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Review paper

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Efficacy of active and passive modified atmosphere packaging on quality preservation and storage life of pomegranate fruit and arils: A review

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Abstract: Pomegranate has nutritional value and health benefits due to its bioactive compounds and antioxidant properties. Fruit consumption is strongly recommended due to its high content of vitamins, fiber, minerals, and polyphenols. Supplying ready-to-eat pomegranate can be a beneficial technique to increase consumption with regard to its nutritional properties. However, maintaining nutritional quality and preventing microbial spoilage is a major challenge. Fruit quality is lost with visible symptoms such as weight loss, shriveling, husk scald, chilling injury, fungal rot, aril color degradation, and off-flavor during long-term storage. Therefore, it is very important to use appropriate strategies to maintain pomegranate whole fruit and aril quality. Gases around the product create a suitable environment for oxidative reactions and aerobic microorganism growth. Therefore, changing the atmosphere around the product can help maintain its quality. One of the effective methods to increase the postharvest life of products is to use modified atmosphere packaging (MAP), which reduces microbial spoilage and chilling injury, preserves the quality, and extends the shelf life by reducing the respiration rate. Modified atmosphere packaging, which uses natural atmospheric components (O_2, CO_2 and N_2), has been widely accepted due to the lack of toxic residues on the product. This review discusses on recent research in terms of MAP application on quality properties and postharvest life of pomegranate fruit and arils during storage.

1. Introduction

Regarding botanical classification, pomegranate belongs to the *Angiospermae* category, *Dicotyledoneae* subcategory, *Myrtales* order, *Lythraceae* family, *Punica* genus, and *P. granatum* species. *P. granatum* species is diploid (16x=2 n=2). It has four subspecies: *plenty-flora*, *spinisia*, *nana*, and *sativa*. Edible pomegranate is in the subspecies of *sativa*

(Jalikop, 2010). This fruit is mainly grown in Spain, Turkey, Egypt, Tanzania, Saudi Arabia, Azerbaijan, Pakistan, Afghanistan, India, and China. Among these countries, India, Iran, China, and Turkey are the main pomegranate producers (Ramezanian and Erkan, 2017). Pomegranate has many nutritional properties and bioactive compounds with anti-inflammatory, antioxidant, anticancer, antihypertensive, antidiabetic and liver damage-reducing effects (Kalaycıoglu and Erim, 2017; Khajebishak *et al*., 2019; Sohrab*et al*., 2019; Barati Boldaji *et al*., 2020; Firdous *et al*., 2023). The pomegranate is considered a non-climacteric fruit, and is harvested at the optimal maturity stage for storage, which has optimal organoleptic characteristics. The harvest index is the ratio of sugar to acid, and the standard index for harvesting is different depending on the cultivar (Artés *et al*., 2000). Post-harvest quality loss due to weight loss, hardening of the husk, cracking husk, chilling injury (CI) symptoms and fungal diseases limit its storage potential (Pareek *et al*., 2015; Porat *et al*., 2016; Ranjbari *et al*., 2018; Candir *et al*., 2019; Lufu *et al*., 2020) (Fig. 1). Moreover, ready-to-eat pomegranate aril is very perishable and rapidly lost its quality during storage. The most important goal of the postharvest industry is to maintain the quality during transportation and storage (El-Ramady *et al*., 2015; Moradinezhad and Dorostkar, 2021). Reducing postharvest losses leads to more available food, reducing cultivated areas, and preserving natural resources. Therefore, it is necessary to use techniques to maintain the fruit quality after harvest and during storage. Changing the atmosphere around the fruit through controlled atmosphere (CA) or modified atmosphere packaging (MAP) is a reliable and safe approach (Caleb *et al*., 2012; Caleb *et al*., 2013 a, b). In MAP, the gas composition inside the package is obtained based on the gas exchange through the semi-permeable layer and fruit respiration rate (Caleb *et al*., 2018). Although the respiration rate of pomegranate fruit is slow in cold temperatures, however, during the respiration process, oxygen (O_2) is consumed and dioxide carbon(CO_2) is produced, which changes the composition of the gas inside the package (passive MAP). In addition to passive MAP, the initial modification of respiratory gases (active

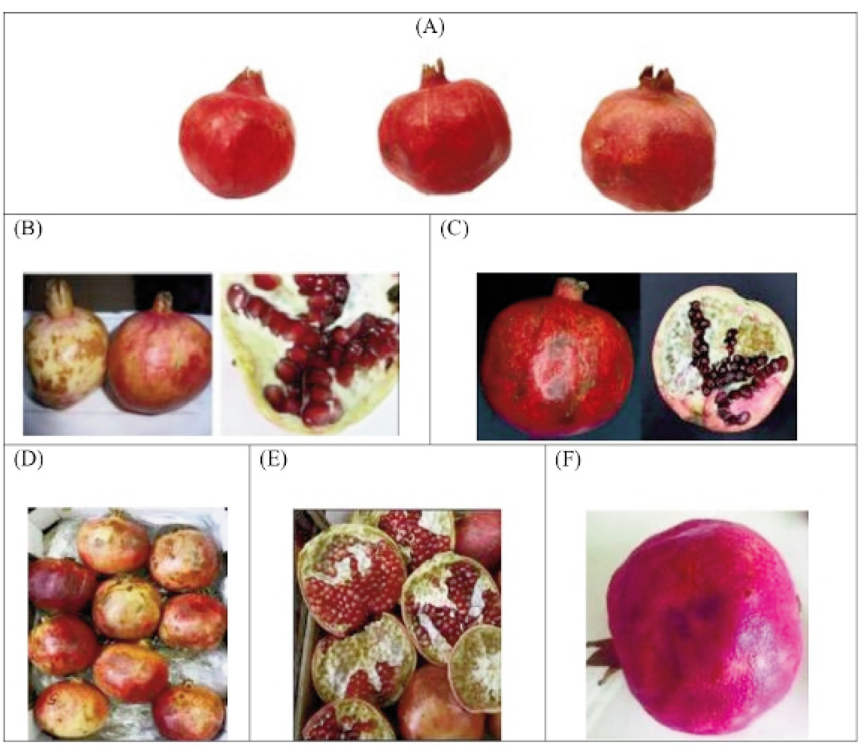

Fig. 1 - Chilling injury development in pomegranate cultivars stored at cold storage. A) The external appearance and weight loss of ‘Wonderful’pomegranate fruit after 4, 8, and 12 weeks of storage at 7°C, photo caption from left to right, respectively (Adetoro *et al*., 2020), B) The external and internal appearance of ‘Mengzi Sweet’ pomegranate fruit after 8 weeks of storage at 2°C (Chen *et al*., 2021), C) Husk scald and chilling injury in pomegranate ‘Wonderful’ fruit skin after 120 days of storage at 3.5°C (Maghoumi *et al*., 2022), D) Husk scald symptoms of ‘Wonderful’ pomegranate fruit after 12 weeks of storage at 7°C (Li *et al*., 2016), E) The internal appearance and discoloration of the texture of ‘Wonderful’ pomegranate fruit after two weeks of storage at 1°C (Kashash *et al*., 2019), F) Hard husk and shriveling symptoms of ‘Hicaznar’pomegranate fruit after 6 months of storage at 6°C (Candir *et al*., 2019).

MAP) based on the physiology of the product, environmental conditions and the properties of the packaging materials has a significant effect in reducing respiratory activity and increasing the shelf life (Opara *et al*., 2015; Opara *et al*., 2017; Belay *et al*., 2018; Dorostkar and Moradinezhad, 2022).

Despite the advantages of MAP, ultra-low or high concentrations of gases inside packages may cause damage to the texture. An excessive increase in O_2 concentration increases the production of radicals that damage the cytoplasm, such as superoxide (O^{-2}), hydrogen peroxide (H_2O_2), and hydroxyl (OH^-), consequently reducing the quality by inhibiting some metabolic activities (Choudhury *et al*., 2017). The reduction of O_2 below the critical limit causes the initiation of anaerobic respiration and fermentation, resulting in an unpleasant aroma and taste (Li *et al*., 2014). Also, excessive accumulation of CO_2 can lead to a decrease in quality by accelerating color changes and increasing the hydrolysis of pectin compounds (Teixeira *et al*., 2016).

With the increasing demand for MAP application, it is necessary to understand the role of gases and their effect mechanism on product quality. Therefore, a simplex lattice design approach was considered to select and identify the optimal gas composition to maximize the quality parameters of pomegranate aril cv. Wonderful under modified atmosphere conditions (Belay *et al*., 2019 a). The partial pressure of gases as visual quality, physicochemical characteristics, antioxidant properties and volatile organic compounds (VOCs) were selected as response variables. The results showed that CO_2 was the most important factor affecting color, texture firmness and volatile organic compounds (aldehydes, ketones, monoterpenes) of the Wonderful cultivar (Li *et al*., 2018; Li *et al*., 2020). O_2 had the greatest effect on color, organic acid, decay development and alcoholic volatile organic compounds. The maximum concentration of sugars, organic acids, total soluble solids (TSS), and color using a gas mixture (6-7 kPa O_2+ 7-8 kPa CO_2),and the maximum release of volatile compounds responsible for the taste of arils was obtained using a gas mixture (2 kPa O_2 + 18 kPa CO_2 + 80 kPa N_2) (Belay *et al*., 2019 a).

Low O_2 inhibits the rate of oxidation by reducing the rate of respiration and delaying fruit ripening (Li and Zhang, 2015; Teixeira *et al*., 2016). The concentration of super atmospheric $O_2$was effective in inhibiting microbial growth and reducing decay by preventing anaerobic respiration on minimally processed pomegranate arils (cv. Wonderful) (Belay *et al*., 2017 b). The qualitative changes of the fruit are related to the change of different metabolic pathways which are presented in the modified atmosphere by determining the genomic interpretation and their transcription frequency under the influence of packaging conditions (Rosales *et al*., 2016). The response of fruits to gas concentration is characterized by the profile of primary metabolite (respiration rate) and secondary metabolite (fermentative metabolites and volatile compounds) (Blanch *et al*., 2015).

Despite the advantages of the modified atmosphere in increasing the shelf life of the product, reducing storage losses without preservatives application, accurate control of storage temperature due to the effect of temperature on the permeability of used films, respiration rate, and solubility of gas in the aqueous phase of the food and the nutrient leakage, and determination of the specific gas composition for each product should be investigated.

Considering the importance of the storage environment, especially the concentration of O_2 and CO_2 in the occurrence of injury symptoms and the shelf life of products, this review aimed to investigate the efficacy of MAP on the overall quality of the whole pomegranate fruit and arils during cold storage.

2. Influence of MAP on quality traits of pomegranate

Chilling injury, weight loss, and overall quality

One desirable approach to minimize weight loss in a modified atmosphere is to reduce respiratory activity, which substantially reduces transpiration (Belay *et al*., 2018). Therefore, in the MAP, it is recommended to choose the appropriate gas composition to control the weight loss of the product. In the investigation of the suitable gas composition to reduce the respiration rate, the concentration of O_2 (2, 10 and 21 kPa) and CO_2 (2, 10 and 20 kPa) on pomegranate arils cv. Hicaznar (Ersan *et al*., 2009), and the concentration O_2 (5, 21, and 30 kPa) and CO_2 (0, 10, and 40 kPa) on the pomegranate arils cv. Wonderful (Banda *et al*., 2015) stored at 5°C showed that low O_2 concentration significantly decreases the respiration rate. Also, the concentration of O_2 2-4 kPa is recommended to maintain the quality of pomegranate arils cv. Mollar de Elche (López-Rubira *et al*., 2005). In a study on pomegranate arils cv. Wonderful in modified atmosphere (4.67kPa O_2, and 12.67kPa CO_2) packed with PropaFilm and Nature Flex showed that arils packed in PropaFilm had lower mass loss than NatureFlex, due to the film's lower water vapor transmission rate (WVTR) (Belay *et al*., 2018). High gas barrier properties PropaFilm, even at high relative humidity, lead to the potential for shelf-life extension. Weight changes are related to changes in respiration and transpiration, which are influenced by the difference in diffusion resistance and the surface to volume ratio of pomegranate arils (Khorshidi *et al*., 2011). Long-term storage of pomegranate arils causes more weight loss due to higher enzyme activity and lower resistance of the cell membrane against water loss (Belay *et al*., 2018). Modified atmosphere packaging reduces the vapor pressure difference between the surface and environment of the product by maintaining the relative humidity around the fruit, accordingly reducing the water loss of the product (Ngcobo *et al*., 2013).

Water loss of whole pomegranate fruit causes husk browning at the storage (Nerya *et al*., 2006). Also, enzymatic browning after microbial infection is the main cause of quality reduction (Ioannou and Ghoul, 2013) that polyphenol oxidase (PPO) and peroxidase (POD) activity increases the brown superficial discoloration of pomegranate fruits (Xie *et al*., 2019; Baghel *et al*., 2021). Storage of pomegranates cv. Mollar de Elche in controlled atmospheres (10kPa O_2 and 5kPa CO_2; 5kPa O_2 and 5kPa CO_2; 5kPa O_2 and 10kPa CO_2;or 5kPa O_2 and 0kPa CO_2) for 8 weeks at 5°C showed that all treatments except 10kPa O_2 and 5kPa CO_2 reduced weight loss, fungal rot and chilling injury symptoms (husk scald) and were efficient for increasing the quality and extending the shelf life of pomegranate fruits (Artés *et al.*, 2000). Moreover, storage of pomegranate fruit in a controlled atmosphere (1 kPa O_2 +15 kPa CO_2 or 5 kPa O_2 +15 kPa CO_2) significantly reduced botrytis rot and scald for up to 6 months at 7°C (Defilippi *et al*., 2006; Palou *et al*., 2007). Pomegranate fruits stored in a modified atmosphere (5kPa CO_2 + 3kPa O_2) for three months at 5°C had wrinkle-free husk and smoother, less chilling injury, fewer disease symptoms and, as a result, better quality compared to fruits stored in a normal atmosphere (Sidhu *et al*., 2019). Pomegranate fruits stored in a modified atmosphere (5-10 kPa CO_2 + 3-5 kPa O_2) increases shelf life due to reduced weight loss, decay and injury symptoms (Selçuk and Erkan, 2015; Porat *et al*., 2016; Maghoumi *et al*., 2022). High CO_2 concentration is effective in maintaining the activity of antioxidant enzymes such as catalase (CAT), superoxide dismutase (SOD) and ascorbate peroxidase (APX) (Song *et al*., 2013), and on the other hand, due to the lower O_2 concentration, POD and PPO enzymes do not catalyse the oxidation of phenols (Ali *et al*., 2019). Also, increasing the concentration of CO_2 and decreasing the concentration of O_2 will inhibit fungal contamination by suppressing respiration (Almenar *et al*., 2006). As mentioned, water stress, oxidative stress, lipid peroxidation and cell membrane instability are key factors in burn development (Singh *et al*., 2018). MAP and CA prevent husk scald by limiting oxygen access, oxidative stress and water loss prevention. It has been proved that MAP is effective in maintaining the external and internal quality of pomegranate fruit by controlling weight loss, and preventing fungal decay and husk scald during cold storage (Selçuk and Erkan, 2015; Porat *et al*., 2016).

Fruit weight loss increases CI symptoms by destroying the membrane integrity (Opara *et al*., 2015; Maghoumi *et al*., 2023). The decrease in unsaturated fatty acid content and membrane fluidity causes damage to the membrane structures and a lack of resistance to cold (Casares *et al*., 2019). It has been reported that CI symptoms coincide with the leakage of electrolytes in the pomegranate peel (Casares *et al*., 2019). Oxidative damage, membrane chilling injury and electrolyte leakage in pomegranate peel are indicated as a function of O_2 levels in the first days of storage (Valdenegro *et al*., 2018). In the modified atmosphere condition, the stability of SOD and CAT enzymes leads to less accumulation of H_2O_2 and malondialdehyde (MDA), more integrity of the membrane and therefore less electrolyte leakage (Li *et al*., 2016; Valdenegro *et al*., 2022), and a higher PAL/PPO ratio reduces oxidative damage (Baghel *et al*., 2021). Researchers have studied extensively the effect of a low-oxygen atmosphere on the quality characteristics of whole pomegranate fruit or arils cv. Primosole (D'Aquino *et al*., 2010), cv. Acco and Herskawitz (Caleb *et al*., 2013 a, b), cv. Wonderful (Banda *et al.,* 2015), cv. Hicaznar (Candir *et al*., 2018), cv. Shishe-Kab (Moradinezhad *et al*., 2013, 2019), and it has been found that the atmosphere with low oxygen has the potential to prevent weight loss, chilling injury, decay and delay in post-harvest ripening (Table 1).

Firmness

The firmness reduction is related to water loss, cell membrane deterioration and senescence (Díaz-Mula *et al*., 2012; Hussein *et al*., 2015). The effect of MAP on maintaining fruit firmness is related to the control of weight loss, which has an important effect on postharvest management (Jouki and Khazaei, 2014). Also, maintaining post-harvest firmness is related to the control of biochemical processes (activities of pectinsterase and polygalacturonase enzymes) (Fagundes *et al*., 2015; Bang *et al*., 2019) and the prevention of ethylene synthesis under a modified atmosphere (Akbudak *et al*., 2012). High CO_2 inhibits ethylene production and delays ripening (Kader and Watkins, 2000). A similar effect of high CO_2 and super atmospheric O_2 has been reported on firmness of aril cv. Wonderful that arils stored under super atmospheric O_2 (70%) showed a slight increase in the firmness compared to low O_2 treatment (5 and 10%) (Belay *et al*., 2017 b). A low respiration rate limits the activity of cell wall-degrading enzymes (such as pectinase and cellulase) and preserves firmness during storage (Fagundes *et al*., 2015; Bessemans *et al*., 2016), and as a result delayed ripening (Mahajan *et al*., 2014; EL-Eryan*et al*., 2020). MAP can lead to structure preservation, less tissue damage and shelf-life quality of aril due to increased vapor pressure and reduced cell wall polysaccharides degradation (Zhao *et al*., 2019).

Color characteristics

Fruit color is related to the breakdown of chloroplasts, chromoplasts and the change of natural pigments (chlorophylls, anthocyanins, carotenoids, flavonoids) that are affected by packaging and storage conditions (Yin *et al*., 2016). L^*, a^*, b^* values represent the lightness, redness and yellowness. Chroma (C^*) and hue angle ($h°$) describe the color intensity and purity, respectively. L^*, C^* and $h°$ indices reflect the intensity of the color. A slight decrease in C^* and an increase in $h°$ indicates the loss of color intensity of pomegranate arils during storage (Palma *et al*., 2015). Loss of the color intensity during MAP can be controlled by regulating enzymatic and non-enzymatic activities through decreasing O_2 concentration or reducing water loss (Belay *et al*., 2018). High CO_2 concentration prevents enzymatic browning by reducing phenolic substrate and PPO activity (Manolopoulou and Varzakas, 2013). Belay *et al*. (2017 b) reported that MAP, storage time and their interaction had a significant effect on color intensity of pomegranates cv. Wonderful stored at 5°C. The highest C^* was observed under a low O_2 atmosphere (5kPa), while the super O_2 atmosphere (70kPa) maintained initial C^* values during storage (Belay *et al*., 2017 b).

Titratable acidity (TA) and total soluble solids (TSS)

The reduction in TA of pomegranate juice cv. Mollar de Elche without changes in TSS was observed under UV-C treatment and super atmospheric O_2 conditions, which is related to metabolic activities and increased catabolism of organic acids in the respiration process (Maghoumi *et al*., 2013). On the other hand, increasing TA of arils cv. Kingdom and MR-100 under the passive modified atmosphere at 5°C were due to fermentation, which was confirmed by the growth of total aerobic bacteria, yeasts, and molds (Adiletta *et al*., 2017). Changes in gas composition (increase and/or decrease O_2 or CO_2) hydrolyze polysaccharides to sugars (Sucrose, glucose, and fructose) by changing the activity of carbohydrate biosynthesis enzymes and sugar compound metabolism. The active modified atmosphere provides high non-reducing sugars at the end of storage, which can affect the chemical, sensory and quality characteristics of pomegranate arils during storage (Patanè *et al*., 2019; Moradinezhad *et al*., 2020). In addition, an increase in sugar content (fructose, glucose, and sucrose) of pomegranate cv. Wonderful was observed in 4.6kPa O_2 and 12.65kPa CO_2 (Belay *et al*., 2018), likely because that exposure to CO_2 preserves energy reserves. The reduction of TSS in the super-atmospheric is due to the reduction of carbohydrates, pectin, partial hydrolysis of protein and breakdown of glycosides into constituent units during respiration (Blanch *et al*., 2015). The effect of MAP on organic acids and sugars of pomegranate fruit reported as inconsistent and were mainly depended on the cultivar and also the duration of storage, as the TSS value on cv. Mridula increased (Barman *et al*., 2011), while on cv. Ruby decreased (Fawole and Opara, 2013), and on cv. Mollar remained unchanged (Sayyari *et al*., 2011). Therefore, the control of respiration rate (RR) and transpiration rate (TR) is crucial to preserve TA and TSS values during storage as much as possible, in order to get a higher TSS to TA ratio index.

Ascorbic acid, antioxidant and anthocyanin content

The reduction of ascorbic acid (AA) was observed in arils cv. Malese Saveh stored under super atmospheric O_2 (70kPa) for 14 days at 4°C (Maghoumi *et al*., 2014). In investigating the effect of the modified atmosphere, low O_2 (5 or 10kPa O_2, 10kPa CO_2), super atmosphere (70kPa O_2, 10kPa CO_2) and normal atmosphere on the AA content of pomegranate cv. Wonderful at 5°C, it was found that oxidation AA was associated with the presence of O_2. As a result, the content of AA decreased in the super atmosphere and normal atmosphere (Belay *et al*., 2017 b). However, super atmospheric O_2 has beneficial effects on other quality characteristics. Excessive amounts of O_2 and CO_2 may cause the oxidation of AA through increasing oxidative stress on plant tissues (Belay *et al*., 2017 b). Besides the atmosphere, the nature of the fruit also affects the concentration of AA during storage, so acidity levels are one of the factors affecting the stability of AA during storage (Wahyuningsih *et al*., 2017). The reduction of AA as an antioxidant agent is due to its use as an electron donor to oxidants for neutralizing free radicals is attributed to fruit respiration and sensitivity to chilling injury (Artés *et al*., 2006).

The effect of packaging with different gas compositions (5 kPa O_2 + 10 kPa CO_2 + 85 kPa N_2; 10 kPa O_2 + 5 kPa CO_2 + 85 kPa N_2; 70 kPa O_2 + 10 kPa CO_2 + 20 kPa N_2; 21 kPa O_2 + 0.03 kPa CO_2 + 78 kPa N_2) was investigated on the physicochemical characteristics, nutrient and volatile organic compounds of aril cv. Wonderful for 12 days at 5°C. It was observed that arils packed with low O_2(5 kPa O_2 + 10 kPa CO_2 + 85 kPa N_2) have more nutrients content (Belay *et al*., 2017 b). Higher values of AA, anthocyanin and phenolic compounds were observed in pomegranate cv. Wonderful stored in low O_2 concentration (5 kPa O_2+ 10 kPa CO_2 + 85 kPa N_2 and 10 kPa O_2 + 5 kPa CO_2 + 85 kPa N_2) at 5°C. Also, maintaining low O_2 concentration using low permeability polypropylene film preserved pomegranate anthocyanin and improved sensory quality (Banda *et al*., 2015). Decreasing the respiration rate reduces the amount of carbohydrates, and the carbohydrates that accumulate in the tissue are used in the production of phenolic compounds (Wang *et al*., 2017).

Increasing the activity of antioxidant enzymes, such as SOD, CAT, and APX removes oxygen free radicals and reduces the activity of PPO and POD enzymes involved in the browning of arils cv. Purple Queen was packed in semipermeable film, which had higher polyphenol and anthocyanin content (Adiletta *et al*., 2019). Also, heat treatment, UV-C and super atmospheric O_2 packaging delayed the PPO and glutathione peroxidase (GPX) activity of pomegranate arils cv. Malese-Saveh and maintained the antioxidant concentration (Maghoumi *et al*., 2013). Accumulation of phenolic compounds exposed to high O_2 can be a physiological stress response, and stimulates phenylalanine ammonia-lyase (PAL) activity during minimal processing (Baenas *et al*., 2014). The increase of O_2 in the first days of storage may increase the antioxidant activity, but in the long-term, it reduces the main antioxidants including anthocyanins and phenolic compounds due to the oxidation stimulated by O_2 (Maghoumi *et al*., 2014). Increasing reactive oxygen species (ROS) causes the oxidation of phenolic compounds due to the increase in PPO activity and loss of membrane compartmentalization (Cisneros-Zevallos *et al*., 2014). At the end of the storage of pomegranate arils cv. Wonderful the lowest anthocyanin concentration was observed n high O_2 atmospheres (30kPa O_2 and 10kPa CO_2) (Banda *et al*., 2015), which could be due to the oxidation of AA (Maghoumi *et al*., 2014). Palma *et al*. (2015) related the changes in anthocyanin content to the presence of organic acids (e.g. ascorbic acid) and titratable acidity, which provide the carbon skeleton for the synthesis of secondary metabolites (e g. anthocyanins) during storage (Palma *et al*., 2015). Changes in anthocyanin content can be attributed to the interaction of arils with gas composition, biosynthesis and stability of individual anthocyanins (Palma *et al*., 2015; Moradinezhad *et al*., 2020). Due to the inhibition of anthocyanin biosynthesis in high CO_2, the anthocyanins of pomegranate cv. Wonderful stored in atmospheres enriched with CO_2 (10-20 kPa) were lower compared to fruit stored in air (Holcroft *et al*., 1998). Higher levels of CO_2 in X5 and X12 packages probably delayed anthocyanin synthesis and reduced the intensity of aril color during storage by reducing anthocyanin and phenol (Selcuk and Erkan, 2015; Tzoumaki *et al*., 2009). The reduction in anthocyanin content, which affects the color of arils, is a disadvantage of storage with high CO_2 levels (Table 1).

Volatile organic compounds (VOCs)

The identified VOCs comprised five compound groups (aldehyde, ketone, alcohol, ester and monoterpene), ester compounds were dominant, followed by ketones and aldehydes, whereas, alcohol and monoterpenes were the least abundant (Belay *et al*., 2018). Increasing VOCs are related to the acceleration of metabolism in response to the atmosphere, which can lead to stress and disruption of enzyme systems (Giuggioli *et al*., 2015). Increased VOCs at low O_2 stimulate the production of fermentative

Table 1 a -Efficacy of modified atmosphere packaging (MAP) on whole pomegranate fruit and arils

Pomegranate cultivar	Treatment	Whole fruit/Aril	Storage time (days)	Outcomes	Reference
Hicaznar	Passive modified atmosphere using Xtend® and ZOEpac	Whole fruit	210	Increase of polyphenols, anthocyanins, antioxidant activity, delay in color change and maintain appearance quality up to day 120, maintain physiological and biochemical properties up to day 180.	(Selcuk and Erkan, 2015)
Hicaznar	Passive modified atmosphere using Xtend®	Whole fruit	180	Maintaining husk color, titratable acidity, and ascorbic acid content, and reducing weight loss and husk scald.	(Candir *et al*., 2018)
Shishe-kab	Pre-treatment with short-term high CO_2 and packaging in polyethylene bags, Nano-bags and Decoo Magic Bag	Whole fruit	90	Reducing respiration rate, weight loss, decay, and chilling injury, and maintaining organoleptic properties	(Moradinezhad *et al*., 2018)
Afganski, Crab, Cranberry, Entek-habi-saveh	Modified atmosphere packaging (5 kPa CO_2 + 3 kPa O_2)	Whole fruit	90	The fruit had a wrinkle-free skin, less chilling injury, less disease symptoms and better quality	(Sidhu *et al*., 2019)
Succary	Passive modified atmosphere using high ethylene absorption (HEA), perforated polyethylene (PPE), polyethylene (PE) film, stretchable cling film, poly vinyl	Whole fruit	90	The fruit had a less chilling injury, lower changes in acidity and soluble solid content, and increased antioxidant activity.	(Serry, 2019)
Wonderful	Passive modified atmosphere using non-perforated 'Decco' and 'Zoe', micro-perforated Xtend®, micro and macro perforated high density polyethylene (HDPE)	Whole fruit	84	Packaging whole fruit with micro- and macro- perforation reduced post-harvest losses by minimizing moisture condensation, fruit rot and shriveling.	(Lufu *et al*., 2021)
Wonderful	Passive modified atmosphere using micro-perforated Xtend® and macro-perforated high-density polyethylene	Whole fruit	42	Fruits packaged in the micro-perforated Xtend® had least weight loss, lowest respiration rates, highest total soluble solids and no fungal decay.	(Kawhena *et al*., 2022)
Wonderful	Passive modified atmosphere using XTend™ bags	Whole fruit	120	Increasing the concentration of anthocyanin in the husk and arils, delaying the symptoms of chilling injury up to 120 days	(Valdenegro *et al*., 2022)
Wonderful	Passive modified atmosphere using 100% cellulose-based film NatureFlex (NF), bi-axial-oriented polypropylene (BOPP)-based film PropaFilm (PF), NF-PF (66:33%) film, and PF-NF (33:66%) film	Aril	9	Pakage NF-PF (66:33%) film, and PF-NF (33:66%) film resulted in lowest in-package water vapour condensation and mold growth, and maintained the quality of arils at storage.	(Belay *et al*., 2018)
Purple Queen	Passive modified atmosphere using micro-perforated (MPP) and semipermeable (SP) films	Aril	16	Arils packaged in the SP system had high polyphenols, anthocyanins contents, antioxidant activity (superoxide dismutase, catalase, and ascorbate peroxidase) and low polyphenol oxidase and peroxidase activity.	(Adiletta *et al*., 2019)
Wonderful	Passive modified atmosphere using Xtend bag, polyethylene bag, polypropylene bag, and silver nano bag	Aril	18	Silver nano bag maintained the taste, aroma and overall acceptability, anthocyanin, vitamin C and antioxidant activity and reduced pectinase activity.	(EL-Eryan, 2020)
Wonderful	The nitrogen and argon-based MAP treatment (MAP Ar)	Aril	16	Arils packaged in the (MAP Ar) had high sugar/acid ratio, and desired sensory quali-	(Tinebra *et al*., 2021)

Table 1 b -Efficacy of modified atmosphere packaging (MAP) on whole pomegranate fruit and arils

Pomegranate cultivar	Treatment	Whole fruit/Aril	Storage time days	Outcomes	Reference
Bhagwa	Passive modified atmosphere using transparent high-density	Aril	5	Increasing titratable acidity, anthocyanins reducing sugars, and total soluble solids,	(Rokalla *et al*., 2022)
Rabbab	Passive modified atmosphere using Polyethylene+ Polyester (PE+PES) and Biaxial oriented polypropylene (BOPP) film	Aril	15	PE+PES film caused delay in decreasing the trend of total antioxidant activity and had the lowest number of aerobic mesophilic bacteria and psychrophilic bacteria.	(Ranjbar and Ramezanian, 2022)
Wonderful	Active modified atmosphere based on high O_2	Aril	12	The gas mixture containing 30 kPa O_2 + 10 kPa CO_2 + 60 kPa N_2 had lower aerobic mesophilic bacteria counts, higher sensory scores and long-term shelf life.	(Banda *et al*., 2015)
Wonderful	Active modified atmosphere based on low O_2 and enriched CO_2	Aril	9	The gas mixture containing 12.67–18 kPa CO_2, 2–4.67 kPa O_2 and 80 – 82.67 kPa N_2 reduced microbial count.	(Belay *et al*., 2017 a)
Wonderful	Active modified atmosphere based on low O_2 and super-atmospheric O_2	Aril	12	The gas mixture containing 5 kPa O_2 + 10 kPa CO_2 + 85 kPa N_2 and 10 kPa O_2 + 5 kPa CO_2 + 85 kPa N_2 maintained phytonutrient content, 70 kPa O_2 + 10 kPa CO_2 + 85 kPa N_2 had low aerobic mesophilic bacteria, yeast and mold counts.	(Belay *et al*., 2017 b)
cv. Wonderful	Active modified atmosphere based on low O_2	Aril	9	The gas mixture containing 2 kPa O_2 +18 kPa CO_2 + 80 kPa N_2 leads to the accumulation of ethanol, increase in respiration quotient and oxidation of organic acids.	(Belay *et al*., 2019 b)

compounds (Zhang *et al*., 2013 a; Cortellino *et al*., 2015) and induce cell damage and senescence by producing anaerobic metabolism (Li and Zhang, 2015). Super atmospheric O_2 affects the synthesis and accumulation of some VOCs related to respiratory metabolism (such as acetaldehyde, ethanol, and ethyl esters). Accumulation of acetaldehyde is the first indicator of fermentation metabolism, which is rapidly converted to ethanol by the enzyme alcohol dehydrogenase (ADH) and negatively effects on sensory properties (Thewes *et al*., 2015; Manolopoulou and Varzakas, 2013). The highest amount of VOCs was observed in arils stored under super atmospheric O_2 and enriched CO_2 (70kPa O_2, 10kPa CO_2) and the lowest amount was observed in arils stored in the normal atmosphere at the end of storage (Belay *et al*., 2017 a). Increasing synthesis of VOCs in response to wound (Amaro *et al*., 2012), or high CO_2 concentration leads to disruption of enzymatic systems, such as the lipoxygenase pathway (Giuggioli *et al*., 2015) which catalyzes the oxidation of unsaturated fatty acids.

Microbial load

Fungi (yeasts and molds) are important pathogenic microorganisms that are resistant to acid conditions (Jacxsens *et al*., 2001; Firdous *et al*., 2023). Yeasts are facultative anaerobes, and in contrast, molds are aerobes, which has been observed high CO_2 (>10%) inhibits mold growth (Molin, 2000). The reduction count of mesophilic bacteria has been reported in minimal processing pomegranate cv. Hicaznar under a high O_2 atmosphere (70 kPa) compared to low O_2 and normal atmosphere at 5°C (Ayhan and Estürk, 2009). A high O_2 atmosphere is used in fresh-cut due to its ability to prevent anaerobic fermentation, enzymatic discoloration and microbial growth (Jacxsens *et al*., 2001) and it is effective by increasing the lag phase of growth and reducing the growth of bacteria and yeast in arils pomegranate (Belay *et al*., 2017 a; Moradinezhad *et al*., 2020). The inhibitory effect of the high O_2 is due to the toxicity of oxygen, which causes damage to the antioxidant system, DNA and nucleoproteins of microorganisms by ROS (O^{2-}, H_2O_2 and OH^-) produced at a partial pressure of O_2 (Tomas-Callejas *et al*., 2011). Pre-storage short-term high CO_2treatment significantly reduced the decay of pomegranate fruits during cold storage (Moradinezhad *et al*., 2018). High CO_2 reduces the microbial load of fruit by penetrating the microbial membrane, changing intracellular pH or forming carbonic acid, which has bacteriostatic effects (Zhang *et al*., 2013 b; Banda *et al*., 2015; Belay *et al*., 2017 b; Ranjbari *et al*., 2018; Van de Velde *et al*., 2019, 2020; Moradinezhad and Dorostkar, 2020). High CO_2 pretreatment has significant potential to prevent water loss, oxidative damage, and control decay. It seems to be related to the induction of specific defense proteins, including dehydrins and pathogenesis-related proteins, as well as endogenous protective osmolytes (Vazquez-Hernandez *et al*., 2018). At ambient air temperature, the active modified atmosphere affected on the chemical and qualitative characteristics of pomegranate arils, which were related to the reduction of microbial load, safety and high organoleptic properties (Rokalla *et al*., 2022).

3. Conclusions and future prospects

Post-harvest loss is one of the main problems in the pomegranate industry worldwide. Since the quality of the fruit is determined by internal and external characteristics, it is necessary to maintain the overall quality of the product for supply to consumers. Considering that pomegranate fruit is non-climacteric, the use of MAP polymer films may have a good potential for the maintenance of its quality.In this study, the mechanism of the effects of MAP on the physicochemical and qualitative characteristics of whole and minimally processed arils of pomegranate werereviewed, and indicated that MAP had a significant effect to prevent chilling injury and maintain fruit quality. Several studies have reported the advantages of the modified atmosphere in extending the shelf life based on low O_2 concentration and enriched CO_2. MAP and vacuum packaging comprising optimal concentrations O_2 and CO_2depends on physiology cultivar is a valuable technique to maintain nutritional quality, and antioxidant activity, reduce weight loss, and control the storage diseases and disorders of whole pomegranate fruit and arils.However, there is a need for extensive studies to develop the MAP system for pomegranate arils and fruit in different commercial cultivars.

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