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Postharvest environmentally and human-friendly pre-treatments to minimize carrot waste in the supply chain caused by physiological disorders and fungi

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ABSTRACT

Background: Carrot is one of the most important horticultural crops, with an annual worldwide production exceeding 40 million tonnes. Carrots are sold either fresh intact or fresh-cut as minimally processed vegetables (MPV). In the postharvest supply chain, physiological disorders, fungal decay, and their combinations reduce the quality of fresh intact and MPV carrots. MPV carrots are more susceptible to quality changes than fresh intact carrots due to a higher loss of protective epidermis, greater number of wounded cells, and increased respiration rates.

Scope and approach: The current review summarizes different environmentally and human-friendly treatments applied in the postharvest supply chain to minimize the adverse effects of handling and storage on physiological disorders and fungal decay.

Key findings and conclusions: Bitterness, white blush, and browning are the most critical physiological disorders of fresh and MPV carrots. Bitterness can be prevented by storing carrots in well-ventilated rooms without ethylene-producing fruit and vegetables, while white blush and browning can be controlled by the application of heat treatment, ultraviolet (UV)-irradiation, hydrogen sulfide (H_2S), and edible films. *Sclerotinia sclerotiorum*, *Botrytis cinerea*, *Alternaria radicina*, and *Berkeleyomyces* spp. (formerly *Thielaviopsis* spp.) are important fungi causing carrot postharvest losses and waste. Fungal decay of carrots can be controlled by selecting healthy carrots and applying natural compounds, ozone (O_3), heat treatment, UV-irradiation, inorganic salt, and/or biocontrol agents, and their combinations. However, a successful combination of different sustainable treatment methods requires treatment compatibility, and -omics techniques may reveal the best combinations of sustainable treatment methods.

1. Introduction

Carrots (*Daucus carota* L.) are among the most important horticultural crops ranked among the top 10 vegetable crops worldwide. Carrot annual worldwide production exceeds 40 million tonnes, with Asia being the leading continent regarding production followed by Europe (Fig. 1). As shown in Fig. 1, there is an increasing trend in worldwide carrot production over the last twenty years. Carrots are sold either intact as fresh or as fresh-cut following the scheme for minimally processed vegetables (MPV). MPV is defined as fresh-cut packaged fresh produce with the advantage of no or minimal need for further processing before consumption (Alegria et al., 2010, 2012). The industrial processing of MPV carrots involves peeling/trimming, cutting/slicing/-shredding, washing, packaging/storage, and distribution of washed and graded intact carrots (Alegria et al., 2010; De Corato, 2020). In contrast, fresh carrots are washed, brushed, graded into various sizes, packaged, and then brought into the food supply chain as a product that needs further handling at households. The quality of both intact and MPV carrots can be deteriorated during the supply chain either due to inappropriate pre-treatments before entering the supply chain (i.e., handling in the packaging houses and the MPV factories) or pathogen decay or their combination, with the MPV carrots being more susceptible to

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deterioration and spoilage due to a higher loss of protective epidermis, more wounded cells, and increased respiration rates (Condurso et al., 2020).

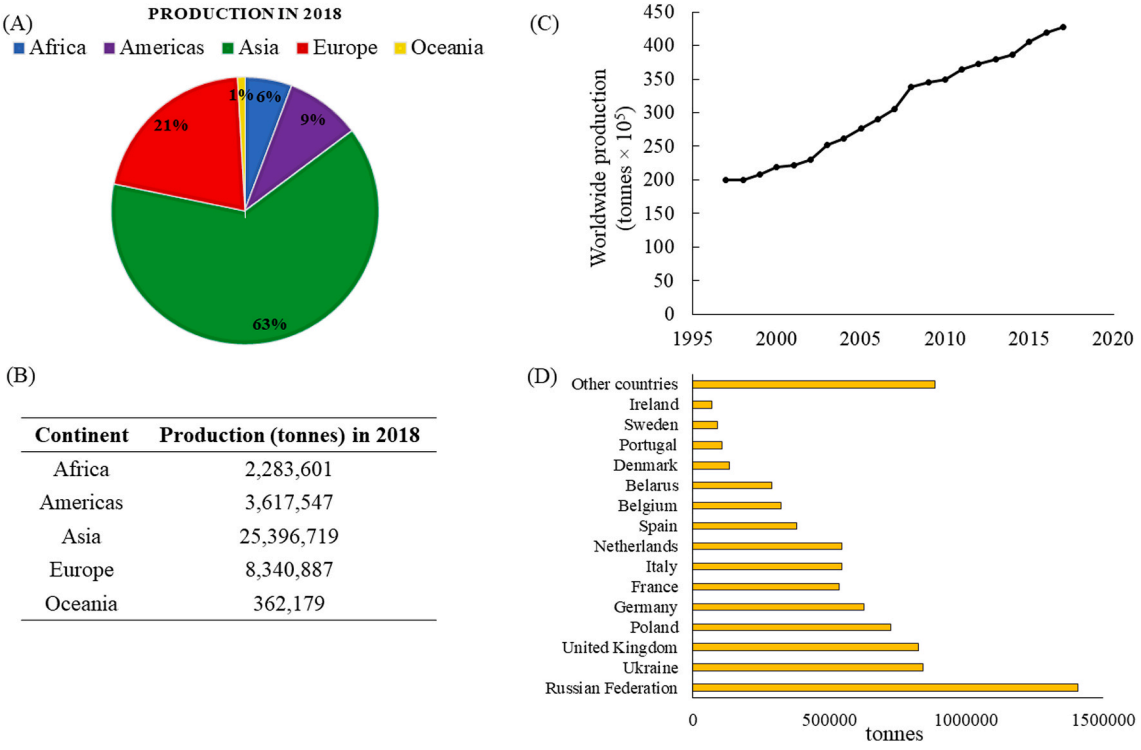
According to the literature, low temperatures of 0–1 °C and high relative humidity (RH) of 98–100% are optimal for the storage of fresh and fresh-cut carrots (Edelenbos, Wold, Wieczynska, & Luca, 2020a, 2020b). Inappropriate storage conditions may result in physiological disorders of carrots, with some genotypes being more susceptible to develop physiological disorders than others. Physiological disorders could be considered as any physical, chemical, or physiological change in a fruit or a vegetable caused by external abiotic factors and not due to a pathogen (i.e., fungi, bacteria, viruses, insects, or nematodes). From an economic point of view bitterness, white blush, and browning are the most important physiological disorders of intact and MPV carrots (Edelenbos, Wold, Wieczynska, & Luca, 2020a, 2020b; Seljasen, Bengtsson, Hoftun, & Vogt, 2001; Vargas, Chiralt, Albors, & González-Martínez, 2009; Zhang, Tan, McKay, & Yan, 2005). Measures that could be employed to avoid carrot quality deterioration by the application of postharvest sustainable treatments are discussed in a following section.

Carrots are also susceptible to pathogen deterioration after harvest caused by fungi, including *Sclerotinia sclerotiorum* (Lib.) de Bary (watery soft rot), *Botrytis cinerea* Pers.:Fr. (grey mold), *Alternaria radicina* (black rot), *Berkeleyomyces* spp. (formerly *Thielaviopsis* spp.) (black root rot) and bacteria, such as *Pectobacterium carotovorum* (formerly *Erwinia carotovorum*). These pathogens are responsible for carrot losses and waste during short- and long-term postharvest storage in response to field conditions and handling of the carrots in the packaging stations (Hildebrand, Forney, Song, Fan, & McRae, 2008; Nel, Duong, de Beer, & Wingfield, 2019; Ojaghian et al., 2016, 2017; Weber & Tribe, 2004). On a commercial scale, all pathogens affecting carrot quality are controlled by synthetic pesticides (Ojaghian et al., 2013, 2014, 2016). However, consumers are concerned about the consumption of fruit and vegetables sprayed with synthetic chemicals since chemical residues are often associated with health issues (Papoutsis, Mathioudakis, Hasperué, & Ziogas, 2019). Also, the European Union (EU) aims to reduce the risks and impacts of chemical use on human health and the environment by promoting the development of sustainable alternatives to synthetic pesticides (Directive 2009/128/EC). Therefore, alternative environmentally and human-friendly solutions to chemical fungicides are required.

Sustainable treatments that can be applied before packaging and storage are required to maintain carrot quality (i.e., color, flavor, texture, and nutritional value) and control pathogen growth, thus, to reduce losses and waste in the retail and households. The current review aims to provide information regarding the maintenance of postharvest carrot quality by the application of sustainable treatments that have been investigated in the last decades. Both physiological disorders and selected fungi that lead to carrot postharvest losses and waste have been reviewed (Fig. 2), and potential mechanisms of action of the sustainable treatments are comprehensively discussed. Future directions aiming to reduce carrot losses and waste are also presented and discussed.

2. Botany of carrots

Carrots (*Daucus carota* L.) are herbaceous biennial plants belonging to the Apiaceae family. Carrot is a cool climate crop, with the taproot being the edible part of the plant. There are two types of cultivated carrots, including Eastern or Asiatic carrots (*D. carota* ssp. sativus var. atrorubens Alef.) and Western carrots (*D. carota* ssp. sativus var. sativus). Western carrots include the carrots with orange, red, or white color, while Eastern carrots include carrots of purple and yellow color (Ma et al., 2017, 2018; Que et al., 2019; Wang et al., 2020). Cultivated carrots are diploid (2n = 2x = 18) and the length of their chromosome is 2.34 μm (Iorizzo et al., 2011; Que et al., 2019). Currently, the most popular carrots are those with orange color. Iorizzo et al. (2016) claimed that the DCAR_032551 is a candidate enzyme that controls carotenoid accumulation along with genes involved in isoprenoid biosynthesis. In orange carrots, α-carotene, β-carotene, and lutein have been determined, with α- and β-carotenes being responsible for the orange color.



Continent	Production (tonnes) in 2018
Africa	2,283,601
Americas	3,617,547
Asia	25,396,719
Europe	8,340,887
Oceania	362,179

Fig. 1. Carrot and turnip production in different continents in 2018 (A, B); worldwide production of carrot and turnips over 20 years (C); Carrot and turnip production in Europe in 2018 (D).

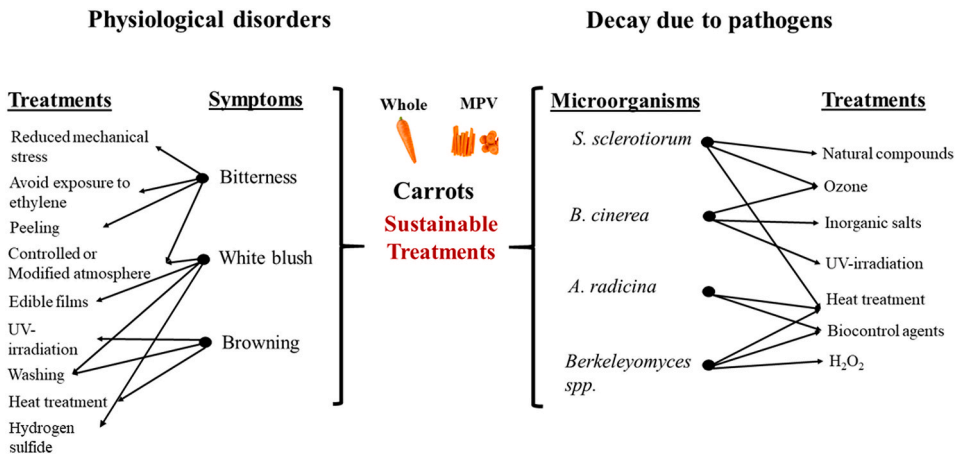


Fig. 2. Summary of sustainable treatments that have been used to maintain carrot postharvest quality during handling and storage.

Carotenoids and their biosynthetic enzymes are found in the plastids, while carotenoid biosynthetic genes are in the nuclear genome (Ma et al., 2017). Lycopene is responsible for the color of red carrots and its accumulation has been linked to the high expression of five genes, including *DcPSY2*, *DcPDS*, *DcZDS1*, *DcCRT1*, *DcCRT2*, and low expression of *DcLCYE* (Wang et al., 2020). In yellow carrots high expression of genes involved in xanthophyll (lutein, zeaxanthin) synthesis has been reported, with lutein mainly being responsible for yellow color (Ma et al., 2017). Specifically, it has been noted that carotene hydroxylase genes (*CHXB2*, *CHXE*, and *CYP97A3*) regulate lutein formation in yellow carrots *via* the degradation of α-carotene and β-carotene (Ma et al., 2017). The color of purple carrots is due to the accumulation of anthocyanins (predominantly derivatives of cyanidin) which are metabolites produced *via* the phenylpropanoid pathway (Wang et al., 2020). Recently, two genes (*DcMYB7* and *DcMYB113*) were reported as key candidates for carrot root anthocyanin accumulation (Iorizzo et al., 2018; Xu et al., 2019, 2020). Both genes were reported to activate the expression of *DcbHLH3* which is related to anthocyanin biosynthesis (Xu et al., 2019, 2020). *DcMYB7* has been also noted to regulate the glycosylation and acylation of anthocyanins (Xu et al., 2019).

3. Sustainable treatments for reducing physiological disorders in carrots

3.1. Bitterness in carrots

Bitterness is an undesirable characteristic of vegetables that results in consumer rejection. Bitterness is considered as a physiological disorder that can develop in carrots either preharvest or postharvest. Preharvest, may develop due to genotype or inappropriate growth conditions (i.e., temperature, soil type, pathogen attack etc.) (Edelenbos, Wold, Wieczynska, & Luca, 2020b; Kreutzmann, Christensen, & Edelenbos, 2008; Rosenfeld, Aaby, & Lea, 2002; Seljåsen et al., 2012, 2013). Postharvest development of bitterness may be due to abiotic stress during storage, transportation, processing, and supply chain management (i.e., inappropriate storage temperature, presence of ethylene, ultraviolet (UV)-irradiation, etc.) (Kreutzmann et al., 2008; Mercier, Roussel, Charles, & Arul, 2000; Seljasen et al., 2001). Studies have noted that the responsible compounds for the bitter taste in carrots are accumulated in carrot peels (Kreutzmann et al., 2008). Compounds from different metabolic pathways have been reported to be involved in carrot bitterness, including acetylenes (i.e., acetylenic diol), polyacetylenes (i.e., falcarindiol, falcarindiol-3-acetate), coumarins (i.e., 6-methoxymellein (6-MM)), phenols (i.e., di-caffeic acid derivative, chlorogenic acid, eugenin), terpenes (i.e., α-terpinene, β-myrcene, trans-caryophyllene, farnesene, α-humulene), terpenoids (i.e., vaginatin, isovaginatin), laserine oxide, laserine, 2-epilaserine, and aromatic aldehydes (i.e., gazarin) (Kreutzmann et al., 2008; Schmiech, Uemura, & Hofmann, 2008; Yang, Yan, & Lu, 2008), with 6-MM having a predominant role. The undesirable bitter perception can be masked to some extent by the accumulation of sugars in carrots (Kreutzmann et al., 2008).

The storage conditions should be carefully selected to maintain carrot quality and avoid bitterness during the postharvest supply chain. Table 1 summarizes studies that have been conducted to date aiming to minimize carrot quality deterioration due to the development of bitterness. Bitterness has been mainly linked to ethylene in the storage environment or during transportation. Ethylene can be either emitted by ethylene-producing fresh produce in mixed loads or due to the mechanical stress of carrots (i.e., shaking and wounding) during processing and handling. Seljasen et al. (2001) noted that the mechanical stress of carrots by shaking increased respiration rate, ethylene production, and 6-MM. Moreover, the content of sucrose and glucose in the mechanically-stressed carrots decreased, which could be justified by the increase in the respiration rate. Similar results were reported by Kramer et al. (2012) who investigated the effect of storage conditions (17 °C for 7 days with or without added ethylene (7–10 μL/L)) on the accumulation of 6-MM, total phenolics, polyacetylenes, terpenoid volatiles, and sugars of three different varieties of carrots. The authors noted that ethylene enhanced carrot bitterness by promoting the accumulation of 6-MM and phenolics. The accumulation of 6-MM was inhibited by the application of 1-methylcyclopropene (also known as 1-MCP). 1-MCP inhibits ethylene action by binding to the ethylene receptors. To avoid the deterioration of carrot quality due to bitterness, storage and handling conditions should be carefully selected. Bitterness of carrots can also be controlled by the application of controlled atmosphere (CA). Simões, Allende, Tudela, Puschmann, and Gil (2011) reported that CA of 5 kPa O_2 and 5 kPa CO_2 maintained the overall visual and sensory quality (including bitterness) of baby carrots up to 8 days at 4 °C. CA decreases bitterness by lowering respiration and ethylene production rates. The following measures can be undertaken to minimize bitterness in carrots: i) storage in well-ventilated rooms without a build-up of ethylene, ii) storage in a CA, iii) avoid storing carrots along with ethylene-producing fresh fruit and vegetables in mixed loads and storage rooms (i.e., apples and tomatoes), and iv) avoid shaking and harsh handling that cause wounding during handling in packaging stations and transportation. Peeling has also been noted to reduce bitterness in carrots (Edelenbos et al., 2020b; Kreutzmann et al., 2008; Zhang, Mahunu, Castoria, Apaliya, & Yang, 2017). However, peeling may cause an increase in respiration rate and transitional ethylene production due to the wounding of the tissue leading to quality deterioration (i.e., bitterness, white blush). Specifically, water loss may occur due to uncontrolled evaporation of moisture through the peeled root and increased respiration, which may lead to white blush, while the ethylene production may lead to the synthesis of compounds that contribute to

Table 1
Summary of studies that have been conducted in intact or MPV carrots examining the effects of sustainable treatments in the reduction of postharvest losses and waste due to physiological disorders.

Disorder	Carrots	Treatment	References
Bitterness			
	Intact carrots	Reduced mechanical stress during postharvest handling	Seljasen et al. (2001)
	MPV baby carrots	Controlled atmosphere	Simões et al. (2011)
	Intact carrots	Pre-treatment application of carrots with 1-MCP	Kramer et al. (2012)
White blush			
	MPV carrots	Hydrogen sulfide (H_2S)	Chen et al. (2018)
	MPV carrots	Edible coatings consisting of emulsions incorporating caseinates with beeswax, stearic acid or acetylated monoglyceride	Avena-Bustillos et al. (1994)
	MPV carrots	Chitosan-based edible films by vacuum impregnation	Vargas et al. (2009)
	MPV carrots	Chitosan-based edible film in conjunction with MAP	Simões et al. (2009)
	MPV carrots	Sodium alginic acid-based edible film in conjunction with MAP (passive or active)	Mastromatteo et al. (2012)
	MPV baby carrots	Chitosan-based coatings in conjunction with MAP	Leceta et al. (2015)
	MPV carrots	Washing treatments with aqueous solutions of marjoram (*O. majorana*) (EO), marjoram Hyd, AA, and their combinations	Xylia et al. (2019)
	MPV carrots	Edible coatings prepared using fruit and vegetable residues	Fai et al. (2016)
Browning			
	Intact carrots	Hot water pretreatment (heat shock)	Alegria et al. (2012)
	Intact carrots	UV-C irradiation application pretreatment	Alegria et al. (2012)
	MPV carrots	Different UV-irradiation types	Surjadinata et al. (2017)
	MPV carrots	Washing treatments with aqueous solutions of marjoram (*O. majorana*) EO, marjoram Hyd, AA, and their combinations	Xylia et al. (2019)

MAP: Modified atmosphere packaging.
MPV: Minimally processed vegetables.
O. majorana: Origanum *majorana*.
EO: Essential oil.
Hyd: Hydrosol.
AA: Ascorbic acid.

the development of bitterness. The adverse effects of peeling on desiccation could be overcome by the application of edible coatings. Specifically, Kowalczyk, Skrzypek, and Łupina (2020) noted that the application of edible coating (ascorbic acid-added carboxymethyl cellulose/candelilla wax emulsion) in MPV carrots followed by storage in boxes wrapped with polyethylene resulted in the maintenance of carrot quality (including the prevention of white blush formation) through 21 days of storage at 5 °C. Further research is encouraged to investigate treatments that prevent bitterness of wounded and peeled carrots following storage and handling in the postharvest supply chain.

3.2. White blush

White blush is a phenomenon mainly occurring on washed and harshly brushed (polished) or MPV carrots. White blush can be determined as a white color developing on the brushed or cut carrot surface (Avena-Bustillos, Cisneros-Zevallos, Krochta, & Saltveit, 1994; Chen, Chang, & Chen, 2020; Edelenbos et al., 2020a; Simões, Ventrella, Moretti, Carnelossi, & Puschmann, 2010; Vargas et al., 2009). Some studies support that this phenomenon is due to the synthesis and accumulation of lignin as a response to the cellular damage since lignin works as a barrier preventing the entrance of pathogens (Howard & Griffin, 1993). However, other studies attributed this phenomenon to the dehydration and moisture loss of uncontrolled evaporation, and structural alterations of carrot external cells due to the damage and wounding that occur *via* brushing or processing (Simões et al., 2010). It has also been reported that when dehydration is not extreme, this phenomenon can be reversible (Simões et al., 2010).

Several studies have been conducted investigating the effect of different environmentally and human-friendly treatments on the reduction of white blush in carrots, including edible films, application of essential oils (EOs), application of ascorbic acid, hydrogen sulfide (H_2S), and modified atmosphere packaging (MAP) (Table 1) (Avena-Bustillos et al., 1994; Chen, Hu, Zhang, Jiang, & Liu, 2018; Leceta, Molinaro, Guerrero, Kerry, & de la Caba, 2015; Mastromatteo, Conte, & Del Nobile, 2012; Simões et al., 2010; Simões, Tudela, Allende, Puschmann, & Gil, 2009; Vargas et al., 2009; Xylia, Clark, Chrysargyris, Romanazzi, & Tzortzakis, 2019). Avena-Bustillos et al. (1994) noted that an emulsion coating formulation of sodium caseinate mixed with stearic acid successfully reduced white blush in peeled carrots stored at 2.5 °C, 70% RH, and an airflow of 20 m/min. Kowalczyk et al. (2020) noted that edible coating (ascorbic acid-added carboxymethyl cellulose/candelilla wax emulsion) of MPV carrots maintained carrot quality and prevented white blush following 21 days of storage at 5 °C in boxes wrapped with polyethylene. The application of edible coatings can be combined either with passive or active MAP (Leceta et al., 2015; Mastromatteo et al., 2012; Simões et al., 2009). Mastromatteo et al. (2012) noted that the quality of MPV carrots coated with sodium alginate and stored at 4 °C under active or passive MAP was maintained. The combination of edible coating with MAP prevented carrot dehydration which is one of the most important factors that lead to white blush. Recently, Xylia et al. (2019) reported that washing shredded carrots with aqueous solutions of marjoram (*Origanum majorana*) EO and ascorbic acid led to less surface whitening compared to the control, during storage at 4 °C for 9 days. The combination of EO with ascorbic acid was found to decrease peroxidase (POD) activity, which is an enzyme involved in lignin synthesis in the plants. H_2S is a gasotransmitter involved in the regulation of various plant physiological processes (Ziogas, Molassiotis, Fotopoulos, & Tanou, 2018). Chen et al. (2018) noted that the postharvest application of H_2S at a concentration of 0.10×10^{-10} mol/L for 12 h, inhibited carrot whitening during 10 day storage at 5 °C by reducing hydrogen peroxide (H_2O_2) accumulation, lipid peroxidation, polyphenoloxidase (PPO), and POD activities. Future studies are encouraged to explore the mechanisms involved in the development of white blush in carrots. The

elucidation of white blush mechanisms will facilitate the development of sustainable treatments that will result in carrot quality maintenance during postharvest storage.

3.3. Browning

Carrot browning is a physiological disorder mainly occurring at MPV carrots during the supply chain and marketing (Zhang et al., 2005). Carrot browning is due to the activity of enzymes such as PPO and POD (found in plastids) which react with phenolic compounds particularly found in the vacuoles of carrot surface (Alegria, Goncalves, Moldao-Martins, Cisneros-Zevallos, & Abreu, 2016; Mayer, 2006). PPO is involved in two distinct reactions, such as hydroxylation of monophenols to *o*-diphenols and oxidation of *o*-diphenols to *o*-quinones which can be converted into brown pigments (i.e., melanin) by condensation (Szczepanska, Barba, Skapska, & Marszalek, 2020). Between the two enzymes, POD seems to be the principal enzyme being responsible for carrot juice browning (Marszałek, Krzyżanowska, Woźniak, & Skąpska, 2016; Szczepanska et al., 2020; Zhang et al., 2005). Specifically, Marszałek et al. (2016) reported that POD activity was approximately 120 times higher in carrot juice than PPO. Additionally, a previous study in carrots reported no correlation between PPO activity and browning during cold storage (Zhang et al., 2005). However, it is difficult to attribute a significant role to POD in the enzymatic browning of carrots, given that H_2O_2 (one of its main substrates) is found at very low concentrations in plant cells. Han et al. (2017) reported that H_2O_2 is accumulated during carrot storage and its content is affected by the storage temperature (i.e., 4, 10, and 20 °C) and wounding intensity (i.e., shreds, slices, and pies). Specifically, the authors reported that higher storage temperatures and increased wounding intensity resulted in a greater accumulation of H_2O_2. Studies have also indicated that POD could enhance browning reactions in the presence of ongoing PPO-mediated browning reactions (Jiang et al., 2016, pp. 508–514). It has been hypothesized that the PPO-mediated generation of quinones can lead to H_2O_2 accumulation (Jiang et al., 2016, pp. 508–514). Further studies are required to explore and elucidate the role of POD enzymes in carrot browning.

Table 1 summarizes studies that have been conducted to date aiming to minimize carrot quality reduction caused due to the development of browning. Alegria et al. (2012) investigated the effects of hot water treatment (heat shock) and UV-C treatments applied to whole carrots before shredding. The authors noted that both heat shock (temperature of 100 °C for 45 s) and UV-C (0.8 ± 0.4 kJ/m^2) treatments resulted in reduced POD activity (30 and 46%, respectively) and higher phenolic content during 10 of days storage at 5 °C compared to the control. UV-treatment has been previously reported to reduce POD activity in MPV carrots and promote phenylalanine ammonia-lyase (PAL) activity (Surjadinata, Jacobo-Velazquez, & Cisneros-Zevallos, 2017), which is an enzyme catalyzing the initial reaction of phenylpropanoid metabolism which leads to polyphenol synthesis. Natural compounds derived from fruit or vegetable wastes can be valuable in reducing carrot browning. Xylia et al. (2019) investigated the effects of various washing treatments (i.e., aqueous solutions of marjoram EO, marjoram hydrosol (Hyd), ascorbic acid, and their combinations) on the quality of shredded carrots during 9 days of storage at 4 °C. The authors noted that washing fresh carrots before storage using ascorbic acid and its combinations with marjoram EO and marjoram Hyd, decreased POD activity (on the application day) by 74%, 78%, and 57%, respectively. At the end of the 9 days of storage, the POD activity in the treated carrots was still lower than the control. Ascorbic acid is known for its anti-browning activities since it reduces *o*-quinones to colorless *o*-diphenol (Szczepanska et al., 2020). However, the results reported by Xylia et al. (2019) show that ascorbic acid also reduces the activity of POD, an enzyme involved in the development of brown color in carrots. This is further supported by the results reported by Sikora, Złotek, and Świeca (2019) who noted that ascorbic acid significantly reduced POD activity in shredded iceberg lettuce.

4. Sustainable treatments for the control of carrot decay caused by fungi

Carrots are susceptible to decay during storage (either in long-term storage, in the supply chain, or households) mainly due to pathogenic decay (Edelenbos et al., 2020a). Most of the fungi that are responsible for carrot decay are soil-borne organisms implying that the infection occurs in the field, and symptoms appear during storage. However, carrots can also be infected after harvest from contaminated surfaces and diseased carrots (Kora, McDonald, & Boland, 2005). Carrot decay can be either due to individual pathogen infection or due to the joint action of different pathogens. *S. sclerotiorum*, *B. cinerea*, *A. radicina*, and *Berkeleyomyces* spp. (formerly *Thielaviopsis* spp) are considered as some of the most important fungi leading to significant carrot postharvest losses and waste.

S. sclerotiorum is a soil-borne necrotrophic fungal pathogen with a wide host range belonging to Ascomycota, Order Helotiales. *S. sclerotiorum* causes Sclerotinia rot of carrot (also known as watery soft rot or cottony rot) and is one of the most important pathogens infecting carrots during pre- and postharvest (Kora, McDonald, & Boland, 2003; Ojaghian et al., 2016). Although pathogen infection starts in the field, the most extensive development of the disease occurs postharvest during long-term storage, transit, and market, resulting in carrot losses up to 50% (Kora et al., 2003; Ojaghian et al., 2013). The symptoms in the harvested carrots appear in the crown as localized softened tissue and white mycelium. Infected carrots can work as a source of mycelium which can spread rapidly to adjacent roots. Mycelium aggregates into sclerotia (black structures (2–5 mm in diameter and up to 25 mm in length) that allow *S. sclerotiorum* to survive in the absence of a host) which are a feature that differentiates *S. sclerotiorum* from other storage pathogens such as *B. cinerea* (fungi causing grey mold), *Rhizoctonia carotae* (fungi causing crater rot), and *Pectobacterium carotovorum* (bacterium causing bacterial soft rot) (Kora et al., 2003).

B. cinerea is a necrotrophic plant fungus with a wide host range (more than 200 species) causing a large amount of fruit and vegetable losses worldwide (Amselem et al., 2011). The economic losses of *B. cinerea* may exceed $10 billion worldwide annually (Hua et al., 2018). The pathogen originally infects carrots in the field where it colonizes the foliage and grows under the crown's petiole. Secondary infections may occur during storage of carrots from *B. cinerea* inoculum present on infested surfaces of containers, handling equipment, or in warehouse air (Hildebrand et al., 2008; Kora et al., 2005).

A. radicina is a seedborne pathogen responsible for the black rot of carrots. Infected carrot roots are characterized by dry, black, sunken lesions (Farrar, Pryor, & Davis, 2004; Troncoso-Rojas & Tiznado--Hernández, 2014). Specifically, carrots are susceptible to *A. radicina* until the seedling stage and after harvest (Farrar et al., 2004). *A. radicina* is responsible for losses of carrots stored in low temperatures (i.e., 0–4 °C). The spores of the fungus (called conidia) germinate and produce germ tubes which penetrate carrot tissues (Jayaraj, Rahman, Wan, & Punja, 2009). The fungus initially colonizes senescing petioles and then spreads in the carrot crown (known as black crown). In the literature, there are only a few studies investigating the effectiveness of sustainable treatments to control *A. radicina*. One of the most important measures that may reduce the possibility of infection, is to reduce the pathogen load by using disease-free seeds and maintaining the cleanliness of all the surfaces in the storage rooms since the pathogen can survive even in the absence of a host (Farrar et al., 2004).

Black root rot is a carrot disease that has been previously reported to be caused by *T. basicola* and *T. thielavioides*, with *T. basicola* being considered as a more severe pathogen than *T. thielavioides* (Weber & Tribe, 2004). According to a recent review study, black root rot pathogens now reside in the newly established genus *Berkeleyomyces* and are now known as *B. basicola* and *B. rouxiae* (Nel et al., 2019). Therefore, in

Table 2
Summary of studies that have been conducted in carrots examining the effects of sustainable treatments in the reduction of postharvest losses and waste caused by *S. sclerotiorum*.

Type of treatment	Highlights	References
Natural compounds	• The *in vitro* and *in vivo* antifungal activity of neem leaves (*Azadirachta indica*) and ginger (*Zingiber officinale*) rhizomes were investigated. • Plant extracts significantly reduced the mycelial growth and carpogenic germination of sclerotia of fungus *in vitro*. • Plant extracts at a concentration of 2 g/L significantly reduced the *in vivo* disease severity of carrot rot.	Ojaghian et al. (2014)
Natural compounds	• The *in vitro* and *in vivo* effects of EC which is the major component of cinnamon extract were investigated. • EC inhibited mycelial growth and carpogenic germination *in vitro*. • EC at a concentration of 10 μL/mL controlled watery soft rot *in vivo*.	Ojaghian et al. (2016)
Natural compounds	• The antifungal activities of a natural fungicide based on the EO of mint (*Mentha piperita*) and ASM were investigated. • Both treatments showed *in vivo* and *in vitro* antifungal activity.	Ojaghian et al. (2019)
Ozone	• The *in vivo* antifungal activity of ozone treatment against *S. sclerotiorum* during storage for up to 6 months at 0.5 °C was investigated. • Ozone treatment reduced lesions on carrots at the beginning of storage. • Ozone negatively affected carrot quality by inducing injury on the carrot periderm.	Hildebrand et al. (2008)
Ozone	• Ozone applied at 5 or 20 °C for 48 h at a concentration of 450 or 600 ppb was investigated. • Ozone inhibited mycelial growth and carrot decay.	Sharpe et al. (2009)
Ozone/1-MCP	• Intact carrots were treated with or without 1-MCP (1 μL/L) at 10 °C for 16 h and then exposed to 300 or 1000 nL/L ozone at 10 °C for up to 4 days. • Ozone was not efficient to reduce carrot decay.	Forney et al. (2007)
Heat treatment	• The optimal application time for steam treatment of intact carrots was 3 s and an exposure temperature of 90 °C. • Steam treatment reduced the decay of carrots inoculated with different pathogens including *S. sclerotiorum*.	Afek et al. (1999)
UV-C irradiation	• Carrots were treated with UV-C (0.88 kJ/m^2) for 5 min. • UV-C inhibited carpogenic germination of sclerotia *in vitro*. • UV-irradiation decreased the severity of carrot rot caused by fungus after 7 and 15 days of storage.	Ojaghian et al. (2017)

EC: E-cinnamaldehyde.
EO: Essential oil.
ASM: acibenzolar-*S*-methyl.
1-MCP: 1-methylcyclopropene.
UV: Ultraviolet.

the current study *T. basicola* is reported as *B. basicola*. *B. basicola and B. rouxiae* are soil-borne pathogens responsible for the development of black root rot (BRR) of carrots (Eshel, Regev, Orenstein, Droby, & Gan-Mor, 2009; Nel, Duong, Wingfield, Wingfield, & de Beer, 2018; Weber & Tribe, 2004). *Berkeleyomyces* spp. (formerly *Thielaviopsis* spp.) have been insufficiently investigated even though *B. basicola* is an important postharvest pathogen worldwide (Australia, Europe, Asia, Middle East, and the United States) not only for carrots (both organic and conventionally produced) but also for other fruit and vegetables, including citrus, lettuce, plum, cherries (Eshel et al., 2009; Hildebrand et al., 2008; Nel et al., 2019; Weber & Tribe, 2004). *Berkeleyomyces* spp. disease (black root rot) shows initially a very fine growth of mold, which later becomes dark grey and powdery turning into distinct, deep black superficial patches on the carrot periderm. The pathogen develops in storage after handling of carrots in the packaging station, and symptoms lead to vast decay of the packaged carrots. It is important to note that almost all carrot samples carry inoculum of *B. basicola*. Infections occur especially in carrots that have been washed before packaging and stored without cooling in polyethylene bags as the pathogen readily invades and feeds on wounded tissue at high humidity (Weber & Tribe, 2004). Only a few studies have investigated the effect of sustainable postharvest application methods on the reduction of carrot decay caused by *Berkeleyomyces* spp.

In conventional production, all the pathogens are mainly controlled by chemical fungicides. Specifically, *S. sclerotiorum* is controlled by the application of fungicides (i.e., boscalid) in the field, while there is no fungicide that can be used during postharvest (Ojaghian et al., 2013, 2014, 2016). *A. radicina* is controlled using chemical fungicides such as iprodione, chlorothalonil, and azoxystrobin, after harvest and before storage (Farrar et al., 2004; Troncoso-Rojas & Tiznado-Hernández, 2014), while *Berkeleyomyces* spp. are commercially controlled by dipping the roots in iprodione. *Berkeleyomyces* spp. can be also controlled by dipping harvested carrots in chlorinated, hydrocooled water or solutions of potassium sorbate and propionic acid (Carrot, Black Root Rot). However, environmentally and human-friendly treatment alternatives to synthetic fungicides are required. Sustainable postharvest treatments for controlling carrot decay are presented in the following sub-sections. Tables 2 and 3 show studies that have examined the effects of different sustainable treatments in the reduction of carrot postharvest losses caused by *S. sclerotiorum and B. cinerea*, respectively.

4.1. Natural compounds

Natural compounds such as polyphenols, ascorbic acid, terpenes, EOs, and polypeptides, that are found in plant extracts (derived either from medical plants or horticultural waste), are known for their antifungal activities (Ojaghian et al., 2014; Ojaghian, Wang, Zhang, & Xie, 2019; Papoutsis et al., 2019; Zhang, Cao, Fan, and Jiang (2020)). To date, most of the studies that have been conducted on carrots have examined the antifungal activity of natural compounds against *S. sclerotiorum*. Ojaghian et al. (2014) investigated the *in vitro* and *in vivo* antifungal activity of two crude extracts derived from the ginger rhizome (*Zingiber officinale*) and neem leaves (*Azadirachta indica*) against three aggressive isolates of *S. sclerotiorum*. Both extracts, when these were incorporated into the growth media, inhibited the radial growth of all *S. sclerotiorum* isolates in a concentration-dependent manner. A concentration of 10 g/L inhibited the *in vitro* germination of the fungal isolates in the range of 9.5–61%, depending on the extract type and fungal isolate (Ojaghian et al., 2014). The *in vivo* experiments showed that extracts derived from both plants species significantly reduced the severity of the disease in artificially infected carrots. Recently, Ojaghian et al. (2016) noted that E-cinnamaldehyde (EC), which is an organic compound with the formula C_9H_8O found in cinnamon extract, completely inhibited the *in vitro* mycelial growth and carpogenic germination of *S. sclerotiorum* at a concentration of 1 μL/mL, while EC at a concentration of 10 μL/mL controlled the *in vivo* disease development. A previous study has shown that EC damages fungal cell wall permeability and integrity (OuYang, Duan, Li, & Tao, 2019) which might be the explanation for the *in vitro* antifungal activity of EC against *S. sclerotiorum*. Regarding the *in vivo* antifungal activity of EC against

Table 3
Summary of studies that have been conducted in carrots examining the effects of sustainable treatments in the reduction of postharvest losses and waste caused by *B. cinerea*.

Type of treatment	Highlights	References
Ozone	• The *in vivo* antifungal activity of continuous ozone treatment against *B. cinerea* during storage for up to 6 months at 0.5 °C was investigated. • Ozone treatment reduced mycelium growth of *B. cinerea*. • Ozone treatment stimulated sporulation of *B. cinerea*.	Hildebrand et al. (2008)
Ozone	• Ozone at a concentration of 450 or 600 ppb applied at 5 or 20 °C for 48 h. • Ozone reduced fungal sporulation and reduced spore viability by over 99.5%.	Sharpe et al. (2009)
Ozone/1-MCP	• Intact carrots were treated with or without 1.0 μL/L 1-MCP at 10 °C for 16 h and then exposed to 300 or 1000 nL/L ozone at 10 °C for up to 4 days. • Ozone reduced carrot decay caused by *B. cinerea* but caused quality deterioration. • The combination of ozone with 1-MCP was not efficient in controlling *B. cinerea*.	Forney et al. (2007)
UV-irradiation	• Disease resistance was induced only in tissues directly exposed to the UV-irradiation. • UV-irradiation had a local effect in stimulating the synthesis of metabolites involved in carrot resistance.	Mercier et al. (2000)
UV-irradiation	• Freshly harvested carrots accumulated more of the phytoalexin 6-methoxymellein than aged carrots. • Carrots with higher content in 6-methoxymellein were more resistant to *B. cinerea* than those with lower levels. • Storage temperature following the UV-irradiation is a crucial factor affecting the efficiency of the treatment.	Mercier, Arul, and Julien (1993)
Aluminum-containing salts	• Carrots were dipped in solutions with aluminum salts. • The minimum inhibitory concentration on mycelial growth varied between 1 and 10 mM *in vitro*.	Kolaei et al. (2012)
Sulfur-containing salts	• Carrots were dipped in solutions with sulfur-containing salts. • Mycelial growth was inhibited at a 10 mM solution *in vitro*. • Sodium metabisulfite and potassium metabisulfite showed strong inhibition growth activity.	Kolaei et al. (2013)

1-MCP: 1-methylcyclopropene.
UV: Ultraviolet.

S. sclerotiorum, the authors noted that EC did not induce systemic acquired resistance (SAR) in carrots (Ojaghian et al., 2016). SAR is a phenomenon where plants acquire an enhanced defensive capacity against subsequent pathogen attack as a result of a primary, limited infection (Shi et al., 2021). Therefore, the *in vivo* mechanism of action of EC needs to be elucidated and understood. EC has the potential of being used in the food industry for controlling microorganisms in food since the U.S. Food and Drug Administration (FDA) has characterized EC as a 'Generally Recognized as Safe' (GRAS) substance. Recently, the *in vivo* and *in vitro* antifungal activity of two environmentally and human-friendly fungicides that are applied preharvest and sold on a commercial scale was investigated against *S. sclerotiorum* (Ojaghian et al., 2019). One fungicide is based on the EO of mint (*Mentha piperita*) and the second on acibenzolar-*S*-methyl (ASM) which is a compound that induces SAR in plants (Errampalli, 2014). Both substances showed *in vitro* and *in vivo* activities in a concentration-dependent manner. The treatment with ASM was more efficient than mint EO regarding the activation of enzymes related to SAR, such as *β*-*N*-acetyl hexosaminidase, endochitinase, chitin 1,4-*β*-chitobiosidase, and *β*-1,3-glucanase, six days after treatment. In contrast, the mint EO was more efficient than ASM in increasing mycelial permeability. Studies have also highlighted the potential of EO derived from medicinal plants to control *B. cinerea* in other vegetables. Specifically, the EO of *Tetraclinis articulata* reduced *B. cinerea* infection on tomato fruit by 54% (Rguez et al., 2020). Indeed, natural compounds have the potential of controlling carrot postharvest losses and waste. However, according to Papoutsis et al. (2019), some obstacles should be carefully considered before the development of commercial sustainable treatment applications for carrots using EO and other natural GRAS compounds; 1) the dose and duration of the treatment application should be as low as possible, 2) the immediate and long-term efficiency of the treatment application should be high, and the residual activity of the applied compounds neglibible or minor 3) the impact on product quality and carrot physiology should be negligible or minor, and 4) the human health and environment toxicity should be zero. The source of extract seems to significantly affect its antifungal activity and its mode of action. Future studies are encouraged to investigate the antifungal activity of mixtures of extracts derived from different plant sources.

4.2. Ozone (O_3)

The antimicrobial and antifungal activities of ozone or trioxygen (O_3) have been reported by several studies (Chen, Zhang, et al., 2020; Luo et al., 2019; Paulikiene, Venslauskas, Raila, Zvirdauskiene, & Naujokiene, 2020). Ozone is an oxidizing agent and its sterilization activity has been attributed to its ability to oxidize organic matter (Sandle, 2013). According to the United States Department of Agriculture (USDA), ozone can be applied in organic agriculture because of its high instability, hence, ozone residues will not remain on produce surfaces (Souza et al., 2018). In carrots, ozone has been applied either as a gas or dissolved in water at different concentrations (Hildebrand et al., 2008; Sharpe et al., 2009; Souza et al., 2018).

In carrots, studies have highlighted the *in vitro* and *in vivo* antifungal activities of ozone treatment against *S. sclerotiorum* and *B. cinerea* (Forney, Song, Hildebrand, Fan, & McRae, 2007; Hildebrand et al., 2008; Sharpe et al., 2009). Hildebrand et al. (2008) investigated the effect of continuous ozone atmosphere 50 ± 10 nL/L on carrot decay caused by *S. sclerotiorum* and *B. cinerea* over a 6-month storage period at 0.5 °C and ≥95% RH. Ozone treatment reduced aerial mycelium of both fungi. In *B. cinerea*, ozone treatment stimulated the sporulation of the fungus, characterized by dense mats of short conidiophores on the lesions, which might be an indicator of stress. The authors noted that *B. cinerea* susceptibility reached a peak at 4 months and then decreased which was linked to carrot moisture loss. It could be also hypothesized that *B. cinerea* susceptibility might be reduced due to the degradation or halt of the synthesis of secondary metabolites implicated in carrots resistance to fungi. At the applied concentration, ozone-induced carrot injury, which appeared as blotches of discolored brown periderm tissue. Similar results reported by Forney et al. (2007) who noted that although ozone had fungistatic activities against *B. cinerea*, it also affected carrot quality. Similar results were reported by Sharpe et al. (2009) who applied gaseous ozone at higher concentrations (450 nL/L) at 5 or 20 °C for 48 h. However, in this study, no quality deterioration was observed, most probably due to a shorter treatment duration than in Forney et al. (2007). The fungistatic activity of ozone has been attributed to the stimulation of the carrot immune system as a response to oxidative stress and specifically to the synthesis of antioxidants and other secondary metabolites (i.e., 6-MM). Additionally, ozone may have a direct effect on fungus by inducing the production of reactive oxygen species, causing

mitochondrial degradation and disintegration of spore structures (Ong & Ali, 2015; Shezi, Samukelo Magwaza, Mditshwa, & Tesfay, 2020). The combination of ozone with other sustainable treatments, such as plant extracts and UV-irradiation might increase ozone efficiency with regards to control of carrot decay caused by *S. sclerotiorum* and other postharvest pathogens. Indeed, ozone is an environmentally friendly technique that does not leave disinfectant residues in the treated carrots due to its rapid decomposition into oxygen (Nuvolone, Petri, & Voller, 2018; Souza et al., 2018). However, long-term staff exposure to ozone (i.e., during ozone application) has been linked to health problems (Nuvolone et al., 2018). Therefore, measures such as the use of respiratory protective equipment should be employed to protect employees dealing with ozone treatment.

4.3. Heat treatment

Heat treatment is an environmentally friendly technique that can be used as pre-treatment after harvest to prolong the shelf life of fruit and vegetables by minimizing pathogen decay (Chen, Cheng, Wisniewski, Liu, & Liu, 2015; Papoutsis et al., 2019). In general, heat treatment can be applied in fruit and vegetables by hot air, dipping, spraying, or steam (plant sauna) applications. In carrots, heat treatment has mainly been applied as steam. It is important to note that steam temperature is an important parameter that significantly affects the post-treated carrot quality. Afek, Orenstein, and Nuriel (1999) investigated the effect of steam treatment (application time of 5 s) on the prevention of carrot decay caused by *S. sclerotiorum* during cold storage (60 days at 0.5 °C plus an additional week at 20 °C). Specifically, a steam of ~0.2 MPa pressure and a temperature of 70 °C was applied. The authors noted that steam treatment significantly reduced carrot decay compared to the control (decay 5 and 65%, respectively), after similar periods of storage. Afek et al. (1999) noted that the steam treatment of 3 s reduced carrot decay caused by *A. radicina*. The efficiency of heat treatment can be enhanced when it is combined with other sustainable treatments (i.e., biocontrol agents, H_2O_2). For instance, Eshel et al. (2009) investigated the efficiency of steam and its combined application with H_2O_2 or yeast to control *B. basicola* (formerly *T. basicola*) in brushed carrots during one month of storage at 0.5 °C and subsequently at 20 °C for 8 days. The authors noted that a steam application (85 °C) of 4 s resulted in decay reduction. However, steam application for more than 4 s resulted in carrot quality deterioration (i.e., tissue-burn damage and color change). The authors highlighted the synergistic effects between steam treatment and a yeast-based product consisting of *Metschnikowia fructicola* at a concentration of 2 g/L, as well as steam and H_2O_2 at a concentration of 0.5 mL/L. The authors hypothesized that the improved efficacy of the combined applications might be due to pathogen weakening and/or induction of carrot tissue resistant compounds (Eshel et al., 2009). Another explanation could be the competition for nutrients on the carrot surface between the biocontrol agent and the carrot pathogen. H_2O_2 has been recognized by the FDA as a safe sanitizing agent that can be applied postharvest (de Siqueira Oliveira, Eça, de Aquino, & Vasconcelos, 2018). To avoid any phytotoxic damage and quality deterioration, H_2O_2 residues should be rinsed off with tap water after treatment (Eshel et al., 2009). The effectiveness of heat treatment when applied as steam can be attributed to different reasons: 1) the hot water or pressure of the steam removes microbial spores and debris from the carrot surface, 2) the heat may destroy microbial cells, 3) the heat may stimulate the synthesis of bioactive compounds with antimicrobial properties (i.e., phytoalexins), and/or 4) the heat may stimulate ethylene production *via* slight wounding of cells, which then stimulates phytoalexin production (Jayaraj et al., 2009; Seljåsen et al., 2013). Future studies are encouraged to explore the mechanism of action of the combined application of heat with biocontrol agents or GRAS compounds.

4.4. UV-irradiation

Several studies have noted the potential of UV-irradiation to reduce microbial decay in fresh fruit and vegetables (Esua, Chin, Yusof, & Sukor, 2019; Ojaghian et al., 2017; Papoutsis et al., 2019; Zhang & Jiang, 2019). UV-irradiation is divided into UV-A, UV-B, and UV-C and each type regulate various metabolic pathways in plant tissues (Papoutsis et al., 2019). Only a few studies have been conducted in carrots investigating the postharvest effect of UV-irradiation on carrot resistance, mainly against *S. sclerotiorum* and *B. cinerea*. Recently, Ojaghian et al. (2017) investigated the *in vitro* and *in vivo* inhibitory effects of UV-C (0.88 kJ/m^2) against four isolates of *S. sclerotiorum*. The authors noted that the disease severity after 15 days of storage at 10 °C and 90% RH was lower in carrots treated with UV-irradiation than the control. UV-irradiation has also been shown to have fungistatic effects against *B. cinerea*. Mercier, Arul, and Julien (1993) reported that UV-C irradiation reduced decay caused by *B. cinerea* in freshly harvested carrots. Specifically, the authors noted that storage temperature (1 or 20 °C) following the UV-irradiation was an important parameter that affected the development of resistance against the fungus, with a storage temperature of 20 °C being reported as the optimal. UV-irradiation induces physiochemical changes in treated fruit and vegetables (Mercier et al., 2000; Papoutsis et al., 2019). The efficacy of UV-irradiation has mainly been attributed to the stimulation of the synthesis of compounds involved in SAR of plants, such as pathogenesis-related (PR) proteins (i.e., chitinases, peroxidases, β-1,3-glucanases), phytoalexins (i.e., 6-MM), and enzymes such as PPO and PAL. Regarding 6-MM stimulation, the authors assumed that 6-MM synthesis was stimulated by ethylene produced as a response to the UV-irradiation (Mercier, Arul, Ponnampalam, & Boulet, 1993) since phytoalexins are bound and cannot be translocated in plant tissues (Ojaghian et al., 2017) and UV-irradiation is a treatment with local effects (Mercier et al., 2000). Therefore, UV-treatment should be either applied on the whole surface of carrots or combined with other sustainable treatments. For instance, in strawberries, it has previously been shown that the combination of UV-C irradiation with heat treatment (45 °C, 3 h in air) was more efficient than single applications, to control decay caused by *B. cinerea* (Pan, Vicente, Martinez, Chaves, & Civello, 2004). More studies are encouraged to be conducted in carrots investigating and comparing the effects of different UV-types. Large scale experiments should also be conducted to investigate the effect of UV-treatment on carrot decay postharvest.

4.5. Inorganic salts

The fungistatic effects of inorganic salts have been previously reported (Kolaei et al., 2012, 2013). Inorganic salts (i.e., aluminum sulfate, potassium metabisulfite etc.) have been used in the food industry as preservatives and antimicrobial agents. Inorganic salts are considered as GRAS and may demonstrate a broad-spectrum antimicrobial activity with little mammalian toxicity and show biocompatibility (Türkkan, 2015). The application of salts can be either by spraying or dipping and they can be applied either pre- or postharvest (Papoutsis et al., 2019). *In vitro* experiments have shown the potential of inorganic salts to control *B. cinerea*. Specifically, sodium and potassium metabisulfite salts at a concentration of 10 mM and aluminum sulfate salts at a concentration of 1 mM showed strong *in vitro* inhibition growth activity of *B. cinerea* (Kolaei et al., 2012, 2013). The antifungal activity of metabisulfite salts has been attributed to the sulfur dioxide (SO_2) which is liberated and interacts with different cell components (i.e., structural proteins or enzymes) through cleavage of disulfide bonds. Future studies are required to investigate the *in vivo* activities of inorganic salts on the control of carrot decay caused by different pathogens.

4.6. Biocontrol agents

Biocontrol agents are yeasts or bacteria that are applied to a host

(fruit or vegetable) and facilitate the prevention of decay caused by a pathogen. Only a few studies have been conducted in carrots investigating the effect of yeasts and bacteria on the control of carrot decay caused by fungi. Chen and Wu (1999) reported that the application of *Burkholderia cepaciano* or *Bacillus amyloliquefaciens* on carrots significantly reduced lesions formed by *A. radicina* compared to the control. Eshel et al. (2009) investigated the effects of a yeast-based product containing *M. fructicola* isolate at 2 g/L and its combination with steam on the control of *B. basicola* (formerly *T. basicola*) in brushed carrots during one month of storage at 0.5 °C and subsequently at 20 °C for 8 days. The authors noted that the biocontrol agent was more efficient when it was combined with a steam treatment. The efficiency of biocontrol agents has previously been attributed to the production of toxins which may destroy fungal cells, the competition for nutrients and space, as well as the stimulation of secondary metabolites with antifungal activities in the plant tissues (Papoutsis et al., 2019). The combined effects of biocontrol agents with other sustainable treatments (i.e., heat) imply the efficacy of biocontrol agents to pathogen weakening (Eshel et al., 2009). However, more studies are required to investigate the effects of different biocontrol agents and their mode of action against carrot decay caused by various pathogens.

5. Conclusions and future directions

Physiological disorders in carrots (i.e., bitterness, white blush, and browning) are caused due to the activity of enzymes and the synthesis of secondary metabolites that impact produce quality (i.e., flavor, texture, and/or appearance) and result in consumer rejection. The physiological disorders in carrots can be mainly managed by preventative measures such as storage in well-ventilated rooms, storage in a CA, MAP, peeling, mechanical stress avoidance, edibe films, washing with natural compounds, heat treatment, UV-irradiation, and H_2S (Fig. 2). Future studies are encouraged to investigate combinations of different preventative measures and investigate the potential application of emerging technologies (i.e., ultrasound, etc.). For example, ultrasound applied as a pre-treatment has been reported to affect carrot metabolic pathways involved in carrot quality changes (Jiang, Zhang, & Xu, 2020). Studies are also encouraged to investigate potential reduction of carrot physiological disorders by the postharvest application of nitric oxide, hydrogen sulfide, melatonin, and jasmonates, which play a regulatory role in fruit and vegetable physiology (Gheysarbigi, Mirdehghan, Ghasemnezhad, & Nazoori, 2020). For instance, nitric oxide has been proved to reduce the activity of both PPO and POD activity in packaged fresh pistachios (*Pistacia vera* L.) (Gheysarbigi et al., 2020; Zhang et al., 2020).

Carrot quality can also be deteriorated during storage due to decay caused by fungi, such as *S. sclerotiorum*, *B. cinerea*, *A. radicina*, *and Berkeleyomyces* spp. Most of the studies that have been conducted to date, are mainly focused on the reduction of carrot decay caused by *S. sclerotiorum* and *B. cinerea.* Among the different fungi, *S. sclerotiorum* is considered the most important fungus in many carrot producing areas worldwide during long-term storage of unwashed carrots. After washing and polishing, *Berkeleyomyces* spp. may cause severe disease symptoms. Currently, chemical fungicides are mainly used for reducing postharvest carrot decay. However, chemical fungicide application is aimed to be reduced worldwide since their use has been linked to environmental and human toxicity. The effects of different sustainable postharvest treatments (i.e., natural compounds, ozone, heat treatment, UV-irradiation, inorganic salts, and biocontrol agents) have been investigated aiming to control carrot decay caused by fungi. Even though sustainable treatments can control carrot decay in the postharvest supply chain, carrot quality deterioration may occur when non optimal conditions are applied. Future studies are encouraged to apply response surface methodology (RSM) to determine the optimal sustainable treatment conditions that can be applied in carrots considering at the same time both quality attributes and decay caused by pathogens and minimize food waste along the supply chain. The combination of different control methods can improve the control efficacy and increase the spectrum of controlled pathogens. However, the successful combination of different sustainable treatment methods requires method compatibility. The elucidation of the mechanism/s of action of each treatment using -omics analysis (i.e., transcriptomics, proteomics, metabolomics) will help in this direction (Papoutsis et al., 2019).

CRediT authorship contribution statement

Konstantinos Papoutsis: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Merete Edelenbos:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

References

Afek, U., Orenstein, J., & Nuriel, E. (1999). Steam treatment to prevent carrot decay during storage. *Crop Protection, 18*(10), 639–642.

Alegria, C., Goncalves, E. M., Moldao-Martins, M., Cisneros-Zevallos, L., & Abreu, M. (2016). Peel removal improves quality without antioxidant loss, through wound-induced phenolic biosynthesis in shredded carrot. *Postharvest Biology and Technology, 120*, 232–239.

Alegria, C., Pinheiro, J., Duthoit, M., Gonçalves, E. M., Moldão-Martins, M., & Abreu, M. (2012). Fresh-cut carrot (cv. Nantes) quality as affected by abiotic stress (heat shock and UV-C irradiation) pre-treatments. *Lebensmittel-Wissenschaft und -Technologie-Food Science and Technology, 48*(2), 197–203.

Alegria, C., Pinheiro, J., Gonçalves, E. M., Fernandes, I., Moldão, M., & Abreu, M. (2010). Evaluation of a pre-cut heat treatment as an alternative to chlorine in minimally processed shredded carrot. *Innovative Food Science & Emerging Technologies, 11*(1), 155–161.

Amselem, J., Cuomo, C. A., van Kan, J. A., Viaud, M., Benito, E. P., Couloux, A., … Dickman, M. (2011). Genomic analysis of the necrotrophic fungal pathogens Sclerotinia sclerotiorum and Botrytis cinerea. *PLoS Genetics, 7*(8), Article e1002230. https://doi.org/10.1371/journal.pgen.1002230

Avena-Bustillos, R. J., Cisneros-Zevallos, L. A., Krochta, J. M., & Saltveit, M. E. (1994). Application of casein-lipid edible film emulsions to reduce white blush on minimally processed carrots. *Postharvest Biology and Technology, 4*(4), 319–329.

Chen, C., Hu, W., Zhang, R., Jiang, A., & Liu, C. (2018). Effects of hydrogen sulfide on the surface whitening and physiological responses of fresh-cut carrots. *Journal of the Science of Food and Agriculture, 98*, 4726–4732.

Chen, C., Chang, X., & Chen, X. (2020). Effect of the control of white-blush of fresh-cut carrot and its process optimization. *IOP Conference Series: Earth and Environmental Science, 474*, Article 032028.

Chen, H., Cheng, Z., Wisniewski, M., Liu, Y., & Liu, J. (2015). Ecofriendly hot water treatment reduces postharvest decay and elicits defense response in kiwifruit. *Environmental Science and Pollution Research, 22*(19), 15037–15045.

Chen, T. W., & Wu, W. S. (1999). Biological control of carrot black rot. *Journal of Phytopathology, 147*(2), 99–104.

Chen, C., Zhang, H., Zhang, X., Dong, C., Xue, W., & Xu, W. (2020). The effect of different doses of ozone treatments on the postharvest quality and biodiversity of cantaloupes. *Postharvest Biology and Technology, 163*, 111124.

Condurso, C., Cincotta, F., Tripodi, G., Merlino, M., Giarratana, F., & Verzera, A. (2020). A new approach for the shelf-life definition of minimally processed carrots. *Postharvest Biology and Technology, 163*, 111138.

De Corato, U. (2020). Improving the shelf-life and quality of fresh and minimally-processed fruits and vegetables for a modern food industry: A comprehensive critical review from the traditional technologies into the most promising advancements. *Critical Reviews in Food Science and Nutrition, 60*(6), 940–975.

Edelenbos, M., Wold, A. B., Wieczynska, J., & Luca, A. (2020a). Chapter 24.3 - roots: Carrots. In M. I. Gil, & R. Beaudry (Eds.), *Controlled and modified atmospheres for fresh and fresh-cut produce* (pp. 597–603). Academic Press.

Edelenbos, M., Wold, A.-B., Wieczynska, J., & Luca, A. (2020b). Chapter 24.4 - roots: Fresh-cut carrots. In M. I. Gil, & R. Beaudry (Eds.), *Controlled and modified atmospheres for fresh and fresh-cut produce* (pp. 605–608). Academic Press.

Errampalli, D. (2014). Chapter 6 - *Penicillium expansum* (blue mold). In S. Bautista-Baños (Ed.), *Postharvest decay* (pp. 189–231). San Diego: Academic Press.

Eshel, D., Regev, R., Orenstein, J., Droby, S., & Gan-Mor, S. (2009). Combining physical, chemical and biological methods for synergistic control of postharvest diseases: A case study of black root rot of carrot. *Postharvest Biology and Technology, 54*(1), 48–52.

Esua, O. J., Chin, N. L., Yusof, Y. A., & Sukor, R. (2019). Effects of simultaneous UV-C radiation and ultrasonic energy postharvest treatment on bioactive compounds and antioxidant activity of tomatoes during storage. *Food Chemistry, 270*, 113–122.

Fai, A. E. C., de Souza, M. R. A., de Barros, S. T., Bruno, N. V., Ferreira, M. S. L., & Goncalves, E. C. B. D. (2016). Development and evaluation of biodegradable films and coatings obtained from fruit and vegetable residues applied to fresh-cut carrot (*Daucus carota* L.). *Postharvest Biology and Technology, 112*, 194–204.

Farrar, J. J., Pryor, B. M., & Davis, R. M. (2004). Alternaria diseases of carrot. *Plant Disease, 88*(8), 776–784.
Forney, C. F., Song, J., Hildebrand, P. D., Fan, L., & McRae, K. B. (2007). Interactive effects of ozone and 1-methylcyclopropene on decay resistance and quality of stored carrots. *Postharvest Biology and Technology, 45*(3), 341–348.
Gheysarbigi, S., Mirdehghan, S. H., Ghasemnezhad, M., & Nazoori, F. (2020). The inhibitory effect of nitric oxide on enzymatic browning reactions of in-package fresh pistachios (*Pistacia vera* L.). *Postharvest Biology and Technology, 159*, 110998.
Han, C., Li, J., Jin, P., Li, X., Wang, L., & Zheng, Y. (2017). The effect of temperature on phenolic content in wounded carrots. *Food Chemistry, 215*, 116–123.
Hildebrand, P. D., Forney, C. F., Song, J., Fan, L., & McRae, K. B. (2008). Effect of a continuous low ozone exposure (50nLL−1) on decay and quality of stored carrots. *Postharvest Biology and Technology, 49*(3), 397–402.
Howard, L. R., & Griffin, L. E. (1993). Lignin formation and surface discoloration of minimally processed carrot sticks. *Journal of Food Science, 58*(5), 1065. &.
Hua, L., Yong, C., Zhanquan, Z., Boqiang, L., Guozheng, Q., & Shiping, T. (2018). Pathogenic mechanisms and control strategies of Botrytis cinerea causing post-harvest decay in fruits and vegetables. *Food Quality and Safety, 2*(3), 111–119.
Iorizzo, M., Cavagnaro, P. F., Bostan, H., Zhao, Y., Zhang, J., & Simon, P. W. (2018). A cluster of MYB transcription factors regulates anthocyanin biosynthesis in carrot (*Daucus carota* L.) root and petiole. *Frontiers of Plant Science, 9*, 1927.
Iorizzo, M., Ellison, S., Senalik, D., Zeng, P., Satapoomin, P., Huang, J., et al. (2016). A high-quality carrot genome assembly provides new insights into carotenoid accumulation and asterid genome evolution. *Nature Genetics, 48*(6), 657–666.
Iorizzo, M., Senalik, D. A., Grzebelus, D., Bowman, M., Cavagnaro, P. F., Matvienko, M., et al. (2011). De novo assembly and characterization of the carrot transcriptome reveals novel genes, new markers, and genetic diversity. *BMC Genomics, 12*, 389.
Jayaraj, J., Rahman, M., Wan, A., & Punja, Z. K. (2009). Enhanced resistance to foliar fungal pathogens in carrot by application of elicitors. *Annals of Applied Biology, 155*(1), 71–80.
Jiang, Y., Duan, X., Qu, H., & Zheng, S. (2016). In B. Caballero, P. M. Finglas, & et al (Eds.), *Browning: Enzymatic browning. Encyclopedia of food and health*. Oxford: Academic Press.
Jiang, Q., Zhang, M., & Xu, B. (2020). Application of ultrasonic technology in postharvested fruits and vegetables storage: A review. *Ultrasonics Sonochemistry, 69*, 105261.
Kolaei, E. A., Cenatus, C., Tweddell, R. J., & Avis, T. J. (2013). Antifungal activity of aluminium-containing salts against the development of carrot cavity spot and potato dry rot. *Annals of Applied Biology, 163*(2), 311–317.
Kolaei, E. A., Tweddell, R. J., & Avis, T. J. (2012). Antifungal activity of sulfur-containing salts against the development of carrot cavity spot and potato dry rot. *Postharvest Biology and Technology, 63*(1), 55–59.
Kora, C., McDonald, M. R., & Boland, G. J. (2003). Sclerotinia rot of carrot: An example of phenological adaptation and bicyclic development by *Sclerotinia Sclerotiorum*. *Plant Disease, 87*(5), 456–470.
Kora, C., McDonald, M. R., & Boland, G. J. (2005). Occurrence of fungal pathogens of carrots on wooden boxes used for storage. *Plant Pathology, 54*(5), 665–670.
Kowalczyk, D., Skrzypek, T., & Łupina, K. (2020). Effect of carboxymethyl cellulose/candelilla wax edible coating incorporated with ascorbic acid on the physicochemical and sensory qualities of prepackaged minimally processed carrots (*Daucus carota* L.) during cold storage. *Journal of Food Processing and Preservation, 44*(9), Article e14713.
Kramer, M., Bufler, G., Ulrich, D., Leitenberger, M., Conrad, J., Carle, R., et al. (2012). Effect of ethylene and 1-methylcyclopropene on bitter compounds in carrots (*Daucus carota* L.). *Postharvest Biology and Technology, 73*, 28–36.
Kreutzmann, S., Christensen, L. P., & Edelenbos, M. (2008). Investigation of bitterness in carrots (*Daucus carota* L.) based on quantitative chemical and sensory analyses. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 41*(2), 193–205.
Leceta, I., Molinaro, S., Guerrero, P., Kerry, J. P., & de la Caba, K. (2015). Quality attributes of map packaged ready-to-eat baby carrots by using chitosan-based coatings. *Postharvest Biology and Technology, 100*, 142–150.
Luo, A., Bai, J., Li, R., Fang, Y., Li, L., Wang, D., … Kou, L. (2019). Effects of ozone treatment on the quality of kiwifruit during postharvest storage affected by *Botrytis cinerea* and *Penicillium expansum*. *Journal of Phytopathology, 167*(7–8), 470–478. https://doi.org/10.1111/jph.12819
Ma, J., Li, J., Xu, Z., Wang, F., & Xiong, A. (2018). Transcriptome profiling of genes involving in carotenoid biosynthesis and accumulation between leaf and root of carrot (*Daucus carota* L.). *Acta Biochimica et Biophysica Sinica, 50*(5), 481–490.
Marszałek, K., Krzyżanowska, J., Woźniak, Ł., & Skąpska, S. (2016). Kinetic modelling of tissue enzymes inactivation and degradation of pigments and polyphenols in cloudy carrot and celery juices under supercritical carbon dioxide. *The Journal of Supercritical Fluids, 117*, 26–32.
Mastromatteo, M., Conte, A., & Del Nobile, M. A. (2012). Packaging strategies to prolong the shelf life of fresh carrots (*Daucus carota* L.). *Innovative Food Science & Emerging Technologies, 13*, 215–220.
Ma, J., Xu, Z., Tan, G., Wang, F., & Xiong, A. (2017). Distinct transcription profile of genes involved in carotenoid biosynthesis among six different color carrot (*Daucus carota* L.) cultivars. *Acta Biochimica et Biophysica Sinica, 49*(9), 817–826.
Mayer, A. M. (2006). Polyphenol oxidases in plants and fungi: Going places? A review. *Phytochemistry, 67*(21), 2318–2331.
Mercier, J., Arul, J., & Julien, C. (1993b). Effect of UV-C on phytoalexin accumulation and resistance to *Botrytis cinerea* in stored carrots. *Journal of Phytopathology, 139*(1), 17–25.
Mercier, J., Arul, J., Ponnampalam, R., & Boulet, M. (1993). Induction of 6-Methoxy-mellein and resistance to storage pathogens in carrot slices by UV-C. *Journal of Phytopathology, 137*(1), 44–54.
Mercier, J., Roussel, D., Charles, M. T., & Arul, J. (2000). Systemic and local responses associated with UV- and pathogen-induced resistance to *Botrytis cinerea* in stored carrot. *Phytopathology, 90*(9), 981–986.
Nel, W. J., Duong, T. A., de Beer, Z. W., & Wingfield, M. J. (2019). Black root rot: A long known but little understood disease. *Plant Pathology, 68*(5), 834–842.
Nel, W. J., Duong, T. A., Wingfield, B. D., Wingfield, M. J., & de Beer, Z. W. (2018). A new genus and species for the globally important, multihost root pathogen *Thielaviopsis basicola*. *Plant Pathology, 67*(4), 871–882.
Nuvolone, D., Petri, D., & Voller, F. (2018). The effects of ozone on human health. *Environmental Science and Pollution Research, 25*(9), 8074–8088.
Ojaghian, M. R., Almoneafy, A. A., Cui, Z.q., Xie, G.-L., Zhang, J., Shang, C., et al. (2013). Application of acetyl salicylic acid and chemically different chitosans against storage carrot rot. *Postharvest Biology and Technology, 84*, 51–60.
Ojaghian, M. R., Wang, L., Cui, Z.q., Yang, C., Zhongyun, T., & Xie, G.-L. (2014). Antifungal and SAR potential of crude extracts derived from neem and ginger against storage carrot rot caused by *Sclerotinia sclerotiorum*. *Industrial Crops and Products, 55*, 130–139.
Ojaghian, M. R., Wang, Q., Li, X., Sun, X., Xie, G.-L., Zhang, J., … Wang, L. (2016). Inhibitory effect and enzymatic analysis of E-cinnamaldehyde against sclerotinia carrot rot. *Pesticide Biochemistry and Physiology, 127*, 8–14.
Ojaghian, S., Wang, L., Zhang, J. Z., & Xie, G. L. (2019). Inhibitory effect of Fungastop and Bion against carrot soft rot caused by *Sclerotinia sclerotiorum*. *Phytoparasitica*. https://doi.org/10.1007/s12600-019-00780-9
Ojaghian, M. R., Zhang, J.-Z., Xie, G.-L., Wang, Q., Li, X.-L., & Guo, D.-P. (2017). Efficacy of UV-C radiation in inducing systemic acquired resistance against storage carrot rot caused by Sclerotinia sclerotiorum. *Postharvest Biology and Technology, 130*, 94–102.
Ong, M. K., & Ali, A. (2015). Antifungal action of ozone against Colletotrichum gloeosporioides and control of papaya anthracnose. *Postharvest Biology and Technology, 100*, 113–119.
OuYang, Q., Duan, X., Li, L., & Tao, N. (2019). Cinnamaldehyde exerts its antifungal activity by disrupting the cell wall integrity of *Geotrichum citri-aurantii*. *Frontiers in Microbiology, 10*, 55.
Pan, J., Vicente, A. R., Martinez, G. A., Chaves, A. R., & Civello, P. M. (2004). Combined use of UV-C irradiation and heat treatment to improve postharvest life of strawberry fruit. *Journal of the Science of Food and Agriculture, 84*, 1831–1838.
Papoutsis, K., Mathioudakis, M. M., Hasperué, J. H., & Ziogas, V. (2019). Non-chemical treatments for preventing the postharvest fungal rotting of citrus caused by *Penicillium digitatum* (green mold) and *Penicillium italicum* (blue mold). *Trends in Food Science & Technology, 86*, 479–491.
Paulikiene, S., Venslauskas, K., Raila, A., Zvirdauskiene, R., & Naujokiene, V. (2020). The influence of ozone technology on reduction of carrot loss and environmental impact. *Journal of Cleaner Production, 244*, 118734.
Que, F., Hou, X. L., Wang, G. L., Xu, Z. S., Tan, G. F., Li, T., … Xiong, A. S. (2019). Advances in research on the carrot, an important root vegetable in the Apiaceae family. *Horticulture Research, 6*(1), 69.
Rguez, S., Ben Slimene, I., Abid, G., Hammemi, M., Kefi, A., Elkahoui, S., et al. (2020). *Tetraclinis articulata* essential oil reduces *Botrytis cinerea* infections on tomato. *Scientia Horticulturae, 266*, 109291.
Rosenfeld, H. J., Aaby, K., & Lea, P. (2002). Influence of temperature and plant density on sensory quality and volatile terpenoids of carrot (*Daucus carota* L.) root. *Journal of the Science of Food and Agriculture, 82*(12), 1384–1390.
Sandle, T. (2013). 8 - gaseous sterilisation. In T. Sandle (Ed.), *Sterility, sterilisation and sterility assurance for pharmaceuticals* (pp. 111–128). Woodhead Publishing.
Schmiech, L., Uemura, D., & Hofmann, T. (2008). Reinvestigation of the bitter compounds in carrots (*Daucus carota* L.) by using a molecular sensory science approach. *Journal of Agricultural and Food Chemistry, 56*(21), 10252–10260.
Seljasen, R., Bengtsson, G. B., Hoftun, H., & Vogt, G. (2001). Sensory and chemical changes in five varieties of carrot (*Daucus carota* L) in response to mechanical stress at harvest and post-harvest. *Journal of the Science of Food and Agriculture, 81*(4), 436–447.
Seljåsen, R., Kristensen, H. L., Lauridsen, C., Wyss, G. S., Kretzschmar, U., Birlouez-Aragone, I., et al. (2013). Quality of carrots as affected by pre- and postharvest factors and processing. *Journal of the Science of Food and Agriculture, 93*(11), 2611–2626.
Seljåsen, R., Lea, P., Torp, T., Riley, H., Berentsen, E., Thomsen, M., et al. (2012). Effects of genotype, soil type, year and fertilisation on sensory and morphological attributes of carrots (*Daucus carota* L.). *Journal of the Science of Food and Agriculture, 92*(8), 1786–1799.
Sharpe, D., Fan, L., McRae, K., Walker, B., MacKay, R., & Doucette, C. (2009). Effects of ozone treatment on *Botrytis cinerea* and *Sclerotinia sclerotiorum* in relation to horticultural product quality. *Journal of Food Science, 74*(6), M250–M257.
Shezi, S., Samukelo Magwaza, S. L., Mditshwa, A., & Tesfay, Z. S. (2020). Changes in biochemistry of fresh produce in response to ozone postharvest treatment. *Scientia Horticulturae, 269*, 109397.
Shi, Q., Ji, Y., Shi, Y., Zhao, Z., Zhu, W., Xu, Y., et al. (2021). Floro-pyrazolo[3,4-d] pyrimidine derivative as a novel plant activator induces two-pathway immune system. *Phytochemistry, 184*, 112657.
Sikora, M., Złotek, U., & Świeca, M. (2019). Effect of basil leaves and wheat bran water extracts on enzymatic browning of shredded storage iceberg lettuce. *International Journal of Food Science and Technology, 55*(3), 1318–1325.
Simões, A. D. N., Allende, A., Tudela, J. A., Puschmann, R., & Gil, M. I. (2011). Optimum controlled atmospheres minimise respiration rate and quality losses while increase

phenolic compounds of baby carrots. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 44*(1), 277–283.
Simões, A.d. N., Tudela, J. A., Allende, A., Puschmann, R., & Gil, M. I. (2009). Edible coatings containing chitosan and moderate modified atmospheres maintain quality and enhance phytochemicals of carrot sticks. *Postharvest Biology and Technology, 51*(3), 364–370.
Simões, A.d. N., Ventrella, M. C., Moretti, C. L., Carnelossi, M. A. G., & Puschmann, R. (2010). Anatomical and physiological evidence of white blush on baby carrot surfaces. *Postharvest Biology and Technology, 55*(1), 45–52.
de Siqueira Oliveira, L., Eça, K. S., de Aquino, A. C., & Vasconcelos, L. B. (2018). Chapter 4 - hydrogen peroxide (H_2O_2) for postharvest fruit and vegetable disinfection. In M. W. Siddiqui (Ed.), *Postharvest disinfection of fruits and vegetables* (pp. 91–99). Academic Press.
Souza, L. P. D., Faroni, L. R. D. A., Heleno, F. F., Cecon, P. R., Gonçalves, T. D. C., Silva, G. J.d., et al. (2018). Effects of ozone treatment on postharvest carrot quality. *Lebensmittel-Wissenschaft und -Technologie Food Science and Technology, 90*, 53–60.
Surjadinata, B. B., Jacobo-Velazquez, D. A., & Cisneros-Zevallos, L. (2017). UVA, UVB and UVC light enhances the biosynthesis of phenolic antioxidants in fresh-cut carrot through a synergistic effect with wounding. *Molecules, 22*(4). https://doi.org/10.3390/molecules22040668
Szczepanska, J., Barba, F. J., Skapska, S., & Marszalek, K. (2020). High pressure processing of carrot juice: Effect of static and multi-pulsed pressure on the polyphenolic profile, oxidoreductases activity and colour. *Food Chemistry, 307*, 125549.
Troncoso-Rojas, R., & Tiznado-Hernández, M. E. (2014). Chapter 5 - Alternaria alternata (black rot, black spot). In S. Bautista-Baños (Ed.), *Postharvest decay* (pp. 147–187). San Diego: Academic Press.
Türkkan, M. (2015). Evaluation of inhibitory effect of organic and inorganic salts against *Ilyonectria liriodendri*, the causal agent of root rot disease of kiwifruit. *Journal of Phytopathology, 163*(7–8), 567–577.
Vargas, M., Chiralt, A., Albors, A., & González-Martínez, C. (2009). Effect of chitosan-based edible coatings applied by vacuum impregnation on quality preservation of fresh-cut carrot. *Postharvest Biology and Technology, 51*(2), 263–271.
Wang, Y. H., Li, T., Zhang, R. R., Khadr, A., Tian, Y. S., Xu, Z. S., et al. (2020). Transcript profiling of genes involved in carotenoid biosynthesis among three carrot cultivars with various taproot colors. *Protoplasma, 257*(3), 949–963.
Weber, R. W., & Tribe, H. T. (2004). Moulds that should be better known: *Thielaviopsis basicola* and *T. thielavioides*, two ubiquitous moulds on carrots sold in shops. *Mycologist, 18*(1), 6–10.
Xu, Z. S., Yang, Q. Q., Feng, K., & Xiong, A. S. (2019). Changing carrot color: Insertions in *DcMYB7* alter the regulation of anthocyanin biosynthesis and modification. *Plant Physiology, 181*(1), 195–207.
Xu, Z. S., Yang, Q. Q., Feng, K., Yu, X., & Xiong, A. S. (2020). *DcMYB113*, a root-specific *R2R3-MYB*, conditions anthocyanin biosynthesis and modification in carrot. *Plant Biotechnology Journal, 18*(7), 1585–1597.
Xylia, P., Clark, A., Chrysargyris, A., Romanazzi, G., & Tzortzakis, N. (2019). Quality and safety attributes on shredded carrots by using *Origanum majorana* and ascorbic acid. *Postharvest Biology and Technology, 155*, 120–129.
Yang, R. L., Yan, Z. H., & Lu, Y. (2008). Cytotoxic phenylpropanoids from carrot. *Journal of Agricultural and Food Chemistry, 56*(9), 3024–3027.
Zhang, W., Cao, J., Fan, X., & Jiang, W. (2020). Applications of nitric oxide and melatonin in improving postharvest fruit quality and the separate and crosstalk biochemical mechanisms. *Trends in Food Science & Technology, 99*, 531–541.
Zhang, W., & Jiang, W. (2019). UV treatment improved the quality of postharvest fruits and vegetables by inducing resistance. *Trends in Food Science & Technology, 92*, 71–80.
Zhang, H., Mahunu, G. K., Castoria, R., Apaliya, M. T., & Yang, Q. (2017). Augmentation of biocontrol agents with physical methods against postharvest diseases of fruits and vegetables. *Trends in Food Science & Technology, 69*, 36–45.
Zhang, Q. J., Tan, S. C., McKay, A., & Yan, G. J. (2005). Carrot browning on simulated market shelf and during cold storage. *Journal of the Science of Food and Agriculture, 85*(1), 16–20.
https://ag.umass.edu/vegetable/fact-sheets/carrot-black-root-rot. (Accessed 20 January 2021).
Ziogas, V., Molassiotis, A., Fotopoulos, V., & Tanou, G. (2018). Hydrogen sulfide: A potent tool in postharvest fruit biology and possible mechanism of action. *Frontiers in Plant Science, 9*, 1375.