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Effect of light quality on leaf photosynthetic characteristics and fruit quality of peach (*Prunus persica* L. Batch)

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Abstract

Different light filters affect leaf photosynthetic features and fruit quality. Consequently, selecting the appropriate covering filter for rain-shelter cultivation of peaches is a key part of successful production. We used a late-maturing peach variety 'Xiahui 8' to study differences in leaf photosynthetic features, chlorophyll fluorescence characteristics, and fruit quality under neutral, red, yellow, green, and blue filter, with natural light as control. The results showed that the leaf photosynthetic ability and internal quality under the neutral filter treatment were elevated compared with the control, and the appearance color was the same as the control. Leaves under neutral filter could maintain higher photosynthetic ability than other filter treatments. In addition, the fruits could also keep higher quality when treated with neutral filter. Therefore, the application of neutral filter in rain-shelter cultivation of 'Xinhui 8' peaches is recommended for maintaining high photosynthetic capacity and for improving fruit quality.

Additional key words: appearance; internal quality; irradiance spectrum.

Introduction

Light is the main factor affecting the photosynthesis, growth, and development of plants (Kircher *et al.* 1999). Furthermore, the growth and development of plants and fruit formation are all based on photosynthesis, photomorphogenesis, and photoperiod adjustments. Under appropriate light conditions, CO_2 fixation and net photosynthetic rates increase with elevated absorption of light energy by chlorophyll (Chl); however, excessive light inhibits photosynthesis and even leads to the photo-oxidation of photosynthetic apparatus (Cleland *et al.* 1986). The photosynthetic organs of fruit trees obtain energy from solar radiation, which the plant uses for its own growth and development. Moreover, the products of photosynthetic assimilation are continuously transported to the fruits and promote their growth and development, which is crucial for fruit tree varieties used in a commercial fruit production.

A previous study showed that the maturation period of 'Jonagold' apples advanced at varying levels of shading (8–12%, 15–17%, and 18–25%), but no significant differences were observed in fruit firmness, soluble solid content (SSC), and titratable acid content (Widmer 2001). However, for 'Mondial Gala' apples, the fruit surface temperature was reduced with 25% shading, which effectively prevented sunburn but decreased SSC (Iglesias and Alegre 2006). In a previous publication, we demonstrated that shading alleviated photoinhibition in red-leaf peach leaves, which acted to prevent photo-oxidative

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Abbreviations: a^* – red saturation; Ant – anthocyanin; b^* – yellow saturation; C – color chroma; Chl – chlorophyll; C_i – intercellular CO_2 concentration; CUE – carbon-use efficiency; DAFB – days after full bloom; E – transpiration; ETR – electron transport rate; F_0 – minimal fluorescence level in dark-adapted leaves; F_0' – minimal fluorescence level in light-adapted leaves; F_m – maximal fluorescence level in dark-adapted leaves; FM – fresh matter; F_m' – maximal fluorescence level in light-adapted leaves; F_s – steady-state fluorescence in the light-adapted state; F_v – variable fluorescence level in dark-adapted leaves; F_v/F_m – maximum quantum yield of PSII; g_s – stomatal conductance; h° – hue angle; HPLC – high performance liquid chromatography; L^* – lightness; LUE – apparent light-use efficiency; L_s – light-saturation point; NPQ – nonphotochemical quenching; P_N – net photosynthetic rate; q_P – photochemical quenching coefficient; R/FR – red to far-red ratio; SSC – soluble solid content; WUE – water-use efficiency; Φ_{PSII} – effective quantum yield of PSII photochemistry.
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damage (Zhang *et al*. 2010). Another study showed that fruit bags of different colors allow radiation of different light qualities on the fruit, and the different bags had different effects on the appearance quality and inner quality of peaches (Ma *et al*. 2014, Zhang *et al*. 2015).

Light quality refers to the composition of the solar radiation spectrum and the energy contained in each band. During the growth and development of plants, light quality not only provides energy for photosynthesis, synthesis of organic matter, and growth (Rapparini *et al*. 1999, Bastías and Corelli-Grappadelli 2012, Shibuya *et al*. 2012), but also serves as an environmental signal to regulate the formation of fruit quality (Adams-Phillips *et al*. 2004, Koyama *et al*. 2012). Phytochrome, cryptochrome, protochlorophyllide, and Chl all play roles in the regulation of chloroplast development. Phytochrome mainly perceives red light and far-red light, as well as blue light and UV light. Cryptochrome primarily detects blue light and UV-A (Batschauer 1998). Plants are selective in that they cannot absorb full-wave band light. Studies have indicated that the development of plant photosynthetic organs is mediated by light quality, and that light with different wavelengths has various impacts on plant growth and development. For example, blue light changed the thickness of the leaf tissue and the phytochrome status in the tissue of peaches (Rapparini *et al*. 1999). Blue light also increased leaf numbers, Chl content, and stomata numbers in grapes (Poudel *et al*. 2008). Red light increased starch accumulation in birch leaves by inhibiting the transportation of photosynthetic products from the leaves (Sæbø *et al*. 1995), and increased the stem internode of grape seedlings (Poudel *et al*. 2008). Light signals with wavelengths over 600 nm had the most significant impact on the skin color chroma (*C*), red saturation (a^*), and yellow saturation (b^*) (Dussi *et al*. 1995).

While most of the studies described above focused on the effect of monochromatic light on plant growth and development, the synergistic effect of compound light has also been investigated. Schuerger *et al*. (1997) explored the growth of sweet pepper under a mixed light treatment of red/far-red and red/blue/far-red, and found that blue light is the dominant light quality affecting the anatomical structure of stems and the changes in leaf tissue. Xiong *et al*. (2011) demonstrated that the variation of light quality substantially influenced the morphology of stems and petioles, dry matter accumulation, and carbohydrate content in cucumbers, but had no dramatic impact on leaves and roots.

Light quality also has significant effects on fruit quality. Tomato fruit grown under light contained 30% more sucrose and one-fold more starch and hexose than fruit grown in the dark (Guan *et al*. 1991). Fruit bags with different colors allow radiation of different light qualities on the fruit, and studies have shown that both the SSC and edible quality decreased in bagged fruit (Ni *et al*. 2011, Hudina and Stampar 2011).

Our study was performed in the middle and lower reaches of the Yangtze River, which is located in the subtropical or tropical monsoon climate zone of China. Consequently, the peach-growing season typically occurs when the groundwater level is generally high due to frequent and strong rainfall. We selected several flood-resistant stocks for peach cultivation (Ma *et al*. 2013), but the expansion of these stocks is difficult to complete in a short period of time because of the slow turnover rate of trees in the peach orchards. Recently, researchers have been studying the potential of rain-shelter cultivation in peach production. Although the trees are grown in a relatively ventilated environment in rain-shelter cultivation, the long-term, low-light environment clearly affects growth, fruit quality, and yield of trees because peach is a species fond of light. Therefore, proper selection of rain-shelter filters is crucial in commercial rain-shelter production.

The purpose of this study was to investigate the effect of light quality on leaf photosynthetic characteristics, leaf Chl fluorescence parameters, and fruit quality in peaches, and to find the type of light quality that is effective in improving or maintaining leaf growth and fruit quality in peaches.

Materials and methods

Plant material and experimental treatments: The experiment was conducted in the experimental peach orchard of the Fenghuang Agricultural Science and Technology Company in Suzhou city (31.75°N, 120.64°E), Jiangsu Province, China. During the experiment, the average temperature was about 28.2°C, and humidity was around 81.9%. A late-ripening peach cultivar 'Xiahui 8', which matures in early August, was used for the experiment. The trees were five-years-old, grown on Maotao (*Prunus persica* L. Batch) rootstocks with a central leader tree form. Different types of filter with different colors were positioned above the trees before the fruit color changing period (100 d after full bloom [DAFB]). The size of the filter covering each tree was 2 × 2 × 3 m (length × width × height). The frame for sustaining the filter was made of lead wire. Trees with no filter were selected for the control group. Six trees were used as replicates. All trees were planted in a south–north direction in single rows and were well managed according to conventional procedures.

Five types of filter (*Shanghai Weikang Colored Filter Co*., China) were employed for this study: neutral, red, yellow, green, and blue filter. The light transmittance of each type of filter was 57.2, 56.7, 56, 55, and 56.5%, respectively. The radiant energy of the spectrum was measured by a *LI-1800* portable spectroradiometer (*LI-COR*, USA). The components of representative irradiance spectrum in different filters were presented in the following table:

The components of representative irradiance spectrum in different filters.

Filter type	Control	Neutral filter	Red filter	Yellow filter	Green filter	Blue filter
Ultraviolet light (300–400 nm) [W m^{-2}]	7.12	4.26	2.40	4.28	5.01	5.30
Blue light (400–510 nm) [W m^{-2}]	29.18	11.89	2.86	13.03	16.56	28.35
Green light (510–610 nm) [W m^{-2}]	48.97	29.59	1.85	31.42	32.10	5.19
Red light (610–720 nm) [W m^{-2}]	56.77	33.50	42.07	32.46	14.38	19.58
Near-infrared light (720–1,100 nm) [W m^{-2}]	134.78	75.58	104.81	71.56	82.38	95.03
Solar radiation (300–1,100 nm) [W m^{-2}]	276.82	154.82	154.00	152.75	150.44	153.45
Red/Far-red (R/FR)	1.08	1.21	1.02	1.18	0.47	0.23
Red/Blue (R/B)	1.95	2.82	14.71	2.49	0.87	0.69

Photosynthesis and Chl fluorescence parameters were measured from 10:00 to 11:00 h (Beijing time) using mature and fully expanded leaves from different treatments at harvest. Leaves at the same position were used for leaf Chl content measurements.

Twenty fruits were collected from each tree for each replication at harvest time (132 DAFB). Harvested fruits were instantly put in ice boxes and carried back to the laboratory for assay. After fruit mass, fruit color, firmness, and soluble solid content measurements, skin and flesh samples were separated and immediately frozen in liquid nitrogen, then stored at −70°C until they were used for other aspects of the study.

Fruit mass, firmness, and SSC: Fruit mass was determined using a digital electrical balance. Texture was measured using a puncture test with an 8-mm-diameter needle in a *TA-XT plus* texture analyzer (*Stable Micro Systems*, UK). The studies were conducted at a pre-test speed of 1 mm s^{-1}, test speed of 2 mm s^{-1}, and a distance of 5 mm. The SSC of the materials was measured using normal commercial procedures. The fruit was juice squeezed from two opposite equatorial locations and read with a digital hand-held pocket refractometer *PAL-1* (*Atago*, Tokyo, Japan) in ºBrix at 20°C (Mitchell *et al.* 1974, Infante *et al.* 2011).

Fruit color and skin pigment: Fruit surface color was measured with a *ColorQuest XE* spectrophotometer (*Hunter Lab*, Reston, USA) in the CIE Lab space using L^* (lightness), a^*, and b^* modes. Six different positions were evaluated for each fruit for each treatment. Values for a^* and b^*, respectively, were averaged and the a^*/b^* ratio was calculated (Brecht *et al.* 1986). The hue angle (h°) and C parameters were also calculated as: $h^\circ = \tan^{-1}(b^*/a^*)$ and $C = (a^{*2} + b^{*2})^{1/2}$ (Voss 1992, Koukounaras *et al.* 2009).

Anthocyanin (Ant) content was determined from skin (2 g) extracted with 10 ml of 1% HCl–methanol for 24 h. The extract was filtered and its absorbance determined at 650, 620, and 530 nm, respectively. The Ant absorbance measurement was based on the formula: $(A) = (A_{530} - A_{620}) - 0.1 \times (A_{650} - A_{620})$ using a spectrophotometer (*UV-6300PC*, *Mapada*, China) and its content was determined using a molar extinction coefficient of 4.62×10^4 (Zapsalis and Francis 1965).

The Chl content was determined from skin (2 g) extracted with 10 ml of 95% ethanol at 25°C overnight. Chl in the supernatant was quantified with a spectrophotometer (*UV-6300PC*, *Mapada*, China) at 665 nm and 649 nm.

$$\text{Chl } a = 13.95\, A_{665} - 6.88\, A_{649}$$
$$\text{Chl } b = 24.96\, A_{649} - 7.32\, A_{665}$$
$$\text{Chl} = \text{Chl } a + \text{Chl } b$$

Assays were carried out three times on duplicate samples. The blank control was 95% (v/v) ethanol (Lichtenthaler and Wellburn 1983). The contents for both Chl *a* and Chl *b* were expressed as mg per g of fresh matter (FM).

Skin antioxidant components: Two grams of frozen skin was homogenized with 10 ml of ice-cold 1% HCl–methanol solution and then extracted at 4°C for 48 h, and then filtered. Absorbance was measured at 325 nm and 280 nm using a spectrophotometer (*UV-6300PC*, *Mapada*, China) and a 1% HCl–methanol solution as reference. Rutin solution was used to form a standard curve of total flavonoid. The content of phenolic compounds was calculated with the standard curve obtained on the basis of content of gallic acid expressed as mg g^{-1}(FM) (Fukumoto and Mazza 2000, Pourmorad *et al.* 2006, Tawaha *et al.* 2007).

Fruit soluble sugar: Flesh sucrose, glucose, fructose, and sorbitol standards were purchased from *Sigma-Aldrich* (St. Louise, USA). Sugars were separated and quantified by high performance liquid chromatography (HPLC) analysis (*Agilent 1100*). The HPLC system was equipped with a quaternary pump, an autosampler, a refractive index detector (RID) with carbohydrate column (*CARBOSep CHO-620 CA*, 10 µm and 6 mm × 250 mm, *Transgenomic Inc.*, USA) at 80°C with a flow rate of 0.5 ml min^{-1}. HPLC conditions were as follows: mobile phase, double distilled water; injection volume, 5 µl. Total sugar content = sucrose content + glucose content + fructose content + sorbitol content.

Fruit organic acid: Organic acid content was also analyzed by the HPLC system using a diode array detector with an *Agilent ZORBAX Eclipse XDB-C18* column (4.6 mm × 250 mm ID, 5 µm) (*Agilent Technology*, USA). The mobile phase was carried out with 0.02 mol l^{-1} KH_2PO_4 (pH 2.7). Chromatography separation was performed at 25°C with a flow rate of 0.5 ml min^{-1}. The detected organic acids were malic acid, citric acid, and quinic acid; absorbance was measured at 214 nm (total acid content = malic acid content + citric acid content + quinic acid content). The ratio between soluble sugar and organic acid was also calculated as the sugar acid ratio.

Net photosynthetic rate (P_N), stomatal conductance (g_s), transpiration (E), and water-use efficiency (WUE) were measured with an open system *CIRAS-1* portable infrared gas analyzer photosynthesis system (*PP System*, USA). WUE was calculated (WUE = P_N/E) as described by Nijs *et al*. (1997). Meanwhile, the following indicators were calculated: apparent light-use efficiency (LUE) = P_N/PAR, carbon-use efficiency (CUE) = P_N/C_i (C_i, intercellular CO_2 concentration), light-saturation point (L_s) = $1 - C_i/C_a$ (Marshall and Biscoe 1980).

Leaf Chl content and Chl fluorescence: The method was the same as the skin Chl content measurement and the mass of the leaf used in this experiment was 0.2 g. Chl fluorescence emissions of leaves of intact peach trees were measured by a fluorometer (*FMS-2*, *Hansatech Instruments Ltd*., UK). Prior to each measurement, a clip was placed on the leaf for 30 min for dark adaptation. Minimum fluorescence level in dark-adapted leaves (F_0) was determined by applying a weak modulated irradiance [6 µmol(photon) m^{-2} s^{-1}] and the maximal fluorescence level in dark-adapted leaves (F_m), was induced by applying a short pulse (0.8 s) of saturating radiation [9,000 µmol(photon) m^{-2} s^{-1}]. Then, the leaves were continuously illuminated with a white actinic light, which was equivalent to the actual growth light, in order to measure steady-state fluorescence in the light-adapted state (F_s) and maximal fluorescence level in the light-adapted leaves (F_m'). The minimal fluorescence level in light-adapted leaves (F_0') was determined by turning off the actinic light and immediately applying a 2-s far-red pulse. The maximum quantum efficiency of PSII photochemistry was calculated as $F_v/F_m = (F_m - F_0)/F_m$ (F_v, variable fluorescence level in dark-adapted leaves). The effective quantum yield of PSII photochemistry was calculated as $\Phi_{PSII} = (F_m' - F_s)/F_m'$ (Genty *et al.* 1989). The electron transport rate was also calculated according to Genty *et al.* (1989) as: ETR = ETR factor × Φ_{PSII} × PAR × 0.5, where ETR factor is 0.84. This factor corresponds to the fraction of incident radiation absorbed by various leaf species. The nonphotochemical quenching was calculated as: NPQ = $(F_m - F_m')/F_m'$ (Maxwell and Johnson 2000). Photochemical quenching coefficient (q_P) was calculated according to van Kooten and Snel (1990).

Statistical analysis: One-way analysis of variance (*ANOVA*) was carried out using an *SPSS* computer package for all datasets. The values were the means of all measurements. Comparisons of means were determined through *Duncan*'s new multiple range tests. All experimental results were presented as the mean of three replicates. A difference was considered significant at $P<0.05$.

Results

Photosynthetic characteristics of peach leaves: As seen in Table 1, Chl contents under filter treatments with various light qualities were significantly higher than the Chl content of the control. When comparing the different filters, the highest Chl contents were observed in plants under the red and yellow filters, followed by the neutral and blue filters, and the lowest one was under the green filter treatment.

Table 1. Effect of light quality on leaf photosynthetic indexes in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at $P<0.05$. Chl – chlorophyll; C_i – intercellular CO_2 concentration; CUE – carbon-use efficiency; E – transpiration; g_s – stomatal conductance; LUE – apparent light-use efficiency; L_s – light-saturation point; P_N – net photosynthetic rate; WUE – water-use efficiency.

Treatment	Control	Neutral filter	Red filter	Yellow filter	Green filter	Blue filter
Chl [mg g^{-1}(FM)]	4.66 ± 0.21[c]	4.97 ± 0.15[b]	5.25 ± 0.09[a]	5.35 ± 0.14[a]	3.58 ± 0.08[d]	4.95 ± 0.12[b]
P_N [µmol(CO_2) m^{-2} s^{-1}]	12.10 ± 0.39[b]	16.22 ± 1.01[a]	13.08 ± 1.50[b]	10.90 ± 0.98[c]	1.18 ± 0.30[d]	2.15 ± 0.49[d]
E [mmol(H_2O) m^{-2} s^{-1}]	3.74 ± 0.24[a]	4.05 ± 0.62[a]	3.82 ± 0.62[a]	3.14 ± 0.41[b]	1.24 ± 0.20[c]	1.32 ± 0.16[c]
WUE [mmol(CO_2) mol(H_2O)$^{-1}$]	3.24 ± 0.13[b]	4.07 ± 0.55[a]	3.78 ± 0.65[a]	3.86 ± 0.31[a]	0.89 ± 0.09[d]	1.74 ± 0.23[c]
LUE	12.13 ± 0.42[b]	16.32 ± 1.01[a]	13.06 ± 1.45[b]	10.97 ± 1.05[c]	1.23 ± 0.37[d]	2.15 ± 0.49[d]
CUE [mol m^{-2} s^{-1}]	0.063 ± 0.001[b]	0.079 ± 0.011[a]	0.055 ± 0.007[c]	0.048 ± 0.006[c]	0.004 ± 0.001[d]	0.008 ± 0.002[d]
C_i [µmol(CO_2) mol^{-1}]	177.00 ± 10.18[d]	214.83 ± 2.31[c]	237.50 ± 14.03[c]	230.33 ± 2.06[c]	337.83 ± 7.49[a]	290.67 ± 8.12[b]
g_s [µmol(H_2O) m^{-2} s^{-1}]	108.00 ± 9.42[b]	158.00 ± 9.30[a]	158.50 ± 9.80[a]	102.00 ± 8.13[b]	32.17 ± 8.04[c]	38.00 ± 6.16[c]
L_s	0.541 ± 0.022[a]	0.507 ± 0.024[a]	0.434 ± 0.033[b]	0.443 ± 0.014[b]	0.199 ± 0.078[d]	0.300 ± 0.081[c]

Among different treatments, the P_N, E, WUE, LUE, and CUE values were the highest under the neutral filter, and the lowest one of these five indicators was seen under the green and blue filter treatments, but the WUE of blue filter was significantly higher than that of the green filter. Compared with the control, the P_N, WUE, LUE, and CUE under neutral filter were significantly higher, but no substantial difference was observed in E. The P_N, E, and LUE in the red filter treatment did not exhibit differences in comparison with those of the control, but these values under the red filter and control were dramatically higher than those in the yellow filter treatment. Both WUE and CUE were similar in the red and yellow filter treatments, with their WUE significantly higher and CUE lower than that of control.

All the filter treatments significantly increased the C_i of leaves, especially, by the green filter. The g_s measured in the yellow filter treatment was similar to that in the control, however, those in the neutral and red filter treatments were higher than control, and that of the green and blue filters was opposite. Regarding L_s, neutral filter was similar to the control, and other filters were all significantly lower than the control, with the lowest value found for the blue filter treatment.

Therefore, the neutral filter treatment could ensure the E of peach leaves, and improve the photosynthetic capacity of leaves and the utilization efficiency of water, light, and CO_2. Those capacities were substantially reduced in the green and blue filter treatments, and were not conducive to maintenance of leaf photosynthetic performance.

Chl fluorescence parameters: No significant difference was observed in F_m between neutral filter and the control, but all other filters were substantially higher than the control (Table 2). The highest F_0 and F_m were seen in the blue filter treatment, and F_m in yellow filter was similar to that of blue filter. For the F_v/F_m, it showed no significant difference between green/blue filters and the control, while the neutral, red, and yellow filters were comparable, with the value substantially higher than that of the control.

Comparing the F_s, F_m', Φ_{PSII}, and q_P of different treatments, the blue filter treatment exhibited the highest level, followed by the green filter. In addition, these indicators in the red and yellow treatments were significantly higher than those of control, while the F_s and F_m' of the neutral treatment were comparable to those of the control group. The q_N and NPQ under various treatments showed the same pattern, and the order from the greatest to the smallest was: control, neutral, red filter > yellow filter > green filter > blue filter. The ETR of all filter treatments was significantly higher than that of the control, with the highest in blue filter, then the red filter. ETR was relatively low in the neutral, yellow, and green treatments, and the values of the latter three were similar.

Skin color: Other than neutral filter, L^* of all other light quality filters was significantly elevated with the highest level in the red and yellow filters (Table 3). Red, yellow, and green filters introduced a substantially higher b^* than the control, while no difference was seen in the neutral and blue filter treatments. The pattern of a^* and a^*/b^* in all treatments was the same with the order of control, neutral, blue filter > green filter > red filter > yellow filter, but the order of the h° was the opposite of a^* and a^*/b^*. In addition, the green filter treatment significantly improved the C of the fruits compared with the control, while yellow filter reduced it, and all others showed no substantial changes. The neutral and blue filter, along with the control, produced a desired red appearance in the color of the fruit (Fig. 1), but other treatments exhibited a light red color, which was consistent with the a^* and a^*/b^*.

Table 2. Effect of light quality on leaf chlorophyll fluorescence parameters in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at $P<0.05$. F_0 – minimal fluorescence level in dark-adapted leaves; F_0' – minimal fluorescence level in light-adapted leaves; F_m – maximal fluorescence level in dark-adapted leaves; F_m' – maximal fluorescence level in light-adapted leaves; F_s – steady-state fluorescence in the light-adapted state; F_v – variable fluorescence level in dark-adapted leaves; F_v/F_m – maximal quantum yield of PSII; NPQ – nonphotochemical quenching; q_P – photochemical quenching coefficient; Φ_{PSII} – effective quantum yield of PSII photochemistry.

Treatment	Control	Neutral filter	Red filter	Yellow filter	Green filter	Blue filter
F_0 [mV]	93.67 ± 2.50^d	87.17 ± 6.82^e	111.83 ± 6.88^b	99.83 ± 1.33^c	102.33 ± 3.01^c	139.33 ± 5.57^a
F_m [mV]	702.50 ± 24.64^d	689.83 ± 21.75^d	950.17 ± 32.15^a	875.67 ± 18.56^b	800.00 ± 13.47^c	980.83 ± 29.43^a
F_v/F_m	0.865 ± 0.003^b	0.874 ± 0.003^a	0.875 ± 0.013^a	0.881 ± 0.004^a	0.865 ± 0.005^b	0.859 ± 0.008^b
F_s	182.00 ± 8.53^d	169.83 ± 7.08^d	197.50 ± 5.24^c	218.50 ± 1.87^b	218.67 ± 2.69^b	274.00 ± 6.72^a
F_m'	285.67 ± 10.42^e	284.33 ± 10.11^e	372.67 ± 9.79^d	399.50 ± 8.93^c	449.83 ± 8.22^b	759.17 ± 8.77^a
Φ_{PSII}	0.374 ± 0.020^e	0.427 ± 0.017^d	0.470 ± 0.007^c	0.502 ± 0.013^b	0.514 ± 0.030^b	0.637 ± 0.029^a
q_P	0.564 ± 0.028^d	0.613 ± 0.030^c	0.686 ± 0.041^b	0.660 ± 0.025^b	0.660 ± 0.025^b	0.790 ± 0.021^a
q_N	0.687 ± 0.017^a	0.673 ± 0.033^a	0.689 ± 0.016^a	0.615 ± 0.024^b	0.505 ± 0.055^c	0.263 ± 0.010^d
NPQ	1.462 ± 0.091^a	1.437 ± 0.180^a	1.553 ± 0.094^a	1.196 ± 0.104^b	0.790 ± 0.160^c	0.292 ± 0.015^d
ETR [μmol m^{-2} s^{-1}]	212.12 ± 8.14^d	297.45 ± 13.54^c	342.72 ± 9.02^b	315.00 ± 8.18^c	316.61 ± 8.70^c	430.03 ± 5.64^a

Table 3. Effect of light quality on skin color in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at P<0.05. a^* – red saturation; b^* – yellow saturation; C – color chroma; h° – hue angle; L^* – lightness.

Treatment	L^*	a^*	b^*	a^*/b^*	C	h°
Control	58.08 ± 0.78^{c}	21.45 ± 2.17^{a}	20.67 ± 1.03^{b}	1.12 ± 0.25^{a}	30.77 ± 0.38^{b}	44.84 ± 1.47^{d}
Neutral filter	58.82 ± 0.55^{c}	19.83 ± 0.58^{a}	22.32 ± 0.79^{b}	0.96 ± 0.18^{a}	30.99 ± 0.22^{b}	49.39 ± 2.59^{c}
Red filter	66.33 ± 1.03^{a}	13.27 ± 0.25^{c}	25.50 ± 0.63^{a}	0.58 ± 0.04^{c}	30.33 ± 0.09^{b}	62.25 ± 1.17^{b}
Yellow filter	68.95 ± 1.23^{a}	9.68 ± 1.33^{d}	26.00 ± 0.28^{a}	0.41 ± 0.11^{d}	28.72 ± 0.28^{c}	69.30 ± 2.14^{a}
Green filter	62.57 ± 0.46^{b}	15.71 ± 0.10^{b}	25.94 ± 0.34^{a}	0.69 ± 0.08^{b}	32.19 ± 0.59^{a}	59.48 ± 2.36^{b}
Blue filter	60.54 ± 0.69^{b}	18.14 ± 2.06^{a}	22.83 ± 0.87^{b}	0.88 ± 0.16^{a}	30.50 ± 0.17^{b}	52.28 ± 3.21^{c}

Fig. 1. Skin color differences between different light quality treatments in peach. Fruit pictures represent control, neutral filter, red filter, yellow filter, green filter, and blue filter from left to right, respectively.

Table 4. Effect of light quality on skin pigment contents in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at P<0.05. Ant – anthocyanin; Chl – chlorophyll.

Treatment	Ant [nmol g^{-1}(FM)]	Chl [mg g^{-1}(FM)]	Flavonoids [mg g^{-1}(FM)]	Total phenolic content [mg g^{-1}(FM)]
Control	27.59 ± 2.24^{a}	2.89 ± 0.33^{d}	0.331 ± 0.022^{d}	0.291 ± 0.016^{c}
Neutral filter	30.51 ± 3.34^{a}	4.96 ± 0.39^{b}	0.408 ± 0.016^{b}	0.339 ± 0.019^{b}
Red filter	14.95 ± 2.20^{c}	4.50 ± 0.44^{b}	0.371 ± 0.018^{c}	0.292 ± 0.025^{c}
Yellow filter	11.97 ± 2.07^{c}	3.68 ± 0.37^{c}	0.359 ± 0.011^{c}	0.278 ± 0.014^{c}
Green filter	23.99 ± 1.07^{b}	6.08 ± 0.87^{a}	0.463 ± 0.014^{a}	0.395 ± 0.032^{a}
Blue filter	27.08 ± 2.39^{a}	5.72 ± 0.52^{a}	0.422 ± 0.021^{b}	0.352 ± 0.027^{b}

Skin pigments content: The Ant content with neutral and blue filters was similar to that of control, but all other filters exhibited a significantly lower values, especially the red and yellow filter treatment (Table 4). Various light quality treatments elevated the Chl content compared with the control, and in a comparison among the different filters, the green and blue filters exhibited the highest contents. The lowest contents were observed for the yellow filter treatment. The variation in flavonoid and total phenolic content was consistent among different filters with the highest amounts found in the green filter treatment, followed by the neutral and blue filters. The flavonoid content of all different light quality treatments was significantly higher than that of control, but no substantial differences were observed in the total phenolic content between the control and the yellow/red filters. Thus, neutral and blue filters could maintain the red appearance of peach fruits, and various light qualities slowed down the degradation of skin Chl prior to fruit maturation in peaches, leading to improved oxidation resistance.

Fruit mass and firmness: The results showed that the effect of light quality on a fruit size was considerable (Table 5). The yellow filter treatment induced the largest fruit, which was 11.7% bigger than that of the control, and the green filter led to the smallest fruits, which was only 75.2% of the control. In addition, the red and blue filters also resulted in significantly smaller fruits compared with the control, while the size in the neutral filter treatment was consistent with the control. Moreover, different light quality treatments elevated fruit firmness. Other than yellow filter, all other filters improved fruit firmness with skin. In terms of firmness without skin, all filters also produced substantial increases compared with the control, especially under the red and blue filters.

Soluble sugar, sugar alcohol, selected organic acid contents, and SSC: The filter treatments had significant impacts on the fruit sugar content in peaches (Table 6). All of the sugar components under the neutral filter treatment exhibited the highest values and were significantly higher than those of the control. The glucose, fructose, and sorbitol contents of the green and blue filters were statistically the same as the control, but the red and yellow filters exhibited relatively low contents of the sugar

Table 5. Effect of light quality on fruit mass and firmness in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at $P<0.05$.

Treatment	Fruit mass [g]	Firmness with skin [N]	Firmness without skin [N]
Control	256.27 ± 7.18^b	58.02 ± 2.41^b	26.07 ± 1.30^d
Neutral filter	252.80 ± 5.66^b	74.48 ± 1.34^a	29.89 ± 0.72^c
Red filter	224.55 ± 9.31^c	74.58 ± 1.72^a	34.99 ± 1.14^a
Yellow filter	286.32 ± 9.86^a	62.43 ± 3.53^b	28.71 ± 0.81^c
Green filter	192.79 ± 8.67^d	73.11 ± 1.39^a	31.75 ± 0.39^b
Blue filter	235.42 ± 9.84^c	75.17 ± 1.50^a	34.30 ± 1.13^a

Table 6. Effect of light quality on soluble sugar, sugar alcohol, and selected organic acid contents (all in g kg^{-1}) in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at $P<0.05$.

Treatment	Sucrose	Glucose	Fructose	Sorbitol	Malic acid	Citric acid	Quinic acid
Control	57.48 ± 1.67^b	15.71 ± 1.92^b	14.05 ± 1.05^b	10.56 ± 2.66^{bc}	3.25 ± 0.10^a	1.11 ± 0.04^c	0.99 ± 0.18^a
Neutral filter	76.96 ± 1.59^a	21.56 ± 2.44^a	18.38 ± 1.02^a	15.33 ± 2.56^a	3.06 ± 0.09^a	1.04 ± 0.09^d	1.07 ± 0.11^a
Red filter	35.20 ± 2.55^d	12.52 ± 1.48^c	11.37 ± 1.18^c	5.50 ± 0.79^d	3.32 ± 0.19^a	1.19 ± 0.06^b	1.10 ± 0.16^a
Yellow filter	41.68 ± 2.99^c	11.96 ± 1.04^c	10.30 ± 1.51^c	8.96 ± 2.12^c	3.06 ± 0.18^a	0.86 ± 0.07^e	0.98 ± 0.15^a
Green filter	45.75 ± 3.51^c	16.09 ± 1.42^b	15.47 ± 0.54^b	11.57 ± 2.57^b	3.33 ± 0.76^a	1.28 ± 0.13^a	1.11 ± 0.16^a
Blue filter	45.06 ± 3.39^c	16.39 ± 1.44^b	15.75 ± 1.48^b	9.76 ± 1.34^{bc}	3.05 ± 0.23^a	1.03 ± 0.05^d	1.19 ± 0.18^a

Table 7. Effect of light quality on soluble solid content (SSC), total sugar, and total acid contents in peach. Data represent means ± SD of three replicates. For each variable, means with *different lowercase letters* are significantly different at $P<0.05$.

Treatment	SSC [°Brix]	Total sugar [g kg^{-1}]	Total acid [g kg^{-1}]	Sugar/acid ratio
Control	17.20 ± 1.44^a	97.79 ± 1.63^b	5.35 ± 0.30^a	18.36 ± 2.58^b
Neutral filter	16.59 ± 1.03^a	132.23 ± 1.73^a	5.17 ± 0.28^a	25.64 ± 2.41^a
Red filter	13.48 ± 0.41^c	64.59 ± 6.66^c	5.62 ± 0.48^a	11.57 ± 1.62^c
Yellow filter	14.41 ± 0.61^b	72.90 ± 5.44^c	4.90 ± 0.53^a	15.10 ± 2.75^b
Green filter	17.00 ± 0.87^a	88.87 ± 2.82^b	5.73 ± 0.69^a	16.23 ± 2.50^b
Blue filter	14.54 ± 0.62^b	86.97 ± 1.87^b	5.27 ± 0.60^a	16.67 ± 1.90^b

components. The sucrose content in the red filter treatment was the lowest, and it was significantly lower than the control in all treatments except the neutral filter. No significant differences in malic acid and quinic acid content were seen between various treatments. Contents of citric acid were higher in both green and red filter treatments than that of control, with the highest in the green filter treatment; while neutral, blue, and yellow filters showed a reduced content compared with the control, with the lowest one found in the yellow filter treatment.

The SSC under the green and neutral filter treatments was comparable to that of the control, and it displayed significantly lower contents for the other filters, especially the red filter treatment (Table 7). The highest total sugar content was observed with the neutral filter, then the green and blue filters, which were similar to the control, and the lowest content was seen in the red and yellow treatments. The amount of total acid was comparable between the different treatments. The sugar acid ratio was increased by the neutral filter but reduced by the red filter compared with the control. The other filters exhibited similar contents as the control.

The above data indicated that the neutral filter treatment facilitated the accumulation of soluble carbohydrates in peach fruits, resulting in an improvement in fruit edible qualities.

Discussion

Light quality *vs.* photosynthetic and Chl fluorescence characteristics: Chl is the main pigment of photosynthesis in plants. Our data indicated that the green filter treatment resulted in the lowest Chl content, which was consistent with the results of Heraut-Bron *et al.* (1999). In addition, the P_N and E were significantly reduced in the blue and green filter treatments, and WUE, LUE, and CUE also dropped to their lowest level, which occurred probably due to the low amount of red light allowed to pass in these two filters (Table 1). The low R/FR ratio further inhibited the synthesis of Chl, and affected the water, light, and CO_2 utilization. However, the present study also demonstrated that, although the photosynthetic indicators of leaves in the blue filter treatment were lower than those of control, the Chl content increased, which is consistent with Buschmann *et al*. (1978). Moreover, due to much more red light and higher R/FR ratio under the neutral filter than other types of filters, the elevation in P_N, WUE, LUE, and CUE under this treatment promoted the transportation of photosynthetic products to fruits, leading to the improvement of the total sugar accumulation in the fruits (Table 2, Table 8). Light quality affects photosynthesis both through effects on the composition of the photosynthetic apparatus and on translocation of carbohydrates from chloroplasts (Sæbø *et al*. 1995). In the present study, P_N and L_s were significantly reduced and C_i increased in the yellow, green, and blue filter treatments compared with the control (Table 2), suggesting that the decrease of P_N under these three filter types was not caused by the change in g_s, but by the lesser transmittance of red light under these filters which caused the reduction of photosynthetic activity in mesophyll cells.

Chl fluorescence parameters are used to describe the photosynthesis mechanisms and photosynthetic physiological status of plant leaves, and to reflect the intrinsic characteristics of plants, which serve as an internal probe for studying the relationship between photosynthesis and the environment (Genty *et al*. 1989). Light quality of different light sources affected leaf PSII photochemical efficiency and electron transport efficiency (Ramalho *et al*. 2002). In the present study, it was observed that F_v/F_m and ETR of neutral, red, and yellow filter treatments, which had higher R/B than the other types of filters, was significantly higher than control, indicating that PSII photochemical efficiency and electron transport capacity in peach leaves were promoted by light quality. In addition, both activity and primary electron transport efficiency of PSII were positively enhanced by R/B. We observed that peach trees grown under neutral, red, and yellow filters showed reduced Φ_{PSII} and q_P compared to the blue filter treatment because more blue light under blue filter was more crucial for the efficient function of PSII than red light. The results suggest that the reduction in Φ_{PSII} under a certain kind of light is mostly attributed to the reduction of q_P since Φ_{PSII} is the product of q_P and the efficiency of excitation energy captured by the open PSII reaction centers (Yu and Ong 2003, Wang *et al*. 2009). However, P_N under the green and blue filters was greatly reduced in comparison with that of control, although Φ_{PSII}, q_P, and ETR were elevated and F_v/F_m did not vary. Although there was not enough red light under green and blue filter, the good ETR could supply sufficient ATP and NADPH for the Calvin-Benson cycle of peach leaves. In addition, q_N and NPQ stayed at a relatively high level under neutral and red filters, resulting in a reduction of Φ_{PSII}, a decrease of the excitation energy of charge separation in the reaction center, and an increase in the dissipation of the xanthophyll cycle.

The skin pigment content and color difference index *vs*. light quality: Many studies have reported that Ant biosynthesis is an important process that depends on light quality (Dussi *et al*. 1995, Ubi *et al*. 2006). The shortwave radiation and altered FR/R around fruits, which are treated by different colored filters, can be improved. As a result, apple, pear, and strawberry skins were influenced by light quality (Dussi *et al*. 1995, Feng *et al*. 2013, Miao *et al*. 2016). We demonstrated that different light quality filters have varying impacts on fruit color. The correlation coefficient of skin a^*, a^*/b^* and Ant content to h° was –0.9936, –0.9983, and –0.9111, respectively, indicating that the higher the skin pigment content is, the higher a^* value is, the redder the fruit is and the smaller the h° is (Francis 1980). No significant difference in a^*, a^*/b^*, and Ant content was observed in neutral and blue filter treatments compared with the control, and the Chl content under the blue filter was higher than that of the control and neutral filter. During the ripening stage, more and more red appearance with less and less green appearance of peach skin turned on (Zhang *et al*. 2015), indicating that the accumulation of Ant and reduction of Chl related to the ripening process. Different filters with various light quality affected skin colors of peach at the maturity stage. Fruits under blue filter having the higher Chl content might be due to the lower R/FR. In addition, light quality may regulate the pigment synthesis of peach fruit by altering the gene expression (Liu *et al*. 2004, Feng *et al*. 2013), and more investigation is needed to illustrate its mechanism.

Internal quality of peach fruit *vs*. light quality: The internal quality of fruit is a comprehensive quality reflected by the inner soluble sugar and titratable acid composition (Widmer 2001, Ni *et al*. 2011).

Sucrose is the major sugar component in the mature peach fruit (Vizzoto *et al*. 1996), followed by glucose, fructose, and sorbital, while malic acid, citric acid, and quinic acid are the main components of organic acids (Wang *et al*. 1993, Svanella *et al*. 1999). Here, we demonstrated that sucrose is still the dominant sugar component in the peach variety 'Xiahui 8' under various light quality treatments. So light quality did not affect the accumulation form of sugars and organic acid components in the peach fruit. Comparing all the treatments, the neutral filter treatment exhibited the highest content of sucrose, glucose, fructose, sorbitol, total sugar content, and sugar acid ratio, and its SSC was similar to that of the control, suggesting neutral filter improved fruit quality. The red filter showed the lowest sugar acid ratio among all treatments, and its SSC and sugar contents were also low, exhibiting a poor comprehensive quality. Further investigations are needed to understand the mechanisms underlying the effects of light quality on the sugar metabolism in peach fruits. The organic acid content of fruits was not significantly affected by different light quality filters, which indicated that the organic acid accumulation in peach fruits is largely influenced by genetic factors rather than environmental conditions such as light quality.

Overall, the yellow filter maintained relatively high P_N and Chl content in peach leaves, and it also increased single fruit mass, but its effect on fruit coloring was poor, leading to a decrease in internal quality. Leaves of green and blue filter treatments exhibited weak light energy and CO_2 utilization. Although the green filter facilitated the inner quality of fruits, the fruit coloring was not good, and the fruit size was small. The blue filter can maintain a good appearance in terms of fruit coloring, but fruits grown under the blue filter showed a significant decline in internal quality. Leaves under red filter treatments showed a relatively high photosynthetic capability, but the fruit quality in terms of SSC and sugar content were greatly reduced, leading to an undesirable taste. The leaf photosynthetic ability and internal quality under the neutral filter treatment were elevated compared with the control, and the appearance color was the same as the control. Therefore, the application of neutral filter in the rain-shelter cultivation of ‘Xiahui 8’ peach is recommended, because it can maintain a relatively high photosynthetic capability and improve the fruit quality.

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