blue netting instead of white nets, supporting previous studies by Hemming et al. and Zheng et al., who reported that shading nets that enhance diffuse light can improve fruit yield in horticultural crops by increasing plant photosynthetic capacity [63,64].

5. Conclusions

In this study, the effects of four photo-selective nets (white, blue, black, and green) on environmental factors, tree growth and development, and fruit yield and quality were investigated in an apple orchard. A principal component analysis was performed for datasets collected in 2020 and 2021 independently, with the findings compared across both years. The blue hail protection net came up top in overall score for both years, followed by black, white, and green nets. These results suggest that deploying the blue hail protection net could potentially optimize apple orchard management and production levels.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae9091061/s1, Figure S1: The relative water content of leaves treated with different photo-selective colored nets; Figure S2: The combined effects of photo-selective colored nets on the external qualities of apple fruits at harvest in 2020; Figure S3: The combined effects of photo-selective colored nets on the external qualities of apple fruits at harvest in 2021; Table S1: The effects of photo-selective colored nets on the relative humidity and air temperature.

Author Contributions: Y.Z. (Yangjun Zou), D.Z. (Dehui Zhang), and Q.G. designed the experiments; Y.Z. (Yutian Zhang), B.C., Q.L. (Qi Li), Q.L. (Qianjin Li), D.Z. (Dongdong Zhang), F.M., Y.Z. (Yangjun Zou), X.L. and Z.L. carried out experiments and analyses; Y.Z. (Yutian Zhang) and D.Z. (Dehui Zhang) wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Key Research and Development Project (2022YFD1602107) and China Agricultural Research System (CARS-27).

Data Availability Statement: All data relevant to this manuscript can be obtained by contacting the corresponding author.

Conflicts of Interest: The authors declare no competing interest.

References

1. Wang, S.; An, J.; Zhao, X.; Gao, X.; Wu, P.; Huo, G.; Robinson, B. Age- and climate-related water use patterns of apple trees on China's Loess Plateau. *J. Hydrol.* **2020**, *582*, 124462. [CrossRef]
2. Mupambi, G.; Anthony, B.; Layne, D.; Musacchi, S.; Serra, S.; Schmidt, T.; Kalcsits, L. The influence of protective netting on tree physiology and fruit quality of apple: A review. *Sci. Hortic.* **2018**, *236*, 60–72. [CrossRef]
3. Rana, V.; Sharma, S.; Rana, N.; Sharma, U.; Patiyal, V.; Banita; Prasad, H. Management of hailstorms under a changing climate in agriculture: A review. *Environ. Chem. Lett.* **2022**, *20*, 3971–3991. [CrossRef]
4. Sivakumar, D.; Jifon, J.; Soundy, P. Spectral quality of photo-selective shade nettings improves antioxidants and overall quality in selected fresh produce after postharvest storage. *Food Rev. Int.* **2018**, *34*, 290–307. [CrossRef]
5. Vuković, M.; Jurić, S.; Maslov Bandić, L.; Levaj, B.; Fu, D.; Jemrić, T. Sustainable food production: Innovative netting concepts and their mode of action on fruit crops. *Sustainability* **2022**, *14*, 9264. [CrossRef]
6. Bastías, R.; Boini, A. Apple production under protective netting systems. In *Apple Cultivation*; Küden, A., Ed.; IntechOpen: Rijeka, Croatia, 2022. [CrossRef]
7. Bastías, R.; Corelli-Grappadelli, L. Light quality management in fruit orchards: Physiological and technological aspects. *Chil. J. Agric. Res.* **2012**, *72*, 574–581. [CrossRef]
8. Manja, K.; Aoun, M. The use of nets for tree fruit crops and their impact on the production: A review. *Sci. Hortic.* **2019**, *246*, 110–122. [CrossRef]

9. Mditshwa, A.; Magwaza, L.; Tesfay, S. Shade netting on subtropical fruit: Effect on environmental conditions, tree physiology and fruit quality. *Sci. Hortic.* **2019**, *256*, 108556. [CrossRef]
10. Brito, C.; Rodrigues, M.; Pinto, L.; Gonçalves, A.; Silva, E.; Martins, S.; Rocha, L.; Pavia, I.; Arrobas, M.; Ribeiro, A.; et al. Grey and black anti-hail nets ameliorated apple (*Malus* × *domestica* Borkh. cv. *Golden Delicious*) physiology under mediterranean climate. *Plants* **2021**, *10*, 2578. [CrossRef]
11. Tanny, J. Microclimate and evapotranspiration of crops covered by agricultural screens: A review. *Biosyst. Eng.* **2013**, *114*, 26–43. [CrossRef]
12. Muskaan; Aggarwal, R.; Bhardwaj, S. Effect of anti-hail net installations on microclimate around apple plants in orchards of Himachal Pradesh. *J. Agrometeorol.* **2022**, *24*, 83–85. [CrossRef]
13. Arthurs, S.; Stamps, R.; Giglia, F. Environmental modification inside photoselective shadehouses. *Hortscience* **2013**, *48*, 975–979. [CrossRef]
14. Kalcsits, L.; Musacchi, S.; Layne, D.; Schmidt, T.; Mupambi, G.; Serra, S.; Mendoza, M.; Asteggiano, L.; Jarolmasjed, S.; Sankaran, S.; et al. Above and below-ground environmental changes associated with the use of photoselective protective netting to reduce sunburn in apple. *Agric. For. Meteorol.* **2017**, *237*, 9–17. [CrossRef]
15. Shahak, Y.; Gussakovsky, E.; Cohen, Y.; Lurie, S.; Stern, R.; Kfir, S.; Naor, A.; Atzmon, I.; Doron, I.; Greenblat-Avron, Y. ColorNets: A new approach for light manipulation in fruit trees. *Acta Hortic.* **2004**, *636*, 609–616. [CrossRef]
16. Bastías, R.; Losciale, P.; Chieco, C.; Rossi, F.; Corelli-Grappadelli, L. Physiological aspects affected by photoselective nets in apples: Preliminary studies. *Acta Hortic.* **2011**, *907*, 217–220. [CrossRef]
17. Peavey, M.; McClymont, L.; Scalisi, A.; Goodwin, I. Netting of different shade factors affect light penetration, fruit and vegetative growth, yield and fruit quality in an Australian blush pear. *Sci. Hortic.* **2022**, *299*, 111001. [CrossRef]
18. Treder, W.; Mika, A.; Buler, Z.; Klamkowski, K. Effects of hail nets on orchard light microclimate, apple tree growth, fruiting and fruit quality. *Acta Sci. Pol. Hortorum Cultus* **2016**, *15*, 17–27.
19. Iglesias, I.; Alegre, S. The effect of anti-hail nets on fruit protection, radiation, temperature, quality and profitability of 'Mondial Gala' apples. *J. Appl. Hortic.* **2006**, *8*, 91–100. [CrossRef]
20. Solomakhin, A.; Blanke, M. Can coloured hailnets improve taste (sugar, sugar: Acid ratio), consumer appeal (colouration) and nutritional value (anthocyanin, vitamin C) of apple fruit? *LWT Food Sci. Technol.* **2010**, *43*, 1277–1284. [CrossRef]
21. Blanke, M. The structure of coloured hail nets affects light transmission, light spectrum, phytochrome and apple fruit colouration. *Acta Hortic.* **2009**, *817*, 177–184. [CrossRef]
22. Shahak, Y. Photoselective netting: An overview of the concept, research and development and practical implementation in agriculture. *Acta Hortic.* **2014**, *1015*, 155–162. [CrossRef]
23. Stamps, R. Use of colored shade netting in horticulture. *Hortscience* **2009**, *44*, 239–241. [CrossRef]
24. Ada, N.; Farkash, L.; Hamburger, D.; Ovadia, R.; Forrer, I.; Kagan, S.; Michal, O. Light-scattering shade net increases branching and flowering in ornamental pot plants. *J. Hortic. Sci. Biotechnol.* **2008**, *83*, 9–14. [CrossRef]
25. Oren-Shamir, M.; Gussakovsky, E.; Eugene, E.; Nissim-Levi, A.; Ratner, K.; Ovadia, R.; Giller, Y.; Shahak, Y. Coloured shade nets can improve the yield and quality of green decorative branches of *Pittosporum variegatum*. *J. Hortic. Sci. Biotechnol.* **2001**, *76*, 353–361. [CrossRef]
26. Ovadia, R.; Dori, I.; Nissim-Levi, A.; Shahak, Y.; Oren-Shamir, M. Coloured shade-nets influence stem length, time to flower, flower number and inflorescence diameter in four ornamental cut-flower crops. *J. Hortic. Sci. Biotechnol.* **2009**, *84*, 161–166. [CrossRef]
27. Solomakhin, A.; Blanke, M. Coloured hailnets alter light transmission, spectra and phytochrome, as well as vegetative growth, leaf chlorophyll and photosynthesis and reduce flower induction of apple. *Plant Growth Regul.* **2008**, *56*, 211–218. [CrossRef]
28. Bastías, R.; Manfrini, L.; Corelli-Grappadelli, L. Exploring the potential use of photo-selective nets for fruit growth regulation in apple. *Chil. J. Agric. Res.* **2012**, *72*, 224–231. [CrossRef]
29. Giaccone, M.; Forlani, M.; Basile, B. Tree vigor, fruit yield and quality of nectarine trees grown under red photoselective anti-hail nets in southern Italy. *Acta Hortic.* **2012**, *962*, 387–394. [CrossRef]
30. Do Amarante, C.; Steffens, C.; Argenta, L. Yield and fruit quality of 'Gala' and 'Fuji' apple trees protected by white anti-hail net. *Sci. Hortic.* **2011**, *129*, 79–85. [CrossRef]
31. Zhang, D.; He, J.; Cheng, P.; Zhang, Y.; Khan, A.; Wang, S.; Li, Z.; Zhao, S.; Zhan, X.; Ma, F.; et al. 4-methylumbelliferone (4-MU) enhances drought tolerance of apple by regulating rhizosphere microbial diversity and root architecture. *Hortic. Res.* **2023**, *10*, uhad099. [CrossRef]
32. Tian, T.; Qiao, G.; Deng, B.; Wen, Z.; Hong, Y.; Wen, X. The effects of rain shelter coverings on the vegetative growth and fruit characteristics of Chinese cherry (*Prunus pseudocerasus* Lindl.). *Sci. Hortic.* **2019**, *254*, 228–235. [CrossRef]
33. Marcais, B.; Desprez-Loustau, M. European oak powdery mildew: Impact on trees, effects of environmental factors, and potential effects of climate change. *Ann. For. Sci.* **2014**, *71*, 633–642. [CrossRef]
34. Landi, M.; Zivcak, M.; Sytar, O.; Brestic, M.; Allakhverdiev, S. Plasticity of photosynthetic processes and the accumulation of secondary metabolites in plants in response to monochromatic light environments: A review. *Biochim. Biophys. Acta Bioenerg.* **2020**, *1861*, 148131. [CrossRef] [PubMed]

35. Yang, F.; Fan, Y.; Wu, X.; Cheng, Y.; Liu, Q.; Feng, L.; Chen, J.; Wang, Z.; Wang, X.; Yong, T.; et al. Auxin-to-gibberellin ratio as a signal for light intensity and quality in regulating soybean growth and matter partitioning. *Front. Plant Sci.* **2018**, *9*, 56. [CrossRef] [PubMed]
36. Musacchi, S.; Serra, S. Apple fruit quality: Overview on pre-harvest factors. *Sci. Hortic.* **2018**, *234*, 409–430. [CrossRef]
37. Shahak, Y.; Ratner, K.; Giller, Y.; Zur, N.; Or, E.; Gussakovsky, E.; Sarig, P.; Raban, E.; Harcavi, E.; Doron, I.; et al. Improving solar energy utilization, productivity and fruit quality in orchards and vineyards by photoselective netting. *Acta Hortic.* **2008**, *772*, 65–72. [CrossRef]
38. Serra, S.; Borghi, S.; Mupambi, G.; Camargo-Alvarez, H.; Layne, D.; Schmidt, T.; Kalcsits, L.; Musacchi, S. Photoselective protective netting improves "Honeycrisp" fruit quality. *Plants* **2020**, *9*, 1708. [CrossRef]
39. Bravetti, M.; Amadei, P.; Pelliconi, F.; Nardini, G.; Paroncini, M.; Neri, D. Photo-selective plastic nets in young peach orchards. *Acta Hortic.* **2021**, *1304*, 229–236. [CrossRef]
40. Neri, D.; Bravetti, M.; Murri, G.; Nardini, G.; Paroncini, M. Light spectrum modifications under photo-selective hail-nets. *Acta Hortic.* **2021**, *1304*, 191–200. [CrossRef]
41. Crescenzi, S.; Zucchini, M.; Neri, D.; Giorgi, V.; Vaccaro, G. Photo-selective plastic nets in pomegranate orchards. *Acta Hortic.* **2022**, *1349*, 105–112. [CrossRef]
42. Stamps, R.; Chandler, A. Differential effects of colored shade nets on three cut foliage crops. *Acta Hortic.* **2008**, *770*, 169–176. [CrossRef]
43. Zheng, L.; Van Labeke, M. Long-term effects of red- and blue-light emitting diodes on leaf anatomy and photosynthetic efficiency of three ornamental pot plants. *Front. Plant Sci.* **2017**, *8*, 917. [CrossRef]
44. Meena, R.; Vashisth, A. Effect of microenvironment under different colour shade nets on biophysical parameters and radiation use efficiency in spinach (*Spinacia oleracea* L.). *J. Agric. Phys.* **2014**, *14*, 181–188.
45. Bastías, R.; Losciale, P.; Chieco, C.; Corelli-Grappadelli, L. Red and blue netting alters leaf morphological and physiological characteristics in apple trees. *Plants* **2021**, *10*, 127. [CrossRef]
46. Miao, Y.; Gao, X.; Li, B.; Wang, W.; Bai, L. Low red to far-red light ratio promotes salt tolerance by improving leaf photosynthetic capacity in cucumber. *Front. Plant Sci.* **2023**, *13*, 1053780. [CrossRef] [PubMed]
47. Tan, T.; Li, S.; Fan, Y.; Wang, Z.; Raza, M.A.; Shafiq, I.; Wang, B.; Wu, X.; Yong, T.; Wang, X.; et al. Far-red light: A regulator of plant morphology and photosynthetic capacity. *Crop J.* **2022**, *10*, 300–309. [CrossRef]
48. Yang, F.; Liu, Q.; Cheng, Y.; Feng, L.; Wu, X.; Fan, Y.; Raza, M.; Wang, X.; Yong, T.; Liu, W.; et al. Low red/far-red ratio as a signal promotes carbon assimilation of soybean seedlings by increasing the photosynthetic capacity. *BMC Plant Biol.* **2020**, *20*, 148. [CrossRef]
49. Basile, B.; Giaccone, M.; Shahak, Y.; Forlani, M.; Cirillo, C. Regulation of the vegetative growth of kiwifruit vines by photo-selective anti-hail netting. *Sci. Hortic.* **2014**, *172*, 300–307. [CrossRef]
50. Morgan, D.; Stanley, C.; Warringtron, I. The effects of simulated daylight and shade-light on vegetative and reproductive growth in kiwifruit and grapevine. *J. Hortic. Sci.* **1985**, *60*, 473–484. [CrossRef]
51. Rajapakse, N.; Young, R.; McMahon, M.; Oi, R. Plant height control by photoselective filters: Current status and future prospects. *Horttechnology* **1999**, *9*, 618–624. [CrossRef]
52. Yue, C.; Tong, C. Consumer preferences and willingness to pay for existing and new apple varieties: Evidence from apple tasting choice experiments. *Horttechnology* **2011**, *21*, 376–383. [CrossRef]
53. Elsysy, M.; Serra, S.; Schwallier, P.; Musacchi, S.; Einhorn, T. Net enclosure of 'Honeycrisp' and 'Gala' apple trees at different bloom stages affects fruit set and alters seed production. *Agronomy* **2019**, *9*, 478. [CrossRef]
54. Aprea, E.; Charles, M.; Endrizzi, I.; Laura Corollaro, M.; Betta, E.; Biasioli, F.; Gasperi, F. Sweet taste in apple: The role of sorbitol, individual sugars, organic acids and volatile compounds. *Sci. Rep.* **2017**, *7*, 44950. [CrossRef]
55. Stampar, F.; Hudina, M.; Usenik, V.; Sturm, K.; Zadravec, P. Influence of black and white nets on photosynthesis, yield and fruit quality of apple (*Malus domestica* Borkh.). *Acta Hortic.* **2001**, *557*, 357–362. [CrossRef]
56. Vanoli, M.; Buccheri, M. Overview of the methods for assessing harvest maturity. *Stewart Postharvest Rev.* **2012**, *1*, 1–11.
57. Wu, B.; Shen, F.; Wang, X.; Zheng, W.Y.; Xiao, C.; Deng, Y.; Wang, T.; Yu Huang, Z.; Zhou, Q.; Wang, Y.; et al. Role of MdERF3 and MdERF118 natural variations in apple flesh firmness/crispness retainability and development of QTL-based genomics-assisted prediction. *Plant Biotechnol. J.* **2021**, *19*, 1022–1037. [CrossRef]
58. Sriskantharajah, K.; El Kayal, W.; Ayyanath, M.M.; Saxena, P.; Sullivan, A.; Paliyath, G.; Subramanian, J. Preharvest Spray Hexanal Formulation Enhances Postharvest Quality in 'Honeycrisp' Apples by Regulating Phospholipase D and Calcium Sensor Proteins Genes. *Plants* **2021**, *10*, 2332. [CrossRef]
59. Tafoya, F.; Yáñez Juárez, M.; López Orona, C.; López, R.; Alcaraz, T.; Valdés, T. Sunlight transmitted by colored shade nets on photosynthesis and yield of cucumber. *Cienc. Rural* **2018**, *48*, e20170829. [CrossRef]
60. Milenković, L.; Ilić, Z.S.; Đurovka, M.; Kapoulas, N.; Mirecki, N.; Fallik, E. Yield and pepper quality as affected by light intensity using colour shade nets. *Agric. For. Meteorol.* **2012**, *58*, 19–23.
61. Goins, G.; Yorio, N.; Sanwo, M.; Brown, C. Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. *J. Exp. Bot.* **1997**, *48*, 1407–1413. [CrossRef]
62. Matsuda, R.; Ohashi-Kaneko, K.; Fujiwara, K.; Goto, E.; Kurata, K. Photosynthetic characteristics of rice leaves grown under red light with or without supplemental blue light. *Plant Cell Physiol.* **2004**, *45*, 1870–1874. [CrossRef] [PubMed]

63. Hemming, S.; Dueck, T.; Janse, J.; Van Noort, F. The effect of diffuse light on crops. *Acta Hortic.* **2008**, *801*, 1293–1300. [CrossRef]
64. Zheng, L.; Zhang, Q.; Zheng, K.; Zhao, S.; Wang, P.; Cheng, J.; Zhang, X.; Chen, X. Effects of diffuse light on microclimate of solar greenhouse, and photosynthesis and yield of greenhouse-grown tomatoes. *Hortscience* **2020**, *55*, 1605–1613. [CrossRef]