

Innovative light management to improve production sustainability, overall quality, and the phenolics composition of nectarine (*Prunus persica* cv. Stark Red Gold)

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SUMMARY

This research was conducted under the framework of the ISAFRUIT Project and aimed to investigate the effects of different light micro-environments on the final overall quality of nectarine fruit production. Experiments were conducted in a commercial orchard of the nectarine (*Prunus persica*) ‘Stark Red Gold’ during 2006 and 2007. Reflective mulches were laid down in the inter-row spaces in mid-May. Those environmental conditions affected by mulching such as temperature and reflected light were monitored until fruit harvest. Fruit production per tree was enhanced by mulch-treatment in both years, but the differences were statistically significant only in 2006, when the average fruit weight was also enhanced. Nectarines became more ripe in the 2006 season, whereas no differences in the main fruit quality indices were detected in 2007. The concentrations of phenolic compounds in ripe nectarines were positively enhanced in both years. The increase in concentration of overall phenolic compounds (in mg 100 g⁻¹ fresh weight) was calculated to be approx. 60% in 2006 and 2007, indicating an interesting improvement of the nutraceutical and anti-oxidant potential of nectarines. Experiments were also conducted using UV plus white light irradiation under controlled conditions. The accumulation of phenolic compounds, specifically anthocyanin concentrations, in nectarines previously screened using paper bags were determined at different times after irradiation. The results clearly indicated an inducing effect of UV plus white light irradiation on the synthesis and accumulation of anthocyanins in fruit skin. The consequences for the colour and health potential of nectarines are discussed.

Efficient management of limited environmental resources in horticulture can be considered one of the most important tasks for sustainable, high quality fruit production. Under the framework of the ISAFRUIT Project, our research focussed on the effects of different light management regimes in an orchard, and under controlled conditions, on the final sustainability of the peach production process.

Horticultural practices have an impact on fruit appearance and quality at harvest. In peach, fruit colouration and other quality traits have been associated with the availability of light within the orchard (Corelli-Grappadelli and Coston, 1991). To increase light penetration within the tree canopy, techniques such as summer pruning (Myers, 1993) and reflective film mulches have been used (Doud *et al.*, 1980). Experiments conducted with a high density polyethylene mulch, characterised by having a reflective metalised surface, on peach cultivars selected for their poor red colouration, showed significant increases in red colour, especially on fruit from the lower part of the canopy. Moreover, such fruits were softer compared to control fruit, whereas the effects of the metalised film on peach size and soluble solids contents (SSC; Layne *et al.*, 2001) were not consistent. Phenolic compounds are important molecules that act as light-filtering pigments in all plant organs, and

are likely to be influenced by the enhanced level of reflected light produced by mulching. These compounds are also present in fruit and are known to play an important role in the health potential of foods (Stoibiecki *et al.*, 2002). Preliminary research had shown that there was an opportunity to change the accumulation of phenolics in fruit at harvest following the application of reflective mulches in the inter-row spaces of an orchard (Andreotti *et al.*, 2007).

Experiments conducted with artificial light have elucidated the role of UV light in peach colouration (Kataoka and Beppu, 2004). Controlled irradiation techniques can be considered to be valuable for investigations into the effects of this environmental parameter on the mechanism of accumulation of phenolics and colour formation in fruit. To our knowledge, however, no information is available on the accumulation of phenolic compounds, especially anthocyanins, in ripened nectarines as affected by light deprivation (on the tree or after harvest) or by artificial irradiation with UV + white light.

Our research investigated the use of a reflecting mulch as a specific cultural technique to optimise the quality of ‘Stark Red Gold’ nectarine under Italian growing conditions, with the specific aim of enhancing the nutritional and health potential of this fruit. Moreover, experiments using controlled irradiation were conducted to understand more clearly the role of this environmental factor on the mechanisms of synthesis and accumulation of phenolic compounds in general and, specifically, the anthocyanins.

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MATERIALS AND METHODS

Experiments with reflective mulches

Plant material: Trials were conducted in two consecutive seasons (2006 and 2007) on 12-year-old trees of the yellow-fleshed nectarine cultivar, 'Stark Red Gold', grafted to *Prunus persica*, trained to a vase-shape and spaced at 3 m × 4 m, for a plant density of approx. 830 trees ha⁻¹. Ten nectarine trees were chosen for their uniformity and, in mid-May, a reflective mulch (Extenday Europe Ltd., Egham, UK) was laid down on both sides of the inter-row of half of the trees (Figure 1 A). The experimental design for the trials in both years was a randomised block with five replicates of one tree each.

Harvesting followed commercial criteria and was split into several picks, depending on the ripening process of the nectarines. Fruit yield (kg tree⁻¹) was determined after harvest from the weight of all fruit from each tree selected for the trials. Samplings were performed at the most representative of the harvest, for the quantity of picked fruit and the homogeneity of quality traits in both years; specifically, the second of three harvests in 2006 (5 August) and the third of four harvests in 2007 (26 July). Twenty fruit per tree were collected at random from the outer part of the canopy at approx. 1–2 m above ground level. Biometric data and quality parameters were measured on each sampled fruit in both years, and three bulk samples per replicate were prepared for both skin and pulp tissues, and stored at –20°C for later analysis.

Environmental parameters: The relative humidity and canopy temperature of mulch-treated and untreated trees were monitored throughout the experiments using a temperature data logger (Easylog USB-2 Data Logger; MicroDAQ.com, Ltd., Contoocook, NH, USA). A lux-meter (TES-1332; CL-Electronics GmbH., Buchs, Switzerland) was used to measure the intensity of the reflected light. Measurements were performed at 12.00 h on five different days during the last month of fruit growth on the trees, and at four levels above the ground (0.5, 1.0, 1.5, or 2.0 m).

Determination of fruit quality traits and analysis of phenolic compounds: An analysis of the main fruit quality parameters was performed at harvest at the end of both seasons of experiments. The fruit quality traits measured were as follows: fruit weight (g); soluble solids content (SSC; in °Brix measured using an Atago digital refractometer; Optolab, Modena, Italy); flesh firmness (FF; in kg cm⁻² measured with an 8-mm probe on an EFFE.GI penetrometer; Ravenna, Italy), and total acidity (TA; measured by titration of 20 ml fresh juice with 0.25 M NaOH using a semi-automatic Compact-S Titrator; Crison, Modena, Italy).

Sample collection and analysis of phenolic compounds were performed following the method described in Andreotti *et al.* (2008), using 0.025 mg ml⁻¹ 6-methoxyflavone in methanol as an internal standard. The HPLC system used (Gilson Inc., Middleton, WI, USA) was set at 280 nm and equipped with a reverse-phase Supelcosil TMLC-18 HPLC column (15 cm long × 4 mm id; ODS particles 5 µm in diameter). The injection volume was 10 µl, and the flow rate was 1 ml min⁻¹.

Identification of phenolic compounds was performed

by comparing their retention times and UV-spectra (recorded at 200–400 nm with a diode array detector) against standard molecules. Catechin, epicatechin, chlorogenic acid, quercetin-3-rutinoside and 6-methoxyflavone were acquired from Sigma-Aldrich (St. Louis, MO, USA). Cyanidin-3-glucoside was from Extrasynthese (Lyon, France). Methanol and phosphoric acid for liquid chromatography were purchased from Carlo Erba (Milan, Italy).

Experiments with artificial light under controlled conditions

Experiment 1: This experiment was conducted on 'Stark Red Gold' nectarines during Summer 2007. Twenty-one bearing branches were selected for their homogeneous position within the tree canopy, and for having similar fruit characteristics (i.e., shape, size, and ripening stage). The selected branches were then detached on 30 July 2007, when the fruits were fully ripe, and transferred in a climate chamber where the temperature and relative humidity were controlled at 25°C and 60%, respectively. The ends of the branches were introduced into 50 ml tubes filled with water, in order to limit the effect of transpiration on the fruit (Figure 1 B). Skin samples from three nectarines were collected immediately after branch-detachment (time = 0 h). Nine of the remaining 18 bearing branches were treated with UV + white light (at 10,820 lux and 234 µW cm⁻²), whereas the other nine nectarine branches were excluded from the light treatment by covering them with a paper bag with a dark internal layer (Figure 1 B). The UV + white light-treated and bagged nectarines were sampled at 1 d intervals (24 h, 48 h, and 72 h) for analyses of the phenolic compounds in the skin following the methodology described above.

Experiment 2: Thirty 'Stark Red Gold' nectarine branches, each bearing one fruit, were selected on 3 July 2007 for their homogeneous characteristics, as described for Experiment 1. Fifteen nectarines still on the trees were covered with paper bags with a dark internal layer (Figure 1 C), whereas the other 15 fruit were considered controls. After 2 weeks (16 July 2007), all bearing branches with bagged or un-bagged nectarines were cut



FIG.1

Modification of the light micro-environment at the fruit level. Panel A, reflective mulches in the orchard. Panel B, bagged and unbagged nectarines exposed to UV + white light under controlled conditions. Panel C, bagged fruit on the tree.

TABLE I
Fruit yield per tree and quality characteristics of 'Stark Red Gold' nectarine at harvest, as affected by reflective mulching in 2006 and 2007

Treatment	Yield (kg tree ⁻¹)		Fruit weight (g)		SSC (°Brix)		Flesh firmness (kg cm ⁻²)		Total acidity (g l ⁻¹)	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
Control	46.0 ± 3.5 [§]	67.5 ± 10.5	162.7 ± 8.8	140.6 ± 2.3	13.7 ± 0.1	12.8 ± 0.6	5.3 ± 0.1	3.7 ± 0.4	10.2 ± 0.4	10.6 ± 0.3
Mulched	66.5 ± 7.6	90.4 ± 5.1	196.6 ± 22.7	142.1 ± 5.4	14.7 ± 0.2	12.4 ± 0.5	4.3 ± 0.2	4.5 ± 0.2	9.6 ± 0.3	10.1 ± 0.4
Significance	*	ns	*	ns	*	ns	*	ns	ns	ns

[§]Mean values ± SE (n = 10 for yield per tree) and (n = 20 for fruit quality indices).

*Significant at $P < 0.05$; ns, not significant.

from the trees and transferred to the climate chamber, set for the conditions reported in Experiment 1. The paper bags were then removed and five fruit skin samples were collected from both treatments, after 0 h, 24 h, and 72 h of UV + white-light treatment. The temperature, relative humidity, and UV + light characteristics were as described for Experiment 1. Skin samples were analysed for their phenolics concentrations using the methodology described above.

Statistical analysis

The results of the Experiments were subjected to analysis of variance and Duncan's Multiple Range Test (LSD for $P < 0.05$) using StatGraphics software Version XV (2005).

RESULTS AND DISCUSSION

Light is an important environmental parameter that determines quality traits in nectarine. Optimised management of this resource is likely to enhance final fruit quality standards. Reflective mulches are able to change major environmental parameters, specifically the light-environment at the tree canopy level (Green *et al.*, 1995). Our monitoring activity, performed throughout the duration of the Experiments with reflective mulches, showed that the average maximum temperature was increased by approx. 5°C and that the reflected light intensity on a sunny day was enhanced seven-fold, on average, at different canopy heights (data not shown).

Fruit yields per tree were higher in trees treated with the reflective mulches (Table I). In 2006, this enhancement was statistically significant and was coupled with an increase in average fruit weight at harvest. In 2007, trees growing on reflective mulch produced approx. 30% higher yield, on average, than control trees, and with fruits that were slightly heavier;

but both differences were not statistically significant. A tendency towards an increase in average fruit weight induced by mulching treatment was also seen in the pear cultivars 'Clara Frijs' and 'Doyenné de Comice' during both high and low bearing seasons (Bertelsen, 2005). Treatment with a reflective mulch induced fruit maturation processes, as shown by the higher SSC and lower FF values of nectarines at harvest in 2006 (Table I). An advancement in the fruit maturation process in peach was also detected by Layne *et al.* (2001), using reflective films laid 2 – 4 weeks before harvest in the middle, between the tree rows. The mulching effect on fruit ripening was not evident in the following year (2007), when all the fruit quality traits measured did not differ significantly.

Phenolics accumulation in 'Stark Red Gold' nectarine was at a similar level to that seen in a previous study by Andreotti *et al.* (2008). A reflective mulch changed the accumulation of phenolics in ripened nectarines. The total accumulation of phenolic compounds in mulch-treated nectarines was significantly higher ($P < 0.05$) than in control fruit in both years, in both skin and fruit pulp tissues (Table II). The average concentration of phenolics for mulch-treated nectarines was approx. 6.5 – 8.0 mg g⁻¹ DW (skin) and 1.7 – 3.0 mg g⁻¹ DW (pulp), whereas it was 3.9 – 5.2 mg g⁻¹ DW (skin) and 1.1 – 1.8 mg g⁻¹ DW (pulp) in control fruit. For each 100 g FW of nectarine [calculated as 80% (w/w) pulp and 20% skin (w/w)], the enhancement in phenolics accumulation induced by mulch-treatment was calculated to be approx. 60% in both years. Thus, the nutraceutical value of nectarines was improved by this technique.

These results may be related to the physiological role of phenolics in plants. They are UV-absorbing pigments that are present in all plant organs and are known to be affected by environmental conditions in general, and,

TABLE II
Concentrations (in mg g⁻¹ DW) of the main classes of phenolic compounds in the skin, pulp, and the edible portion of both tissues (in mg 100 g⁻¹ FW) of 'Stark Red Gold' nectarine as affected by reflective mulching

Treatment	Cinnamic acids		Flavan-3-ols		Anthocyanins		Flavonol glycosides		Total phenols	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
Control (A)										
Skin	1.7 ± 0.1 [§]	1.0 ± 0.1	1.8 ± 0.2	0.7 ± 0.1	0.7 ± 0.2	0.9 ± 0.2	0.9 ± 0.1	0.3 ± 0.1	5.2 ± 0.1	3.9 ± 0.1
Pulp	0.9 ± 0.1	0.9 ± 0.1	0.8 ± 0.1	0.2 ± 0.0	–	–	0.1 ± 0.0	–	1.8 ± 0.1	1.1 ± 0.1
Edible portion									24.4 ± 0.9	16.0 ± 0.7
Mulch (B)										
Skin	2.5 ± 0.1	2.5 ± 0.1	3.4 ± 0.2	1.0 ± 0.1	0.6 ± 0.1	2.2 ± 0.2	1.2 ± 0.1	0.3 ± 0.1	7.9 ± 0.4	6.5 ± 0.4
Pulp	1.3 ± 0.1	1.2 ± 0.1	1.6 ± 0.1	0.4 ± 0.0	–	–	0.1 ± 0.0	–	3.1 ± 0.2	1.7 ± 0.1
Edible portion									39.4 ± 2.5	25.4 ± 0.4
Significance (A vs. B) for:										
Skin	*	*	*	ns	ns	*	ns	ns	*	*
Pulp	*	*	*	*	–	–	ns	–	*	*
Edible portion									*	*

[§]Mean values ± SE (n = 3).

*Significant at $P < 0.05$; ns, not significant; –, not detected.

specifically, by light intensity and light quality (Burchard *et al.*, 2000; Kolb *et al.*, 2003; Andreotti *et al.*, 2006). Changes in the light micro-environment induced by reflective mulches are likely to be responsible for the increased accumulation of specific classes of compounds in the fruit. In our study, reflective mulching was found to enhance cinnamic acids and flavan-3-ols accumulation in nectarine skin and pulp significantly in both 2006 and 2007 (Table II). In contrast, flavonol glycosides were detected mainly in skin tissues and their accumulation was not affected by mulching in either year.

Anthocyanins accumulated mainly in fruit skin tissue. Mulching did not cause any detectable effect on their concentration in 2006; whereas their accumulation in 2007 was significantly higher, at 0.9 mg g⁻¹ DW and 2.2 mg g⁻¹ DW in control and mulch-treated nectarines, respectively. Anthocyanins are compounds characterised by having a light-dependent metabolism and their biosynthesis and accumulation are increased by enhanced irradiation, as demonstrated in other fruit species (Bakhashi and Arakawa, 2006). The influence of irradiation on phenolics accumulation in nectarines was investigated in experiments conducted under controlled conditions and by artificial irradiation with UV + white light. In Experiment 1, the concentrations of the main classes of phenolic compounds in nectarines (cinnamic acids and flavan-3-ols) were only slightly affected by UV + white light irradiation, and mainly followed the usual ripening trend (data not shown). Anthocyanins were the class of compounds most directly influenced by the different light environments imposed on harvested fruit. Nectarines analysed for anthocyanin accumulation in their skin at time 0 h, immediately after harvest from the tree, showed an average concentration of approx. 0.4 mg g⁻¹ DW (Figure 2). This concentration did not change significantly in fruit that were bagged during controlled irradiation (at 24 h, 48 h, or 72 h). However, nectarines that were exposed to UV + white light significantly increased their accumulation of anthocyanins in the fruit skin, reaching 0.8 and 1.2 mg g⁻¹ DW after 48 h and 72 h exposure, respectively. The inducing effect of UV + white light on anthocyanin accumulation in nectarine skin was confirmed in Experiment 2 (i.e., fruits bagged on the tree, then unbagged, exposed to artificial UV + white light, and compared to controls). Control fruit enhanced (doubled) their anthocyanin accumulation after exposure to artificial UV + white light (from 0.2 to 0.4 mg g⁻¹ DW)

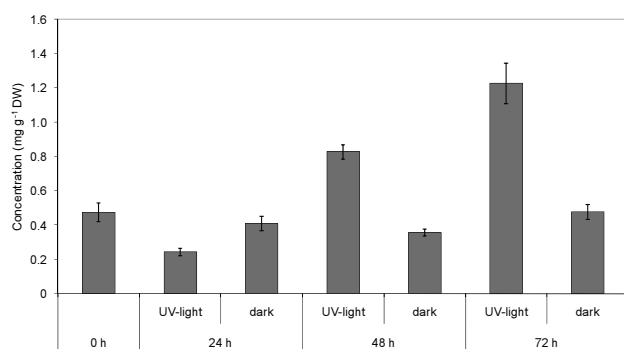


FIG. 2

Anthocyanin concentrations (in mg g⁻¹ DW) in the skin of nectarine treated with UV + white light or untreated (dark conditions) at 0, 24 h, 48 h, and 72 h sampling times (\pm SE; n = 3).

after 24 h, and reached approx. 0.8 mg g⁻¹ DW after 72 h, at the end of the Experiment (Figure 3). In those nectarines that were bagged on the tree, anthocyanin accumulation was markedly inhibited (0.05 mg g⁻¹ DW in skin tissue). UV + white light treatment of these fruit induced anthocyanin biosynthesis in the fruit skin. Higher accumulations of anthocyanins, compared to 0 h, were detectable 72 h after the application of UV + white light, when their concentration increased to 0.5 mg g⁻¹ DW (Figure 3). Enhancement of the anthocyanin content of whole fruit irradiated with UV light was also detected in the peach cultivar 'Hakuho', and the concentration was dependent on the intensity of UV irradiation, as shown in a skin disc model proposed in the same study by Kataoka and Beppu (2004). The involvement of UV irradiation in increasing the expression of genes for key enzymes involved in phenolics synthesis such as phenylalanine ammonia-lyase (PAL) and chalcone synthase (CHS) has been shown in several plant tissues (Fuglevand *et al.*, 1996) and in cells (Takeda *et al.*, 1997). A similar mechanism is also likely to be present in peach, and further UV studies may lead to improvements in final fruit colour together with nutritional value.

The main goal of the ISAFRUIT Project is to promote greater fruit consumption through a multidisciplinary approach, to enhance the quality of products using safe, sustainable, and environmentally-friendly methods. Our results consistently showed how it is possible to improve the production and quality of nectarines by optimising the light micro-climate at the fruit level. Moreover, increasing the accumulation of specific metabolites such as phenolics compounds, leading to a higher nutritional value, is an important goal of modern horticulture (Schijlen *et al.*, 2004), especially when achieved with an environmentally-safe technique such as reflective mulching. Such methods should be tested for their economic viability and sustainability under different European market conditions. Experiments using artificial light focussed on the relationship between UV light and anthocyanin levels, represent a first approach to study the biosynthesis and accumulation of these compounds in ripening nectarines and will be completed by analysing the expression of the key target genes involved in this response.

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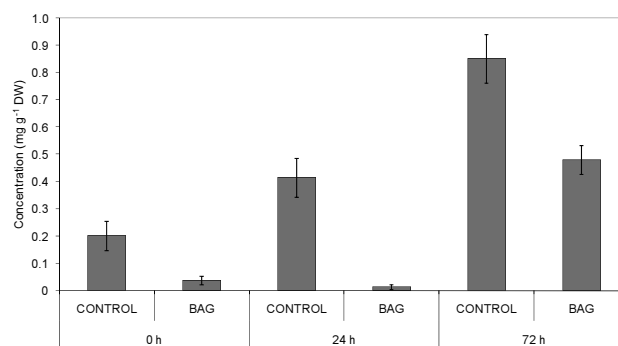


FIG. 3

Anthocyanin concentrations (in mg g⁻¹ DW) as affected by UV + white light in nectarines that were previously covered with paper bags on the trees (BAG) or in un-bagged nectarines (CONTROL) at 0, 24 h, and 72 h sampling times (\pm SE; n = 5).

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