Review

Effect of pre-harvest and post-harvest conditions and treatments on plum fruit quality

G. A. Manganaris[1,*], A. R. Vicente[2] and C. H. Crisosto[3]

Address: [1] Department of Environmental Agronomy and Crop Science, University of Padova, Viale dell'Università, 16-Agripolis, I-35020 Legnaro (Padova), Italy. [2] College of Agriculture, University of La Plata, 60 and 119, La Plata CP 1900, Argentina. [3] University of California, Davis, Department of Plant Sciences, Kearney Agricultural Centre, Parlier, CA 93648, USA.

***Correspondence:** Tel: ++390498272845. Fax: ++390498272850. Email: manganar@agro.auth.gr

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Abstract

Plums belong to the *Rosaceae* family and include the European species (*Prunus domestica* L.), which is consumed fresh or dried, and the Japanese species (*Prunus salicina* Lindell), mainly freshly consumed. Plums are considered climacteric, although some plum cultivars do not show the typical increase in ethylene production and respiration until late ripening. They respond to exogenous ethylene, which is a key ripening regulator, while treatments with 1-methylcyclopropene (1-MCP), an ethylene action inhibitor, are effective in delaying fruit ripening. Plum fruit is characterized by high softening rate and, so far, the sequence of events leading to cell wall degradation, as well as changes in the proteins responsible for these modifications, has not been thoroughly investigated. Post-harvest diseases (brown rot, grey mould and *Rhizopous* rot) are also a main concern in plum post-harvest handling and storage. Prompt cooling and low-temperature storage (0°C) are recommended to delay ripening and maintain plum fruit quality. However, when the fruit is held for long periods at low temperature, chilling injury (CI) symptoms, usually manifested as translucency, bleeding, flesh browning and/or failure to ripen, might develop. Although softening can be delayed by controlled and modified atmospheres, this technology is not widely used commercially, since the benefits are not as pronounced as in other fruit species. Other post-harvest strategies tested to date with apparent usefulness at a laboratory scale include heat treatment, ozone, polyamine and calcium treatments, as well as fumigation with environmentally friendly compounds; such strategies might be useful under particular circumstances to complement other post-harvest treatments. Pre-harvest treatments, such as application of synthetic auxins and calcium, regulation of canopy light conditions and orchard soil management, have been reported to affect plum fruit quality and its post-harvest behaviour. Overall, the present review discusses the influence of field and post-harvest practices on plum fruit quality and market life.

Keywords: *Prunus salicina* Lindell, *Prunus domestica* L., Chilling injury, Market life, Post-harvest, Ripening, 1-MCP, Fruit quality, Harvest indices, Post-harvest pathogens

Review Methodology: We searched the ISI Web of Knowledge database using mainly the keywords listed above. The full-text articles of the abstracts of interest were retrieved. In addition we used the references from the articles obtained by this method to check for additional relevant material. Furthermore, data from the authors' previous work on plum fruit quality are reported.

Introduction

Plums are members of the Rosaceae family and include 'Japanese plums', belonging to the species *Prunus salicina* Lindell, native to China and domesticated in Japan 400 years ago; and 'European plums', belonging to the species *Prunus domestica* L., are believed to have originated in the Near East and with a long history of cultivation, especially in Europe [1]. Japanese plums are mainly used for fresh consumption, while European

plums can be eaten fresh (if a very sweet fruit is desired) or dried. The dried plums are known as prunes. Plum fruit composition is available online (http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list_nut_edit.pl, source: USDA National Nutrient Database for Standard Reference, 2007).

The plum is classified as a climacteric fruit, showing a peak in ethylene production and respiration during development. However, two distinct types of ripening behaviour have been observed for several cultivars [2–5]: those showing a typical climacteric behaviour and those considered suppressed climacteric. The latter group is characterized by low ethylene production until late stages of development, which is thought to be insufficient to coordinate ripening. In these cultivars, ethylene production may be suppressed 15–500-fold compared with normal climacteric cultivars. Aminocyclopropene-1-carboxylic acid (ACC) concentrations were reported to be similar in both fruit types, suggesting that the suppressed-climacteric phenotype is the result of an impaired ability of the fruit to convert ACC into ethylene [3]. Despite their different ethylene production rates, the suppressed climacteric cultivars were shown to be sensitive to ethylene and its analogues [2, 6], and exogenously applied ethylene might be particularly useful in these cultivars to accelerate post-harvest ripening.

According to FAO statistical information (http://faostat.fao.org/), world production of plums in 2006 was 9.4 million metric tonnes, and it has increased by 12% over the last 10 years. However, plum *per capita* consumption has remained the same or even decreased in the USA and some European countries. Plum consumers' complaints include 'off flavour', improper ripening, astringency, flesh browning and textural characteristics associated with low quality and chilling injury (CI) symptoms [7]. Meeting consumers' demands would require an understanding of the pre-harvest and post-harvest factors involved in quality determination and applying appropriate technologies to control them. Field practices are crucial factors governing fruit quality, and post-harvest treatments may simply aim to maintain fruit characteristics which were mainly determined in the orchard. In order to reach the market with high quality fruit, it would be necessary to identify the factors affecting the biochemical changes occurring during plum storage and ripening, such as the production of characteristic volatiles and aroma compounds, accumulation of anthocyanins leading to colour development, reduction in fruit acidity and changes in the cell walls contributing to softening, and then to implement technologies to control these modifications. The development and promotion of ripening protocols at the shipping and receiving ends with the aim of enhancing flavour or even giving an added value to the fruit would also be useful. The present study discusses the effect of pre- and post-harvest practices on plum quality and storage capacity.

Fruit Quality and Composition

Fruit Size

Small fruit size is one of the limiting factors in marketing the fruits of many species. Fruit size depends on the cultivar considered, cultural practices and environmental conditions [8]. Final plum fruit size is highly affected by water availability during development [9], and early harvest may lead to fruit with decreased size. Light exposure also affects fruit size in stone fruits [10]. Another factor affecting fruit size is crop load, and hand bloom and fruit thinning are the practices commonly used to control this factor [11]. Chemical treatments have also been used for this purpose. Auxin treatments in Japanese plum cultivars at the beginning of pit hardening were effective in stimulating cell enlargement in the mesocarp and in increasing fruit size and total yield [12].

Fruit Colour

Plum fruit colour is associated with the accumulation of carotenoids and anthocyanins. Both groups of pigments are more abundant in the peel but anthocyanins are mainly responsible for the surface colour of the fruit.

The main anthocyanins present in plums are cyanidin 3-rutinoside, cyanidin 3-glucoside and peonidin 3-rutinoside [13–16]. The accumulation of anthocyanins depends on the cultivar considered, with red-flesh plums having higher anthocyanin content [17], but is also highly affected by pre-harvest factors such as on-tree position and shading [18]. Besides their role in determining fruit colour, anthocyanins are relevant from a nutritional perspective, since they are considered natural antioxidants [19]. However, anthocyanidin content and antioxidant activity are not always correlated [17].

Carotenoids are natural fat-soluble pigments derived from isoprene. The main carotenoids present in plum include β-carotene mainly and cryptoxanthin [20] and, in many cases, they contribute to the yellow/orange colour observed in the flesh of several plum cultivars.

Soluble Solids Content (SSC) and Titratable Acidity (TA)

Fruit sugars are the main components of the soluble solids content, accounting for 65–80% of them [21]. The main sugars found in fresh plums are glucose, fructose and sucrose, although sorbitol, a sugar alcohol, is also present [22]. Fruit SSC is a critical factor in determining fruit quality, and early-season plum cultivars are usually characterized by lower SSC than late-season plum cultivars. Mean SSC measured in ripe plum cultivars (firmness 8.8–13.2 N) ranged from 9.0% ('Earliqueen') to 19.8% ('October Sun') [7]. Plums with SSC higher than 12.0% had ~75% consumer acceptance [23]. An SSC threshold is

suggested for picking some cultivars, e.g. 16% in 'Moyer' and 19% in 'French' plums.

Fruit acidity is another important factor affecting consumer acceptance. The main acid present in plum is malic acid and its level decreases during ripening. TA is not related to the time of season and it ranges from 0.18 to 0.87% malic acid [7]. For ripe plum fruit within the most common SSC range (10.0–11.9%), TA plays a significant role in consumer acceptance [23]. Plums within this SSC range combined with low TA ($\leq$0.6%) were disliked by 18% of consumers, while plums with TA higher than 1.0% were disliked by 60% of consumers. The development of a minimum quality index based on ripe SSC and/or ripe TA for fruit to be marketed might be useful for increasing consumer satisfaction [7].

Antioxidants

Plum fruits contain several important secondary metabolites such as flavonoids and phenolic acids [14], with a strong antioxidant capacity [24, 25]. However, great differences exist among the plum cultivars regarding their accumulation of phytochemicals and antioxidant capacity [17].

Most phenolic compounds are present in the fruit skin and a direct correlation between skin colour intensity and total phenolic content is observed [13, 14]. However, within the selections of dark purple colour skin fruits, some contained over 2-fold higher total phenolic content than others. Besides anthocyanins, the other group of phenolic compounds found in plums was identified as hydroxycinnamic acid derivatives (chlorogenic acid and neochlorogenic acid) [13, 16] and quercetin [16]. A correlation between total phenolics and antioxidant capacity has been reported for plums [15, 16, 20, 26]. Ascorbic acid is another antioxidant present in plum fruit, essential for higher primates and a small number of other species. Although plum does not rank among the fruits with the highest ascorbic acid content, its level is higher than that found in banana, apple, apricot and blackberry, ranging from 51 to 169 and from 20 to 90 mg/kg fresh weight in the peel and the flesh, respectively, depending on the cultivar considered [20].

Fruit Firmness

Excessive softening is a major factor limiting the shelf-life of plums [23]. Fruit softening is the ripening-related process most sensitive to ethylene [27] and a suitable predictor of potential shelf-life for plums, when decay or CI symptoms are not limiting factors. Plums ripened to a soft melting texture are considered 'ready to eat'.

As with other fruit species, the cell wall extracted from plum fruit showed considerable increase in swelling and high pectin solubilization during ripening [28, 29]. Interestingly, and in contrast to many other fruits, the increased solubilization of pectins is not associated with galactose loss during ripening [30]. In addition, depolymerization of polyuronides is observed but to a lower extent compared with other fruits. To date, the modifications in cell-wall components such as cellulose and hemicellulose have not been extensively studied. Some cell-wall-degrading agents, such as galactosidase, pectin methylesterase and poygalacturonase, have been identified in plums [31–33], but the actual contribution of these proteins to fruit softening is not clearly established. Characterization of the differences in cell-wall disassembly in cultivars showing differences in their softening rate stands as a challenging future investigation. Flesh firmness can be used as an index together with SSC to determine the appropriate developmental stage at which fruit can be more tolerant to manipulation but without compromising fruit flavour. Other aspects such as fruit drop, environmental conditions, hand labour availability, market prices, distance to market, potential transportation damage and temperature management at the receiving location should also be taken into account to determine the optimum time to harvest.

Physiological and Pathological Disorders

CI symptoms

Besides many other advantages, refrigerated storage is a widely used strategy to reduce ethylene production and sensitivity during post-harvest storage of horticultural products [34]. Refrigerated storage is recommended in many cases to extend the post-harvest life and maintain the quality of fresh commodities. However, the use of low-temperature storage has to be carefully managed in plum in order to avoid the incidence of CI symptoms [1, 7, 33, 35].

The term 'chilling injury' includes a number of processes having in common that they are triggered by exposure of the commodities to low temperatures. In plums the disorder is manifested mainly as flesh translucency (gel breakdown) and, in some cases, lack of juiciness, flesh browning, red pigment accumulation (bleeding) and failure to ripen (Figure 1) [23, 31, 35–38]. The susceptibility to CI is variable and dependent on the cultivar considered, but most plum cultivars are susceptible to CI symptoms when stored at 5°C [1, 35]. Consequently, storage at 0°C and 95% relative air humidity is recommended to extend fruit post-harvest life [39]. Storage at 0°C reduces the manifestation of CI symptoms probably because the symptoms observed are associated with fruit physiological responses that could still occur at a relatively high temperature during storage (2–8°C). However, the disorder is not eliminated but delayed when the fruit is stored at 0°C for long periods [35].

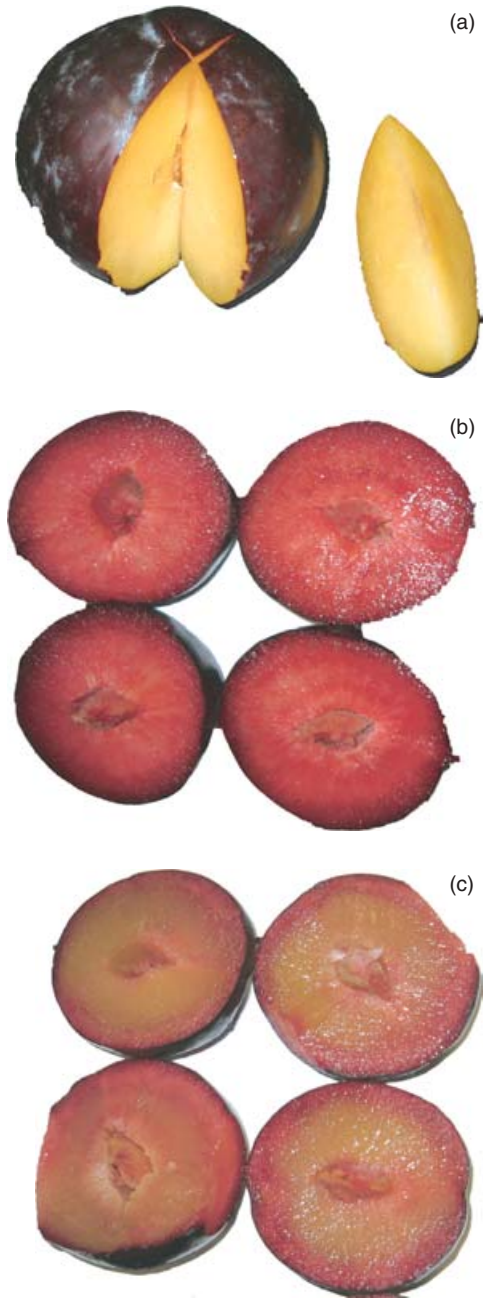

Figure 1 (**a**) 'Friar' plums after harvest and ripening at room temperature (23°C) for 4 days and with incidence of CI symptoms after removal from 4 weeks at 5°C and additional ripening at room temperature (23°C) for 4 days evident as (**b**) reddening and (**c**) a combination of gel breakdown (translucency) and flesh browning (internal breakdown) (G. A. Manganaris and C. H. Crisosto, unpublished data).

Ethylene seems to be involved in CI development in some products, but its role is still controversial. In many cases, chilling-injured fruit presented higher production of ethylene but the interpretation of whether the hormone is an effector of the disorder or whether it is just a by-product of tissue damage is not known. In many commodities, such as avocado, pineapple and pear [40–42], CI-associated disorders have been reduced by ethylene inhibition through 1-methylcyclopropene (1-MCP) treatments, while in other cases (such as in nectarines) it has been induced [43].

In contrast to other commodities, such as peaches, in which the underlying mechanisms of CI symptoms have been determined [44, 45], the physiological basis of CI symptoms in plums is not clearly established. The symptoms have been well described but the underlying causes and effectors leading to this phenomenon remain elusive. In normal ripening, the cell-wall components are usually solubilized and pectins show moderate depolymerization. Recent work indicates that the development of CI symptoms in 'Fortune' plums, evident as dry-mealy texture (lack of juiciness), is associated with abnormalities in cell-wall metabolism, including a reduction in pectin solubilization and depolymerization and decreased degradation of galactose-rich pectin polymers [33]. In particular, mealiness development was associated with a higher level of tightly bound pectin and a lower proportion of loosely bound pectin than the juicy controls. Lower pectin depolymerization and reduced solubilization of neutral sugars were also detected in the chilling-injured tissues, confirming an alteration in polyuronide metabolism. Intriguingly, no differences were found for several cell-wall-degrading enzymes, such as polygalacturonase, pectin methylesterase or 1,4-β-glucanase/glucosidase, between normally ripening and chilling-injured fruit. However, the latter presented lower β-galactosidase activity and this was associated with an increased proportion of galactose-rich polyuronides remaining covalently bound to the wall.

CI symptoms in plums were reported to be related to their climacteric behaviour and especially to their capacity to respond to low-temperature stress, which increases ethylene production after removal from storage [6]. Using 1-MCP, a competitor of ethylene for common binding sites, CI was effectively reduced in plums. In the case of 'Royal Diamond' plums, continuous ethylene exposure caused higher anthocyanin accumulation, phenylalanine ammonia-lyase activity and flesh reddening than untreated fruit, suggesting that the hormone is important for the development of the disorder and is not just a consequence of CI (G. A. Manganaris, unpublished data).

Post-harvest Diseases

Brown rot is the main post-harvest disease of stone fruit. It is caused by *Monilinia fructicola* G. Wint., which infects the plants during flowering. Fruit disease caused by conidia produced on infected blossoms, mummies or thinned fruit occurs secondarily and can cause economically serious yield losses [46]. Although fruit fungal colonization may occur during the growing season, beginning at flowering and causing fruit rot before harvest, disease is often manifested during post-harvest storage.

Orchard sanitation, to minimize infection sources, pre-harvest fungicide applications, careful handling and prompt cooling after harvest are the recommended control strategies [1]. Post-harvest fungicide treatments are used to a limited extent.

Botrytis cinerea is one of the major pathogens responsible for post-harvest grey mould decay, a disease commonly occurring in plum blossoms in local stone fruit orchards [47]. The fungus does not enter the plum fruit via flower parts when it establishes latent infections. *B. cinerea* can cause serious damage during wet and warm weather. It is not until the last phase of rapid fruit cell enlargement that disease development occurs. Although plums are less susceptible to bruising than most peach and nectarine cultivars at comparable firmness (C. H. Crisosto, unpublished data), mechanical injuries usually play an important role in harvested fruit susceptibility. Infections can occur during storage in contaminated fruits through harvest and handling-caused wounds. Thus, avoiding mechanical injuries and eliminating infected or damaged fruit is crucial to reduce the incidence of grey mould. Although the fungus can develop at low temperatures, refrigerated storage can delay the ripening process, decrease fungal growth rate and consequently reduce decay.

Rhizopus rot is caused by *Rhizopus stolonifer* (Ehrenb.:Fr.) Vuill. As for the other diseases, it is more common in advanced ripening-stage fruit. *Rhizopus* is also an opportunistic pathogen; therefore one of the main control measures is to avoid mechanical damage during harvest and handling operations. Although the fungus grows well at temperatures near 20–25°C, if the fruit is cooled properly at temperatures below 5°C its spores would not be able to germinate. In all cases, integrated pest management practices throughout the production chain are recommended to control post-harvest diseases effectively.

Influence of Pre-harvest Factors and Treatments on Plum Fruit Quality

Non-uniform fruit quality within export consignments of plums compromises retailer and consumer satisfaction and, thus, profitable marketing. Variability of ripening stage and quality at harvest and following storage and ripening periods is thought to be strongly influenced by canopy light conditions during fruit development, in conjunction with once-off harvesting practices [18]. As with other fruit trees, plum fruit ripen from the top of the tree to the bottom, a consequence of light environment. Lower fruit can be delayed in maturity by as much as 10–14 days compared with well-exposed fruits at the top of the tree. Unlike peaches and nectarines, the first harvest in plums is commonly the largest pick. In full-colour cultivars, harvest is limited to only a portion of the tree (usually segregated by light exposure), such as the top third of the tree in the first harvest and the middle third in the second harvest, so that labourers can proceed more quickly. Shaded 'Laetitia' plums showed delayed ripening (firmer with a greener ground colour, lower SSC and poorer red colour) and reduced size compared with sun-exposed fruit, therefore suggesting that plum tree canopies should ensure light exposure in all bearing positions [18].

Pre-harvest calcium sprays were conducted on plum trees in combinations with two bio-activators containing titanium to study the effects on the commercial quality of fruit, with special reference to their resistance to post-harvest handling damage [48]. Interestingly, titanium treatments increased fruit size, maintained firmness retention, reduced weight loss during storage and improved surface colour [49].

Orchard soil management could also have an influence on fruit secondary metabolites accumulation. Lombardi-Boccia *et al.* [50] found that fruit growing in orchards in which the soil was covered with natural meadow accumulated more tocopherol, β-carotene and total phenolic compounds than fruit grown on tilled soil or covered with *Trifolium*.

It has been recently shown that the application of synthetic auxins at the beginning of pit-hardening stimulated fruit cell enlargement and increased fruit size and yield in Japanese plum without negative effects either on fruit quality or on return yield in the following year [12].

Influence of Post-harvest Treatments on Plum Fruit Quality

Ripening Stage, Harvesting and Handling

Harvest date is usually determined by skin colour changes. Measurement of fruit firmness is recommended for cultivars where skin ground colour is masked by full red or dark colour development. Despite the possibility of doing early harvests and allowing the fruit to ripen off the tree, plums harvested at a more advanced ripening stage are characterized by higher SSC and lower TA, and have higher consumer acceptance [23]. Plums are often hand-picked into bags and then dumped in bins for transportation to the packinghouse. Keeping harvested fruit in the field for long periods or delaying cooling operations should be avoided in order to prevent rapid softening. Precooling methods (forced-air cooling or hydrocooling) are suggested for fast removal of field heat [1].

Low Temperature Storage

Refrigeration and proper relative air humidity control are the main techniques used to extend the shelf-life of fresh produce [51]. However, as mentioned previously, plums are chilling-sensitive and cold storage is limited to a few

weeks because of the appearance of CI symptoms beyond that [31, 33, 35, 37, 38, 52]. Maximum fruit market life varies from 1 to 6 weeks, depending on the cultivar and the post-harvest handling [35].

Temperatures within the range −1.1–0°C and relative air humidity within the range 90–95% are recommended for plum storage [1]. In plum cultivars, consumed both fresh and dried (cvs 'French' and 'Moyer'), a delay in flesh breakdown development has been attained by storing cultivars susceptible to flesh browning at −1.1°C. However, to store plums at this low a temperature, high SSC and precise thermostatic control are essential to avoid freezing damage.

Controlled and Modified Atmospheres

Controlled atmosphere (CA) and modified atmosphere (MA) storage have been shown to be effective in maintaining quality and they extend post-harvest life in many commodities, primarily apple (*Malus domestica* Borkh) and pear (*Pyrus communis* L.), although their application in many other fruits and vegetables has not been nearly as successful. In the case of plums, the major benefits of CA during storage and shipment (1–2% O_2+3–5% CO_2) are retention of fruit firmness, reduced decay incidence and delay of ground colour changes [1]. Currently, CA has seen a limited use for some cultivars stored for more than 1 month [53–56]. However, the benefits observed are cultivar-dependent. For instance in 'Friar' plums, flesh firmness, SSC, TA and pH were not affected by modified atmosphere packaging, when different plastic materials were analysed [57]. Furthermore, after 60 days of low-temperature storage, fruit from the MAP box liners that presented the highest CO_2 and the lowest O_2 internal concentration showed increased susceptibility to flesh translucency (gel breakdown).

1-MCP Treatment

Several research groups have evaluated the effect of the ethylene inhibitor 1-MCP on numerous plum cultivars [4, 58–66] (for a general review on 1-MCP, see [67]). The effects of 1-MCP on plum have been tested in a range of concentrations (0.05–1 μl/l), resulting in marked delay of fruit softening, as well as a reduction in the activity of several cell-wall-degrading enzymes, such as polygalacturonase, galactosidase and endo-glucanase/glucosidase [64, 66]. 1-MCP effects are concentration- and storage-duration-dependent and, in general, a saturation fruit response to 1-MCP has been observed at concentrations near 0.5 μl/l. The ripening stage at harvest is another factor determining the efficacy obtained. In general, the beneficial effects observed on fruit ripening are reduced when the fruit is treated at more advanced ripening stages. Exposure to 0.5 μl/l 1-MCP at low temperature showed similar results to treatments at room temperature [60]. Thus, applying 1-MCP at the temperature intended for subsequent storage of the fruit is recommended. An exposure time of at least 12 h has been shown to be effective in slowing down softening during shelf-life [60]. Furthermore, 1-MCP reduced the incidence of CI disorders and also appeared to be a promising tool for controlling this kind of disorder in non-suppressed climacteric plums [6].

Most 1-MCP applications include mixing of the product with water or a buffer solution to release the 1-MCP gas in enclosed areas. However, the availability of the proper facilities to treat the fruit could be a limitation under certain commercial situations. The identification of compounds or new formulations that do not require a closed system for applications might increase the usefulness of ethylene action inhibitors for post-harvest management [68, 69]. Manganaris *et al.* [66] evaluated the effect of post-harvest dips of plums in a solution of a 1-MCP-generating formulation (AFxRD-038, Rohm & Haas®) on the ripening, quality and incidence of physiological disorders after harvest or after refrigerated storage. Results indicated that immersions in 1-MCP-generating solutions were effective in delaying plum fruit ripening and controlling CI symptoms, evident as reddening. In addition, such an immersion-type 1-MCP formulation significantly extended the post-harvest life of plums harvested at advanced ripening stages [65].

Heat Treatments

Controlled post-harvest heat treatments of fruit have been shown to be beneficial for extending fruit shelf-life [70]. Serrano *et al.* [71] reported that heat treatment (hot water dips at 45°C for 10 min) reduced physiological changes induced by mechanical damage in plum and reduced 'wound-induced' increase in ethylene production and respiration rate. In plums, heat-treated as above, an increase in cell-wall-bound spermidine that induced higher cell-wall stability and plum firmness was monitored [72]. Such post-harvest heat treatments are, in general terms, effective, and the issue of whether high temperatures experienced by fruit on the tree prior to harvest have a similar post-harvest effect was raised [73]. However, to date, no data are available to answer this question.

Other Post-harvest Treatments

Other post-harvest strategies tested to date with apparent usefulness at a laboratory scale include ozone, polyamine and calcium treatments, as well as fumigation with environmentally friendly compounds; such strategies might be useful under particular circumstances to complement other post-harvest treatments.

Calcium treatments (1 mmol/l $CaCl_2$) reduced plum fruit susceptibility to mechanical damage and, in turn, alleviated the physiological changes that usually occur in damaged tissues, such as increased ethylene production and respiration rate [71]. Calcium-treated plums increased the conjugated forms of putrescine (conjugated-soluble and cell-wall-bound) resulting in higher firmness values [72].

Regarding treatments with polyamines, the application of putrescine through infiltration on mechanically damaged plums led to a reduction in the extent of damage, and higher firmness retention [74].

'Autumn Giant' plums were coated with edible hydroxypropyl methylcellulose–lipid composite coatings. The coatings consisted of beeswax or shellac, at two lipid content levels (20 and 60% dry basis). Weight loss of coated plums decreased only at the high lipid content. Fruit firmness was not affected by coating after short-term storage at 20°C. However, for prolonged storage at 20°C, the coatings significantly reduced softening and internal breakdown compared with uncoated and water-dipped plums [75].

Fumigation with thymol vapour reduced conidia germination and retarded mycelial growth of *Monilinia fructicola* (G. Wint.) [76, 77]. When plums inoculated with conidia of *M. fructicola* were fumigated with thymol, the incidence of brown rot was reduced from 88 to 24%, without causing phytotoxicity [76]. While the mechanism of the fungicidal action is not known, the main effect of the thymol vapours appeared to be on the fungal spores and surface mycelia. Electron micrographs showed that sections of germ tubes, appressoria and surface hyphae of the fungus exposed to thymol vapours presented disrupted and disorganized cytoplasmic organelles [77].

Ozone is a strong, naturally occurring oxidizing agent. Several studies have shown that ozone exposure prevents microbial growth and extends the shelf-life of treated produce [78]. Benefits of adding ozone to air in packing houses and storage rooms include control of post-harvest diseases on fruit, retarding the production of spores from decaying fruit, sanitation of surfaces and ethylene removal. The gas is known to be effective against a wide spectrum of microorganisms [79]. Tzortzakis *et al.* [80] found that ozone treatment led to a significant reduction in *B. cinerea* spores production in 'Black Amber' plums. Ozone's mode of action on microorganisms has been associated with the direct oxidation of cell components [81]. However, some studies showed that it could promote ethylene and salicylic acid synthesis, as well as the activation of certain genes and biosynthetic pathways associated with defence against pathogens [82].

Conclusions

The physiological control of plum ripening and how the different processes ultimately affecting fruit quality attributes are triggered is far from being understood. Plum softening rate is associated with cell-wall swelling and pectin solubilization, which unlike other fruits occurs without a pronounced loss of galactose. Moderate depolymerization of pectins is usually observed as the plum ripening progresses, but the modifications in cross-linking glycans or a detailed analysis of the sequence of cell-wall events leading to fruit softening has not been thoroughly analysed. Only some potential agents responsible for cell wall disassembly, such as pectin methylesterase and galactosidase, have been partially studied, but it is not clear to date which might be the key factors determining softening. It would be interesting to characterize the differences in cell-wall disassembly in cultivars showing significant differences in their softening rate.

In order to minimize deterioration and supply the market with high quality fruit, proper harvesting, handling and post-harvest operations are required. Low temperature storage at 0°C is recommended to delay ripening and maintain plum fruit quality. However, if fruit is held for long time periods at low temperature (especially in the 2–8°C range), CI, usually manifested as translucency, bleeding, flesh browning and/or failure to ripen, might develop. The benefits of modified and controlled atmospheres and packaging are not so pronounced as in other fruit commodities and, consequently, this technology is not widely used commercially. Several works have shown that 1-MCP treatments (either gas applications or dips in a liquid-generating 1-MCP formulation) are effective in delaying plum fruit ripening, softening and reducing the manifestation of CI symptoms. Other strategies to maintain quality, such as heat, ozone, polyamine and calcium treatments, have been used with relatively good results and might be useful in particular circumstances to complement common post-harvest treatments.

Plum production and commercialization requires taking into account several aspects, such as the selection of appropriate cultivars not only in terms of yield but also in relation to fruit quality attributes, adequate management of the orchards, harvesting at the right ripening stage, prompt cooling and careful handling and distribution. Besides delaying softening and reducing decay, fruit production systems should focus on supplying fruit with superior flavour and aroma, two main characteristics affecting consumer acceptance. An approach integrating all the available cultural and post-harvest techniques would be necessary to achieve the goal of satisfying consumer expectations with high quality plums.

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