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The Effect of Different Colors of Film on the Quality and Physiological Characteristics of Mulberry Fruits

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Abstract. **The mulberry cultivar Seedless da shi was covered with purple, red, blue, green, white, and yellow films, and quality and physiological characteristics of the mulberry fruits were assessed during the green ripening, pink, full red, purple ripening, and black ripening stages. The results indicated that yellow and white films demonstrated the highest transmittance, at 67.00% and 65.00% of that of uncovered cultivation as the control (CK), respectively, and that red film exhibited the lowest transmittance, at 13.00% of that of CK, as well as a significant main wavelength shift of 109.4 nm more than that of CK. The yellow film increased green light, red light, and the red-to-blue light ratio, which were 5.11%, 16.37%, and 61.31% of that of CK, respectively. The yellow film treatment significantly increased single fruit weight and moisture and achieved peaking during the purple maturity stage, which was 40.97% higher than that that of CK. The green film treatment resulted in the slowest fruit growth rate. The anthocyanin contents of yellow and white film treatments exceeded that of CK by 44.85% and 8.19%, respectively, in the purple maturity stage, while the red film treatment reduced anthocyanin content by 55.99% compared with that of CK; the other treatments showed overall lower anthocyanin levels than that of CK. Purple and red films effectively increased phenylalanine ammonia-lyase (PAL) and catalase (CAT) activities in the fruits. The photosynthetic rate of leaves under all treatments was not significantly different from that of CK. The total nitrogen (N) content of fruits under red film treatment peaked during the green ripening stage, at 12.26% higher than that of CK. After the black ripening stage, red, blue and green films significantly increased the total N and potassium contents in the fruits. It was concluded that white and yellow film treatments accelerated the color conversion process of mulberry fruits. Yellow film treatment had an overall positive impact on fruit quality. Purple and green films significantly delayed ripening, thus producing higher-quality fruit upon maturity. For mulberry production, white/yellow films or purple/green films can be selected for rain avoidance cultivation based on specific production goals to adjust ripening periods and improve fruit quality.**

Mulberry, scientifically known as *Morus alba* L., is the mature fruit of a plant in the mulberry family. With a long history of cultivation in China, it is among the first fruits recognized for its medicinal and edible purposes. Rich in anthocyanins and various antioxidant compounds, mulberries possess significant nutritional and medicinal value, making them highly valuable for commercial development (Wang 2022). Often referred to as "ginseng on the tree," the fruit enjoys widespread popularity (Chen 2024). However, the short fruiting period and heavy rainfall during ripening often result in problems such as fruit drop, decay, and quality degradation, severely impacting its market availability and commercial value. Rainproof cultivation can effectively address issues associated with excessive rainfall, severe fruit drop, concentrated ripening, and reduced fruit quality (Qi et al. 2023). In a previous study, fruit hardness and soluble solids content in chinese bayberry grown under rain shelters were increased by 15.18% and 5.75%, respectively, compared with those of the control group; additionally, titratable acid content and fruit drop rates were reduced by 8.86% and 30.19%, respectively, and the harvesting period was delayed by 1 to 2 d compared with those of the control group (Ren et al. 2018). Rain shelter treatments during the ripening stage of green crisp plum effectively blocked water absorption through the skin, significantly reducing fruit cracking and drop rates (Liu et al. 2022). Similarly, rain avoidance cultivation notably improved the sugar-to-acid ratio in kiwifruit, increased catalase (CAT) activity in leaves during late fruit development, and increased both vitamin C (Vc) content and average fruit weight (Liu et al. 2022).

Light quality is a crucial factor that influences plant growth and development because it alters the intensity and frequency of light across various bands (Vitale et al. 2020, 2023). These changes affect photosynthesis and carbohydrate transport and accumulation (Sun et al. 2016; Vitale et al. 2020, 2023), thereby exerting complex effects on fruit growth and quality formation (Qi et al. 2021; Sun et al. 2016; Vitale et al. 2020, 2023). Numerous studies have explored the impact of light quality on fruit quality. For instance, citrus fruits from different parts of a tree experience varying light intensities, resulting in differences in fruit size, soluble solids content, and color (Verreynne et al. 2004). Similarly, light quality influences photosynthesis and regulatory substances such as ABA in grape plants, thus affecting fruit size, shape index, and total sugar content (Zhang et al. 2017). Additionally, light quality plays a key role in anthocyanin synthesis during fruit development and color transitions, with blue light promoting anthocyanin accumulation in grapefruit, while red light promotes carotenoid accumulation (Xu 2004). Colored rainproof films influence the photosynthetic characteristics of chinese bayberry leaves and fruit quality. Treatments with green and yellow rainproof films resulted in a significantly higher net photosynthetic rate compared with that of the control (Liang et al. 2019). A red-to-blue light ratio of 4:1 had the most beneficial effect on strawberry fruits, increasing the total soluble solids (TSS) content by 0.87% and yield by 26.92% (Zhang et al. 2019). Light quality treatments improved grape leaf photosynthesis and fruit quality, with blue light yielding the highest TTS and reducing sugar contents, while a red-to-blue ratio of 4:1 produced the highest sugar-to-acid ratio (Liu et al. 2016). Blue light treatment of peaches improved the transport and transformation of photosynthetic compounds from leaves to fruits (Zhao et al. 2018). The critical period for increasing the sugar-to-acid ratio occurred during light supplementation after the hard-core stage. Similar findings have been reported by studies of apples (Wang et al. 2024), pears (Kong et al. 2018), dragon fruit (Chen et al. 2019), jujube (Li 2022), eggplants (Yuan et al. 2013), ginger (Zhang et al. 2008), chili peppers (Cui et al. 2009), tomatoes (Chen et al. 2009), tobacco (Lin et al. 2008), bell peppers (Liu et al. 2010), and radishes (Fu et al. 2011). These studies revealed that different light quality treatments influence yield, quality, and other aspects of crops, although the effects varied across different crops.

Currently, research of mulberry cultivation primarily focuses on water and fertilizer management, branch pruning, and pest control (Wang et al. 2022), which significantly

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contribute to improving mulberry yield and quality. However, under the ecological conditions of the Three Gorges Reservoir area, characterized by continuous rainfall and low sunshine, a substantial number of mulberries fall and rot during the maturity stage. This shortens the market period and causes yield losses exceeding 60%, severely affecting the economic returns of fruit farmers. Despite these challenges, limited research of the impact of rain shelter cultivation on the growth and development of mulberries has been conducted. Moreover, systematic studies of the ripening and quality of mulberries under rain shelter cultivation are lacking. Furthermore, no research has systematically assessed how rain shelters affect the ripening and quality of mulberries. Therefore, this study aimed to evaluate the effects of rain shelter cultivation on mulberry growth and development. Specifically, this study examined how colored rainproof films influence mulberry ripening and quality. We expected that they would effectively increase the anthocyanin content and regulate maturation progress of tested mulberries. These findings may guide strategies for regulating mulberry ripening periods and improving fruit quality.

Materials and Methods

Experimental materials. The widely cultivated mulberry cultivar Seedless da shi, which is a predominant fresh mulberry cultivar in production, was used for this experiment. This cultivar is popular in mulberry-picking gardens because of its favorable traits, including large size, seedlessness, sweetness, tartness, and juiciness. The experimental site was the Ganning Experimental Base of the Chongqing Three Gorges Academy of Agricultural Sciences (lat. 30.66789738°N, long. 108.24691792°E), which is part of the Three Gorges Academy of Agricultural Sciences. The site is located at an altitude of 320 m, with sandy-loam soil, an average temperature of 18 °C, and an annual precipitation of 1200 mm.

Experimental design. The experiment began on 25 Mar. Six mulberry plants of similar age were selected. An arched bamboo canopy (dimensions: 11 m × 1.5 m × 2.5 m) was erected over the plants, and PET film (16 m × 2.5 m × 0.05 mm) served as the rain shelter. Six color treatments—purple, red, blue, green, white, and yellow—were applied, with uncovered cultivation as the control (CK). Treatments started after peak flowering on 25 Mar. In April and May, fruits were collected at the following five stages: green ripening stage (1 Apr); pink stage (8 Apr); full red stage (17 Apr); purple ripening stage (30 Apr); and black ripening stage (8 May). At each stage, five fruits were taken from four directions at mid-canopy level from each tree, with a total of 20 fruits per tree. A combined sample of 40 fruits from two trees was prepared, with three replicates for each treatment. Collected samples were immediately placed in an ice box and transported to the laboratory. One portion was used for documenting fruit appearance, and the other was stored at −80 °C for further analysis.

Test method. On a sunny morning during the full red stage of fruits, light quality was measured in the center of each treated plant using a handheld spectrophotometer (HP 350 UVP; Hangzhou Double Color Intelligent Detection Instrument Co., Ltd., Hangzhou, China) with a wavelength range of 380 to 800 nm. The photosynthetic performance of mulberry leaves was assessed using a portable photosynthesis analyzer (LI-6400 XTP; LI-COR, USA) during 9:00 AM to 11:00 AM on a sunny day and selecting one leaf from each of the four directions of each tree to be measured. Only healthy undamaged fruits were analyzed. Fruit appearance was documented using photography, and fruit color (L* value, a* value, and b* value) at the middle of each fruit was quantified by a portable colorimeter (Konica Minolta, Tokyo, Japan). Fruit weight was determined using an electronic scale, and dimensions were measured with a digital caliper. Fruit moisture content was evaluated according to the direct drying method according to GB 5009.3-2016. Ascorbic acid (Vc) content was assessed via the 2,6-dichloroindophenol titration method (Li 2000). Contents of amino acids, cellulose, total sugar, and anthocyanins (Qiu et al. 2019; Yang 2007) were measured using an ultraviolet-visible spectrophotometer (NKY 052; Unico Instrument Co., Ltd., Shanghai, China). The TSS content was determined with a digital refractometer (PAL-1; Atago, Tokyo, Japan).

Enzyme activities of catalase (CAT), superoxide dismutase (SOD), peroxidase (POD), polyphenol oxidase (PPO), and phenylalanine ammonia-lyase (PAL) (Li et al. 2019; Zhang et al. 2018) were measured using another spectrophotometer (Evolution One Plus; Wuhan Wofu Technology Co., Ltd., Wuhan, China) according to the manufacturer's protocols (Soleibao, Beijing, China). The total nitrogen (N), total phosphorus (P), and total potassium (K) contents were determined using H_2SO_4-H_2O_2 digestion, followed by the alkali diffusion method, molybdenum antimony colorimetric method, and flame photometer method, respectively (Dou et al. 2017). Nutrient contents [total N, P, K, calcium (Ca), magnesium (Mg)] were determined using standard methods, including H_2SO_4-H_2O_2 digestion, molybdenum antimony colorimetric analysis, and atomic absorption spectroscopy after dry ashing (Dou et al. 2017). Each experiment was conducted in triplicate.

Statistical analysis. Data were analyzed using Excel 2007 (Microsoft, Redmond, WA, USA), while the variance analysis was conducted using SPSS 26.0 (SPSS Inc., Chicago, IL, USA). Graphs were generated using Origin 2021 software.

Results and Discussion

Analysis of light quality of films with different colors. Significant differences were observed in the light transmittance and spectral composition among the colored films (Table 1, Fig. 1). The results indicated that white and yellow films exhibited the highest light transmittance, with both exceeding 65.0%, followed by that of green film, with light transmittance of 52.0%; however, red film displayed the lowest transmittance (13.0%). Regarding the dominant wavelength, defined as the main wavelength of visible light emitted by the source, the results obtained with green and white film treatments were similar to those of CK, with each exceeding 490 nm. The red film treatment showed a significant deviation, with a dominant wavelength of 600 nm. The purple film treatment presented values that were not calculable within the measured range.

Regarding the peak wavelength, defined as the wavelength with the highest spectral luminescence intensity or radiation power, the purple, red, blue, and white film treatments showed significant shifts, with all exceeding 750 nm. These values represented increases of 56.27%, 56.08%, 62.27%, and 61.19%, respectively, compared with that of CK. Even the green film, which had the lowest peak wavelength among the treatments, demonstrated an increase of 5.96% compared with that of CK.

From a spectral perspective, compared with CK, the green film treatment was the only one among the six tested films to increase blue light in the wavelength range of 400 to 500 nm, whereas all other treatments

Table 1. Parameters of light quality of colored films.

Treatment	Transmittance (%)	Dominant wavelength (nm)	Peak wavelength (nm)	Ratio of light quality/%			Red/blue
				Blue (400–500 nm)	Green (500–600 nm)	Red (600–700 nm)	
Purple	29.00	NA	752.60	17.10	4.70	78.30	4.58
Red	13.00	600.40	751.70	8.60	16.40	75.00	8.72
Blue	30.00	484.50	781.50	27.90	19.50	52.60	1.89
Green	52.00	492.20	510.30	35.40	39.80	24.70	0.70
White	65.00	501.60	776.30	26.40	30.60	43.00	1.63
Yellow	67.00	565.80	530.50	20.90	32.90	46.20	2.21
CK	100.00	491.00	481.60	29.00	31.30	39.70	1.37

CK = uncovered cultivation as the control; NA = unmeasurable.

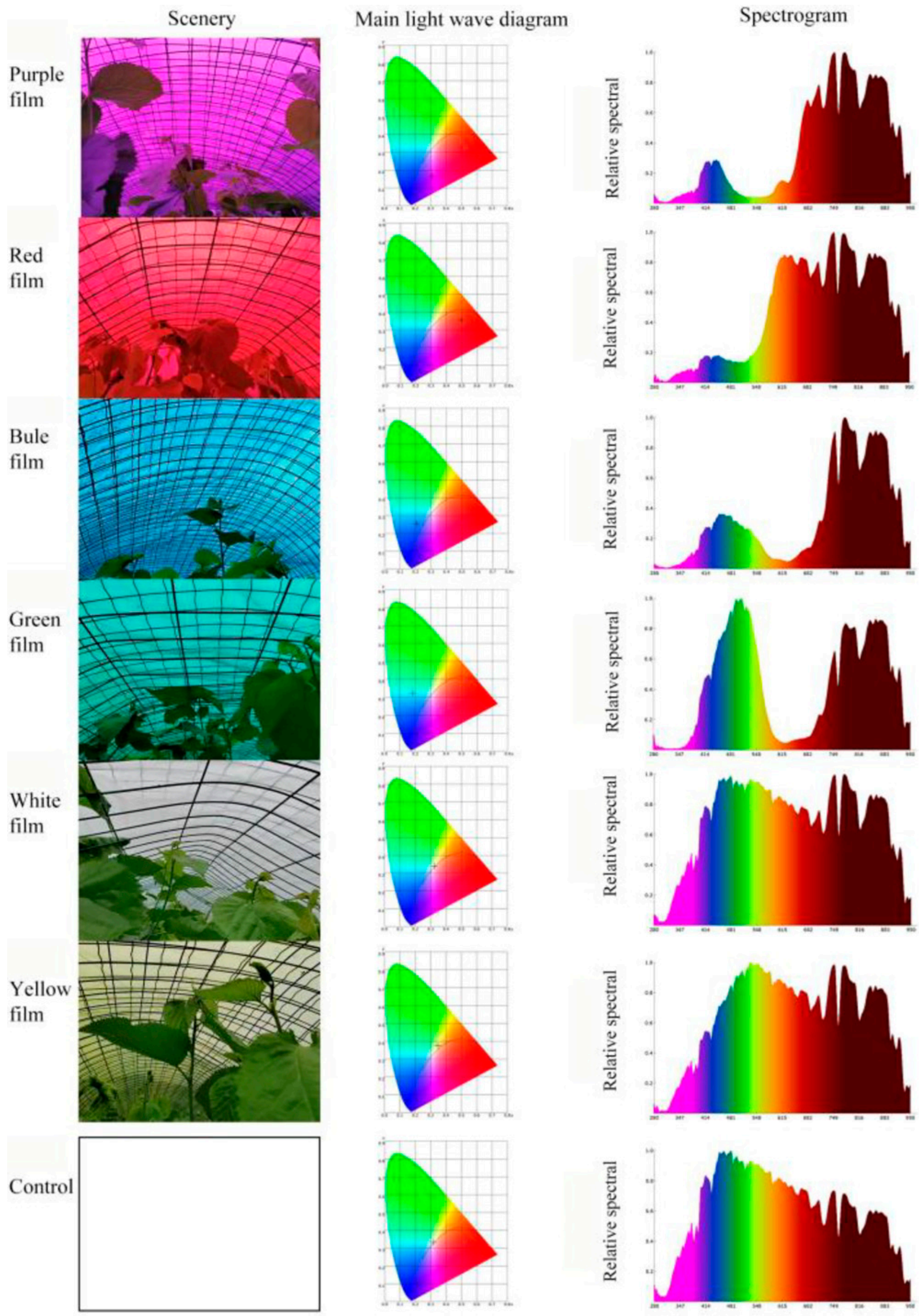

Fig. 1. Optical quality analysis of films with different colors.

showed decreases. The red film treatment exhibited the largest reduction in blue light (70.34%). For green light in the wavelength range of 500 to 600 nm, no significant differences were observed between the white and yellow film treatments. In contrast, the purple, red, and blue film treatments demonstrated reductions of 84.98%, 47.60%, and 37.70%, respectively. In the wavelength range of 600 to 700 nm representing red light, all treatments except the green film treatment showed increases that ranged from 8.31% to 97.23%. Among these, the purple film treatment exhibited the largest increase, while the white film treatment had the smallest increase. For red-to-blue light ratios, the trend mirrored that of red light in the range of 600 to 700 nm. The green film treatment resulted in a decrease in red-to-blue ratios, while the other treatments showed increases. The red film treatment had the largest increase (536.50%) compared with that of CK, followed by that of the purple film (234.31%).

Covering with films of different colors not only reduces the intensity of light radiation but also affects the quality of light (Qi et al. 2021). The most important physiological processes in plants are blue light (400–500 nm), green light (500–600 nm), and red light (600–700 nm) (Fu et al. 2020), and changes in these light bands can significantly affect the ripening process and quality of fruits. In this study, the yellow film exhibited the highest transmittance among the treatments. The green film treatment had the lowest values of red and red/blue light within the wavelength range of 600 to 700 nm. The yellow film treatment showed increases in all measured indicators except for the proportion of blue light. It is speculated that the change in light quality caused by covering the film also affects the maturity and quality of mulberries.

Effect of film color on color transition in mulberry fruits. Significant differences in fruit color transformation were observed under various film treatments (Figs. 2 and 3). Compared with CK, fruits treated with yellow and white films exhibited a shorter color

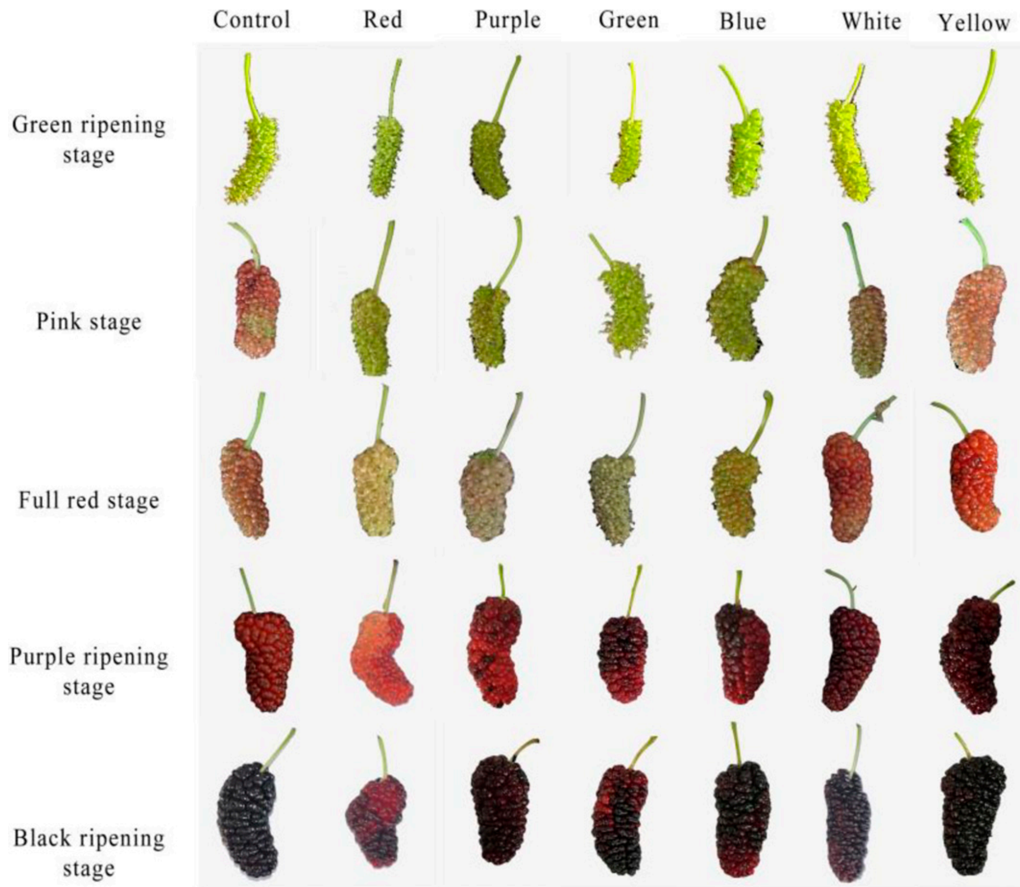

Fig. 2. Ripening process of mulberry fruits under films with different colors.

transition period and developed darker colors. During the purple ripening stage, the anthocyanin contents of fruits under these treatments were 44.85% (yellow film) and 8.19% (white film) higher than that of CK, respectively. Additionally, these fruits reached maturity 7 d earlier than CK. The red film treatment resulted in the slowest color transformation, with anthocyanin levels consistently lower than those of CK throughout the entire color change period. In contrast, treatments with purple, green, and blue films led to a slower onset of color change, with fruits beginning to show slight coloration only during the full red stage. The anthocyanin content under these treatments remained consistently lower than that of CK throughout the fruit development stages. During the purple ripening stage, fruits under red film treatment displayed a more pronounced red hue, while their anthocyanin contents were reduced by 69.61%, 59.32%, and 55.99%, respectively, compared with those of yellow film, white film, and CK treatments. By the postripening stage, fruits under all treatments except the red film had transitioned to a black–purple color. Fruits treated with the red film, however, remained predominantly dark red, with an anthocyanin content 58.31% lower than that of CK, indicating delayed ripening.

At the black ripening stage, fruits treated with the white film had the highest L, a, and b values, which were 48.60%, 746.81%, and 750.00% higher than those of CK, respectively. Conversely, fruits under green film treatment had the lowest L value, which was 4.91% lower than that of CK. Across all six treatments, the a and b values of the fruits were higher than those of CK.

Anthocyanins are highly light-dependent quality attributes in fruit development. Red film treatments have been shown to promote

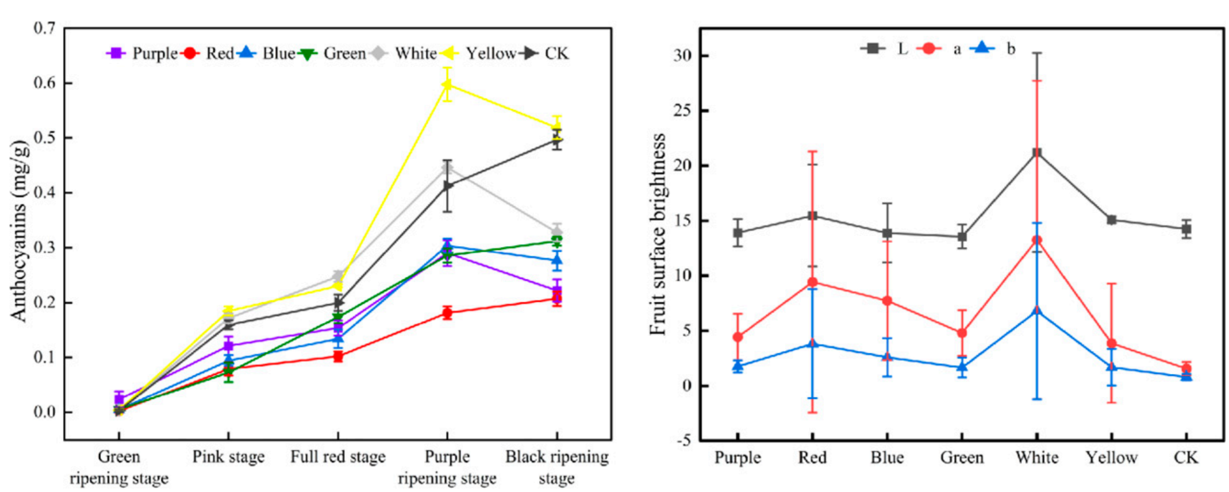

Fig. 3. Anthocyanin content of mulberry fruits under films with different colors.

the expression of anthocyanin-related genes in apple fruits, accelerating the coloration of their peels (Feng et al. 2013). Similarly, blue light supplementation has been demonstrated to improve the coloration and quality of grape fruits (Liu et al. 2021). Furthermore, red and yellow film treatments have significantly increased the anthocyanin content in strawberry fruits (Miao et al. 2016) Additionally, specific ratios of red and blue light have distinct effects; a 6:1 ratio promotes vegetative growth, while a 3:1 ratio improves fruit quality by regulating soluble sugar and anthocyanin content (Wang 2020). In this study, white and yellow film treatments accelerated the process of fruit color transformation and increased anthocyanin accumulation compared with CK, while other treatments, such as purple, red, and blue films, slowed the color change and delayed fruit ripening. This study also revealed that green film treatment notably prolongs the flowering period and delays fruit development. These findings align with and reinforce previous research. It is noteworthy that although mulberries treated with CK have 100% transmittance, the fruit coloration is less uniform. In contrast, white and yellow film treatments, despite having lower transmittance than that of CK, provide a similar proportion of blue, green, and red light while protecting the fruit from rain damage. As a result, fruits under these treatments exhibit faster color transformation and earlier ripening compared with CK. In the Three Gorges Reservoir area, using yellow or white films for rain-resistant cultivation effectively accelerates fruit ripening and increases anthocyanin accumulation in mulberries.

In summary, fruits under yellow film treatment showed the fastest color transformation and ripening, achieving peak anthocyanin content during the purple ripening stage. Purple, green, and blue film treatments also achieved peak anthocyanin content during the purple ripening stage but at levels lower than those of the yellow film treatment. The red film treatment caused the slowest color transformation and delayed ripening, with anthocyanin content gradually increasing throughout all five measurement periods and peaking during the black ripening stage, similar to CK.

Effects of film color on appearance quality of mulberry fruits. Compared with CK, fruits treated with yellow film demonstrated the fastest increase in single fruit weight during the full red stage, peaking at the purple ripening stage with a weight 40.97% higher than that of CK. Fruits under yellow film treatment then exhibited a gradual decrease in weight after this stage. In contrast, fruits under green film treatment had the slowest increase in single fruit weight; by the black ripening stage, their weight was 30.29% lower than that of CK. Water content in fruits treated with all six film colors steadily increased after the pink stage. However, water content in fruits treated with yellow film gradually decreased after reaching the purple ripening stage ($P < 0.05$), in contrast to other treatments. No significant differences in fruit vertical or horizontal diameters were observed among treatments ($P > 0.05$) (Fig. 4).

Effect of film color on intrinsic quality of mulberry fruits. Films with different colors significantly influenced the Vc content of mulberry fruits. The Vc content in fruits treated with different films showed distinct trends. Under red film and green film treatments, Vc content followed fluctuating dynamic patterns. In contrast, under blue film treatment, Vc content gradually decreased, reaching the lowest level (32.96% lower than that of CK) during the black ripening stage. Fruits under the white, yellow, and green film treatments showed continuous increases in total sugar content. At the black ripening stage, fruits treated with white and yellow films exhibited the highest total sugar contents, which were 34.82% and 27.00% higher than that of CK, respectively. The amino acid content in fruits under red film treatment showed a gradual increase and peaked at the black ripening stage, with a value 200.95% higher than that of CK. In contrast, fruits treated with green film experienced dynamic fluctuations in amino acid content, reaching the lowest level at the black ripening stage (90.86% lower than that of CK). Regarding the cellulose content, fruits treated with colored films underwent dynamic changes, including initial slow decreases, rapid

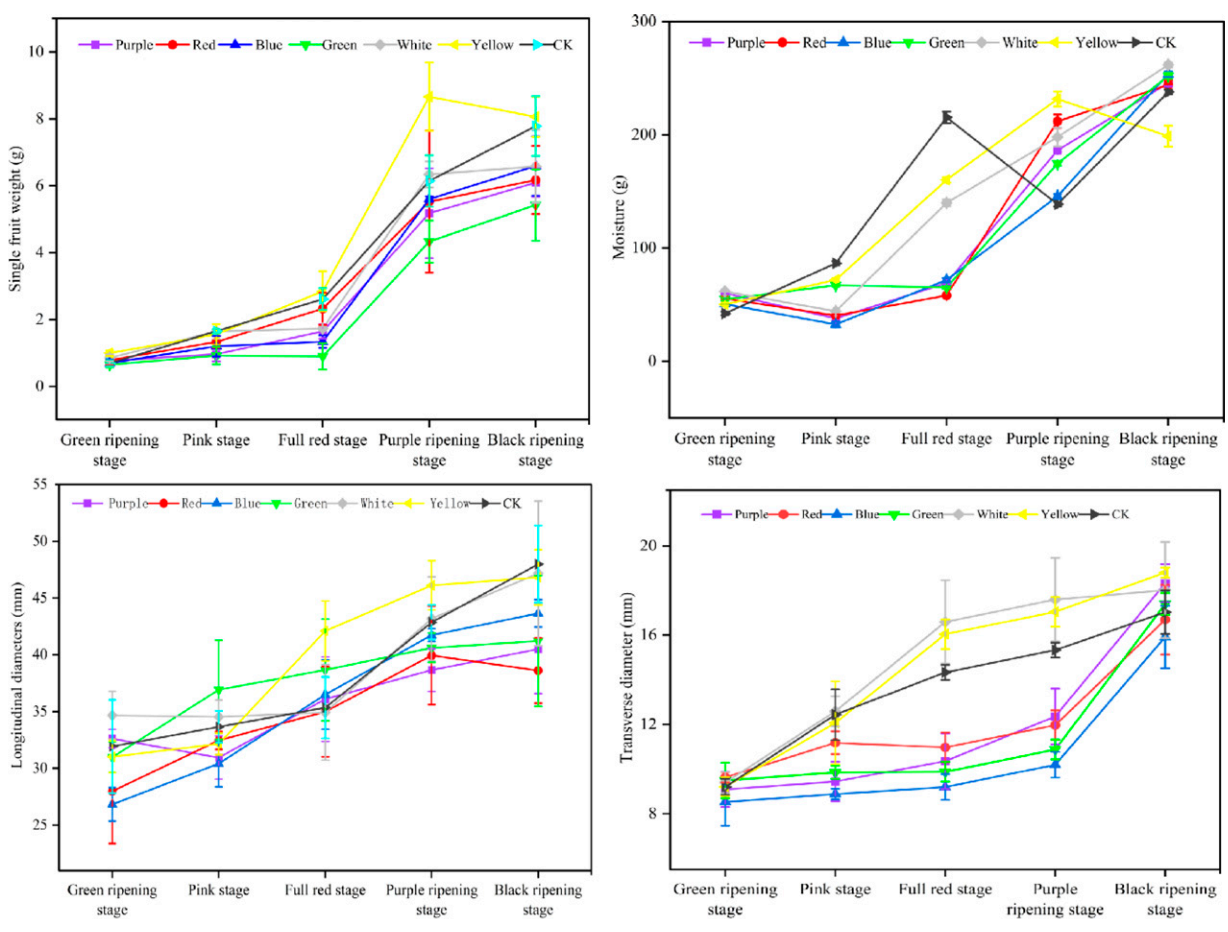

Fig. 4. Changes in the main appearance quality indicators of mulberry fruits under films with different colors.

increases, and subsequent rapid decreases. At the end of the purple ripening stage, cellulose levels reached their lowest point and remained stable or slightly increased afterward. At the black ripening stage, fruits treated with yellow film displayed the highest TSS content (34.82% higher than that of CK), followed by that of fruits treated with purple film (27.80% higher than that of CK) (Fig. 5).

Research has shown that different colors of filter films have varying effects on grape quality. For instance, yellow film treatment resulted in significantly higher TSS and Vc contents in grape fruits compared with those of the control (Wang et al. 2019). Similarly, another study found that tomato fruits treated with red/blue light in a 3:1 ratio exhibited the highest soluble sugar content (Dong et al. 2018). Red and blue light supplementation has been reported to increase the yield of facility-cultivated dragon fruit while also increasing sucrose and soluble solids content in the fruit (Chen et al. 2019). In this study, mulberries under yellow film treatment showed the fastest growth in single fruit weight and had a higher TSS content than that of CK. Fruits treated with white film displayed the highest total sugar content, whereas those under green film treatment exhibited the slowest single fruit weight growth and the lowest amino acid content. Even during the black ripening stage, the single fruit weight under green film treatment remained significantly lower than that of CK ($P < 0.05$). Additionally, fruits treated with red film had the lowest TSS content among all treatments. Overall, yellow film treatment proved effective for improving mulberry fruit quality, reaffirming the critical role of light components in determining fruit quality attributes.

Effect of film color on enzyme activity in mulberry fruits. Significant differences in enzyme activity of mulberry fruits were observed under different colored films (Fig. 6). In fruits treated with purple film, SOD activity decreased significantly, reaching its lowest value (44.81% lower than that of CK) during the full red period. Under red film treatment, SOD activity increased slowly from the green to purple ripening stages and then declined rapidly, reaching its lowest value (45.19 U/g) during the black ripening stage. Under the white film treatment, SOD activity increased steadily throughout fruit ripening.

The red film treatment significantly influenced PPO and POD activities. The PPO activity peaked during the purple ripening stage (247.65% higher than that of CK), and then sharply decreased, reaching its lowest value (94.86% lower) during the black ripening period. Similarly, POD activity showed a gradual increase and peaked in the purple ripening stage at 893.58% higher than that CK, followed by a sharp decline.

Regarding PAL activity, fruits under red film treatment displayed significant fluctuations characterized by an initial increase, rapid decline, and another increase, and they peaked during the black ripening stage (405.19% higher than that of CK). Fruits under purple film treatment showed a dynamic pattern of slow increase, rapid decrease, and then rapid increase across the five stages.

The CAT activity initially decreased slowly in the early stages, increased rapidly after the purple ripening stage, and peaked during the black ripening stage. This treatment resulted in the highest CAT activity among all groups.

Red light treatment has been shown to maximize the activities of SOD and POD in blueberry fruits, enhancing their antioxidant capacity (Wei et al. 2023). In this study, red film treatment significantly increased the PAL and POD activities in mulberry fruits during the later stages of development. However, SOD activity under red film treatment was lower than that observed with the other five color films during the early stages. This discrepancy may be attributed to differences in crop species and treatment methods.

Effects of different colored films on photosynthesis in mulberry leaves. Table 2 demonstrates that the net photosynthetic rate in mulberry leaves under all treatments, except for the yellow film treatment, was 5.32% higher than that of CK. However, stomatal conductance was lower in all treatments compared with that of CK, with the most significant reductions observed under white and yellow film treatments, with values 57.14% and 42.86% lower than that of CK, respectively. These differences were statistically significant. Carbon dioxide (CO_2) concentrations in the leaves under all treatments were significantly reduced compared with those of CK, with the yellow film showing the greatest decrease (93.50% lower than that of CK).

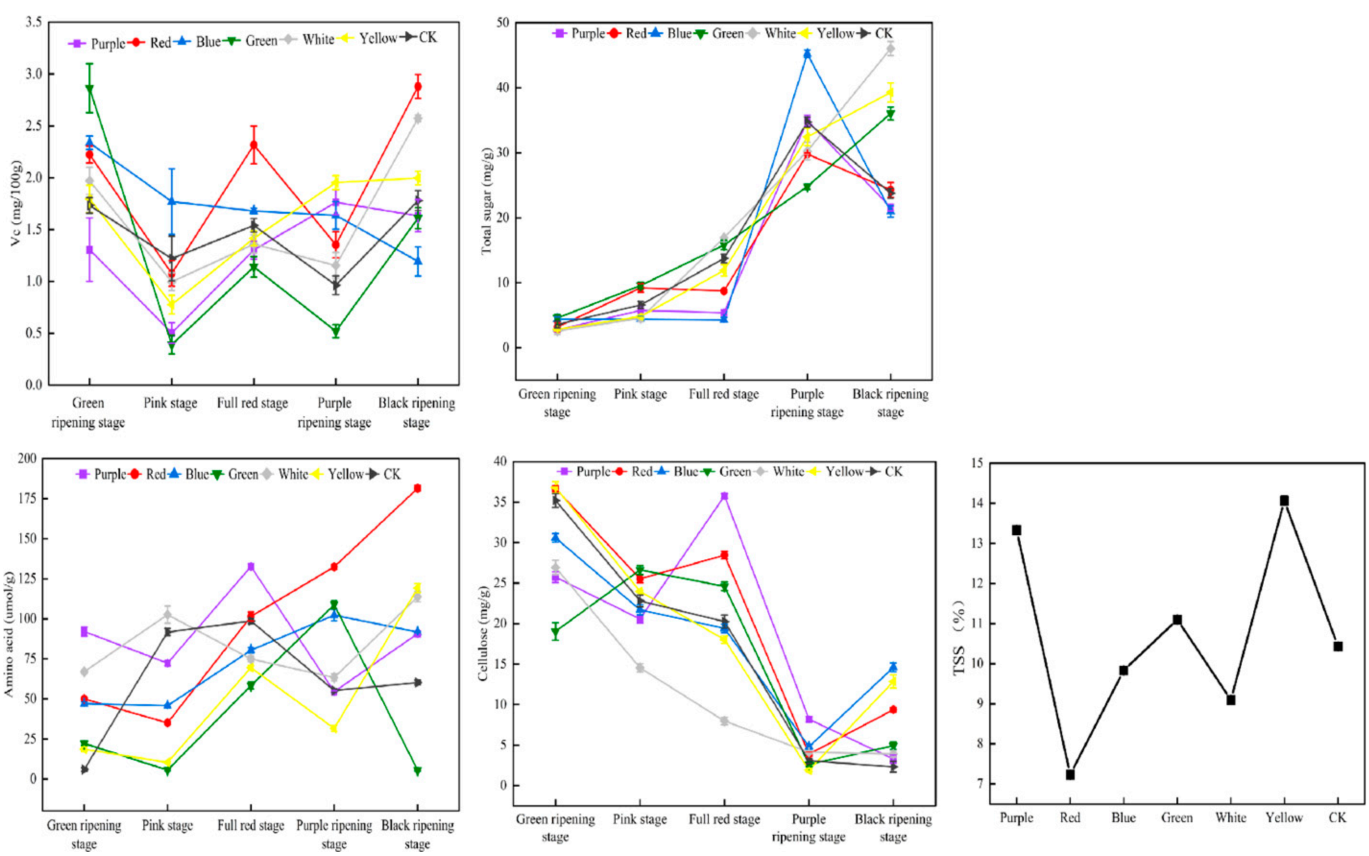

Fig. 5. Changes in main intrinsic quality parameters of mulberry fruits under films with different colors.

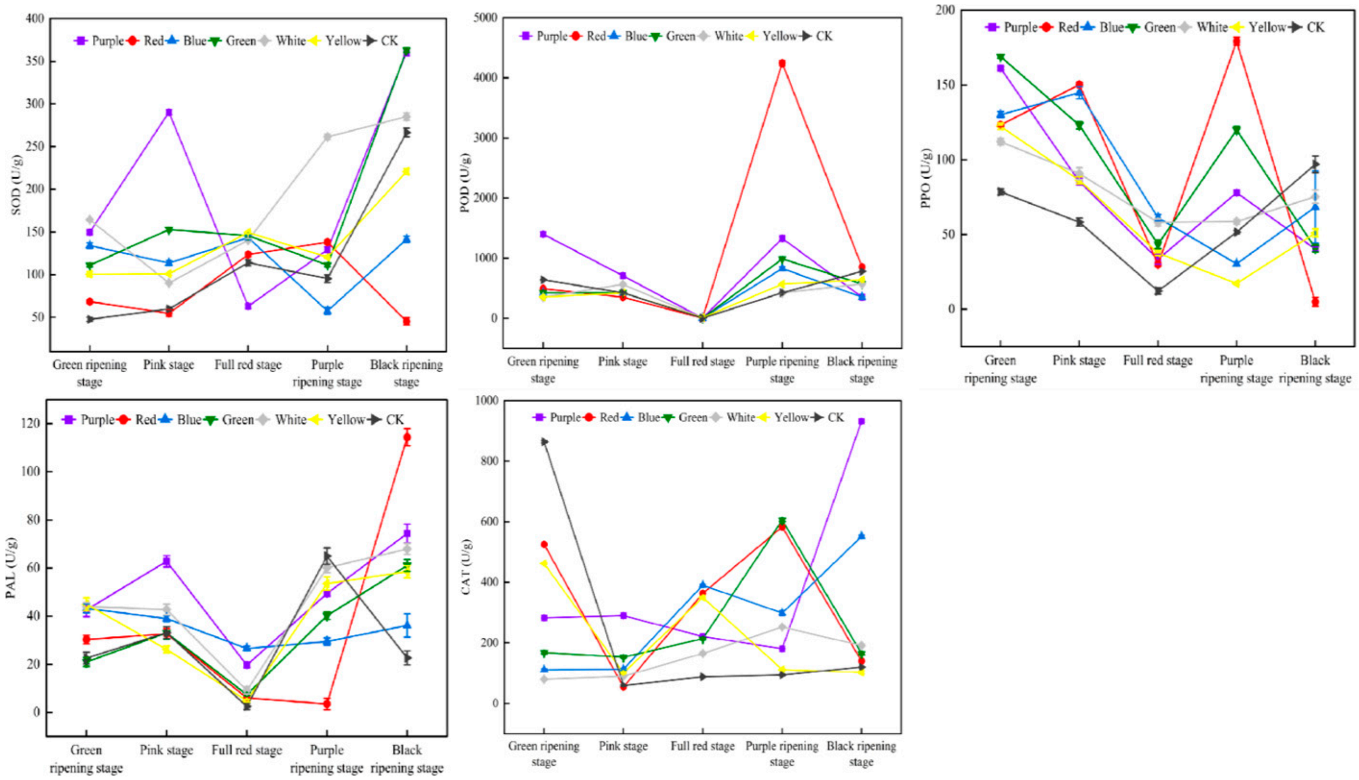

Fig. 6. Changes in enzyme activity during mulberry fruit ripening under films with different colors.

However, for other treatments, the differences in the CO_2 concentration compared with that of CK were not statistically significant. Transpiration rates also varied across treatments, with the white film treatment showing a 48.43% reduction compared with that of CK, which was a statistically significant difference. In contrast, the differences in transpiration rates between other treatments and CK were not significant.

Leaves, as vital organs for plant photosynthesis, play a key role in plant growth (Zhang and Xu 2008). Zhang et al. (2015) reported that ginger had the highest photosynthetic rate under green light treatment, while Liang et al. (2019) found that the net photosynthetic rate under green and yellow film treatments was significantly higher than that of the control. In contrast, this study revealed that yellow film treatment slightly enhanced photosynthesis in mulberry leaves, while other treatments weakened it to varying extents. The difference may be caused by the unique environmental conditions of the Three Gorges Reservoir area, which is characterized by sparse rainfall, low light intensity, and slow temperature increases in spring. These factors, combined with the use of rain shelter films, may have reduced light transmittance and altered light quality, ultimately leading to decreased photosynthetic efficiency.

Effect of mineral element content in mulberries under different colored films. Table 3 indicates that mineral element content in mulberries at various maturation stages varied with the color of the film. During the green ripening stage, significant differences in the total N content were observed among the treatments ($P < 0.05$). Red film-treated fruits exhibited the highest total N content (42.77 g/kg), followed by that of fruits under yellow film treatment (41.97 g/kg). Fruits under green film contained the lowest total N, which was only 11.10% of that in red film-treated fruits. In contrast, fruits under green film showed the highest total P (10.79 g/kg) and K (3.95%) among all treatments. Their total N, Ca, and Mg contents were the lowest, at 11.10%, 17.69%, and 30.06% of the maximum values found in red film-treated fruits, respectively. By the full red stage, the total N, Ca, and Mg content in fruits under green film increased significantly by 69.23% and 43.29%, respectively. The total N content decreased in all other treatments during this stage. Fruits under red film experienced a decline in the total P content from the green ripening stage, while the total K and Ca contents increased. Among all treatments, fruits under red film exhibited the highest total K and Ca contents, with significant differences from other treatments ($P < 0.05$). Fruits under yellow film had the lowest Ca and Mg contents during the full red stage. Fruits under the CK treatment displayed the lowest values for total N (15.13 g/kg), total P (1.87 g/kg), and total K (1.30%), which continued to decline during this stage. At the black ripening stage, the total content of all five elements in fruits under red film declined but remained the highest for the total N among all treatments,

Table 2. Differential expressions of photosynthetic characteristics of mulberry leaves under films with different colors.

Treatment	Net photosynthetic rate (mmol/m^2/g)	Stomatal conductance (mol/m^2/g)	Carbon dioxide concn (μmol/mol)	Transpiration rate (mmol/m^2/g)
Purple	26.09 ± 0.80 ab	0.18 ± 0.04 abc	60.22 ± 34.99 bc	3.06 ± 0.51 ab
Red	30.03 ± 4.44 ab	0.25 ± 0.05 ab	101.75 ± 55.02 ab	3.67 ± 0.50 a
Blue	27.06 ± 4.06 ab	0.22 ± 0.04 abc	138.23 ± 24.97 a	3.64 ± 0.41 a
Green	25.77 ± 2.57 ab	0.2 ± 0.04 abc	75.75 ± 38.6 ab	3.16 ± 0.45 ab
White	24.37 ± 2.87 b	0.12 ± 0.10 c	130.27 ± 21.19 a	1.64 ± 1.01 c
Yellow	33.27 ± 8.56 a	0.16 ± 0.03 bc	6.61 ± 4.79 c	2.21 ± 0.30 bc
CK	31.59 ± 0.51 ab	0.28 ± 0.04 a	101.73 ± 24.70 ab	3.18 ± 0.24 ab

There was a significant difference between different letters representing different maturity levels ($P < 0.05$).

CK = uncovered cultivation as the control.

Table 3. Differential of mineral element content in mulberry fruits under different colored films.

Stage	Treatment	Total N (g/kg)	Total P (g/kg)	Total K (%)	Ca (g/kg)	Mg (g/kg)
Green ripening stage	Purple	37.23 ± 0.76 e	7.40 ± 0.23 c	3.06 ± 0.11 ab	12.79 ± 0.87 c	5.50 ± 0.32 b
	Blue	39.55 ± 0.67 d	8.79 ± 0.37 b	2.94 ± 0.24 ab	11.8 ± 0.50 c	5.22 ± 0.17 b
	Red	42.77 ± 0.86 c	7.88 ± 0.68 bc	2.38 ± 0.35 b	15.94 ± 0.54 b	6.22 ± 0.63 a
	Green	4.75 ± 0.86 f	10.79 ± 0.84 a	3.95 ± 0.57 a	2.82 ± 0.71 e	1.87 ± 0.49 d
	White	40.69 ± 0.44 d	7.44 ± 0.21 c	2.70 ± 0.17 b	9.78 ± 0.56 d	4.50 ± 0.23 c
	Yellow	41.97 ± 0.80 c	8.71 ± 0.23 b	2.40 ± 0.23 b	10.65 ± 0.38 d	4.86 ± 0.20 bc
	CK	38.10 ± 0.60 e	6.07 ± 0.58 d	3.05 ± 1.42 ab	12.29 ± 0.37 c	5.22 ± 0.23 b
Full red stage	Purple	31.79 ± 0.28 b	3.39 ± 0.22 bc	2.47 ± 0.12 b	10.78 ± 0.79 d	3.73 ± 0.17 bc
	Red	31.25 ± 0.46 b	4.57 ± 0.42 a	2.98 ± 0.46 a	47.44 ± 0.77 a	3.49 ± 0.15 c
	Blue	35.78 ± 0.68 a	3.94 ± 0.64 ab	2.42 ± 0.26 b	12.33 ± 0.57 c	3.94 ± 0.15 ab
	Green	31.92 ± 0.27 b	3.32 ± 0.28 bc	2.24 ± 0.12 b	13.58 ± 0.47 b	4.25 ± 0.13 a
	White	23.13 ± 0.61 c	2.65 ± 0.28 c	1.49 ± 0.23 c	2.92 ± 0.12 ef	1.86 ± 0.20 d
	Yellow	17.47 ± 0.90 d	2.81 ± 0.69 c	1.68 ± 0.27 c	2.50 ± 0.27 f	1.51 ± 0.24 e
	CK	15.13 ± 0.61 e	1.87 ± 0.29 d	1.30 ± 0.23 c	3.8 ± 0.75 e	1.80 ± 0.25 de
Black ripening stage	Purple	12.27 ± 0.50 d	2.25 ± 0.46 ab	1.34 ± 0.44 b	1.41 ± 0.27 d	1.15 ± 0.15 bc
	Red	16.00 ± 0.56 b	2.74 ± 0.26 a	1.73 ± 0.19 b	1.12 ± 0.09 d	1.42 ± 0.25 ab
	Blue	14.70 ± 0.46 c	2.35 ± 0.24 ab	2.52 ± 0.54 a	1.45 ± 0.26 cd	1.42 ± 0.21 ab
	Green	18.77 ± 0.55 a	2.94 ± 0.34 a	1.86 ± 0.08 b	2.02 ± 0.28 b	1.37 ± 0.09 abc
	White	7.63 ± 0.45 e	1.88 ± 0.31 bc	1.33 ± 0.31 b	1.79 ± 0.18 bc	1.37 ± 0.23 abc
	Yellow	7.14 ± 0.31 e	1.30 ± 0.43 c	1.24 ± 0.22 b	1.22 ± 0.12 d	0.96 ± 0.12 c
	CK	13.03 ± 0.31 d	2.37 ± 0.45 ab	1.39 ± 0.36 b	1.83 ± 0.13 bc	1.75 ± 0.37 a

There was a significant difference between different letters representing different maturity levels ($P < 0.05$).
Ca = calcium; Mg = magnesium; K = potassium; N = nitrogen; P = phosphorus; CK = uncovered cultivation as the control.

with significant differences ($P < 0.05$). However, the Ca content under red film treatment was the lowest among all treatments, but not significantly different from that of fruits treated with yellow film ($P > 0.05$). For fruits under yellow film treatment, the total N, total P, total K, and Mg contents all decreased to the lowest levels among all treatments.

Previous studies have reported that red and blue films can increase the distribution of N in sweet pepper stems and leaves, with blue film promoting the accumulation of P and K in leaves (Tian et al. 2013). The results of this study are consistent with those findings. Mulberry fruits treated with red film exhibited the highest total N content during the green and black ripening stages. During the full red stage, these fruits also showed the highest P, K, and Ca contents among all treatments. Conversely, mulberries treated with blue film had the highest total N content during the full red stage. These findings suggest that appropriately increasing the ratio of blue/green light can improve the accumulation of P and Ca in mulberries, while increasing the proportion of red light can promote the accumulation of the total K content.

Quality-based clustering and principal component analysis. A cluster analysis of the quality parameters of mulberries treated with different colored rain shelter films was conducted. Setting the clustering distance at 20, the seven treatments were divided into two categories. The first category included yellow film, CK, and white film treatments. Within this group, the fruit quality under yellow film and CK treatments was more closely related, clustering into a narrower phylogenetic branch, whereas the white film treatment was distinct from both yellow film and CK treatments. The second category comprised treatments with purple film, blue film, red film, and green film, indicating a significant difference in fruit quality from the first category (Fig. 7).

By calculating the comprehensive score of different colored transparent films, the score can directly reflect the fruit quality after different film covering treatments (Zhang et al. 2018). A principal component analysis identified three principal components (PCs; PC1, PC2, and PC3) with eigenvalues of 4.8199, 2.1834, and 1.0438, accounting for 53.55%, 24.26%, and 11.60% of the variance, respectively (Table 4). Additionally, PC1, PC2, and PC3 served as evaluation indicators for fruit quality. A comprehensive analysis revealed that the yellow film treatment achieved the highest comprehensive score (6.85), thus ranking highest in overall fruit quality. This score was followed by those of CK, white film, red film, purple film, and green film treatments. The blue film treatment achieved the lowest comprehensive score (1.66), indicating the poorest fruit quality (Table 5).

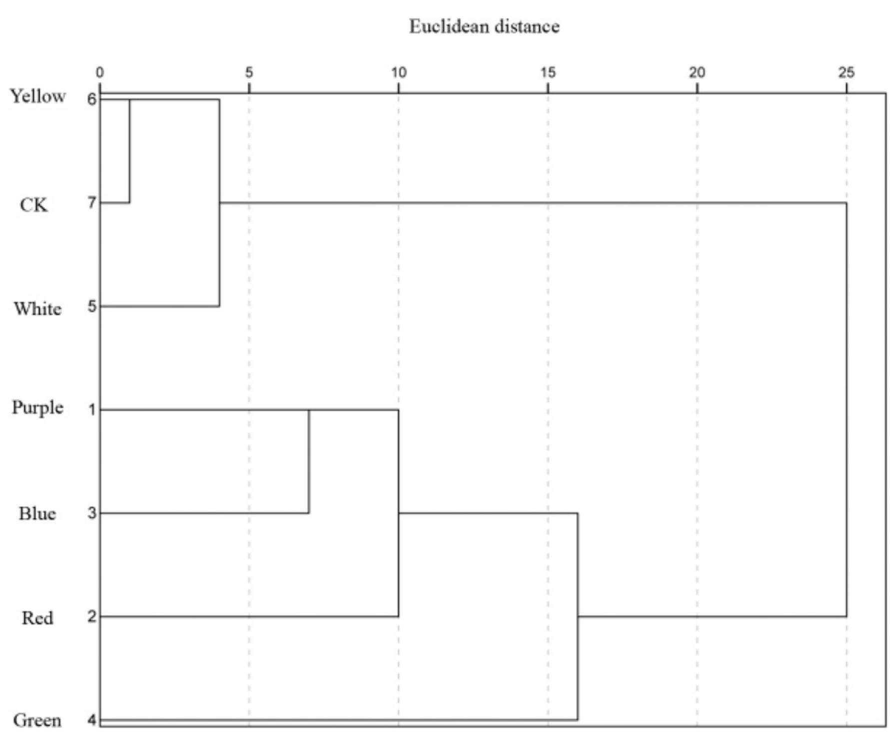

Fig. 7. Cluster analysis of the colored films.

Conclusion

After treatment with white and yellow films, the color transformation of mulberry fruits was accelerated and the fruits ripened in advance. The content of anthocyanins, TSS, and net photosynthetic rate in mulberry fruits treated with yellow film increased, resulting in the best quality in the tested treatments. Purple and green films significantly

Table 4. Extraction of principal components.

Principal component	Eigenvalue	Variance contribution rate %	Cumulative variance contribution rate %
1	4.8199	53.5542	53.5542
2	2.1834	24.2604	77.8146
3	1.0438	11.5975	89.4121

Table 5. Comprehensive analysis of principal components.

Treatment	PC1	PC2	PC3	Comprehensive score	Ranking
Purple	−2.6899	0.256	1.9715	2.372206	5
Red	−1.7825	2.1395	−1.3948	2.98623	4
Blue	−2.0942	−0.5799	−0.8033	1.659418	7
Green	−0.7369	−2.6704	−0.37	2.045697	6
White	2.7578	−1.1091	−0.174	5.907172	3
Yellow	2.7528	0.8932	−0.0418	6.852662	1
CK	1.7929	1.0706	0.8124	6.348775	2

CK = uncovered cultivation as the control; PC = principal component.

delayed the ripening of mulberry fruits, and the quality was better. In mulberry production, white or yellow films can be used for rain avoidance cultivation to promote earlier ripening and improve quality, while purple or green films can be used to delay ripening and improve fruit quality.

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