



Review

Application of physical and chemical postharvest treatments to enhance storage and shelf life of pomegranate fruit—A review



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ABSTRACT

There has been recent interest in pomegranate fruit production and research due to its high nutritional and health benefits. The increase in demand of the fruit necessitates the need to improve quality, storability and shelf life to meet consumers' expectations of consistent supply of quality fruit. However, pomegranate fruit is susceptible to various postharvest quality problems including high weight loss, decay and susceptibility to physiological disorders such as chilling injury and husk scald. To improve fruit storability and shelf life, physical and chemical postharvest treatments have been applied. However, these treatments have varied effects on the external and internal quality attributes of fruit. This review therefore discusses the different postharvest treatments applied to enhance storage of pomegranate whole fruit and arils and highlights the effects of the treatments on the fruit quality.

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1. Introduction

Pomegranate (*Punica granatum* L.) is an ancient known fruit belonging to the family Punicaceae (Holland et al., 2009). It is an important fruit in the tropical and sub-tropical regions of the world and mainly cultivated in the Mediterranean countries due to their moderate climates (Ozguven and Yilmaz, 2000; Nanda et al., 2001). As a result of its high adaptability to many soils and climates, pomegranate is now grown in various countries including South Africa, Iran, India, Pakistan, Russia, Turkey, Japan, Greece, Sultanate of Oman, China, Egypt and U.S.A (Elyatem and Kader, 1984; Köksal, 1989; Holland et al., 2009; Fawole and Opara, 2013a,c). The fruit colour varies from yellowish-green to deep red depending on cultivar (Sepúlveda et al., 2000; Faria and Calhau, 2011). The fruit is made up of a hard leathery outer skin (rind), an albedo, septa, membranes and many arils. Each aril, which is edible, is surrounded by a translucent sac that contains juice and a seed constituting about 80% and 20% of an aril, respectively (D'Aquino et al., 2010). The fresh juice is mainly made up of water (85%), sugars (10% majorly glucose and fructose), ascorbic acid, anthocyanins, polyphenolic flavonoids, pectins, amino acids and minerals (Roy and Waskar, 1997).

According to Kader et al. (1984), pomegranate is classified as a non-climacteric fruit due to its low respiration and ethylene production rates after harvest. In spite of its non-climacteric nature, the fruit still undergoes both qualitative and quantitative losses due to postharvest handling processes resulting in chilling injuries, husk scald, weight loss, and decay (Kader et al., 1984). Storage of pomegranates at room temperature reduces the shelf life due to increased desiccation and incidence of decay. To prolong storability, there is need to store fruit at low temperatures (Barman et al., 2011; Fawole and Opara, 2013b). However, when fruit are exposed to temperatures below 5 °C, they are susceptible to chilling injury (Sayyari et al., 2010). These symptoms are noticeable as brown discoloration of the peel, surface pitting and susceptibility to decay organisms. In most cases these symptoms reach the arils, which decrease both internal and external quality of the fruit (Elyatem and Kader, 1984; Kader, 2006; Fawole and Opara, 2013b). Husk scald, considered to be a symptom of chilling injury develops faster and more severely in fruit stored between 6 and 10 °C than in fruit stored at lower temperatures (Ben-Arie and Or, 1986). Decay is another major cause of postharvest loss which limits storability of pomegranate fruit, especially when stored at temperatures above those that cause chilling injury. Decay usually develops at the recommended storage conditions (5–8 °C and 90–95% RH) and is caused by various pathogens such as *Aspergillus* spp., *Alternaria* spp., *Penicillium* spp., and *Botrytis cinerea* (Roy and Waskar, 1997).

Global demand for pomegranate fruit as fresh aril, dried or value-added processed products has increased globally in recent

years due partly to reported high content of healthful phytochemicals (Fawole et al., 2012). This increase in demand and popularity among consumers has led to steady increase in production in both Northern and Southern hemisphere countries including the Sultanate of Oman and South Africa (Opara et al., 2009; Mditshwa et al., 2013). A number of treatments have been applied to improve quality and increase the shelf life of pomegranate whole fruit and arils, these include intermittent warming, curing, film wrapping, waxing, polyamines, controlled atmosphere, honey treatments and modified atmosphere packaging, among others (Artés et al., 1998; Nanda et al., 2001; Hess-Pierce and Kader, 2003; Mirdehghan et al., 2007a; Ergun and Ergun, 2009; Waskar, 2011; Caleb et al., 2013, 2012a,b).

Despite the availability of various postharvest treatments, high incidence of postharvest loss of pomegranates still occurs, often exceeding 30% for some cultivars in one season (Shete and Workar, 2005). This results in loss of nutritional and quality attributes as well as financial loss which greatly reduces profitability and growth of the industry. Therefore, there is need for more research to increase storability and reduce postharvest loss of pomegranate if the full potential of the fruit is to be realized. Furthermore, there is need for research focusing on the application of postharvest treatments and innovative technologies to maintain or enhance the nutritional and bioactive ingredients of the fruit. The objective of this review was to review current knowledge on the application of postharvest treatments to enhance the storage and shelf life of pomegranate fruit.

2. Physical treatment of pomegranate fruit

2.1. Curing and intermittent warming

2.1.1. Effects on physiological response

Studies have shown that curing of pomegranate fruit results in weight loss, depending on the storage temperature. For instance, pomegranate fruit cured at 33 °C for 3 days resulted in high fruit weight loss, with higher losses observed in fruit stored at 5 °C compared to 2 °C (Artés et al., 2000). However no symptoms of shriveling were observed after cold storage and shelf life periods of 6 days at 15 °C (Table 1). This was similar to previous findings that intermittent warming of fruit led to higher weight loss than conventionally stored fruit after cold storage for at 0° and 5 °C for 80 days and an additional 7-day shelf life period at 15 °C (Artés et al., 1998). Susceptibility of pomegranate fruit to weight loss after curing or intermittent warming was suggested to be due to easy passage of water vapour through numerous minute openings on pomegranate peel.

Decay incidence in pomegranate can also be reduced by intermittent warming. According to Artés et al. (1998), lower decay rate

Table 1
Effects of postharvest treatment on quality attributes of pomegranate whole fruit.

Fruit treatment	Cultivar	Treatment description	Key finding	Reference
<i>Physical</i>				
Curing and intermittent warming	Mollar de Elche	Curing at 33 °C and 95% RH for 3 days and storage at 2 °C or 5 °C Cycles of intermittent warming (IW) of 1 day at 20 °C every 6 days at 2 °C or 5 °C	IW fruits had lowest chilling injury and highest anthocyanin concentrations, titratable acidity and best visual appearance	Artés et al. (2000)
Shrink film wrapping and skin coating with a sucrose polyester (SPE)	Ganesh	Fruits shrink wrapped with two polyolefin films (BDF-2001 and D-955) and skin coating with a sucrose polyester and stored at 8 °C, 15 °C and 25 °C	Best obtained with shrink-wrapped with BDF-2001 film and storage at 8 °C	Nanda et al. (2001)
Gamma irradiation	California cultivar	The fruits were irradiated with doses of 0, 0.4, 1 and 2 kGy	Chemical attributes were unaffected up to 1 kGy treatment. Total anthocyanin and phenolic content decreased	Shahbaz et al. (2014)
Heat treatment	Mollar de Elche	Heat treatment (hot water dip at 45 °C for 4 min) and storage at 2 °C for 90 days	Chilling injury symptoms were reduced. Increase in free putrescine and spermidine observed	Mirdehghan et al. (2007b)
<i>Chemical</i>				
Application of polyamine by pressure or immersion	Mollar de Elche	Fruits treated with putrescine or spermidine and stored at 2 °C for 60 days	All changes were delayed by polyamine treatments	Mirdehghan et al. (2007a)
Oxalic acid treatment	Mollar de Elche	Oxalic acid applied and fruits stored at 2 °C for 84 days	CI symptoms were reduced. Total phenolics loss reduced and ascorbic acid increased.	Sayyari et al. (2010)
Spermidine and calcium chloride treatments	Mala-e-Yazdi	Fruits treated with CaCl and spermidine and stored at 2 °C for 4 months	Treated fruit had higher CAT and SOD activity and lower POX activity	Ramezani and Rahemi (2010)
Salicylic acid treatment	Malas saveh	Fruits treated with salicylic acid and stored at 2 °C at 85% RH for 3 months	2 mM was the most effective concentration in reducing CI, EL and for maintenance of AA levels	Sayyari et al. (2009)
Methyl jasmonate and methylsalicylate vapor treatments	Mollar de Elche	Fruits were treated with methyl salicylate (0.1 and 0.01 mM) and methyl jasmonate (0.1 and 0.01 mM)	The CI symptoms were significantly reduced. Total phenolics and anthocyanins increased	Sayyari et al. (2010)
Lecithin application	Primosole	Fruits dipped in Xedabio (a soy lecithin based formulation) alone or in combination with fludioxonil and stored at 8 °C 90–95% RH for 6 or 12 weeks	Xedabio maintained the commercial value of fruit. Minor changes occurred in nutritional	D'Aquino et al. (2012)
<i>Combined</i>				
Fludioxonil application and film wrapping	Primosole	Fruit dipped in fludioxonil, wrapped with a polyolefinic film and stored at 8 °C and 90% RH for 6 or 12 weeks	Film wrapping maintained freshness for all the storage periods. FLU reduced the incidence of decay	D'Aquino et al. (2009)
Putrescine and carnauba wax	'Mridula'	Fruits treated with putrescine and carnauba wax alone or in combination	All the undesirable changes were delayed by putrescine + carnauba wax application	Barman et al. (2011)
Wax and carbendazim	Bhagwa	Fruits treated with wax (waxol) alone and in combination with carbendazim and stored at 8 °C and 90–95% RH	Treated fruits stored longer and application of fungicides with wax gave excellent effects	Waskar, 2011

in fruit subjected to intermittent warming was observed compared to those stored conventionally. However, the choice of cold storage temperature during intermittent warming is important. For instance, after cold storage (0 °C, 2 °C and 5 °C) for 12 weeks and additional shelf life period of 6 days at 15 °C and 75% RH, fruit stored at 0 °C showed no decay while fruit stored at 2 °C had lower fungal attacks compared to those stored at 5 °C after shelf life (Artés

et al., 2000). In the same study comparing curing and intermittent warming (Table 1), it was observed that curing of pomegranate resulted in higher weight loss than a day intermittent warming at 20 °C every 6 days of fruit stored at 2 °C or 5 °C while control fruit had the lowest weight loss (Artés et al., 2000). Curing has also been reported to reduce incidence of decay in pomegranate fruit. After curing pomegranate fruit, Artés et al. (2000) observed no symp-

toms of decay after 12 weeks of cold storage at 2 °C and 5 °C until during a 6-day shelf life at 15 °C and 75% RH. The authors observed higher decay incidences at higher storage temperature, with decay incidence of 28.7% at 5 °C as opposed to 8.7% at 2 °C.

The physical appearance of pomegranate fruit is of great relevance because it affects consumer appeal and purchasability of the produce. Artés et al. (2000) observed that curing pomegranate whole fruit at 33 °C for 3 days before storage at 2 °C and 5 °C for 12 weeks did not affect the skin colour, with higher L*, C* and H° colour parameters on the skin than those obtained on the arils, however, curing decreased the visual colour appearance of arils after cold storage of fruit (Artés et al., 2000). For intermittent warming however, no changes were observed in fruit lightness (L*) with only slight changes in the colour intensity (C*) and hue angle (h°) values of fruit after 80 days of storage at 0 °C and 5 °C (Artés et al., 1998). According to the author, intermittent warming and storage at 0 °C showed a better result for maintaining the desirable red colour of pomegranate fruit.

2.1.2. Effects on chemical properties

The effect of postharvest treatments on the nutritional and chemical composition of the fruit is of paramount importance in evaluating the relevance of the treatments. Intermittent warming resulted only in a slight decrease in the soluble solids content (SSC) after 80 days of cold storage (0 °C and 5 °C) and shelf life periods of six additional days at 15 °C and 75% RH (Artés et al., 1998). Similarly, Artés et al. (2000) observed that both curing and intermittent warming of pomegranate whole fruit ('Mollar de Elche') resulted in a slight but non-significant decrease in the soluble solids content after cold storage for 12 weeks at 2 °C and 5 °C. Generally, curing resulted in slight changes in the SSC, pH and TA (titratable acidity) of pomegranate fruit in comparison to fruit at harvest (Artés et al., 2000). In addition, Artés et al. (2000) observed that although anthocyanin concentration decreased with storage, curing maintained the anthocyanin concentration of pomegranate fruit while slight increases were observed in intermittent warmed and control fruit stored at 5 °C for 12 weeks.

Artés et al. (1998) also found that the appearance of arils from intermittent warmed fruit was scored good and remained unchanged during 80 days of storage. This was further buttressed in a later study that intermittent warming and storage at 5 °C yielded arils with the best visual appearance (Table 1) (Artés et al., 2000). Curing on the other hand resulted in loss of flavour with storage at 5 °C having the lowest flavour (Artés et al., 2000). In comparison with curing, intermittent warming with 2 °C storage was a better treatment for pomegranate whole fruit as it resulted in the best flavour, higher total anthocyanin content, lowest total losses and maintained quality and shelf life for up to 13 weeks (Artés et al., 2000).

2.2. Hot water treatment

2.2.1. Physiological responses

Several studies have reported the use of hot water as a postharvest treatment for pomegranate. Mirdehghan and Rahemi (2005) observed that treatment of 'Malas Yazdi' pomegranate whole fruit with hot water at 50 °C resulted in the least fruit weight loss compared to chemical (Imazil and Benzyladenine) and control treatments. In addition, the rate of fruit weight loss increased with increasing hot water temperature, with significant weight loss and heat injury observed at 65 °C. In another study, it was observed that hot water treatment decreased weight loss by 5.86% in comparison to the control, with the suggestion that the decrease could be associated with improvement in cells membrane function or in skin cuticular properties (Ramezani and Rahemi, 2010). Furthermore, a study reported that skin browning was lowest in fruit treated

with hot water at 50 °C compared to control and chemical treatments (Imazil and Benzyladenine) stored at 1.5 °C for 4.5 months (Mirdehghan and Rahemi, 2005). Hot water treatment (HWT) at 45 °C for 2 and 5 min significantly reduced skin browning, however, at 65 °C, slight heat injury and increased percentage of browning was observed when fruit were stored for 3 months (Mirdehghan and Rahemi, 2005). Similarly, hot water treatment at 45 °C for 4 min also significantly reduced the rate of browning by 9% in comparison to control treatment (Ramezani and Rahemi, 2010). In addition, the authors recommended HWT at 45 °C for 4 min as the best heat treatment to control chilling injury of 'Malas Yazdi' and 'Malas Saveh' whole fruit. This observation is in agreement with a previous study by Mirdehghan et al. (2007b) where heat treatment (45 °C for 4 min) significantly reduced chilling injury on 'Malas Yazdi' pomegranate in comparison to control fruit. The authors suggested that heat treatment maintained membrane integrity and unsaturated fatty acids during cold storage thus reducing the incidence of chilling injury.

Electrolyte leakage was significantly reduced with hot water treatment (HWT) at 50 °C for 2 and 5 min when compared to other treatments (Imazil and Benzyladenine), which had no effect (Mirdehghan and Rahemi, 2005). Mirdehghan et al. (2007b) also observed that electrolyte leakage was higher in control than in hot water treated (45 °C) fruit, suggesting that hot water dipping reduced leakage of electrolytes from the fruit. In agreement with other studies, Ramezani and Rahemi (2010) also found that hot water treatment reduced electrolyte leakage by 20% in comparison with the control for 'Malas Yazdi' pomegranates stored at 2 °C for 4.5 months plus a further 3 days of shelf life.

2.2.2. Effects on physical and chemical properties

According to Mirdehghan et al. (2007b), hot water dipping at 45 °C for 4 min retarded skin browning of pomegranate fruit ('Mollar de Elche') and maintained fruit firmness during storage for 90 days. The author attributed improved fruit firmness to the broad effect of heat on cell wall degrading enzymes (Mirdehghan et al., 2007b).

Although hot water treatment was shown to have no significant effects on the TSS, TA, pH and ascorbic acid of fruit after storage for 3 months (Mirdehghan and Rahemi, 2005; Ramezani and Rahemi, 2010), antioxidant activity increase significantly and this observation attributed to minimal degradation of phenolic compounds (Ramezani and Rahemi, 2010). In addition, dipping pomegranate fruit ('Mollar de Elche') in hot water (45 °C for 4 min) preserved the fatty acids concentrations in the juice (Mirdehghan et al., 2007b). It was observed that the concentration of all fatty acids remained significantly higher in fruit treated with hot water than control throughout the storage period. Furthermore, it was also observed that decrease in fatty acids in untreated pomegranate fruit was highly correlated with increase in electrolyte leakage (Mirdehghan et al., 2007b).

2.3. Film wrapping

2.3.1. Physiological responses

Respiration rate of 'Ganesh' pomegranate fruit wrapped in shrink film was significantly reduced due to the low permeability of the films used for wrapping (Nanda et al., 2001). Interestingly, after 10 weeks of storage, unwrapped (control) fruit exhibited lower respiration rate than wrapped fruit. This was primarily due to reduced number of living cells in the peel of control fruit resulting from excessive dehydration (D'Aquino et al., 2010). Moreover, weight loss was greatly reduced in shrink wrapped fruit stored at 8 °C, 15 °C and 25 °C, with BDF and D-955 films having 1.5% and 2.3% weight loss, respectively compared to 14% loss in control fruit stored at 25 °C for 25 days (Nanda et al., 2001). This was in agree-

ment with D'Aquino et al. (2010), who also reported 0.6% weight loss in film wrapped 'Primosole' pomegranate as opposed to 5.1% weight loss in unwrapped fruit after 6 weeks of storage at 8 °C. Film wrapping has also shown to prevent symptoms of husk scald in pomegranate fruit. For instance, wrapping resulted in no signs of scald, discolouration or browning during a 6-week storage period at 8 °C whereas skin of control fruit developed yellow to dark yellow and brown colouration as storage progressed (D'Aquino et al., 2010). Furthermore, Nanda et al. (2001) reported spoilage mainly due to *Penicillium* spp. with 12% spoilage in unwrapped fruit while the wrapped fruit were fresh with high scores for good appearance (Table 1).

2.3.2. Effects on physical and chemical properties

Fruit firmness of pomegranate ('Ganesh') wrapped with BDF-2001 and D-955 films was maintained throughout a 12-week storage period whereas unwrapped fruit were less firm, tough and desiccated (Nanda et al., 2001). In addition, loss in skin colour was minimized in film wrapped fruit compared to control fruit for 'Primosole' cultivar (D'Aquino et al., 2010).

Decrease in acidity was considerably lower in wrapped than those of unwrapped fruit during 12 weeks of storage (Nanda et al., 2001). This was attributed to the higher respiration rate in unwrapped fruit and a concurrent loss in acidity which was attributed to the ongoing metabolism in the fruit. D'Aquino et al. (2010) observed a higher increase in pH and decrease in TA of wrapped fruit compared to unwrapped ones during 12 weeks of storage at 8 °C for 'Primosole'. Another advantage of film wrapping on pomegranate is its ability to minimise loss of vitamin C in pomegranate juice. In the study by Nanda et al. (2001), film wrapping minimised loss of vitamin C by 3.21–5.11% during 12 weeks storage period at 8 °C. On the other hand however, film wrapping has been reported to result to significant reduction in total phenolics and anthocyanin content during storage, resulting to continuous decrease in antioxidant activity of the fruit (D'Aquino et al., 2010).

2.4. Coatings

2.4.1. Physiological responses

The application of coatings on fruits provides a partial barrier to movement of water thus reducing moisture loss from fruit surface and also establishes a modified atmosphere around the fruit thus slowing down respiration and senescence (Mahajan et al., 2014). A number of studies have reported the use of skin coating on pomegranate fruit. Coating of pomegranate whole fruit ('Ganesh') with sucrose polyester (SPE) reduced weight loss during storage at 8 °C and 25 °C (Nanda et al., 2001). Similarly, application of lecithin (Table 1) significantly reduced fruit weight loss as well as incidence and severity of husk scald in 'Primosole' cultivar (D'Aquino et al., 2012). In addition, starch based edible coating (containing cold pressed oil from *Nigella sativa*) had about 6-fold weight loss reduction in pomegranate arils (Table 1). The reduced weight loss was attributed to improved water vapour barrier properties of the coatings by providing hydrophobicity and increased resistance to water transmission (Oz and Ulukanli, 2012). Furthermore, the use of *Aloe vera* gel (Table 2) has been reported to influence respiration rate of 'Mollar de Elche' arils. This was evidenced by significant increase in CO₂ concentration with a concomitant decrease in O₂ over time (Martínez-Romero et al., 2013). Coating arils with starch and oil has also been reported to reduce browning (Oz and Ulukanli, 2012).

2.4.2. Effects on physical and chemical properties

Coating of arils with either starch or oil significantly reduced the aril softening ratio, with the combination of starch and oil

being more effective than starch alone. The softening ratio was 3% and 5% when treated with starch and oil, respectively compared to 18% in control arils (Oz and Ulukanli, 2012). Pomegranate arils treated with either 10% or 20% honey solution (Table 2) did not lose firmness as much as those of control samples after 5 days of storage at 4 °C for 'Hicaznar' cultivar (Ergun and Ergun, 2009). Similarly, Martínez-Romero et al. (2013) reported that aril firmness was better maintained when arils were treated with *Aloe vera* either alone or in combination with acids. Martínez-Romero et al. (2013) also observed decrease in hue angle in arils treated with *Aloe vera* while the control arils showed increased hue angle during storage for cultivar Mollar de Elche. It was suggested that increase in aril colour was due to the increase in anthocyanin pigments during postharvest storage of pomegranate fruit (Sayyari et al., 2011a; Martínez-Romero et al., 2013).

Coating pomegranate fruit ('Primosole') with soy lecithin resulted in slight but significant changes in pH values and decrease in TA over storage while TSS was not affected (D'Aquino et al., 2012). Coating with sucrose polyester (SPE) resulted in a slight decrease in TSS after storage at 8 °C, 15 °C and 25 °C although the treatment did not minimise loss of vitamin C content during storage (Nanda et al., 2001). Similarly, coating with SPE did not prevent loss of acidity in 'Ganesh' pomegranate between 9 and 12 weeks of storage at 8 °C, 15 °C and 25 °C (Nanda et al., 2001). Oz and Ulukanli (2012) observed that pomegranate arils ('Silifke aşısı 33 N 16') coated with starch and oil from *Nigella sativa* (Table 2) had 14.2% loss in TSS content of arils during storage compared with 17% loss in control fruit. Studies have shown that vitamin C content of pomegranate arils reduces with increasing storage duration (Oz and Ulukanli, 2012; O'Grady et al., 2014); however, the application of oil and starch coating minimised vitamin C loss in 'Silifke aşısı' pomegranates stored for 12 days at 4 °C (Oz and Ulukanli, 2012). According to the authors, vitamin C diminished by 66% (from 24 to 8 mg/100 g) in control fruit whereas only 12% (from 58 to 51 mg/100 g) was diminished in fruit treated with the combination of oil and starch coating. Total antioxidant capacity (TAC) of pomegranate arils treated with the combination of oil and starch was observed to decrease during initial storage (from 4 to 6 days) and stabilised at the later days (6–12 days) of storage (Oz and Ulukanli, 2012). Shelf life of pomegranate fruit (Ganesh cultivar) was only marginally extended by coating with a sucrose polyester (Table 1) during storage for 12 weeks (Nanda et al., 2001). Martínez-Romero et al. (2013) found that scores for sensory attributes such as colour, aroma, texture, flavour and purchase decision were lowest (below 2) in control arils but arils treated with combination of *Aloe vera* gel and acids had high scores with no detection of off-flavour. Similarly, studies by Ergun and Ergun (2009) showed that aroma scores for control arils declined below the acceptable limit whereas arils treated with honey had excellent aroma scores throughout storage for 10 days (Table 2). Similar findings have been reported by Martínez-Romero et al. (2013) who found that arils treated with *Aloe vera* had aroma of fresh fruit while the aroma of control (untreated) arils corresponded with over ripe fruit. The authors concluded that shelf life of arils coated with *Aloe vera* gel could be extended for up to 12 days compared to 8 days for control arils.

2.5. Waxing

2.5.1. Physiological responses

Treatment of 'Mridula' pomegranate fruit with carnauba wax in combination with putrescine (PUT) lowered fruit respiration and ethylene production rates due to reduced gas interchange and low oxygen available for respiration during 60 days of storage at 3 °C (Barman et al., 2011). Combination of carnauba wax and putrescine (Table 1) also reduced fruit weight loss by 10% in treated compared to 17% in control fruit due to the overlapping platelets of carnauba

Table 2
Effects of postharvest treatment on quality attributes of pomegranate arils.

Aril treatment	Cultivar	Treatment description	Key findings	Reference
<i>Chemical</i>				
Washing with chlorine, ascorbic acid and citric acid and MAP	Mollar de Elche	Arils washed in chlorine, ascorbic acid and/or citric acid, sealed in POPP or OPP and stored at 8 °C, 4 °C and 1 °C	Best results obtained with chlorine, followed by antioxidant solution and packaged in polypropylene films and storage at 1 °C	Gil et al. (1996)
Honey treatments	Hicaznar	Arils treated with diluted honey solutions for 5 min and held at 4 °C for 10 days	Honey extended the fresh-like quality and delayed microbial development	Ergun and Ergun (2009)
Aloe vera gel coating	Mollar de Elche	Arils treated with aloe vera alone or in combination with ascorbic and citric acid and stored in rigid propylene boxes for 12 days at 3 °C	The combination of A. vera gel at 100% + ascorbic acid and citric acid at 1% was the most effective treatment	Martínez-Romero et al. (2013)
Edible starch-based coating (with glycerol plus <i>Oleum nigella</i>)	Silifkeasisi	Arils coated with a solution of starch (only) and starch (with oil)	Coating with 300 ppm oil + starch yielded best results	Oz and Ulukanli (2012)
<i>Combined treatment</i>				
Combined heat treatment, UV-C and superatmospheric oxygen packaging	Mollar de Elche	Fresh-cut arils subjected to hot water dipping (55 °C), UV-C and passive modified atmosphere packaged or high oxygen packaging	The combination of UV-C and high oxygen maintained the antioxidant compounds	Maghoughi et al. (2013)
UV-C and modified atmosphere packaging	Mollar of Elche	Arils chlorine disinfected, exposed to UV-C radiation, packaged in polypropylene baskets and stored for 13–15 days at 5 °C	No benefits were found with different UV-C radiation doses	López-Rubira et al. (2005)
UV-C treatment	Hicaznar	Arils were illuminated with UV-C and stored at 2 °C for 6 days	UV-C had effect phenolics but not on SSC and citric acid	Nunes et al. (2009)
Hot air treatment, superatmospheric O ₂ and elevated CO ₂	Malese-Saveh	Arils treated with hot air, packed in PET sealed on top with PE and packaged using different gas compositions and stored at 4 °C, 90% RH	The combination of HOA and HT 45 °C enhanced the benefits of applying each treatment separately obtained the best aril quality	Maghoughi et al. (2013)

wax which act as a barrier for diffusion thus resist penetration of water vapour from the fruit (Barman et al., 2011). This also explains why very low weight loss (0.1%) was observed for pomegranate fruit ('Bhagawa') coated with wax mixed with carbendazim during 80 days of storage (Waskar, 2011). No decay was observed during storage at 3 °C for 60 days after treatment of 'Mridula' pomegranate fruit with carnauba wax and putrescine (Barman et al., 2011).

2.5.2. Effects on physical and chemical properties

Pomegranate fruit ('Mridula') treated with PUT + carnauba wax and stored for 60 days at 3 °C retained firmness due to less occurrence of dehydration and slower degradation of cell wall components (Barman et al., 2011). Interestingly, there was lower reduction in juice content for waxed 'Bhagawa' pomegranate as a result of minimal moisture loss and respiration thereby retaining juice percentage (Waskar, 2011). The shelf life of pomegranate fruit ('Bhagawa') treated with waxol (9%) and carbendazim (9%) was extended by 30 days at room temperature and by 65 days at 8 °C, with fruit having good acceptance scores and organoleptic rating in terms of colour, flavour and texture (Waskar, 2011).

2.6. Irradiation

2.6.1. Physiological responses

Irradiation has been used as a treatment in a number of fruits but its use is limited due to the health concerns surrounding its impact on human health. Irradiation of pomegranate whole fruit is limited as it has been more commonly applied to the juice. However a few studies have reported the effect of irradiating pomegranate fruit (Tables 1 and 2). López-Rubira et al. (2005) observed that ultraviolet-C (UV-C) irradiation of pomegranate arils ('Mollar') had no effect on respiration rate of on-time and late-harvested fruit although the late harvested fruit generally had a higher respiration rate, which was attributed to increase in metabolic activity as a signal of decay. Likewise, the gas composition of the arils was also not

affected by irradiation with increased CO₂ and decreased O₂ levels observed in the packages throughout storage at 5 °C for 16 days (López-Rubira et al., 2005).

2.6.2. Effects physical and chemical properties

Irradiation has been shown to affect the physical and chemical parameters of pomegranate fruit. Pomegranate juice from irradiated fruit was observed to have a lighter colour compared to the control as redness (a*) and yellowness (b*) increased with increasing irradiation dose due to a decrease in polyphenoloxidase activity by irradiation (Shahbaz et al., 2014).

Chemical compounds in fruit are sensitive to irradiation in particular, bioactive compounds such as anthocyanins have been shown to be affected by irradiation (Maghoughi et al., 2013; Shahbaz et al., 2014). Lower irradiation doses (0.4 and 1 kGy) had no effect on titratable acidity, pH and total soluble solids but losses were reported when higher dosage levels (2 kGy) were applied (Shahbaz et al., 2014). In addition, total phenolic content and anthocyanin content of juice from irradiated pomegranate fruit (California cultivar) decreased gradually with increase in dosage from 0.4 kGy to 2 kGy due to immediate oxidation of phenolic compounds as these play an antioxidant role by reducing the free radicals and the reactive oxygen species produced by irradiation (Shahbaz et al., 2014). Combined use of ultraviolet-C irradiation (UV-C) and high oxygen packing was useful for keeping fresh-cut 'Mollar de Elche' pomegranate arils quality at 5 °C and extending their shelf life to 15 days. However, anthocyanin content declined while total phenolic content remained unchanged with ultraviolet-C irradiation and high oxygen packing during storage of arils ('Mollar de Elche') at 5 °C for 14 days (Maghoughi et al., 2013). Sensory evaluation of juices from low dose irradiated fruit (0.4 and 1 kGy) were preferred among panelists compared to juice from control and high dose treated fruit (2 kGy) as high doses of irradiation can induce an off-odour called "irradiation odour" in fruit juices (Shahbaz et al., 2014). On the contrary however, no desirable changes resulted from

irradiation although overall visual quality and shelf life of late harvested fruit were 4 days shorter than on-time harvested 'California cultivar' (López-Rubira et al., 2005).

3. Chemical treatment of pomegranate fruit

3.1. Polyamines

3.1.1. Physiological responses

Polyamines (PAs) are naturally occurring compounds that are involved in many developmental processes of plants. Exogenous application of polyamines such as putrescine, spermidine and spermine on pomegranate has been reported in several studies (Table 1). Barman et al. (2011) attributed the reduced ethylene production rate of pomegranate fruit ('Mridula') treated with putrescine to the anti-ethylene function of polyamines because both (PAs and ethylene) use the common precursor SAM (S-adenosyl methionine) for their biosynthesis. While putrescine reduced the respiration rate of 'Mridula' pomegranate fruit (Barman et al., 2011), spermidine did not affect the respiration rate of 'Mollar de Elche' pomegranate during 60 days of storage at 2 °C (Mirdehghan et al., 2007a). Putrescine, either alone or in combination with carnauba wax reduced chilling injury and skin browning of pomegranate ('Mridula') by 65% due to induced cold acclimation which led to maintenance of membrane fluidity at lower temperatures and consequently reduced electrolyte leakage and skin browning (Barman et al., 2011). Similarly Mirdehghan et al. (2007a) also observed that application of putrescine or spermidine either by pressure or immersion reduced skin browning by 25% and weight loss by 13% and 15% for putrescine and spermidine, respectively.

3.1.2. Effects on physical and chemical properties

Treatment of 'Mridula' pomegranate with putrescine (PUT)+carnauba wax maintained the highest fruit firmness after 60 days of storage at 3 °C (Table 1). The effect of polyamines on maintaining fruit firmness was ascribed to their cross-linkage to the carboxyl group of the pectic substances in the cell wall, resulting in rigidification. The binding between PAs and pectin also blocks the access of cell wall degrading enzymes such as pectinmethylesterase, pectinesterase and polygalacturonase, thereby reducing the rate of softening during storage (Barman et al., 2011). This binding effect was evidenced in the report by Mirdehghan et al. (2007a) who observed reduction in loss of fruit firmness by application of polyamines during 45 days of storage at 2 °C. Treatment of pomegranate fruit ('Mridula') with PUT + carnauba wax resulted in fruit with higher hue angle and lower chroma values with red shinning colour as opposed to deep tan red dull colour in control fruit after 60 days of storage at 3 °C (Barman et al., 2011).

Highest total sugars and TA and lowest TSS were observed in PUT + carnauba wax treated fruit compared to control fruit during a 60-day storage period. This was attributed to lower respiration, maturation process and water loss in treated fruit in comparison to control fruit (Barman et al., 2011). However, on the other hand, Mirdehghan et al. (2007a) observed no effect of polyamine treatment on the SSC and acidity during 60 days storage (Table 1). The changes were associated to delayed maturation due to application of PUT or SPD treatments as a result of their anti-senescence properties (Mirdehghan et al., 2007a).

According to Barman et al. (2011), total anthocyanin content increased for the first 15 days at 3 °C but later decreased with putrescine treated fruit, having 30–40% higher amounts than control after 60 days of storage (Barman et al., 2011). This was attributed to putrescine protecting the membrane lipids from being converted from liquid-crystalline to a solid-gel state thereby pre-

venting lipid peroxidation. Treatment with PUT + carnauba wax also retained 20% more ascorbic acid compared to control after storage at 3 °C for 60 days due to the anti-senescence properties of putrescine (Barman et al., 2011).

3.2. Fungicides

3.2.1. Physiological responses

Fungicides have been widely used to control spoilage of pomegranate fruit. A number of studies have shown the effect of these compounds on fruit quality. Fludioxonil (FLU) was effective in reducing decay of pomegranate fruit caused by *penicillium* spp. At the end of 7 days of shelf life, decay in fruit ('Primosole') treated with FLU alone or in combination with film wrapping was between 8 and 12%, which was between 2 and 3 fold less than in control fruit stored for 12 weeks at 8 °C (D'Aquino et al., 2010). Furthermore, D'Aquino et al. (2012) observed that decay development significantly reduced when 'Primosole' pomegranate was treated with fludioxonil whereas lecithin treatment did not affect decay rates. Interestingly, fludioxonil when applied alone showed better performance than in combination with lecithin. After one week of storage, no decay was detected in fruit treated with fludioxonil while control fruit showed 35–60% decay, and after 2 weeks of storage there was 100% decay incidence in control fruit while fruit treated with fludioxonil had only 2.5–7.5% decay even in the third week of storage (D'Aquino et al., 2009). However, fludioxonil had no significant effect on weight loss, husk scald severity and overall appearance (D'Aquino et al., 2012).

3.2.2. Effects on physical and chemical properties

Generally, there is limited information on the effects of fludioxonil on the physical and chemical parameters of pomegranate fruit. Residues of fludioxonil were detected only on the skin but not in the edible flesh part of 'Primosole' pomegranate and residue levels increased with increase in fludioxonil concentration and dipping temperature after 2 weeks at 20 °C (D'Aquino et al., 2009). It was also observed that efficacy of fludioxonil decreased substantially when the infections occurred more than 24 h before treatments due to the fact that fludioxonil is a contact fungicide as opposed to being systemic (D'Aquino et al., 2009).

3.3. Organic acids and their derivatives

3.3.1. Physiological responses

Organic acids are naturally occurring compounds in plants that play different important roles in the survival of the plant. A number of studies have reported the use of these compounds in postharvest treatment of pomegranates (Table 1). Treatment of pomegranate fruit ('Mollar de Elche') with acetyl salicylic acid (ASA) reduced respiration rate by 22–38% compared to control due to retard of fruit metabolism and reduced chilling injury during 84 days of storage at 2 °C (Sayyari et al., 2011b). In another study, Sayyari et al. (2011a) observed that the application of methyl salicylate (MeSa) and methyl jasmonate (MeJa) on 'Mollar de Elche' pomegranates significantly reduced the chilling injury by 2–3 folds lower than control fruit during storage for 84 days. The mechanism of MeJa in reducing chilling injury was attributed to enhancing the activities of superoxide dismutase, catalase and ascorbate-peroxidase and lowering the activity of lipoxygenase. Similarly, treating fruit ('Mollar de Elche') with oxalic acid reduced respiration, weight loss and electrolyte leakage after 84 days of cold storage at 2 °C (Sayyari et al., 2010). The effects of oxalic acid in reducing the incidence of chilling injury was attributed to the inhibition of polyphenoloxidase and peroxidase activities. Sayyari et al. (2009) also observed reduced chilling injury symptoms when fruit were treated with salicylic acid and the effectiveness increased with higher concen-

tration. Similarly, acetyl salicylic acid reduced chilling injury in 'Mollar de Elche' pomegranate, an effect ascribed to its conversion to salicylic acid (Sayyari et al., 2011b).

3.3.2. Effects on physical and chemical properties

MeJa and MeSa delayed softening of 'Mollar de Elche' pomegranate fruit, with MeSa being more effective than MeJa (Sayyari et al., 2011a). It was postulated that MeJa reduces pectinmethylesterase (PME) activity, decreasing de-esterification of pectin and thus maintaining fruit texture (Sayyari et al., 2011a). In another study, oxalic acid treatment had no significant effect on fruit firmness after 84 days of storage (Sayyari et al., 2010).

Treating fruit with oxalic acid limited the reduction in titratable acidity (TA) but had no effect on the total soluble solids (TSS) content of 'Mollar de Elche' pomegranates after storage at 2 °C for 84 days (Sayyari et al., 2010). Similarly, TSS and TA were not affected by treatment with salicylic acid (Sayyari et al., 2009). Furthermore, decrease in the organic acids during storage was reduced with MeJa and MeSa (Sayyari et al., 2011b). According to the authors, these could be as a result of organic acids being the main respiratory substrates during pomegranate postharvest storage (Sayyari et al., 2011b). Application of oxalic acid reduced loss of phenolics, and significantly increased ascorbic acid during cold storage at 2 °C for 84 days (Sayyari et al., 2010). Moreover, acetyl salicylic acid had no effect on total phenolic content throughout storage for 12 weeks at 2 °C (Sayyari et al., 2011b). On the contrary however, Sayyari et al. (2011a) found that total phenolic content increased during storage in fruit treated with MeSa and MeJa. In addition, acetyl salicylic acid increased total anthocyanins during storage by 15% compared to control during 12 weeks of storage of 'Mollar de Elche' pomegranate (Sayyari et al., 2011b). Increase in anthocyanin concentration due to oxalic acid treatment of pomegranate ('Mollar de Elche') was associated with advancement of the ripening process during storage. According to the authors exogenous oxalic acid could possibly act as an elicitor of anthocyanin biosynthesis and a natural antioxidant thereby suppressing lipid peroxidation (Sayyari et al., 2010).

4. Application of controlled and modified atmospheres

4.1. Effects on fruit physiological response

In controlled atmosphere storage (CAS) and modified atmosphere packaging (MAP), the gas composition inside the store or package containing produce is altered, and often CO₂ concentration is increased while O₂ concentration is reduced. Researchers on the effects of applying CA/MA as postharvest on pomegranate fruit is limited. In their study on scald development in 'Wonderful' pomegranates, Defilippi et al. (2006) reported that storing fruit under CA effectively controlled the disorder, especially with atmospheres of 15 kPa CO₂ which completely controlled development scald for up to 6 months at 7 °C storage. Investigating the effects of passive MAP on pomegranate arils ('Acco' and 'Herskawitz'), Caleb et al. (2013) observed that headspace O₂ concentration inside the packages decreased while the CO₂ levels increased significantly during storage at different temperatures. To prevent excessive accumulation of CO₂ inside the package, the authors proposed the use of polymeric films with higher permeability to CO₂.

4.2. Effects on physico-chemical quality attributes

Defilippi et al. (2006) reported that after 6 months of CA storage, 'Wonderful' pomegranates maintained a lighter red color relative to control fruit and this effect on CA-stored fruit was attributed to delayed synthesis of anthocyanins and other phenolics responsible for the red colour of the skin. Higher peel colour lightness was also observed in fruit stored under CA. The authors concluded that CA

treatments maintained very good fruit visual quality up to 6 months in cold storage.

In their recent study on two pomegranate cultivars ('Acco' and 'Herskawitz') grown in South Africa, Caleb et al. (2013) reported an overall steady weight loss of arils during storage under passive MAP. The initial increase in aril weight observed during the early part of storage period was attributed to rapid evaporation of moisture from aril surface and condensation inside the package. No significant changes were observed in the firmness and titratable acidity when pomegranate arils stored for 14 days at 5 °C, 10 °C and 15 °C; however, total anthocyanin content decreased with storage duration. Furthermore, the authors found low total aerobic mesophilic bacterial and fungal counts below detection limits.

5. Conclusions and future prospects

There are several physical and chemical postharvest treatments that can be applied to enhance the quality, storage and shelf life of pomegranate fruit. The use of chemicals like fungicides has been debated over the years because of the potential side effects they impart on both human health and the environment. This review identified natural plant compounds like polyamines such as putrescine, as well as organic acids such as oxalic acid, methyl jasmonate which have been successfully applied to control the incidence of spoilage and physiological disorders in pomegranates. The application of a combination of physical and chemical treatments, often referred to as hurdle technology, results in fruit with better quality. The additive properties of both treatments enhance quality attributes better than when treatments are used individually due to a broad spectrum effect. In addition to postharvest treatments, good crop management strategies should be emphasised if the full potential of the fruit is to be realised as preharvest factors affect the postharvest quality of the fruit.

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