Impact of fruit bagging and postharvest storage conditions on quality and decay of organic nectarines

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ABSTRACT

Abiotic factors such as light influence the physicochemical properties of fruit and may alter the response of the fruit to the environment. This study aimed to investigate the effect of two postharvest storage conditions on the overall quality and natural fungal disease incidence (fruit decay) of organic nectarines. Experiments were conducted with four organically grown nectarine cultivars (two early-mid season and two late-season) that were unbagged or bagged during preharvest. After harvest, they were stored for 7-9 days in darkness or under a treatment with lighting. Quality parameters (weight, diameter, firmness, soluble solids content, titratable acidity, and single index of absorbance difference), ethylene production, and fruit decay (as a percentage of rot incidence) were evaluated. Preharvest bagging reduced fruit decay in the late-season cultivars, in which storage under darkness reduced fungal decay (up to 100%) more than storage under lighting treatment (47.1% of reduction). Bagging altered the initial fruit quality, but values were within official recommendations. Storage conditions reduced differences attributed to bagging, especially under storage with lighting. This work highlighted the importance of modulating the light, both in the field by fruit bagging and during postharvest, to reduce fruit decay and improve fruit quality. This may serve as a tool for both farmers and postharvest chain managers.

Keywords: Fungal diseases; late-season cultivars; lighting treatment; postharvest chain; stone fruit; sustainable fruit production

Introduction

Peach, nectarine, plum, cherry, and apricot (*Prunus* genus) are the most economically important species of stone fruit (Mari et al. 2019). In 2019, the worldwide production of peach and nectarine was 25.7 Mt and China, Spain, Italy, and Greece were the main producers (FAO 2021). Stone fruit can suffer pathological diseases and physiological disorders, which lead to fruit losses (Mari et al. 2019; Manganaris and Crisosto 2020). Fruit decay can occur both preharvest and during the postharvest chain (Eckert and Ratnayake 1983), although postharvest losses tend to be greater than orchard losses (Porat et al. 2018). The most destructive and economically important fungal disease is brown rot, caused by *Monilinia* spp. (Mari et al. 2019; Mustafa et al. 2021), producing up to 7% and over 60% of incidence at harvest and after postharvest, respectively (Villarino et al. 2012). Other relevant diseases are caused by pathogens such as *Rhizopus* spp., *Mucor* spp., and *Geotrichum candidum* (Mari et al. 2019).

Currently, fungal diseases are mainly controlled with a combination of cultural practices (e.g. tree management and removal of natural inoculum sources) (Villarino et al. 2012; Bussi et al. 2015; Casals et al. 2015), biological control, and chemical fungicide programs applied in the orchard (De Oliveira Lino et al. 2016; Mari et al. 2019). Nevertheless, health concerns related to the environmental footprint and toxicological risks have led to a demand for chemical-free fresh fruit (Usall et al. 2015), encouraging more sustainable systems and organic agriculture.

Fruit bagging is an environmentally friendly strategy for plant protection in organic production that is extensively used in several fruit crops [e.g. apple (*Malus* spp.), pears (*Pyrus* spp.), mango (*Mangifera* spp.)] (Sharma et al. 2014). It is also a required agricultural practice in the ‘Calanda peach’ origin appellation from Teruel, Aragón (Spain) (Faci et al. 2014). This mechanical technique consists of introducing the fruit into a bag during the stone hardening phase until harvest when it is removed. Bags can be made of many materials (e.g. paraffin, plastic, paper) and can be of different colours (e.g. white, yellow, brown) (Ali et al. 2021). Bagging reduces physical injuries, fruit decay [e.g. brown rot (*Monilinia* spp)], and cracking and russeting incidence in peaches (*Prunus* *persica*) (Keske et al. 2014; Sharma et al. 2014; Campbell et al. 2021), as well as improving visual quality (e.g., colour development) and altering fruit quality (Zhou et al. 2019; Ali et al. 2021) by affecting the solar radiation that fruit receives on the tree. However, the results of this strategy are contradictory among investigations, probably due to external factors (i.e. type of bag and storage conditions) or the fruit's intrinsic properties (Sharma et al. 2014).

After harvest, the conditions in which stone fruit is stored are crucial to avoid disease and physiological disorders (Manganaris and Crisosto 2020). Temperature and relative humidity have been extensively studied. Still, the effect of white artificial lighting along the postharvest chain (i.e. packinghouses, markets, and consumers' homes) on fruit quality and disease incidence (fruit decay) has not been studied. Artificial lighting can alter many physicochemical fruit properties and improve fruit quality in peaches. For example, blue light increases total sugar content in peaches (Gong et al. 2015), and UV-B radiation reduces firmness, but it does not affect the soluble solids content and titratable acidity (Santin et al. 2019). UV-B radiation also affects plant defence signalling (Ballaré 2014) and the peach phenolic response to *Monilinia fructicola* (Santin et al. 2018). Recently, Balsells-Llauradó et al. (2021) studied the effect of postharvest storage under a photoperiod of unbagged and bagged fruit in response to artificial inoculations of *Monilinia* spp. These authors found that the light received by nectarines during preharvest modified the intrinsic fruit properties, influencing the response to *Monilinia* spp. once stored under postharvest treatments with lighting. Still, the effect of photoperiod and fruit bagging on fruit quality after postharvest storage remains unknown.

Fruit quality includes all aspects related to physical, mechanical, sensory, nutritive, and appearance properties, and properties related to food safety (Crisosto and Costa 2008). The purposes of this study were i) to evaluate the effect of bagging on fruit quality and ethylene production of four nectarine cultivars at harvest, ii) to assess the effect of fruit bagging on natural fungal disease incidence (fruit decay) under two postharvest storage treatments (darkness and lighting treatment), iii) to decipher the effect of these postharvest storage treatments on fruit quality.

Materials and methods

Plant material and fruit bagging

Four yellow-fleshed cultivars of nectarines (*P. persica* var. *nucipersica* (Borkh.) Schneider) were used for the studies. Two early-mid season cultivars (Fantasia and Venus) and two late season cultivars (Albared and Nectatinto) were obtained from organic orchards located in Lleida (Catalonia, Spain), which followed the European and national standards of organic agriculture (Generaliat de Catalunya 2022). The incidence of fruit decay and the quality measurements were assessed on unbagged fruit and fruit that was bagged in the orchard (bagged fruit). Commercial single layer white paper bags (16.5 x 21.5 cm, 32 g m^{-2}) (Gràfiques Salaet, Gandesa, Catalonia), impregnated with paraffin wax, were used to bag fruit before harvest (185, 172, 185, and 197 Julian days (Julian days = January 1st was considered as day 1) for Fantasia, Venus, Albared, and Nectatinto, respectively) using a staple to fasten the bag to the branch. The harvest date was at commercial fruit maturity based on the grower’s recommendations. Fruit was harvested at 218, 221, 250, and 260 Julian days for Fantasia, Venus, Albared, and Nectatinto, respectively. Bagged and unbagged fruit from the same sun-side of trees to avoid fruit position effects (Minas et al. 2018) were randomly harvested. Fruit was homogenized based on the single index of absorbance difference (I_{AD}) using a portable DA-Meter (TR-Turoni, Forli, Italy). A lux meter was used to assess the incident solar radiation inside the bags. Bags were removed upon arrival at the laboratory before conducting the assays and postharvest storage.

Storage conditions and evaluation of postharvest decay losses

Fruit was stored as described by Balsells-Llauradó et al. (2021). Briefly, the fruit was stored at high humidity (20 ºC, 90 ± 3 % RH) for 24 h at darkness, and then placed in a postharvest chamber under two controlled shelf-life conditions, both at 22 ± 2 ºC and 50-90 % RH. The darkness treatment consisted of complete darkness, and the treatment with light consisted of a photoperiod of 12h/12h (light/darkness) with four incandescent white TL-D 36 W/827 fluorescent lights (temperature = 2700 K, 3350 lm, 350 - 740 nm, 630 nm max.; Philips, Madrid, Spain). Experiments were conducted with 4 replicates of 5 fruits each in each bagging condition and postharvest storage combination for each cultivar. Fruit was examined daily to detect decayed tissue. The evaluation was recorded for 9 days in early-mid season cultivars. Due to the early and high perishability in late-season cultivars, evaluations were conducted for up to 7 days. The incidence of fruit decay was calculated as the percentage of fruit with natural fungal disease symptoms. Identification of fungal agents was carried out following the EPPO standard PM 7/18 (3) (Bulletin OEPP/EPPO 2020) and Mari et al. (2019).

An economic evaluation between bagged and unbagged fruit was conducted considering the production of an organic orchard of one hectare in Ebro Valley area. Orchard characteristics and average prices (cost of paper bags and labour input for bagging and bag removal) are listed in Table 1. Once the results of fruit decay after postharvest storage were obtained, the cost-effectiveness of fruit bagging was also calculated in Table 2.

Quality characteristics and ethylene measurements

Quality characteristics were measured according to Baró-Montel et al. (2019), i.e. weight, cheek diameter (CD), flesh firmness (FF), soluble solids content (SSC), titratable acidity (TA), and the I_{AD}. These measurements were performed on the harvest day (initial fruit quality) and at the end of the postharvest storage period. Experiments were conducted with 4 replicates of 5 fruits each in each bagging condition and postharvest storage combination for each cultivar. After postharvest storage, changes in quality were calculated in relation to initial fruit quality (as percentages) for each cultivar, bagging condition, and postharvest storage, following the formula [(initial quality - final quality) / initial quality x 100]. Ethylene measurements of fruit at harvest were determined as described by Giné-Bordonaba et al. (2017). Fruit was placed in 3.8 L sealed flasks for 2 h. After ethylene measurements, the fruit was returned to their respective postharvest storage condition. Ethylene was measured using 4 replicates of 3 fruit each, for each bagging condition and postharvest storage combination per cultivar.

Statistical analysis

JMP® software version 14.2.0 (SAS Institute Inc., Cary, NC, USA) was used to analyse the data statistically. All data were checked for the assumptions of parametric statistics and were transformed when needed. Ethylene production data (nL kg^{-1} h^{-1}) were subjected to Log transformation. Analysis of variance (ANOVA) was applied to the data, and when the analysis was statistically significant, Tukey's HSD test ($p \leq 0.05$) was used to compare the incidence of fruit decay at each time point for each cultivar. To compare the two different means of bagging conditions or the two postharvest storage conditions, Student's T-test ($p \leq 0.05$) was used. Pearson correlation analyses were conducted between fruit decay and fruit quality at the end of the storage for cv Albared using the software SigmaPlot (v. 13.0). Correlations were significant at $p \leq 0.05$.

Results

Preharvest fruit bagging slightly impaired fruit quality and ethylene at harvest

To assess the effect of fruit bagging on quality, and the decay of nectarines after postharvest storage, the quality at harvest (initial quality) was initially evaluated. Paper bags allowed up to 76% of the light intensity to pass on the south-south-east side of the trees. This led to significant differences in all quality parameters based on the different bagging conditions of the cultivars (Table 3). In cv. Venus, bagged fruit had significantly smaller weight and CD than unbagged fruit (15.5% and 6.5% lower, respectively), whereas only Albared bagged fruit was significantly larger (25.7% and 8.3% higher weight and CD, respectively) than unbagged fruit. Bagging the fruit also significantly ($p \leq 0.05$) impaired the I_{AD} (e.g., reduced maturity) in the early-mid season cv Venus (Table 3). In contrast, in the late season cultivars the I_{AD} was significantly smaller (more mature fruit) in the bagged fruit than in the unbagged fruit. Fruit bagging also altered FF in both early-mid season cultivars, although not in the same direction (Table 3). Ethylene levels differed significantly in Fantasia only, i.e., unbagged fruit produced 6.9-fold higher ethylene levels than bagged fruit.

Fruit bagging reduced fruit decay during postharvest and was cost-effective

In unbagged fruit, the incidence of disease was higher in the late cultivars (up to 75 - 85%) than in the early-mid season ones (up to 30 - 35%) (Figure 1). The onset of disease was observed earlier (one day after storage) in the late cultivars than in the early-mid ones (4 – 6 days after storage). The fungal pathogens detected were mainly *Monilinia* spp. (especially *M. fructicola*), and *Rhizopus* spp.

Overall, fruit bagging reduced and even prevented the appearance of decay during postharvest, in some cases to 0 (Figure 1). In unbagged cv Fantasia, fruit decay was found to be 5% under darkness and 10% under lighting storage, which was slightly higher than bagged fruit (0 and 5%, respectively) at the end of storage, although not statistically significant (Figure 1A). Unbagged nectarines of cv Venus had more disease under both darkness and lighting (35 and 20%, respectively) than bagged fruit (0% in both postharvest conditions) after 9 days of storage (Figure 1B). This represented a 100% reduction in both postharvest conditions.

In both late season cultivars, fruit decay was observed from the first day of storage, and gradually increased along storage time (Figure 1C, D). Fruit decay was observed in cv Nectatinto in all conditions on all days of storage. In unbagged fruit of Nectatinto, decay was already 15 and 10% under darkness and lighting after 1 day of storage, respectively, and increased steadily thereafter. At day 7, decay of fruit ranged from 35 to 65%, although the differences among bagging and storage conditions were not significant on any individual day. In cv Albared, the disease incidence in unbagged fruit was prominent at day one of storage in both treatments (35 and 50%, respectively. Figure 1D). Decay increased with increasing storage time and reached 75 and 85%, respectively, at 7 days. Interestingly, no decay was observed in the bagged fruit stored under darkness. Contrarily, the bagged fruit stored in the lighting treatment developed disease symptoms on day 4 of storage. Decay in unbagged fruit was significantly higher ($p \leq 0.05$) than bagged fruit under both postharvest treatments (100 and 47.1% of reduction, respectively).

The economic evaluation indicated that fruit bagging was cost-effective for the four nectarine cultivars tested in this study. For example, the organic nectarine orchard produced approximately 22.5 t ha^{-1} of fruit and achieved up to 27 k € ha^{-1} (Table 1). In this study, the unbagged early-mid season cultivars showed 25% postharvest losses (after 6 days of storage under darkness at 20 °C) representing a loss of 6750 € ha^{-1} (Table 2).

Similarly, the late season cultivars displayed postharvest losses of up to 60% (after 3 days of storage under darkness at 20 °C), representing a loss up to 16,200 € ha^{-1}. Considering the cost of the paper bags and the labour input for bagging and bag removal (Table 1), fruit bagging was still worthwhile compared to production without bags, being much more cost-effective when considering the late cultivars (+ 10,575 €) compared with the early-mid season cultivars (+ 1,125 €).

Postharvest storage minimised fruit quality differences between bagging conditions

The effect of bagging was also evaluated in terms of fruit quality changes suffered after postharvest storage. Under darkness, most of the quality parameters were similar in bagged and unbagged fruit, although there were small but significant differences in two cultivars (Table 4). Unbagged Fantasia fruit was significantly larger (i.e. weight and CD) and had lower I_{AD} and FF compared to bagged fruit. However, in Albared, unbagged fruit had significantly higher I_{AD}, FF, and SSC/TA ratio but lower SSC and TA than bagged fruit.

Under storage with lighting storage, the quality of bagged and unbagged fruit was more uniform in all cultivars (Table 5). Bagged fruit of Fantasia had significantly higher firmness, SSC, and TA values than unbagged fruit (9 vs 6.6 N, 12.7 vs 11.9 °Brix and 7.5 vs 5.8 g L^{-1}, respectively). However, no effect attributable to bagging was observed in Venus under lighting, and only a significant difference in weight or CD was observed in the late cultivars (Table 5).

To putatively relate fruit quality with fruit decay, a correlation analysis was conducted. The results showed that, for example, in Albared, TA was negatively correlated with fruit decay (R^2 = - 0.97, p = 0.026) whereas the correlation between SSC/TA ratio and decay was positive (R^2 = 0.93, p = 0.0067; Figure 1, Table 4, Table 5).

Changes in fruit quality under darkness vs lighting in relation to harvest day

To evaluate which postharvest storage condition triggered a greater change in fruit quality, the percentage of reduction or increase was calculated relative to the initial quality for each postharvest condition, bagging condition, and quality parameter. There were differences between storage conditions within each bagging condition in some cultivars (Figure 2). Size parameters (weight and CD) altered the least in comparison to initial quality; reductions were below 19% for all cultivars except Nectatinto (16 – 33%) and Albared bagged and stored under darkness (30%). In contrast, reductions in FF and I_{AD} were the highest (40 to 92% reduction).

In bagged fruit, the reductions of weight and CD under darkness were significantly greater than under lighting conditions, in both Fantasia and Albared (Figure 2A). The reduction in I_{AD} under darkness was significantly lower than under lighting in Nectatinto, and in Fantasia the reduction in FF under darkness was significantly lower than under lighting (Figure 2B). In addition, the SSC/TA ratio increased in Fantasia and Nectatinto cultivars under both storage conditions. However, the changes in SSC/TA ratio in darkness vs lighting were significant in Venus and Albared, but in opposite directions (Figure 2C).

Changes observed in unbagged fruit were like those observed for bagged fruits. The reduction of weight and CD under darkness was significantly higher than under lighting in both Fantasia and Nectatinto nectarines (Figure 2D). Although there were no differences in the I_{AD}, the reduction of FF was significantly smaller in Fantasia under darkness than under lighting (Figure 2E). The increase of SSC/TA ratio under lighting was higher than under darkness in all unbagged cultivars, although the difference was significant only in Fantasia (Figure 2F).

Discussion

Effects of preharvest fruit conditions on fruit quality at harvest

Fruit undergoes physiological changes throughout its development, and external factors are crucial in determining fruit quality. Bagging fruit during its development influences the quantity (intensity) of solar irradiation that it receives in the field but also the light quality (wavelength of electromagnetic spectrum, i.e. colour) that irradiates the fruit. In the work reported here, the reduction of light intensity was around 24%, suggesting that bagging could have impaired some fruit quality parameters. This could explain the differences between bagged and unbagged fruit in FF and SSC in Fantasia and Venus, and the relatively small effect in Nectatinto and Albared. In a study conducted with UV-B radiation, it was shown that UV-B radiation reduced the activity of cell wall-modifying enzymes (e.g. pectin methylesterase and polygalacturonase), leading to loss of firmness, but without affecting the SSC and the titratable acidity (Santin et al. 2019). This suggests that a better understanding of the mechanisms underlying the effects of white light quality on FF and sugar content could help to ensure desired quality.

In organic peaches, fruit bagging was also found to alter the I_{AD} (Campbell et al. 2021), and I_{AD} values were correlated with chlorophyll content (Spadoni et al. 2016). In the presented work, the I_{AD} in 3 out of 4 of the bagged cultivars was strongly differentiated on the harvest day. This could also be explained by the cultivar-dependent effect that influence the fruit quality (e.g. FF, SSC, and TA) (Iglesias and Echeverría 2009). The bagging process as well as shortening the bagging duration, can delay chlorophyll degradation and improve the anthocyanin content in peach peel, respectively (Zhou et al. 2019). Overall, changes related to FF, chemical content, and pigmentation were related to the presence or absence of bags in the field. This suggests that the producer should consider the type of bag and the specific cultivar response before bagging the fruit.

Altered fruit quality and fruit decay incidence

Host susceptibility to pathogens can depend on the ongoing physicochemical and physiological changes during fruit development and ripening, as well as the fruit characteristics intrinsic to the cultivar (Baró-Montel et al. 2020). In the work reported here, TA and SSC/TA were negatively and positively correlated, respectively, with fruit decay. Sugars are the major soluble solids in fruit juice and have been implicated in biotic (Kou et al. 2018) and abiotic stress responses (Wang et al. 2013). Among sugars, sucrose was the major soluble sugar, ranging from 55.74% to 72.96% of the total sugar content (Reig et al. 2013). The development of brown rot (*Monilinia* spp.), the main disease of stone fruit, has been positively associated with sucrose (Baró-Montel et al. 2020) and SSC (Gradziel 1994) as nutrients for fungal growth. Hence, fruit quality of different cultivars stored under different conditions either favoured or restricted the onset of fruit decay.

Ethylene is also involved in the responses to abiotic (Müller and Munné-Bosch 2015) and biotic stresses, either acting against necrotrophic pathogens (Glazebrook 2005) or being conductive to disease susceptibility (Van Der Ent and Pieterse 2012). Here, ethylene production was reduced by fruit bagging in Fantasia (6.9-fold difference between unbagged and bagged fruit), but increased slightly in the other cultivars tested (Table 3). Ethylene is required for fruit softening (Hayama et al. 2006), and, as expected, the highest ethylene production was accompanied by a reduced FF. The high ethylene production in unbagged Fantasia fruit may have increased susceptibility to fruit decay, as well as the high ethylene production in late-season cultivars, which presented an increased fruit decay incidence. In nectarines artificially inoculated with *Monilinia* spp., fruit bagging altered ethylene production during postharvest, but all fruit was susceptible to *Monilinia* spp. under both treatments (Balsells-Llauradó et al. 2021). In the study reported here, ethylene production in late cultivars may have favoured ripening-associated events, such as loss of FF, which made the fruit more susceptible to decay.

The reduction of fruit decay by fruit bagging was cultivar- and postharvest storage-dependent, but was cost-effective

Infections occurring along the postharvest chain can remain quiescent or cause latent infections until favourable factors trigger disease development (Luo et al. 2005; Garcia-Benitez et al. 2020). Incubation in humidity with photoperiod lighting favours naturally occurring diseases in peaches (Villarino et al. 2012). Here, the incubation period of the observed decay suggested that the early-mid season cultivars probably had relatively more quiescent conidia that developed later in time. In contrast, the late cultivars probably had relatively more field-occurring infections that remained briefly latent and were visible early in storage (Figure 1A, B). For peaches, bagging is common in late cultivars, which are exposed to more favourable climatic conditions for pests and diseases than early cultivars, to protect the fruit against insects such as the Mediterranean fly (*Ceratitis capitata*) (Faci et al. 2014) and other fungal diseases such as brown rot caused by *Monilinia* spp. (Mari et al. 2019). However, in orchards with high brown rot disease pressure, neither biological nor chemical treatment were completely effective (Casals et al. 2021). Thus, the low efficacy of bagging could be attributed to a high inoculum pressure in the field, especially in Nectatinto.

In this study, exposure to darkness also reduced fruit decay, in a cultivar- and bagging-dependent manner (Figure 1B, D). Roeber et al. (2021) found that impaired solar radiation affected both abiotic and biotic stress-triggered responses. UV-B radiation can also regulate plant metabolisms such as gene expression of terpene synthases and the content of terpenoids and phytoalexins in peaches (Liu et al. 2017; Santin et al. 2021). In particular, the expression of terpenoids and phenylpropanoids has been implicated in both susceptibility and resistance of nectarines to *Monilinia laxa* (Balsells-Llauradó et al. 2020). Hence, in this study, the distinct level of solar radiation caused by fruit bagging may have induced changes in fruit that differentially affected their ability to face pathogens under different postharvest storage conditions. Deciphering the role of secondary metabolites (e.g. phenolics, terpenoids, and phenylpropanoids) in response to both pathogens and lighting conditions could improve our understanding of the disease development.

Scarce information exists related to the economic viability of fruit bagging (Blasi et al. 2017), which does not specify whether or not the losses occurring during the postharvest chain are considered. The economical evaluation conducted in this study to test the differences between an orchard with or without bagged fruit, suggested that if fruit bagging is applied in similar orchards to the ones reported in this study (i.e. Ebro Valley area), bagging would be cost-effective, especially in late-season cultivars.

Fruit quality parameters were within official and recommended ranges

All cultivars were harvested at commercial maturity date according to grower's recommendation, and all quality characteristics on harvest day and after either storage condition were within international recommendations (OECD 2010; European Commission 2019). Fruit size on harvest day and after the different storage conditions (Tables 3, 4, 5) was within specifications and accepted tolerances (European Commission 2019). There are no official recommendations for I_{AD}, but all cultivars were within the limits for nectarines at harvest date (0.3- 1.5), as described by Reig et al. (2012). Values of I_{AD} after postharvest storage were also within commercial maturity limits (0 – 1.5) described by Spadoni et al. (2016). Published studies report that FF values should range from 40 to 65 N after harvest, depending on the intended use, and decrease during postharvest storage (Reig et al. 2017). This range was slightly below our results except for cv Albared (Table 3), but we also found that FF decreased during storage. The recommended FF at consumption ranges from 3 to 13 N (Crisosto 2002; Bonany et al. 2014), which was in line with the results of this study (except for cv Nectatinto), after both storage conditions.

SSC should be ≥ 8 °Brix (OECD 2010; European Commission 2019), although some studies suggest at least 10 °Brix for consumer acceptance (e.g., Crisosto and Crisosto 2005). Initial TA values ranged from 3.3 to 10 (which included the range of sweet and nonsweet nectarine cultivars; Colaric et al. 2005; Reig et al. 2012), except for Nectatinto, which had TA < 3.3, placing this cultivar in the sub-acid category (Iglesias and Echeverría 2009; Reig et al. 2012). However, eating quality is better described by the sugar-to-acid ratio (SSC:TA) rather than TA or SSC alone (Crisosto et al. 2006; Iglesias and Echeverría 2009; Bonany et al. 2014). After storage, Nectatinto remained in the sub-acid cultivar under both postharvest storage conditions due to its high SSC/TA ratio (> 2). After storage at both postharvest conditions, also Albared nectarines became sub-acid, especially after storage with lighting for both bagged and unbagged fruit.

Fruit quality was better maintained under storage with lighting

After postharvest storage under darkness, the bagging condition had more pronounced effects on the quality of fruits stored under darkness than those stored under lighting conditions in comparison to the initial quality (Tables 4 and 5). The bag effect was conspicuous mainly in Fantasia and Albared under darkness and lighting. In addition to changes attributable to cultivar (Iglesias and Echeverría 2009), a recurrent photoperiod can reduce the response to subsequent stresses (Roeber et al. 2021). This suggested that the effect of sunlight on fruit may have subsided after storage under darkness or lighting in Fantasia and Albared.

The percentage change relative to initial quality suggested which postharvest storage condition had a greater effect on fruit quality for each bagging condition. A moderate weight loss was observed after both treatment storages, with some exceptions (Figure 2). Loss of 5 to 8% of the fruit's water content may cause visual shrivelling in peaches and nectarines, although the degree of shrivelling is cultivar-dependent (Crisosto et al. 2020). In cv. Nectatinto, which presented the highest weight loss in almost all conditions, shrivelling was barely appreciable (data not shown). Interestingly, storage with lighting induced a lower weight reduction than darkness in half of the cultivars, suggesting that lighting may have maintained fruit integrity. However, further research integrating all factors that affect water loss in fruit is needed (Lufu et al. 2020).

The I_{AD} and FF values differed little between storage conditions within each bagging condition. The I_{AD} values decreased greatly in all cultivars (53 and 92%), probably because of the ongoing ripening during shelf life (Manganaris et al. 2017), causing a decrease in the chlorophyll content and an increase in other pigments, such anthocyanins (Bassi and Monet 2008; Ramina et al. 2008). No studies have reported the effect of white lighting on these quality parameters, but a combination of white, blue, and green light irradiation was reported to increase the anthocyanin content and phenylalanine ammonia lyase activity in sweet cherries (Kokalj et al. 2019). In the work reported here, FF was also reduced sharply (75 to 92%) in all cultivars. Flesh firmness is regulated by a variety of cell wall modifications, including depolymerization and modifications of polymers (Brummell et al. 2004). Beyond the white light spectrum, blue light treatment reduces firmness in peaches during storage (Gong et al. 2015). Hence, investigation of the effects of white light on factors related to ripening (e.g., I_{AD} and FF) is needed.

Depending on the bagging condition and cultivar, storage conditions with lighting increased the SSC/TA ratio in some cases (Figure 2), suggesting that light irradiation can favour the conversion of starch to sugars, and hence, decrease the acidity. Although there are no previous reports of the effect of white artificial lighting on fruit quality, a treatment with artificial blue light enhances total sugar content in peaches during storage (Gong et al. 2015). Hence, the results reported here suggested that lighting during the postharvest chain influenced the fruit quality, although dependent on the preharvest conditions (bagging or not).

Conclusions

The results demonstrated that fruit bagging reduced the incidence of fruit decay during postharvest storage, especially in fruits from orchards with high inoculum pressure (late-season cultivars). Fruit bagging was cost-effective for both late and early-mid season cultivars. Postharvest storage under lighting increased fruit losses, and hence, storage under darkness was preferable. Fruit quality on harvest day and after storage were within international recommendations, irrespective of bagging conditions. Therefore, both preharvest and postharvest management (bagged fruit and postharvest storage like the described darkness condition) should be considered by growers and distributors for sustainable fruit production and to ensure desirable fruit quality for the marketplace.

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Table 1. Orchard characteristics for one hectare and average costs (bags, labour, removal of bags) in Ebro Valley area, Catalonia, Spain.

Orchard data		
	Trees ha^{-1}	625
	Fruits $tree^{-1}$	180
	Average fruit weight (kg $fruit^{-1}$)	0.2
	Fruit yield ha^{-1} (kg ha^{-1})	**22,500**
	Price kg^{-1} (€ kg^{-1})	1.2
	Total production (€ ha^{-1})	**27,000**
Bagged orchard		
Base data	Cost of white paper bags (€ bag^{-1})	0.008
	Bagging rate by worker (bags $hour^{-1}$)	400
	Labour time input for bagging (hours ha^{-1})	281.3
	Average cost for labour (€ $hour^{-1}$)	10
	Costs of bag removal (€ kg^{-1})	0.085
Costs of bagging		
	Cost of bags (€ ha^{-1})	900.00
	Cost of labour for bagging (€ ha^{-1})	2812.50
	Cost of labour for bag removal (€ ha^{-1})	1912.50
	Total cost of bagging (€ ha^{-1})	**5625.00**

Table 2. Cost-effectiveness of fruit bagging between a bagged and unbagged orchard. Percentages of postharvest losses were taken from Figure 1.

Bagged orchard				
Assuming 0% postharvest losses	Production - cost of bagging	**21,375 € ha^{-1}**		
Unbagged orchard			**Differences between bagged and unbagged production**	
Mid-early cv. (assuming 25% losses)				
	Losses	6,750 € ha^{-1}		
	Final production	**20,250 € ha^{-1}**	Bagged - unbagged	1,125 € ha^{-1}
Late cv. (assuming 60% losses)				
	Losses	16,200 € ha^{-1}		
	Final production	**10,800 € ha^{-1}**	Bagged - unbagged	10,575 € ha^{-1}

Table 3. Fruit quality on harvest day of four nectarine cultivars. Quality parameters are listed with the measurement unit in brackets. Weight, cheek diameter (CD), single index of absorbance difference (I_{AD}), flesh firmness (FF), soluble solids content (SSC), titratable acidity (TA), SSC/TA ratio, and ethylene levels of preharvest bagged fruit (B) and unbagged fruit (UB). Values represent the mean (4 replicates, 5 fruits each) ± the standard error of the mean. Lower case letters indicate significant differences ($p \leq 0.05$) between bagging conditions within each cultivar. No letter indicates no significant differences.

Cultivar	Pre-harvest	Weight (g)	CD (mm)	I_{AD}	FF (N)	SSC (°Brix)	TA (g L^{-1})	SSC/TA ratio	Ethylene (nL kg^{-1} h^{-1})
Fantasia	B	144.5 ± 7.1	63.4 ± 1.1	0.9 ± 0.0	75.7 ± 1.2 a	12.2 ± 0.1 a	8.1 ± 0.6	1.6 ± 0.1	139.8 ± 67.3 b
	UB	160.1 ± 7.2	65.4 ± 1.0	1.0 ± 0.0	70.2 ± 1.8 b	11.9 ± 0.1 b	9.7 ± 0.4	1.3 ± 0.1	961.6 ± 298.1 a
Venus	B	178.9 ± 9.8 b	67.3 ± 1.3 b	0.7 ± 0.0 a	68.8 ± 1.3 b	10.6 ± 0.2 b	6.6 ± 0.6 b	1.5 ± 0.1	58.2 ± 8.2
	UB	211.7 ± 10.2 a	72.0 ± 1.2 a	0.6 ± 0.0 b	74.1 ± 2.1 a	11.5 ± 0.2 a	8.6 ± 0.2 a	1.3 ± 0.0	54.9 ± 2.8
Nectatinto	B	249.0 ± 11.1	77.8 ± 1.2	1.1 ± 0.0 b	73.7 ± 3.7	11.7 ± 0.3	2.9 ± 0.1	4.2 ± 0.2	208.9 ± 40.0
	UB	221.2 ± 10.7	75.4 ± 1.0	1.2 ± 0.0 a	68.9 ± 3.8	12.3 ± 0.3	3.0 ± 0.1	4.1 ± 0.1	158.5 ± 24.1
Albared	B	251.5 ± 7.1 a	77.1 ± 0.7 a	0.7 ± 0.0 b	59.6 ± 2.0	14.8 ± 0.3	7.9 ± 0.5	2.0 ± 0.1	237.9 ± 103.0
	UB	200.0 ± 8.3 b	71.1 ± 1.0 b	0.8 ± 0.0 a	58.9 ± 3.1	13.7 ± 0.6	7.3 ± 0.7	1.9 ± 0.1	193.6 ± 65.4

Table 4. Fruit quality of four nectarine cultivars after darkness postharvest storage. The storage period (22 ± 2 ºC and 50-90 % RH) was 9 days for Fantasia and Venus cultivars, and 7 days for Nectatinto and Albared cultivars. Weight, cheek diameter (CD), single index of absorbance difference (I_{AD}), flesh firmness (FF), soluble solids content (SSC), titratable acidity (TA), and SSC/TA ratio. Values represent the mean (4 replicates, 5 fruits each) ± the standard error of the mean. Lower case letters indicate significant differences ($p \leq 0.05$) between bagging conditions, within each cultivar. No letter indicates no significant differences.

Cultivar	**Pre-harvest**	**Weight (g)**	**CD (mm)**	**I_{AD}**	**FF (N)**	**SSC (°Brix)**	**TA (g L^{-1})**	**SSC/TA ratio**
Fantasia	B	116.9 ± 6.4 b	57.3 ± 1.0 b	0.3 ± 0.0 a	13.9 ± 1.7 a	12.7 ± 0.2	7.1 ± 0.6	1.8 ± 0.2
	UB	134.7 ± 5.5 a	60.6 ± 0.9 a	0.2 ± 0.0 b	7.4 ± 0.4 b	12.6 ± 0.2	8.1 ± 0.3	1.6 ± 0.1
Venus	B	160.1 ± 7.9	62.3 ± 1.2	0.2 ± 0.0	7.7 ± 0.6 a	12.8 ± 0.4	7.3 ± 0.2	1.8 ± 0.1
	UB	177.6 ± 5.7	66.7 ± 0.9	0.2 ± 0.0	6.1 ± 0.3 b	12.5 ± 0.5	7.8 ± 0.5	1.6 ± 0.1
Nectatinto	B	168.0 ± 8.0	66.7 ± 1.2	0.7 ± 0.1	15.5 ± 1.1	14.2 ± 0.5	3.3 ± 0.1	4.5 ± 0.3
	UB	161.2 ± 8.6	66.7 ± 1.2	0.5 ± 0.1	17.2 ± 1.4	13.0 ± 0.5	3.1 ± 0.2	4.2 ± 0.2
Albared	B	175.0 ± 6.2	65.3 ± 1.0	0.1 ± 0.0 b	6.0 ± 0.4 b	15.7 ± 0.3 a	7.0 ± 0.4 a	2.2 ± 0.1 b
	UB	174.0 ± 5.9	66.2 ± 0.8	0.1 ± 0.0 a	8.4 ± 0.8 a	14.7 ± 0.4 b	4.5 ± 0.3 b	3.4 ± 0.4 a

Table 5. Fruit quality of four nectarine cultivars after postharvest storage under light. The storage period 22 ± 2 ºC and 50-90 % RH) was 9 days for Fantasia and Venus cultivars, and 7 days for Nectatinto and Albared cultivars. Weight, cheek diameter (CD), single index of absorbance difference (I_{AD}), flesh firmness (FF), soluble solids content (SSC), titratable acidity (TA), and SSC/TA ratio. Values represent the mean (4 replicates, 5 fruits each) ± the standard error of the mean. Lower case letters indicate significant differences ($p \leq 0.05$) between bagging conditions, within each cultivar. No letter indicates no significant differences.

Cultivar	**Pre-harvest**	**Weight (g)**	**CD (mm)**	I_{AD}	**FF (N)**	**SSC (°Brix)**	**TA (g L^{-1})**	**SSC/TA ratio**
Fantasia	B	137.4 ± 7.9	62.4 ± 0.9	0.3 ± 0.1	9.0 ± 0.7 a	12.7 ± 0.2 a	7.5 ± 0.2 a	1.7 ± 0.0
	UB	152.9 ± 4.8	63.8 ± 0.9	0.2 ± 0.0	6.6 ± 0.4 b	11.9 ± 0.2 b	5.8 ± 0.2 b	2.0 ± 0.1
Venus	B	168.4 ± 6.1	64.8 ± 1.0	0.2 ± 0.0	7.6 ± 0.6	11.8 ± 0.2	8.2 ± 0.3	1.5 ± 0.1
	UB	181.8 ± 7.3	67.1 ± 0.9	0.2 ± 0.0	7.1 ± 0.5	12.8 ± 0.2	7.5 ± 0.3	1.7 ± 0.1
Nectatinto	B	166.6 ± 10.6	66.8 ± 1.4 b	0.5 ± 0.1	15.9 ± 1.5	12.5 ± 0.5	3.2 ± 0.3	4.2 ± 0.6
	UB	185.5 ± 6.0	70.1 ± 0.9 a	0.6 ± 0.1	15.0 ± 1.1	13.5 ± 0.4	3.0 ± 0.2	4.8 ± 0.3
Albared	B	227.1 ± 12.3 a	72.3 ± 1.3	0.1 ± 0.0	7.8 ± 0.7	15.6 ± 0.5	4.9 ± 0.3	3.2 ± 0.2
	UB	183.1 ± 7.2 b	69.0 ± 1.0	0.1 ± 0.1	7.1 ± 1.1	14.7 ± 0.7	4.1 ± 0.2	3.3 ± 0.0

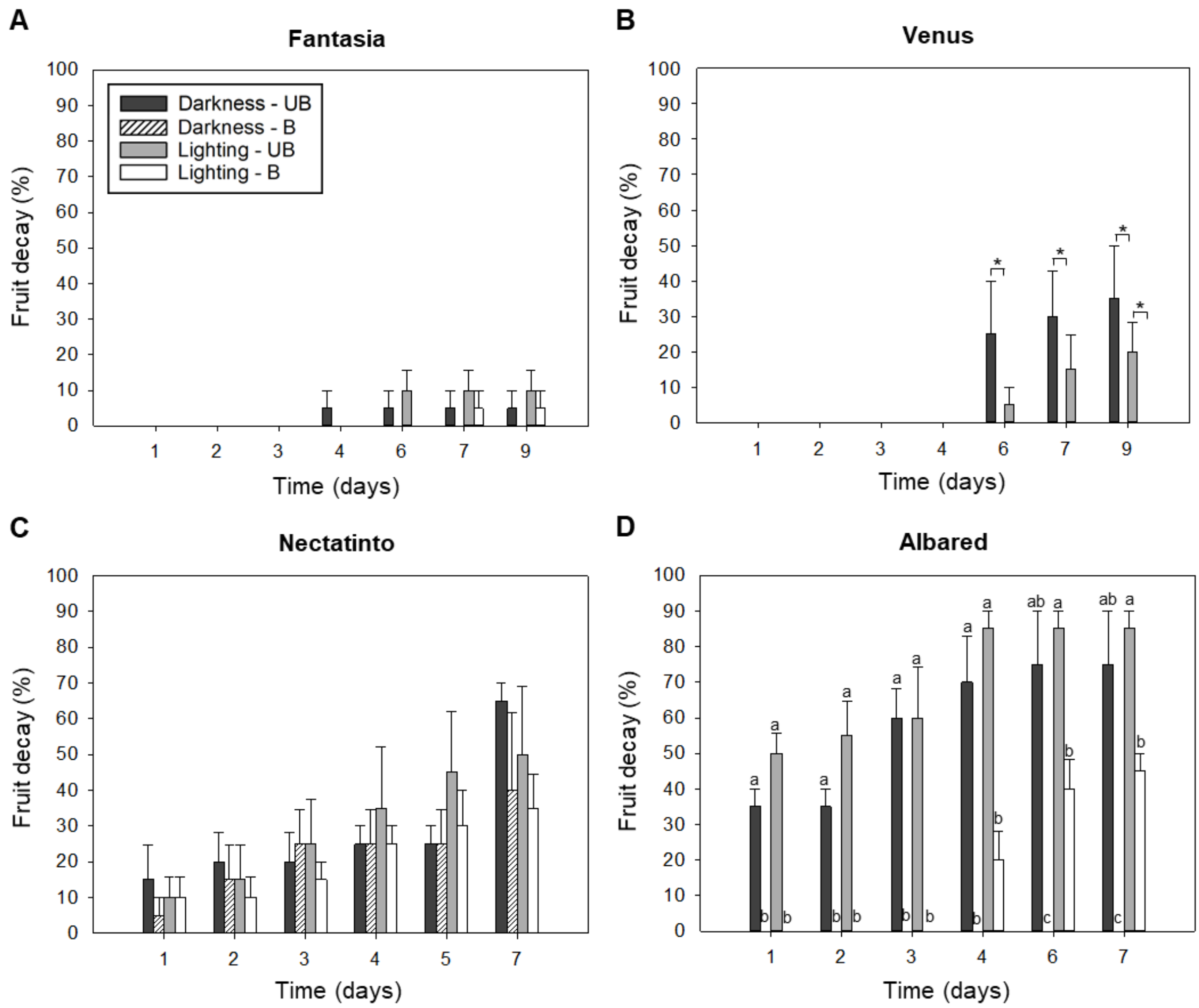

Figure 1. Fruit decay of nectarines after darkness and light postharvest conditions. Incidence of fruit decay (%) during storage in unbagged (UB) and preharvest bagged (B) fruit stored under darkness or light, of Fantasia (A), Venus (B), Nectatinto (C), and Albared (D) cultivars. Bars represent the mean of fruits with disease symptoms (*n* = 4 replicates, 5 fruits per replicate), and error bars represent the standard error of the means. Different lower-case letters indicate significant differences ($p \leq 0.05$) of fruit decay incidence among postharvest storage × bagging conditions at each time point. No letters indicate no significant differences. Asterisks indicate significant differences ($p \leq 0.05$) at each time point between bagged and unbagged fruit for each postharvest condition.

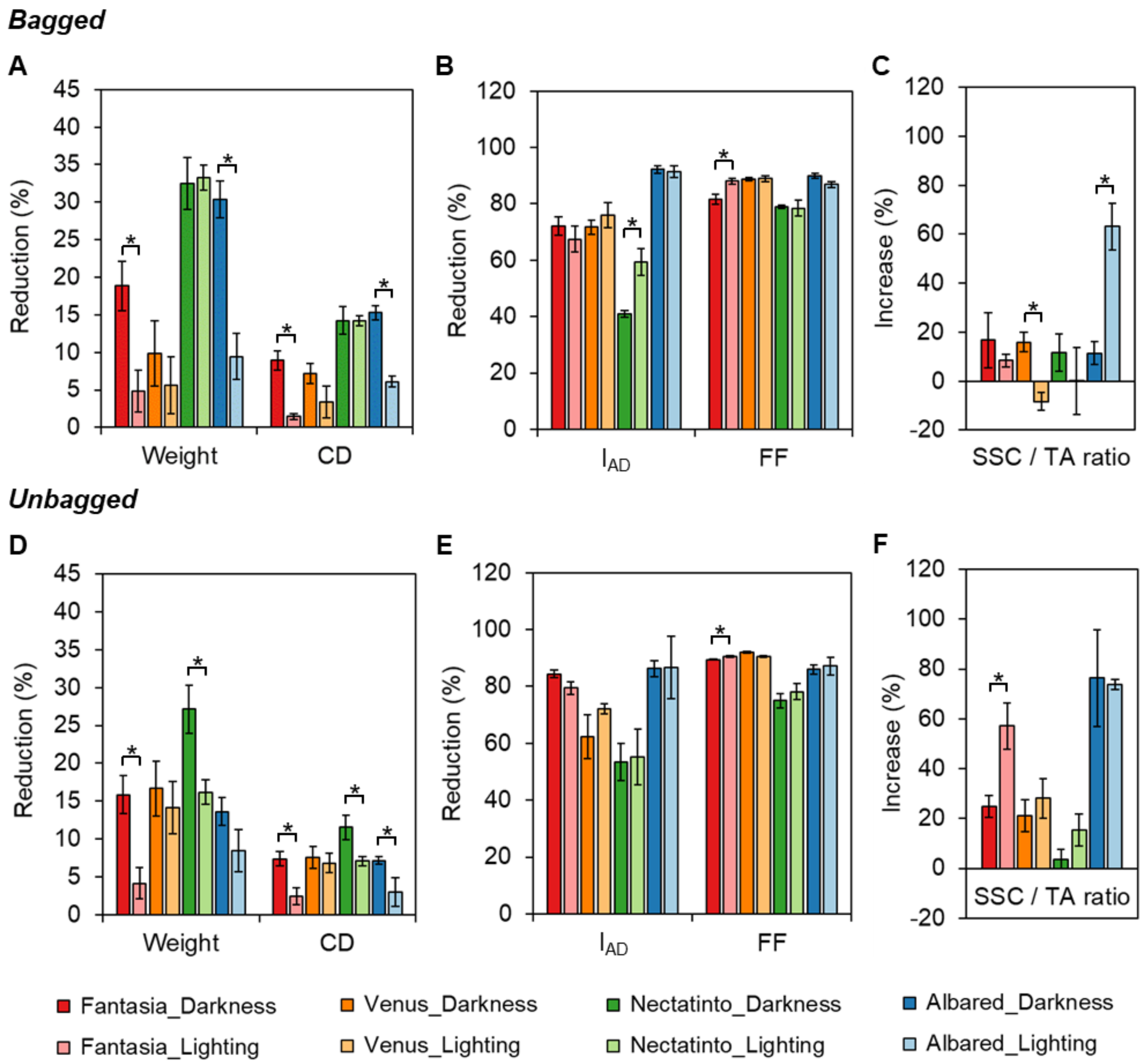

Figure 2. Changes in quality characteristics relative to initial fruit quality of nectarine cultivars after postharvest storage. Percentage change calculated for bagged (A-C) and unbagged (D-F) fruit, stored under darkness or light. Weight and cheek diameter (CD) (A, D); I_{AD} and flesh firmness (FF) (B, E); SSC/ TA ratio (C, F). Bars represent the mean (n = 4 replicates, 5 fruits each) and error bars represent the standard error of the means. Asterisks indicate significant difference ($p \leq 0.05$) between postharvest storage conditions, within each cultivar and bagging condition.