12-1-2023

Oxalic acid: A blooming organic acid for postharvest quality preservation of fresh fruit and vegetables

Mahmood Ul Ul Hasan
Edith Cowan University

Zora Singh
Edith Cowan University

Hafiz Muhammad Shoaib Shah
Edith Cowan University

Jashanpreet Kaur
Edith Cowan University

Andrew Woodward
Edith Cowan University

See next page for additional authors

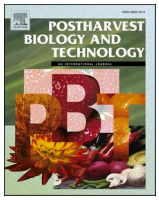
10.1016/j.postharvbio.2023.112574
Ul Hasan, M., Singh, Z., Shah, H. M. S., Kaur, J., Woodward, A., Afrifa-Yamoah, E., & Malik, A. U. (2023). Oxalic acid: A blooming organic acid for postharvest quality preservation of fresh fruit and vegetables. Postharvest Biology and Technology, 206, 112574. https://doi.org/10.1016/j.postharvbio.2023.112574

Postharvest Biology and Technology 206 (2023) 112574

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio



Oxalic acid: A blooming organic acid for postharvest quality preservation of fresh fruit and vegetables

Mahmood Ul Hasan [a], Zora Singh [a,*], Hafiz Muhammad Shoaib Shah [a], Jashanpreet Kaur [a], Andrew Woodward [a], Eben Afrifa-Yamoah [a], Aman Ullah Malik [b,c]

[a] Horticulture, School of Science, Edith Cowan University, Joondalup, Western Australia 6027, Australia
[b] Postharvest Research and Training Centre, Institute of Horticultural Sciences, University of Agriculture, Faisalabad 38040, Pakistan
[c] The University of Faisalabad, Faisalabad 38000, Pakistan

ARTICLE INFO

Keywords:
Oxalic acid
Fruit ripening
Chilling injury
Enzymatic browning
Postharvest senescence

ABSTRACT

Oxalic acid (OA) is a unique organic acid that commonly occurs in plants with distinct functions in modulating metabolic processes. To date, the role of OA has primarily been studied in the deactivation of copper-containing preservatives, detoxification of aluminium toxicity and remediation of organic pollutants. During the last two decades, OA has been considered as an antioxidant compound with focus on its potential to enhance crop yield, improve fruit quality, boost nutritional profile, and delay postharvest senescence in fruit and vegetables. It has been established that pre- and postharvest OA application delays ripening and senescence by down-regulating physiological processes such as water loss, ethylene production and respiration. OA treatment controlled adverse storage effects including chilling injury, enzymatic browning, as well as flesh softening by lowering oxidative stress. OA application has also been found to reduce decay in fresh fruit and vegetables by inducing systemic resistance against pathogens, decontamination from surficial microbial load and pesticide residues. Additionally, OA treatments have shown to effectively improve enzymatic and non-enzymatic antioxidants and maintain attributes for eating quality. Effectively, OA application has been deemed to be a potentially food-safe natural and suitable alternative to synthetic chemicals for up-regulating bioactive compounds in harvested fruit and vegetables and extending storability within the postharvest supply chain. This extensive review covers aspects of OA including its: history, chemistry, biosynthesis in plants, quantification in fruit and vegetables, crosstalk with ripening physiology, past attempts and recent advancements in storage life extension, safety as well as quality management of fruit and vegetables.

1. Introduction

Food and nutritional security is a key concern in feeding the world's rapidly increasing population, which is expected to exceed 9.7 billion in 2050 (UNO, 2019). A major aspect of food security is the production and storage of fresh fruit and vegetables, especially given their high-water content, increasing their susceptibility to qualitative loss as high as 60% (Porat et al., 2018). A holistic approach that encompasses pre and postharvest management of fresh horticultural produce may be helpful in reducing the wastage in their supply chains, thereby increasing the availability of food for humans.

Postharvest quality preservation of fresh fruit and vegetables is an ongoing and major challenge for researchers, where they seek to combat high postharvest losses that occur in transitioning from 'the farm to the fork'. In this regard, various technologies have emerged globally, after extensive research and development on postharvest quality management of fresh horticultural produce during the supply chain. Notably, cold storage, modified atmosphere packaging (MAP), controlled atmospheres (CA), low-pressure storage (hypobaric), ozonation, ultraviolet light, ultrasound application, and pre-storage heat treatments have shown significant results in extending storage life and maintaining quality during the postharvest period (Hasan et al., 2020; Maryam et al., 2021; Singh, 2022; Zhang and Jiang, 2019). Due to certain limitations in using these technologies and variations in responses of fresh horticultural produce, several food-safe chemical compounds have been tested, where a few have qualified for the next phase of commercialization. Among such chemicals, the application of 1-methylcyclopropene (1-MCP) (Dias et al., 2021), melatonin (Shah et al., 2023), nitric oxide

* Corresponding author.
E-mail address: z.singh@ecu.edu.au (Z. Singh).

https://doi.org/10.1016/j.postharvbio.2023.112574
Received 17 July 2023; Received in revised form 11 September 2023; Accepted 12 September 2023
Available online 19 September 2023

(Madebo et al., 2022; Manjunatha et al., 2014), and organic edible coatings (Hasan et al., 2021) have received much attention with regard to their potential to preserve quality of fresh horticultural produce during storage either alone or in combination with other technologies.

The exogenous application of different organic acids plays a significant role in upregulating resistance against biotic and abiotic stresses, and ensuring the modulation of ripening and senescence during the postharvest period (Walker and Famiani, 2018). Oxalic acid is a commonly occurring organic acid in higher plants that has been identified for its prime role in different metabolic processes during growth and development. The metabolism of OA has also been reported in fungal cultures and as an end product in human urine (Munir et al., 2001). OA is a simplest dicarboxylic acid with low molecular weight (Li et al., 2022), considered as robust metal chelator and a good source of protons and electrons. The acidic strength of OA is pKa - 1.27 for the dissociation of the first H^+, which is higher than acetic acid (pKa - 4.76). OA is also regarded as a reducing agent, while its conjugate base acts as cations (Ca, Mg, Zn, Mn and Fe) and a chelating agent, which might result in formation of a variety of oxalates. Accordingly, OA is being widely employed in dyeing industries for bleaching purposes and for old wood restoration (Prasad and Shivay, 2017). OA has inherent ecological quality characteristics that include organic pollutant remediation, biodegradation of lignin, aiding in deactivation of wood preservatives containing copper by employing wood rotting fungi, detoxification of aluminium toxicity, and a significant role in nitrogen fixation of legume crops in symbiotic rhizobia due to it being an electron source (Munir et al., 2001). The OA performs various indirect functions in higher plants and fleshy fruit, such as for storage of calcium, protection from pests, providing resistance to toxicity of metal ions in the soil, regulation of pH intricately linked with nitrate assimilation, and acting as a substrate for biosynthesis of hydrogen peroxide used for fungal responses and establishing cross-linkage between polymers and peroxidases in an extracellular matrix (Walker and Famiani, 2018). Additionally, due to its antioxidant properties, OA plays a vital role in programmed cell death, redox homeostasis, inducing systemic resistance in plants and delaying senescence in harvested fruit and vegetables (Ding et al., 2007; Huang et al., 2013a; Wu et al., 2011).

During the last two decades, OA application has received much attention with regard to its pre- and postharvest application in fruit and vegetables, serving to improve quality and prolong storage life. Primarily, the exogenous application of OA exhibits significant effects in developing systemic tolerance against various types of diseases caused by fungi, bacteria and viruses, intrinsic heat and aids in enhancing antioxidant capacities in plants and fleshy fruit at pre- and postharvest levels (Tian et al., 2013; Zheng, Brecht., 2017; Zheng and Tian, 2006). Zheng, Brecht. (2017) have reported that OA is present in high concentration in a variety of crops including beet greens (*Beta vulgaris* L.), poppy seeds (*Papaver somniferum* L.), purslane (*Portulaca oleracea* L.), rhubarb (*Rheum rhabarbarum* L.), sweet peppers (*Capsicum annuum* L.), sorrel (*Rumex acetosa* L.), Swiss chard (*Beta vulgaris* L. subsp. cicla), and spinach leaves (*Spinacia oleracea* L.). OA is regarded as a GRAS (generally recognized as safe) food safe compound due to its eco-friendly nature (Ali et al., 2020) and commercially used in the honeybee industry to control the attack of Varroa mites (*Varroa destructor*) in beehives, where as a product it is registered with the environmental protection agency (EPA) (USDA., 2021). Previously, there were concerns about the role of OA as an antinutrient in human diets, which makes minerals unavailable for the body and pronounces the deposition of calcium oxalate, eventually leading to kidney stones (Libert and Franceschi, 1987). In contrast, natural foods that are rich in OA usually have higher amount of minerals, which may not interfere with availability of calcium and magnesium in diets. Additionally, OA has been viewed as a potential antioxidant compound that can markedly preserve fresh and processed products from oxidation and deterioration (Zheng and Brecht., 2017). Pre- and postharvest OA application has been deemed worthwhile for improving physical and biochemical fruit quality at harvest, maintaining antioxidant capacity, downregulating metabolic processes, and reducing storage rot and disorders. Previously, Zheng and Brecht. (2017) have summarized the influence of postharvest application of OA on delaying ripening and senescence, increasing resistance, preventing decay, mitigating enzymatic browning, and attenuating chilling injury in fruit and vegetables. In addition, Li et al. (2022) have described the oxalate biosynthesis in plants, and reviewed the role of OA in plant metabolism, growth, and development, as well as their response against biotic and abiotic stresses. Whilst there has been several research works published on the effects of OA on quality of different fruit and vegetables at harvest and during postharvest periods, particularly, the beneficial effects of pre- and postharvest application of OA on improving fruit quality, extending storage life and preserving quality of stored fruit and vegetables have not been recently reviewed. Considering this gap, we compiled this comprehensive review on OA, which encompasses its background, biosynthesis, levels in fruit and vegetables, interaction with ripening processes, previous efforts, recent developments in extending storage life, safety considerations, and quality control practices for fresh fruit and vegetables.

2. Biosynthesis of OA in plants

OA is a widely studied organic acid in the animal and plant kingdom, with many possible biosynthetic pathways. OA was initially extracted from wood sorrel (*Oxalis acetosella* L.), which was regarded as a rhizomatous plant by Francois Pierre Savary in Switzerland in approximately 1773 (Prasad and Shivay, 2017). The biosynthesis of OA in plants can occur through multiple metabolic pathways, which might vary in accordance with type of cell or tissue, though glyoxylate and L-ascorbic acid are regarded as prime precursors of OA (Çalişkan., 2000; Walker and Famiani, 2018). Li et al. (2022) have recently summarised the biosynthesis of oxalates in plants into three pathways such as glycolic or glyoxalic acid pathway, oxaloacetic acid pathway and the ascorbic acid pathway even though debatable issue regarding their considerable contribution remain exists (Fig. 1.). Oxaloacetate or glyoxylate (derived from photorespiration) could also be possible precursors/pathways for oxalate synthesis; however, these pathways of oxalate synthesis have been questioned (Franceschi and Loewus, 1995; Yu et al., 2010). Further, oxalate synthesis has been reported from ascorbate or isocitrate. Different enzymes, such as oxalate decarboxylase, oxalate oxidase, and oxalyl- CoA synthetase have been involved in breaking down oxalate, which varies with plant species, cell or tissue type. However, the oxalate decarboxylase breakdown pathway is regarded as minor or insignificant in plants (Franceschi and Loewus, 1995). Davies and Asker (1983) reported that lactate dehydrogenase in cytosol and glycolate oxidase in the peroxisome are involved in oxalate synthesis in lettuce leaves. The vacuole has been proposed as a primary site of OA deposition produced from the L-ascorbic acid pathway (Wagner, 1981). *Idioblasts* are the production sites of OA in many plant tissues, involving certain vacuole in cells where OA is synthesised as crystals of calcium oxalate (Franceschi and Horner, 1980). OA produced in *idioblasts* is derived from ascorbic acid, while oxalate breakdown occurs in the presence of the oxalyl-CoA synthetase pathway (Foster et al., 2016).

3. Availability of endogenous OA in fruit and vegetables

Several fruit and vegetables are frequently consumed as fresh or processed to meet daily dietary requirements which subsequently provides a wide range of phytonutrients and multi-vitamins thereby reducing the risk of diseases. A variety of organic acids, including OA, are part of various fruit and vegetables with varying potential health benefits. However, their quantity may vary among species, portion of plants, maturity stage and cultivars (Walker and Famiani, 2018). After establishing the role of OA in plant metabolism, many scientists have attempted to quantify its concentrations and possible functions (Bhandari and Kawabata, 2004; Ergönül and Nergiz, 2010; Nguyễn and

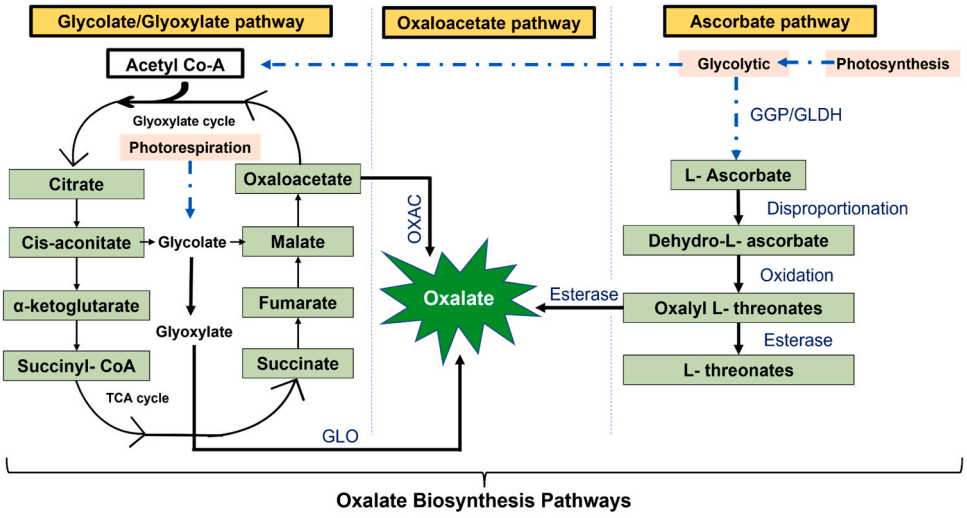


Fig. 1. The schematic diagram presents the oxalate biosynthesis pathways in plants (Li et al., 2022). Abbreviations: GGP/GLDH, GDP-L-galactose phosphorylase/L-galactono-1,4-lactone dehydrogenase, GLO = glycolate oxidase, OXAC = oxaloacetate acetylhydrolase, TCA = tricarboxylic acid.

Savage, 2013a; Nisperos-Carriedo et al., 1992; Pereira et al., 2013). The detection of OA in fruit and vegetables has been achieved by employing high-performance liquid chromatography (HPLC) and ultra-fast liquid chromatography (UFLC) coupled with photodiode array detector techniques (Nguyễn and Savage, 2013a; Nguyễn and Savage, 2013b; Pereira et al., 2013). Table 1 presents endogenous concentrations of OA and detection techniques reported in several edible fruit and vegetables. The concentration of OA varies with respect to commodity and genotypes assessed with similar methods. The total OA content has been noted as highest (75.67 g kg^{-1}) in Indian gooseberries (*Phyllanthus emblica* L.) and lowest (0.01 and 0.02 g kg^{-1}) in carambola (*Averrhoa carambola* L.) and table grapes (*Vitis vinifera* L.) across analysed fruit and vegetables (Nguyễn and Savage, 2013a). Similarly, yam tubers of different wild species have shown significant variation in OA concentrations (Bhandari and Kawabata, 2004) (Table 1). OA concentration can also be diversly distributed within fruit at the same maturity stage. For instance, total oxalate content was observed to be higher in seeds of green (*Actinidia deliciosa* L.) and golden kiwifruit (*Actinidia chinensis* L.), followed by

Table 1
Endogenous concentrations of oxalic acid in edible fruit and vegetables.

Crop	Scientific name	Cultivar	Detection technique	Concentration (g kg^{-1})	Maturity stage	Reference
Blueberry	*Vaccinium corymbosum* L.	-	HPLC	0.032	Mature (ripe)	Nguyễn and Savage (2013a)*
Carambola	*Averrhoa carambola* L.	-	HPLC	0.01	Mature green	Nisperos-Carriedo et al. (1992)
Cherry (sweet)	*Prunus avium* L.	-	HPLC	0.04	Mature (ripe)	Nguyễn and Savage (2013a)*
		0900 Ziraat	HPLC	0.03	Mature (ripe)	Özkaya et al. (2015)
Fig	*Ficus carica* L.	Tondo Nero	HPLC	0.104	Mature (ripe)	Palma et al. (2023)
Grapes	*Vitis vinifera* L.	-	HPLC	0.029	Mature (ripe)	Nguyễn and Savage (2013a)*
Indian gooseberry	*Phyllanthus emblica* L.	-	HPLC	75.67	Mature (ripe)	Nguyễn and Savage (2013a)*
Kiwifruit (Gold)	*Actinidia chinensis* L.	hort16A	HPLC	0.153	Mature (ripe)	Nguyễn and Savage (2013a)*
Litchi	*Litchi chinensis* Sonn.	Feizixiao	HPLC	0.38	Immature (unripe)	Wang et al. (2006)
		Nuomici	HPLC	0.25	Immature (unripe)	
Medlar	*Mespilus germanica* L.	İstanbul	HPLC	1.11	Mature (ripe)	Ozturk et al. (2019)
Olives	*Olea europaea* L.	Domat	HPLC	0.75	-	Ergönül and Nergiz (2010)
		Memecik	HPLC	0.67	-	
		Uslu	HPLC	0.66	-	
Persimmon	*Diospyros kaki* L.f.	-	HPLC	0.074	Mature (ripe)	Nguyễn and Savage (2013a)*
Pomegranate	*Punica granatum* L.	01-N-07	HPLC	1.59	Mature (ripe)	Poyrazoğlu et al. (2002)
		07-N-06	HPLC	2.96	Mature (ripe)	
		33-N-24	HPLC	6.72	Mature (ripe)	
		33-N-25	HPLC	3.54	Mature (ripe)	
Pineapple	*Ananas comosus* L.	-	HPLC	0.05	Mature (ripe)	Nguyễn and Savage (2013a)*
Plum	*Prunus domestica* L.	-	HPLC	0.11	Mature (ripe)	Nguyễn and Savage (2013a)*
Raspberry	*Rubus idaeus* L.	-	HPLC	0.18	Mature (ripe)	Nguyễn and Savage (2013a)*
Rhubarb	*Rheum rhabarbarum* L.	-	HPLC	6.4	Petiole	Nguyễn and Savage (2013a)*
Spinach	*Spinacia oleracea* L.	-	-	6.0	Leaves	Attalla et al. (2014)*
Tomato	*Lycopersicon esculentum* L.	Amarelo	UFLC	0.76	Mature (yellow ripe)	Pereira et al. (2013)
		Batateiro	UFLC	0.81	Mature	
		Comprido	UFLC	0.97	Mature	
		Coração-de-boi	UFLC	0.86	Mature	
Watercress	*Nasturtium officinale* R. Br.	-	UFLC	7.5	Stalks and leaves	Pinela et al. (2016)
Yam	*Dioscorea bulbifera* L.	Wild	HPLC	0.67	Tuber	Bhandari and Kawabata (2004)
	Dioscorea versicolor Buch.	Wild	HPLC	0.70	Tuber	
	Dioscorea deltoidei Wall.	Wild	HPLC	1.97	Tuber	
	Dioscorea triphylla L.	Wild	HPLC	1.04	Tuber	

Abbreviations: HPLC = High-performance liquid chromatography, UFLC = Ultra-fast liquid chromatography. * This information was noted from Walker and Famiani (2018) who have presented OA concentration (mg g^{-1} FW) on the basis of Nguyễn and Savage (2013a), and Attalla et al. (2014).

levels in skin, with lowest concentrations observed in flesh at eating ripe stage (Nguyễn and Savage, 2013b). Higher OA in skin might prevent fruit from harsh environmental conditions and pest infestation. Moreover, OA concentration is also affected by variations in cultural and nutritional practices. It is evident from a previous study by Aloni et al. (1994) that sweet peppers subjected to a high dose of nitrogen based fertilizer significantly increased calcium oxalate crystals in the flesh. OA concentration reduces with advancement of maturity stage in climacteric fruit (Walker and Famiani, 2018).

4. Role of OA in fruit ripening physiology

OA plays an imperative role in fruit ripening and senescence during the postharvest period (Fig. 2). Endogenous OA biosynthesis affects the internal quality of fruit, which is evident in earlier report on grapes that determined ascorbate metabolism during fruit ripening. The accumulation of ascorbic acid in grapes cv. 'Shiraz' is highly dependent on biosynthesis of OA and tartaric acid during early berry development stage, which determines both fruit and wine quality (Melino et al., 2009). The endogenous accumulation of oxalate or OA content varies with the stage of fruit development. OA concentration decreases with advancements in ripening stage as earlier reported in mume (*Prunus mume* (Siebold) Siebold & Zucc.), persimmon (*Diospyros kaki* L.f.) and fig (*Ficus carica* L.) fruit (Walker and Famiani, 2018). Shimokawa et al. (1972) have investigated the decarboxylation of oxalic acid that has been identified to critically influence the ripening of banana (*Musa sapientum* L.) fruit. In their study, OA was not found to be metabolized in banana fruit at the green hard stage, and subsequently declined when the fruit approached the soft green stage. A rise in climacteric respiration (CO_2) was revealed as directly associated with decarboxylation of

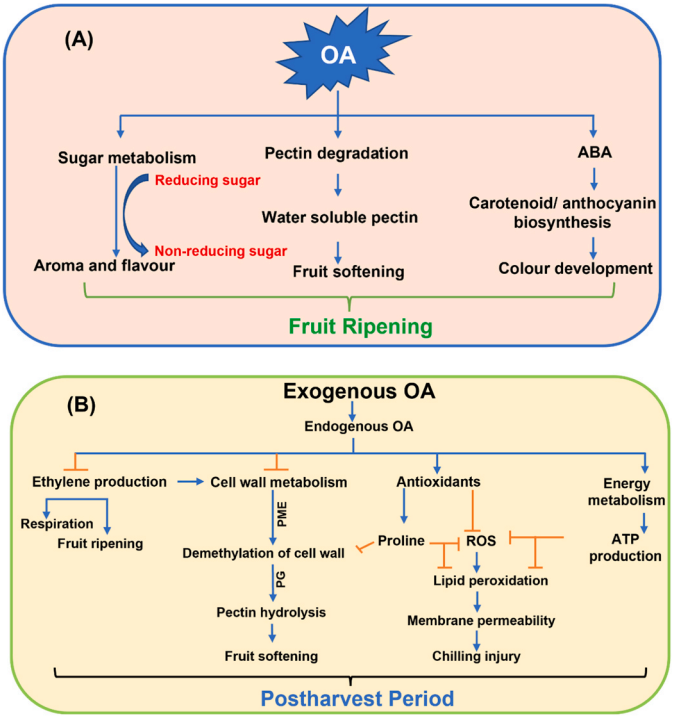


Fig. 2. The role of OA in fruit ripening (A), modulation of endogenous OA content by exogenous application which helps in restricting postharvest metabolic activities, softening, and chilling injury by accelerating antioxidant system and mitigating ROS-induced oxidative stress during storage (B) (García-Pastor et al., 2021; Jin et al., 2014; Martínez-Esplá et al., 2019; Serna-Escolano et al., 2021; Wu et al., 2011; Zhu et al., 2016). The '⊥' indicates the inhibition of a certain process or activity. Abbreviations: ABA= abscisic acid, ATP = adenosine triphosphate, PG = polygalacturonase, PME = pectin methyl esterase, ROS = reactive oxygen species.

oxalate content, when banana fruit were analysed at soft green and yellow with green tips stages. In another study, organic acids including OA have been reported to increase in stone fruit during the early stages of development within 30–60 days after full blossom (DAFB), after which they gradually decreased as the fruit approached ripening (Bae et al., 2014). Similarly, OA concentration in litchi fruit has only been detected in young fruit (Wang et al., 2006) (Table 1). Accordingly, changes in fruit growth and ripening have been found to be associated with endogenous levels of OA, confirming possible effects of its exogenous application.

5. Response of preharvest spray application of OA on nutritional and storage quality

The application of various types of plant growth regulators (PGRs), bio-stimulants, ethylene antagonists, natural elicitors, and edible coatings have emerged as popular industry practices for modulating fruit ripening, delaying harvest maturity and extending storage life of fresh fruit and vegetables. The preharvest spray application of OA has been reported in China, in which 'Zill' mango (*Mangifera indica* L.) trees were sprayed with 5 mM OA 30 days before commercial harvest. The OA treated fruit exhibited uniform pericarp and external flesh enriched with increased calcium (Ca) and starch content due to higher deposition of Ca in cell vacuoles, which resulted in the development of tough skin that might increase fruit firmness (Zhu et al., 2010). Subsequently, a research group in Spain has made considerable efforts to unveil the effects of preharvest spray application of OA on fruit growth, harvest quality and storage of different fruit and vegetables (García-Pastor et al., 2021; García-Pastor et al., 2020; Giménez et al., 2017; Martínez-Esplá et al., 2017; Martinez-Espla et al., 2014; Martínez-Esplá et al., 2019; Serna-Escolano et al., 2021). Table 2 shows that OA spray application has many benefits such as increased yield in terms of number and weight of fruit, as well as improvements in fruit quality attributes including size, firmness, juice content, soluble solids content, sugar acid ratio, and better eating quality with more overall acceptability. Strawberry (*Fragaria* × *ananassa* Duch.) cv. 'Chandler' plants sprayed with 1 mM OA eight times after transplantation markedly increased the number of fruit and upregulated levels of ascorbic acid at commercial harvest (Anwar et al., 2018). Apart from physiochemical quality, preharvest spray application of OA can also reduce metabolic activities, as evident from earlier studies on plum and apricot (*Prunus armeniaca* L.) in which fruit harvested from OA treated trees exhibited significant suppression of ethylene biosynthesis and respiration rate during postharvest period (Martínez-Esplá et al., 2019; Üzümcü et al., 2020). Similar results have been noted in artichokes (*Cynara cardunculus* L.) and lemons (*Citrus limon* L.) for suppression of respiration peaks in OA treatment (Martínez-Esplá et al., 2017; Serna-Escolano et al., 2021). This has also been investigated in relation to ethanol fermentation metabolism, which can be regulated via OA application in fruit. Ali et al. (2019) have reported that preharvest spray application of OA markedly reduced the development of off-flavour, acetaldehyde, ethanol content in kiwifruit cv. 'Bruno' during 13 days of storage. This might be due to OA's role in regulation of ascorbate metabolism, maintaining higher ascorbic acid in fruit as also evidenced in grapes (Melino et al., 2009). Additionally, OA spray applications can significantly reduce incidence of blue mould rot in kiwifruit by inhibiting accumulation of patulin content and inducing higher production of defence related enzymes including chitinase, β-1, 3-glucanase, phenylalanine ammonia-lyase, peroxidase and polyphenol oxidase during the postharvest period (Zhu et al., 2016). OA preharvest sprays have also been shown to be successful in triggering production of bioactive compounds by increasing enzymatic and non-enzymatic antioxidants in fruit and vegetables harvested from treated plants (El-Zaeddi et al., 2017; Martínez-Esplá et al., 2017; Razavi and Hajilou, 2016; Zhu et al., 2016) (Table 2). The OA concentration may also have influence on quality of harvested fruit and vegetables. Table 2 presents that the variable concentrations from 1 mM to 10 mM as preharvest

Table 2
Influence of preharvest oxalic acid application on overall quality and antioxidant capacity of fruit and vegetables at harvest and during the postharvest period.

Crop (cultivar)	Concentration	Number and time of spray (s)	Quality inference	Antioxidant capacity	Reference
Apricot (Red flesh)	2 mM	1- Fruit set stage	↑ firmness, average fruit weight, juice yield, taste, overall acceptability, ↓ water loss, SSC, SSC:TA ratio	↑ ascorbic acid, TPC, DPPH inhibition activity, SOD, POD, CAT activities	Ahmed et al. (2021)
Apricot (Roxana)	1 mM	1–7 DBH	↓ water loss, ethylene production, respiration rate, ↔ colur values	-[a]	Üzümcü et al. (2020)
Artichoke (Blanca de Tudela)	2 mM	3–45, 24 and 3 DBH	↓ respiration rate	↑ total hydrosoluble antioxidant activity, total phenolics, luteolins, hydroxycinnamic	Martínez-Esplá et al. (2017)
Blueberry (Kirra™ and Stella blue™)	2 mM	3–21, 14 and 7 DBH	↑ firmness	↑ total anthocyanins, antioxidant capacity	Retamal-Salgado et al. (2023)
Cherries (Sweet Heart)	2 mM	-	↑ fruit weight, firmness, SSC	-[a]	Giménez et al. (2017)
Cherries (Sweet Heart, Sweet Late)	2 mM	3–98, 112, and 126 DAFB	↑ fruit volume, weight, firmness colour values, SSC, acidity	↑ TPC, individual anthocyanins, individual flavenoids	Martinez-Espla et al. (2014)
Coriander (-[b])	1 mM	1–7 DBH	-[a]	↑ phenolic compounds (quercetin-3-O-rutinoside, dimethoxycinnamoyl hexoside), antioxidant activity (ABTS, FRAP and ORAC)	El-Zaeddi et al. (2017)
Grapes (Magenta)	5 mM	3- before onset of variation, after 18 d at variation stage, 3 DBH	↑ ABA, berry percentage, colour, firmness, ↓ decay	↑ individual and total anthocyanins, ascorbic acid, tartaric acid, succinic acid, antioxidant enzymes (APX, CAT, POD)	García-Pastor et al. (2021)
Kiwifruit (Bruno)	5 mM	3–130, 137 and 144 DAFB	↓ blue mould rot, lesion diameter, ↑SSC, ○TA	↑ ascorbic acid, defense related enzymes, ↓ patulin content	Zhu et al. (2016)
Kiwifruit (Bruno)	5 mM	3–130, 137 and 144 DAFB	↓ SSC, TA, off-flavour, acetaldehyde and ethanol content	↑ ascorbic acid, tartaric acid	Ali et al. (2019)
Lemon (Fino)	1 mM	5–30 days interval until three DBH	↑ fruit firmness, SSC, TA, ↓ water loss, respiration, decay, ○ colour values (hue angle)	↑ TPC, antioxidant enzymes (APX, CAT, POD)	Serna-Escolano et al. (2021)
Peach (Anjirymaleki)	5 mM	1–15 DBH	↑ fruit firmness	↑ TPC, total flavonoids, total antioxidants (DPPH, FRAP), CAT, SOD, POD	Razavi and Hajilou (2016)
Pineapple (Queen)	5 mM	-	↓ internal browning, ○ SSC, TA	○ ascorbic acid	Youryon et al. (2017)
Plums (Black Splendor, Royal Rosa)	2 mM	3–63, 77 and 98 DAFB	↑ fruit weight, yield, ↓ ethylene production, SSC, TA	↑ TPC, individual phenolics, anthocyanins, total antioxidant activity, APX, CAT, SOD, POD	Martínez-Esplá et al. (2019)
Pomegranate (Mollar de Elche)	10 mM	4–80, 110, 140, and 170 DAFB	↑ fruit weight, yield, firmness, SSC, glucose, TA. Overall acceptability, sensory properties	↑ ascorbic acid, maleic acid, TPC, anthocyanins, total antioxidant activities,	García-Pastor et al. (2020)
Strawberry (Chandler)	1 mM	8–100 DATP and weekly interval till harvest	↑ fruit number, sensory attributes, SSC:TA ratio, non-reducing sugars	↑ ascorbic acid	Anwar et al. (2018)

Abbreviations: ABA = abscisic acid, ABTS = 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid), APX = ascorbate peroxidase, CAT = catalase, DAFB = days after full blossom, DATP = days after transplantation, DBH = days before harvest, DPPH = 2,2-diphenyl-1-picryl-hydrazyl-hydrate, EL = electrolyte leakage, FRAP = ferric reducing antioxidant power, H-TAA - Hydrophilic total antioxidant activity, SSC = soluble solids content, SSC:TA = soluble solids content and titratable acidity ratio, TA = titratable acidity, TPC = total phenolic content, SOD = superoxide dismutase, ORAC = oxygen radical absorbance capacity, POD = peroxidase, ↑ = increased, ↓ = decreased, ↔ = maintained, ○ = non-significant, - [a] = not investigated, - [b] = not mentioned

spray application have been exhibiting better results than other concentrations regardless of crop, cultivar, and number of spray applications. However, the spray application of 2 mM OA solution as preharvest treatment is more frequently showing significant results for enhancing fruit size, antioxidant potential, delaying ripening and maintaining quality during postharvest period (Ahmed et al., 2021; Giménez et al., 2017; Martínez-Esplá et al., 2017; Martinez-Espla et al., 2014; Martínez-Esplá et al., 2019; Retamal-Salgado et al., 2023). Additionally, the response of concentration effect may be inconsistent with respect to crop, as earlier revealed by García-Pastor et al. (2021) who have reported that 5 mM spray application to grapes is optimized dose resulted in better yield, attributes related to berry maturity and augmentation of bioactive compounds among 1 mM, 5 mM, 10 mM assessed during two growing seasons. Contrarily, the preharvest spray application significantly enhance pomegranate yield, firmness and colour, and advanced harvest maturity in concentration dependent manner (1, 5, and 10 mM) and 10 mM outclassed other treatments (García-Pastor et al., 2020). It has been noted in various studies that application of OA can be more beneficial if applied multiple times (three or more sprays) starting after full blossom or fruit set stage. Accordingly, this warrants further investigation for commercial scale application on high value horticultural crops.

6. OA application and postharvest quality management of fruit and vegetables

Recent literature has identified that OA exhibits great potential in regulating key indicators that influence postharvest quality, thereby prolonging storage life of fresh fruit and vegetables. For instance, OA dip application can overcome storage constraints such as chilling injury (CI), enzymatic browning, fruit softening and pathogenic decay during the postharvest period.

6.1. Water loss and textural quality

Physiological water loss from fresh fruit and vegetables is one of the many constraints that leads to shrivelling, wilting, loss of saleable weight, accelerated browning and quick postharvest senescence. OA has been reported to significantly reduce water loss in fresh fruit and vegetables. However, its reduction rate may vary among genotypes,

cultivars and storage conditions during the postharvest period. Table 3 summarizes the effect of OA dipping application on lessening total water loss, as noted at the end of the storage period and water loss percentage per day in fresh horticultural produce. Ali et al. (2021) have reported that litchi fruit cv. 'Gola' subjected to 2 mM OA dip treatment following storage under CA comprising of 5% CO_2 + 1% O_2, and 5 ± 1 °C with 90 ± 5% RH conditions, exhibited 3.2% water loss as compared to untreated control fruit under air storage showing 11.1% water loss after 28 days of storage. This substantial reduction in water loss suggests that OA application could maintain the vapour pressure between the treated fruit and storage environment, and as a result reduce metabolic activity and tissue permeability whilst retaining membrane integrity, thereby increasing the postharvest life of fresh horticultural produce. It is evident that water loss reduction in response to OA treatment may vary among cultivars under similar storage conditions. Batool et al. (2022) have indicated that apricot fruit cv. 'Rival' treated with 8 mM OA

Table 3
Response of pre or postharvest oxalic acid application on water loss in fruit and vegetables during storage.

Crop	Cultivar	Concentration	Storage condition and period	Water loss (% d^{-1})	Total water loss (%)	Reference
Apricot	Rival	Control	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	0.24	7.2	Batool et al. (2022)
		8 mM		0.11	3.4	
	Harcot	Control	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	0.26	7.9	
		8 mM		0.14	4.2	
	New castener	Control	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	0.22	6.6	
		8 mM		0.14	4.3	
	Erani	Control	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	0.18	5.5	
		8 mM		0.15	4.5	
	Roxana	Control	20 ± 1 °C, 50–60% RH, 8d	0.75	6.0	Koyuncu et al. (2018)
		8 mM (preharvest)		0.66	5.3	
	Red flesh	Control	25 ± 1 °C, 60–65% RH, 5d	3.30	16.5	Ahmed et al. (2021)
		2 mM		2.24	11.2	
Artichoke	Blanca de Tudela	Control	2 °C, 85% RH, 21d	1.36	28.7	Martínez-Esplá et al. (2017)
		2 mM (preharvest)		1.37	28.8	
	Blanca de Tudela	Control	20 °C, 85% RH, 3d	4.4	13.4	Ruíz-Jiménez et al. (2014)
		1 mM		3.7	11.1	
Bamboo shoots	-[a]	Control	6 ± 1 °C, 85–90% RH, 20d	0.13	2.6	Zheng et al. (2019)
		10 mM		0.07	1.4	
Banana	Giant Cavendish	Control	24 ± 1 °C, 58 ± 2% RH, 10d	3.1	31.3	Lo'ay andDawood (2017)
		15 mM		2.1	21.9	
Bell pepper	Jin 3	Control	4 ∘C ± 0.5 °C, 90 – 95% RH, 28d	0.22	6.2	Wang et al. (2022)
		5 mM		0.14	4.1	
Guava	Maamoura	Control	7 ± 1 °C, 90 ± 5% RH, 21d	0.81	17.2	Abd El-Gawad (2021)
		6 mM		0.43	9.2	
Litchi	Gola	Control	5 ± 1 °C, 90 ± 5% RH, 5% CO_2 + 1% O_2, 28d	0.39	11.1	Ali et al. (2021)
		2 mM		0.11	3.2	
Lemon	Fino	Control	10 °C, 85% RH, 35d	0.19	6.82	Serna-Escolano et al. (2021)
		1 mM (preharvest)		0.12	4.21	
Mango	Samar Bahisht Chaunsa	Control	32 ± 3 °C, 7d	1.32	9.3	Razzaq et al. (2015)
		5 mM		1.08	7.6	
Orange	Valentia	Control	8 °C, 15d + 7d at 18–23 °C	1.10	16.6	Mohamed et al. (2016)
		10 mM		0.88	13.2	
	Midknight Valencia	Control	3 °C, 90 ± 5% RH, 84d	0.1	9.7	Azzu (2016)
		2 mM		0.08	6.9	
Plum	Black amber	Control	0–1 °C, 90 ± 5% RH, 40d	0.20	8.2	Bal (2019)
		1 mM (in alginate coating)		0.10	4.1	
	Angelino	Control	20 ± 1 °C, 60 ± 5% RH, 14d	1.9	27.2	Azzu (2016)
		2 mM		1.4	21	
	Angelino	Control	0 ± 1 °C, 95 ± 3% RH, 56d	0.5	29.4	
		2 mM		0.3	22.3	
	Tegan Blue	Control	20 ± 1 °C, 60 ± 5% RH, 14d	0.9	12.4	
		2 mM		0.8	12.1	
	Tegan Blue	Control	0 ± 1 °C, 95 ± 3% RH, 42d	1.6	23.1	
		2 mM		0.4	18.6	
Pomegranate	Hicaznar	Control	6 °C, 90 ± 5% RH, 5% O_2 and 15% CO_2, 180d	0.03	6.8	Koyuncu et al. (2019)
		6 mM		0.01	2.3	
Rambutan	Anak Sekolah	Control	10 °C, 90–95% RH, 20d	1.23	24.7	Hafiz et al. (2017)
		10%		0.85	17.1	
Tomato	Pusa Gaurav	Control	20 ± 1 °C, 70–5% RH, 17d	1.95	33.3	Kant et al. (2013)
		4 mM		1.75	29.9	

Abbreviations: - [a] = not mentioned, CO_2 = carbon dioxide, D = days, RH = relative humidity, O_2 = oxygen

showed a significant lower water loss of 3.4% followed by cvs. 'Harcot' (4.2%), 'New castener' (4.3%) and 'Erani' (4.5%) stored for 30 days under CA setting (5% O_2 and 15% CO_2) (Table 3). Similarly, storage conditions also affect water loss reduction in OA treated fruit. For example, Azzu (2016) reported that plums cv. 'Tegan Blue' stored at ambient conditions (20 ± 1 °C) displayed non-significant results between control and OA treated fruit. However, plums stored under low temperature conditions (0 ± 1 °C) exhibited significant reduction of water loss in OA treated fruit (Table 3). Additionally, water loss and firmness are associated quality attributes, where higher water loss results in accelerated rate of perishability due to increased shrivelling on skin, flesh softening and loss of texture which limits marketability (Hasan et al., 2021). Among different metabolic changes, the activity of a hydrolytic enzyme (polygalactonurase) accelerates as water loss increases, and is associated with firmness loss and enhanced degradation of middle lamella cell wall, along with progression in the postharvest period (Maringgal et al., 2020). Accordingly, OA dip treatment also preserves textural quality and maintains higher firmness in various fruit crops including apricots (Batool et al., 2022), cherries (Giménez et al., 2017; Martinez-Espla et al., 2014), grapes (García-Pastor et al., 2021), lemons (Serna-Escolano et al., 2021), and peaches (*Prunus persica* L. Batsch.) (Razavi and Hajilou, 2016) during the entire period of storage.

6.2. Ethylene and respiration

Ethylene production and cellular respiration are the foremost physiological activities that determine quality during ripening and the storage potential of harvested fruit and vegetables. Fresh horticultural produce is classified as climacteric and non-climacteric based on autocatalytic productions of ethylene, and respiration (as release of CO_2) during fruit ripening. Postharvest scientists are constantly seeking sustainable solutions for managing these metabolic changes to delay postharvest senescence. Pre- and postharvest OA application have been shown to play an inevitable role in mitigating ethylene production and lowering respiration rate during storage (Fig. 2B). In this way, the application of OA (1 mM) to apricot cv. 'Roxana' trees sprayed twice; 1 and 7 days before harvest has significantly reduced ethylene production and respiration following 6 days of ambient storage (Üzümcü et al., 2020). Similarly, preharvest application of 2 mM OA has been shown to inhibit ethylene production in 'Black Splendor' and 'Royal Rosa' plum fruit, and respiration rate in 'Blanca de Tudela' artichoke respectively (Martínez-Esplá et al., 2017; Martínez-Esplá et al., 2019). The substantial reduction of ethylene production in response to preharvest spray application indicates OA effects in downregulating cell metabolism rate in developmental phase and intact with plant which in turn, extended the storage life (Martínez-Esplá et al., 2017). Further to this, postharvest OA dip treatments have exhibited reduced ethylene biosynthesis and respiration during storage. Wang et al. (2009) found that Chinese jujube (*Ziziphus jujuba* Mill.) fruit cv. 'Dongzao' dipped in 5 mM OA for 10 min exhibited suppressed ethylene biosynthesis via restricting the activity ACC (1-aminocyclopropane-1-carboxylic acid) synthase during a postharvest shelf period of 8 days. In addition, cystathionine β -synthase (CBS) containing protein was observed as upregulated in response to OA application in jujube fruit. The disruption of CBS can directly influence S-adenosylmethionine (SAM) synthesis, which is the main precursor of ethylene biosynthesis and might strengthen the synergistic role of the CBS domain and robust changes in ethylene biosynthesis as earlier revealed by He et al. (2006) in *Pichia pastoris*. Huang et al. (2013a) have elaborated that Banana cv. 'Brazil' subjected to 20 mM treatments markedly suppressed ethylene production and respiration rate, reducing oxidative damage by inhibiting the accumulation of hydrogen peroxide, superoxide anion and malondialdehyde (MDA) content, lowered chlorophyll degradation, maintained colour and flesh firmness, and thereby delayed fruit ripening at ambient conditions. Similar results of modulating ethylene biosynthesis and respiration rate are evident in mango (Razzaq et al., 2015), persimmon (Li et al., 2018) and plum (Wu et al., 2011) when treated with exogenous OA dip treatment (Table 6).

6.3. Colour

The colour of fresh fruit and vegetables is one of the important attributes in defining the status of quality at harvest and during the postharvest and marketing periods. Pre- and postharvest application of OA have expressed positive effects in enhancing fruit colour and restraining changes during storage. It is evident from a previous study in which pomegranate cv. 'Mollar de Elche' trees were sprayed with 10 mM OA four times, resulting in significantly brightened skin colour with enhanced anthocyanin contents and increased average weight of fruit, yield, and aril firmness (García-Pastor et al., 2020). Recently, it has been shown that pre-harvest OA application regulates the abscisic acid (ABA) biosynthesis pathway by increasing endogenous ABA and ABA glucose ester in 'Magenta' table grapes and expressed upregulated relative gene *VvNCED1*, thereby enhancing fruit colour and total anthocyanins in berries at harvest (García-Pastor et al., 2021) (Fig. 2A). Martinez-Espla et al. (2014) have reported that sweet cherry cvs. 'Sweet Heart' and 'Sweet Late' trees sprayed with 2 mM OA four times before harvest exhibited notably improved colour and deepened red tint with higher colour index and concurrent higher concentrations of total anthocyanins, phenolics and flavonoids in fruit at commercial harvest. In contrast, lemon cv. 'Fino' trees sprayed five times with 1 mM OA showed non-significant results irrespective of maintaining postharvest quality and reduced decay incidence during 35 days of storage (Serna-Escolano et al., 2021). Colour deviation in lemon fruit contradicts previous findings, which might be due to the fact that OA response is genotype dependent. Postharvest OA dip treatments have also displayed significant results in retaining higher colour values in different fruit including banana (Huang et al., 2013b; Lo'ay and Dawood, 2017), litchi (Saengnil et al., 2006), loquat (*Eriobotrya japonica* Lindl.) (Öz et al., 2016), pomegranate (Koyuncu et al., 2019) and rambutan (*Nephelium lappaceum* L.) (Hafiz et al., 2017) during the entire period of storage. OA dip treatment has been shown to possess the capacity to delay the decline in chlorophyll fluorescence, chlorophyll degradation, and postharvest ripening of fruit during storage (Huang et al., 2013a; Huang et al., 2013b). Similarly, OA treatment also preserved green colour of leafy vegetables may be due to delayed degradation of chlorophyll as earlier reported in rocket (*Eruca sativa* Mill. cv. Bengi) leaves during entire period of cold storage (Erbaş, 2023).

6.4. Chilling injury

CI is a crucial physiological disorder that usually occurs in subtropical and tropical fruit and vegetables when stored under unsuitable low temperature conditions. Cold stress manifests in CI in various forms such as surface pitting, water staining on skin, abnormalities in colour development, uneven ripening, flavour, texture and aroma loss, skin and flesh browning, gelling, flesh reddening or bleeding, mealiness, and leatheriness. These undesirable symptoms appear on the skin and flesh of stored fruit and vegetables depending on their response due to genetic makeup and duration of exposure. Accordingly, it is essential to treat susceptible fresh produce with respective treatments to attenuate CI during cold storage and the marketing supply chain. Pre-storage OA dip treatment has shown good influence in alleviating CI in different fruit and vegetables (Fig. 2B). The postharvest application of OA substantially reduced CI in cold stored apricots (Batool et al., 2022), bell peppers (Wang et al., 2022), melons (*Cucumis melo* Naud.) (Jing et al., 2018), mangoes (Li et al., 2015; Li et al., 2014), peaches (Jin et al., 2014), persimmons (Li et al., 2018), pomegranates (Awad et al., 2013; Sayyari et al., 2010) and tomatoes (Li et al., 2016) without compromising fruit quality (Table 4). The rate of CI reduction seems to be dependent on the genotype, treatment concentrations applied and storage conditions. For example, pomegranate fruit treated with OA reduced CI by 9.5- and 7.8-fold as compared to control at the end of the storage period in

Table 4
Effect of postharvest oxalic acid application on chilling injury and browning index in cold stored fruit and vegetables.

	Cultivar	Concentration	Storage condition and period	Reduction (fold)	ROS and energy metabolism	Reference
CI						
Apricot	Rival	8 mM	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	2.0	-[a]	Batool et al. (2022)
	Harcot	8 mM	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	3.0	-[a]	
	New castener	8 mM	0 °C, 90–5% RH, 5% O_2 and 15% CO_2, 30d	2.5	-[a]	
	Diaogan	5 mM	2 ± 1 °C, 85 ± 90% RH, 35d	1.8	↓ EL, MDA and H_2O_2 content, glucose, sucrose, fructose, sorbitol, sugar metabolism enzymes (SS-synthesis, SPS, SS-cleavage, AI and NI activities)	Wang et al. (2016)
Bell pepper	Jin 3	5 mM	4 °C ± 0.5 °C, 90 – 95% RH, 28d	1.4	↓ EL, MDA, H_2O_2, and superoxide radical production, proline content	Wang et al. (2022)
Hemi melons	Xizhoumi 25 hao	15 mM	3 °C, 90% RH, 42d + 2d at 25 °C	1.4	↓ EL, MDA, H_2O_2 content and superoxide radical production	Jing et al. (2018)
Mango	Tommy Atkins	5 mM	5 °C, 90% RH, 18d + 4d at 25 °C, 85% RH	1.2	-[a]	Li et al. (2015)
	Zill	5 mM	10 ± 0.5 °C, 49d + 4d at 25 °C	1.5	↑ ATP, ADP content, energy charge, ↓ SSC, proline dehydrogenase, AMP content	Li et al. (2014)
Peach	Baifeng	5 mM	0 °C, 35d + 3d at 20 °C	1.4	↓ EL, MDA content, AMP content, ↑ ATP, ADP content, energy charge, H^+ -ATPase, Ca^{2+} -ATPase, SDH and CCO activities	Jin et al. (2014)
Persimmon	Youhou	5 mM	1 ± 0.5 °C, 90–95% RH, 70d + 5d at 25 °C	1.3	↓ EL, MDA content, POD activity, protopectin	Li et al. (2018)
Pomegranate	Mollar de Elche	2 mM	2 °C, 84d	7.8	Reduced respiration, EL	Sayyari et al. (2010)
	Taify	7 mM	2 or 5 °C, 90–95% RH, 90d + 3d at shelf	9.5	-[a]	Awad et al. (2013)
Tomato	Oumeiyuan	10 mM	4 ± 0.5 °C, 20d + 12d at 25	1.3	↓ EL, MDA content, ↑ ATP, ADP content, H^+ -ATPase, Ca^{2+} -ATPase, SDH and CCO activities, ○ energy charge, AMP	Li et al. (2016)
BI						
Abiu	-[b]	10 mM	28 ± 1 °C, 80 ± 5% RH, 12d	[c]1.88, 1.56	↓ MDA content, PPO activity	Arif et al. (2023)
Banana	Williams	20 mM	24 ± 1 °C, 58 ± 2% RH, 10d	3.6	↓ Cell membrane leakage, MDA content	Lo'ay and Dawood (2017)
	Brazil	20 mM	23 ± 2 °C, 75–90% RH, 24d	1.5	↑ reducing power	Huang et al. (2013b)
Bamboo shoots	-[b]	10 mM	6 ± 1 °C, 85–90% RH, 20d	1.6	↓ EL, MDA content	Zheng et al. (2019)
Litchi	Hong Huay	15%	25 ± 1 °C, 74% RH, 5d	2.8	↓ polyphenol oxidase activity	Saengnil et al. (2006)
	Gola	2 mM	5 ± 1 °C, 90 ± 5% RH, 5% CO_2 + 1% O_2, 28d	1.7	↓ soluble quinones, EL, MDA, H_2O_2 content and superoxide radical production	Ali et al. (2021)
	Huaizhi	2 mM	25 ± 1 °C, with 80–90%, 8d	1.8	↓ EL, MDA content, peroxidase activity, ↑ pH, anthocyanins,	Zheng and Tian (2006)
Longan	Daw	5%	25 °C, 3d	2.2	↓ PPO activity	Whangchai et al. (2006)
Loquat	Hafif Çukurgöbek	6 mM	5 °C, 90% RH, 30d	2.1	↓malic acid	Öz et al. (2016)
Lotus root	-[b]	10 mM	20 ± 1 °C, 85–90%	1.6	↓ soluble quinones, EL, MDA, H_2O_2 content and superoxide radical production	Ali et al. (2020)

Abbreviations: AI= acid invertase, ADP = adenosine diphosphate, ATP = adenosine triphosphate, AMP = adenosine monophosphate, CCO = cytochrome C oxidase, CO_2 = carbon dioxide, D = days, EL = electrolyte leakage, H_2O_2 = hydrogen peroxide, MDA = malondialdehyde, NI= neutral invertase, RH = relative humidity, O_2 = oxygen, ROS = reactive oxygen species, SDH = succinic dehydrogenase, SPS= sucrose phosphate synthase, SS-synthesis= sucrose synthase synthesis activity, SS-cleavage= sucrose synthase cleavage activity, POD = peroxidase, PPO = polyphenol oxidase, ROS = reactive oxygen species, ↑ = increased, = decreased, ↔ = maintained, ○ = non-significant, - [a] = not investigated, - [b] = not mentioned, c = peel, pulp

separate studies (Awad et al., 2013; Sayyari et al., 2010). The application of 8 mM OA to apricot fruit markedly reduced CI in cv. 'Harcot' (3.0-fold) followed by 'New Castener' (2.5-fold) and 'Rival' (2.0-fold) stored at similar storage condition under CA settings (5% O_2 and 15% CO_2, 0 °C, 90–95% RH) (Batool et al., 2022). Furthermore, the apricot cv. 'Diaogan' treated with 5 mM OA showed 1.8-fold CI reduction after 35 days of cold storage at 2 ± 1 °C, 85 ± 90% RH (Wang et al., 2016). CI reduction in response to OA application primarily occurs due to mitigation of oxidative stress by modulating the interplay between reactive oxygen species (ROS) and energy metabolism (Wang et al., 2016) (Fig. 2B). OA treatment significantly downregulates electrolyte leakage, accumulation of MDA, hydrogen peroxide (H_2O_2), production of superoxide radical, proline content and declines the activity of proline dehydrogenase in cold stored fruit and vegetables (Table 4). Additionally, OA also established sugar accumulation associated with CI tolerance as influenced by OA application. Wang et al. (2016) have reported the role of OA in sugar metabolism variations of cold stored apricot fruit and for inducing CI tolerance. The exogenous application of 5 mM OA in apricots reduced CI damage by lowering the lipid peroxidation and declining the contents of glucose, sucrose, fructose, and sorbitol. In addition, sugar metabolism enzymes including sucrose synthase synthesis, sucrose phosphate synthase, sucrose synthase cleavage, acid invertase and neutral invertase were also downregulated during the entire period of storage. Furthermore, CI tolerance is also directly driven by cellular energy metabolism in stored fruit and vegetables. Postharvest OA treatments have shown positive effects in alleviating CI and maintaining higher levels of adenosine triphosphate (ATP), adenosine diphosphate (ADP), energy charge and their respective enzymatic activities including cytochrome C oxidase, H^+ -ATPase, Ca^{2+} -ATPase, and succinic dehydrogenase, as previously reported in mango (Li et al.,

2014), peach (Jin et al., 2014) and tomato (Li et al., 2016) during cold storage.

6.5. Enzymatic browning

Enzymatic browning is a key limitation in the fresh horticultural produce during postharvest period which ends up in lower marketability and less profit to industry stakeholders. Enzymatic browning frequently occurs in freshly harvested susceptible fruit and vegetables when exposed to unsuitable conditions or subjected to bruising, peeling, cutting, and disease incidence, which pronounces the rate of browning through the oxidation of phenolic compounds by polyphenol oxidase (PPO) and peroxidase (POD) enzymes, and leads to higher polymerized melanin pigment. OA has been regarded as a potent antioxidant, where its application has been shown to increase postharvest browning resistance in various types of fruit and vegetables by mitigating lipid peroxidation mediated oxidative stress (Table 4). Previously, OA is an integral part of commercial pectins that are used in different juice industries, with a key role in attenuating juice browning during its processing and shelf period (Tong et al., 1995). Ali et al. (2021) have elucidated the key role of OA dip treatment (2 mM) in litchi cv. 'Gola' fruit stored under CA comprising of 5% CO_2 + 1% O_2 for 28 days. OA dip treatment significantly delayed pericarp browning by lowering reactive oxygen species (ROS) and accelerating higher preservation enzymatic and non-enzymatic antioxidants during storage. Similarly, the exogenous application of OA treatment has been shown to inhibit browning in abiu fruit (*Pouteria caimito* (Ruiz & Pavon.) Radlk) (Arif et al., 2023), bananas (Lo'ay and Dawood, 2017), bamboo shoots (Zheng et al., 2019), longans (*Dimocarpus longan* Lour.) (Whangchai et al., 2006), loquats (Öz et al., 2016), and lotus roots (*Nelumbo nucifera* Gaertn.) (Ali et al., 2020) during the postharvest period.

6.6. Fruit softening and cell wall disassembly

Fruit softening is a main determinant of storage life and is a hallmark of ripening, which can lead to early senescence in most fleshy fruit. Excessive softening is undesirable and exacerbates pathogenic decay, resulting in loss of market value. Cell wall integrity is important for regulating softening during ripening and postharvest period. In this way, it is a programmed process of progressive development that leads to the depolymerization of cell wall fractions into pectin, cellulose and hemicelluloses in the presence of hydrolytic enzymes such as pectin methyl esterase (PME), polygalacturonase (PG), pectate lyase (PL), cellulase (Cel) and β-galactosidase (β-Gal). OA dip treatment also assists in maintaining textural quality and lowering softening during storage (Fig. 2B). For instance, Razzaq et al. (2015) have reported that 5 mM OA dip treatment to 'Samar Bahisht Chaunsa' mangoes effectively delayed ripening and senescence by restricting climacteric ethylene production and respiration, maintaining higher firmness and lowered the activity of *exo*- polygalacturonase (*exo*-PG) thereby reducing softening during cold storage and ripening at ambient conditions. In addition to this, OA treated mangoes exhibited higher ascorbic acid content, phenolic concentrations, antioxidants and activities of superoxide dismutase (SOD), POD, and catalase (CAT) during the entire postharvest period. Previously, similar results have been reported that OA treatment significantly reduced the *exo*-PG activities in 'Damili' plum and 'Zill' mango during ripening period (Wu et al., 2011; Zheng et al., 2012a). The decline in cell wall disassembly and subsequent softening in OA treated fruit may be attributed to suppressed expression of respective genes as previously reported in mango cv. 'Zill' treated with 5 mM OA dip treatment for 10 min notably downregulated the *MiExpA1* expansin gene in peel and flesh of fruit, synergistically delayed ripening and decreased the activities of pectolytic enzymes (Zheng et al., 2012b). It is therefore important to extensively explore the potential of pre-storage exogenous OA treatment, which could be a possible strategy to delay softening in fleshy fruit and vegetables and extend storability for longer periods.

6.7. Pathological decay

Freshly harvested produce is highly perishable, due to excessive water content that makes them susceptible to microbial infection (bacteria, fungi or viruses), during extended storage conditions. OA application has been reported as a strong elicitor for inducing resistance against pathogenic diseases via up-regulating defence related metabolism in stored fruit and vegetables. The first report on induction of postharvest disease resistance in response to OA application was published by Tian et al. (2006), who reported that 1 mM OA dip treatment effectively reduced lesion diameter and disease incidence of *Alternaria* rot in pears cv. 'Yali' caused by *Alternaria alternata* (Fr.) Keissler, as compared to control. Additionally, OA enhanced the activities of PPO and POD enzymes, aiding in triggering defence systems and lead the pear fruit to incur lower postharvest decay after 7 days of shelf period. In another study, mango cv. 'Zill' treated with 5 mM OA significantly inhibited disease incidence caused by *Colletotrichum gloeosporioides* Penz. by 2.0-fold and maintained higher antioxidants during 35 days of cold storage, as compared to untreated control fruit. The disease reduction in OA treated mangoes might be attributed to increased activities of SOD, POD, CAT and ascorbate peroxidase (APX) enzymes, which vitally mitigate ROS induction as SOD transforms superoxide anions into H_2O_2 which subsequently removed by POD, CAT and APX thereby expressed strengthened defence metabolism during the postharvest period (Zheng et al., 2007a). Zheng et al. (2012a) have reported that 10 min dip treatment of oxalate salt 30 mM 'potassium oxalate' significantly reduced (1.5-fold) of disease index in mango cv. 'Xiaojinhuang' as compared to control fruit after 12 days of shelf period (Fig. 3 A). Additionally, the histological structure presented significant difference for inhibiting disease spread as earlier reported in 'Yindi' melons treated with 50 mM OA, under transmission electron micrographs (TEM) shows increased cell wall thickness as compared to control or challenge inoculation respectively (Deng et al., 2015) (Fig. 3B). The effects of OA application in reducing disease incidence in a variety of horticultural crops are summarised in Table 5. Furthermore, the preharvest spray application of 5 mM OA to kiwifruit cv. 'Bruno' trees 130 DAFB, repeated three times with 7-days intervals, effectively reduced postharvest disease incidence by 2.6-fold and inhibited *Penicillium expansum* Link. growth during storage and inoculation period (Zhu et al., 2016). The disease incidence has been reported to be efficiently reduced with OA preharvest spray application as compared to postharvest dip treatment (Table 5). OA pre-harvest application may thus induce systemic resistance in plants and provide a protective shield against the intrusion of pathogens (bacteria, fungi or viruses) in edible fruit and vegetables. Whilst the pre- and postharvest application of OA has exhibited significant results in a few crops for attenuating disease incidence and these findings warrant further investigation regarding its antimicrobial impact on a varied range of horticultural crops.

6.8. Nutritional quality

The consumption of fresh fruit and vegetables is reliant on nutritional quality attributes in addition to sensory characteristics, which needs to be maintained at different stages of the postharvest supply chain. The exogenous application of OA either as a pre- or postharvest treatment has been shown to actively prevent nutritional loss in addition to maintaining postharvest quality during storage. Pre- and postharvest OA treatment significantly preserve the sugar profile, acidity and sugar acid ratio, which indicates better eating quality in different fruit as previously reported in apricot, cherries, kiwifruit, pineapple, plum, strawberry, and mango (Ahmed et al., 2021; Ali et al., 2019; Batool et al., 2022; Ding et al., 2007; Giménez et al., 2017; Razzaq et al., 2015; Valero et al., 2011; Youryon et al., 2017). OA is a powerful antioxidant, and its exogenous application effectively enhances bioactive compounds and antioxidant capacity at harvest and during postharvest period. Martinez-Espla et al. (2014) have demonstrated that sweet cherries

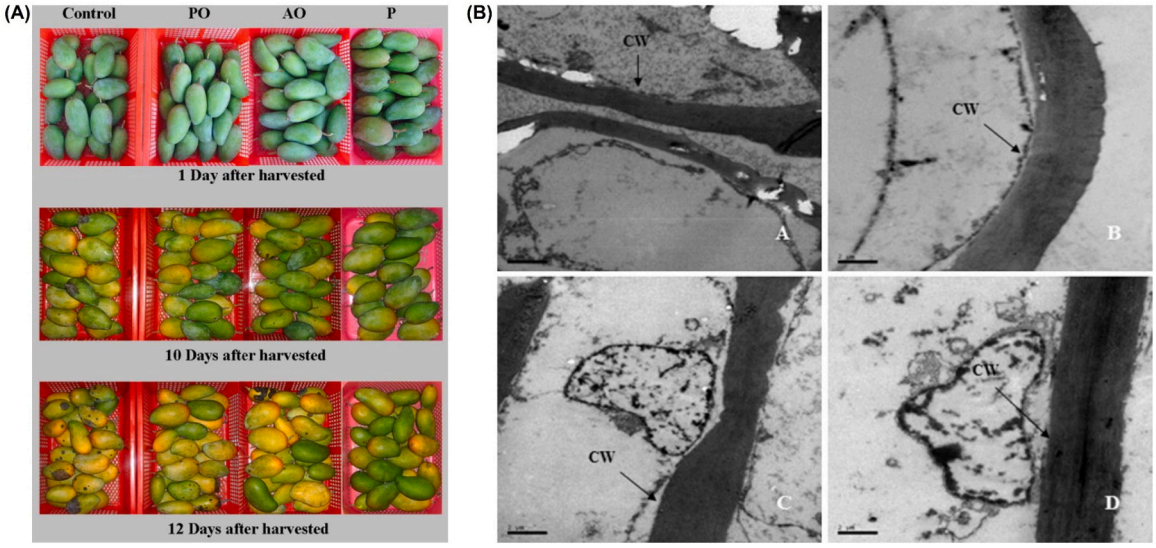


Fig. 3. (A) Postharvest dip treatment (30 mM) of potassium oxalate (PO) and ammonium oxalate (AO) on fruit quality of mango cv. Xiaojinhuangdi at ambient conditions (Zheng et al., 2012a). (B) The transmission electron micrographs (TEM) present the effects of OA treatment alone or following inoculation (b and d), on an increase in cell wall thickness as compared to control (a), and inoculated sample in the peel of 'Yindi' muskmelon fruit (Deng et al., 2015).

Table 5
Impact of oxalic acid application on disease spread in fruit and vegetables during postharvest period.

Pathogen (disease)	Crop	Cultivar	Concentration and treatment time	Reduction (fold)	Temperature and assessment period	Reference
Alternaria alternata (Fr.) Keissler	Pear	Yali	1 mM	1.3	25 °C, 7d	Tian et al. (2006)
Botrytis cinerea Pers. (gray mould)	Strawberry	Festival	10% (w/v) for 2 min	1.7	5 °C, 15d	Thabet (2019)
Colletotrichum gloeosporioides Penz.	Mango	Zill	5 mM for 10 min	2.0	14 ± 1 °C, 35d	Zheng et al. (2007a)
Mesophilic aerobics[a]	Artichoke	Blanca de Tudela	1 mM for 10 min	1.3	20 °C, 3d	Ruíz-Jiménez et al. (2014)
Rhizopus stolonifer Vuillemin (rhizopus rot)	Strawberry	Festival	10% (w/v) for 2 min	1.4	5 °C, 15d	Thabet (2019)
Penicillium expansum Link (blue mould)	Jujube	Dongzao	5 mM for 10 min	1.1	20 °C, 3d	Wang et al. (2009)
Penicillium expansum Link	Kiwifruit	Bruno	5 mM (preharvest spray)	2.6	20 °C, 30d	Zhu et al. (2016)
Trichothecium roseum (Pers.) Link (pink rot)	Muskmelon	Yindi	50 mM for 10 min	1.2[b]	22 °C, 7d	Deng et al. (2015)
Yeast and moulds[c]	Artichoke	Blanca de Tudela	1 mM for 10 min	1.2	20 °C, 3d	Ruíz-Jiménez et al. (2014)

[a] = bacterial count, [b] = based on change in lesion diameter, [c] = fungal count

sprayed with 2 mM OA strikingly improved total antioxidants in terms of hydrophilic and lipophilic total antioxidant activities, enhanced individual anthocyanins including cyanidin 3-glucoside, cyanidin 3-rutinoside, and pelargonidin 3-rutinoside, increased contents of individual flavonoids such as quercetin 3-rutinoside and kaempferol 3-rutinoside, as well as augmented chlorogenic acid derivatives, which substantially enriched harvested fruit quality (Table 2). The considerable effects of postharvest dip treatments in significantly increasing ascorbic acid, phenolic concentrations, glutathione content, total anthocyanins, and antioxidant capacity during the entire period of storage are summarised in Table 6. Valero et al. (2011) studied the effects of OA concentration on postharvest quality of sweet cherries in preliminary trials, the concentrations higher than 1 mM OA dipping for 10 min displayed non-significant results for delaying postharvest senescence. However, 1 mM treated sweet cherries cvs. 'Cristalina' and 'Prime Giant' showed higher levels total anthocyanins and total phenolics during cold storage. Furthermore, the banana fruit treated with 20 mM OA markedly enhanced activities of antioxidant enzymes such as SOD, PPO and POD enzymes, maintained higher antioxidants (DPPH scavenging activity) as compared to those treated with lower OA concentrations during postharvest period (Huang et al., 2013a; Huang et al., 2013b). The higher concentration in banana fruit found effective in maintaining quality attributes may be due to thick peel as compared to other crops. Recently, Wang et al. (2022) have reported that OA dip treatment mitigated CI in sweet pepper during low temperature storage by lowering oxidative stress, conserving higher ascorbic acid, proline content, and maintaining increased Δ^1-pyrroline-5-carboxylate synthetase and ornithine δ-aminotransferase activities, during 28 days of storage. Moreover, OA treatments up-regulated activities of antioxidant enzymes which helps in prolonging storability of fresh fruit and vegetables. OA dip treatment delays postharvest senescence and displayed higher activities of SOD, POD, CAT, APX and glutathione reductase (GR) enzymes in several stored fruit such as banana (Huang et al., 2013a; Huang et al., 2013b), hemi melons (Jing et al., 2018), jamun (*Syzygium cumini* L.) (Aslam et al., 2020), litchi (Ali et al., 2021), mango (Razzaq et al., 2015), peach (Zheng et al., 2007c) and persimmon (Li et al., 2018) (Table 6). Thus, OA application has been demonstrated to diminish the loss of bioactive and antioxidant compounds in addition to maintaining quality during the postharvest period.

6.9. Sensory attributes

Among several parameters of quality assessment, the evaluation of sensory attributes is important criteria for determining the efficacy of

Table 6
Influence of postharvest dipping application of oxalic acid on overall quality and antioxidant capacity of fruit and vegetables during the postharvest period.

Crop (cultivar)	Concentration	Quality inference	Antioxidant capacity	Reference
Apricot (Rival, Harcot, New Castener, Diaogan)	8 mM	↔ colur values, ↑ firmness, titratable acidity, SSC, ↓ pH, percent decay	↑ ascorbic acid, TPC, DPPH inhibition activity, ↓ carotenoids	Batool et al. (2022)
Apricot (Diaogan)	5 mM	↓ internal browning, El, sucrose, sorbitol, SPS, ↑ glucose, fructose, SS-synthesis, SS-cleavage, NI, AI activities	-[a]	Wang et al. (2016)
Artichoke (Blanca de Tudela)	1 mM	↓ decay, softening, chlorophyll degradation, ○ colour values	○ TPC, total antioxidants	Ruíz-Jiménez et al. (2014)
Asparagus (Grande, Vegalim, Purple Passion)	3 mM	↑ overall appearance, ↓ dehydration	○ ascorbic acid, TPC, total antioxidants, ↑ individual anthocyanins	Barberis et al. (2019)
Bamboo shoots (-[b])	10 mM	↓ respiration, disease incidence, ↑ firmness, lignin, cellulose content, sugar content	↑ TPC, ↓ PAL, POD, CAD, 4CL, PPO activities	Zheng et al. (2019)
Banana (Brazil)	20 mM	↑ chlorophyll fluorescence, clolour values	↑ TPC, POD, PPO activities	Huang et al. (2013b)
Banana (Brazil)	20 mM	↑ flesh firmness, colour values (hue value), ↓ ethylene production, respiration rate	↑ SOD activity	Huang et al. (2013a)
Banana (Williams)	20 mM	↑ colour values, chlorophyll content, ↓ fruit softening, cellulase, lipoxygenase, pectinase	↑ TPC, ↓ PAL, PPO activities	Lo'ay andDawood (2017)
Bell pepper (Jin 3)	5 mM	↓ water loss, CI, ↑ chlorophyll content	↑ ascorbic acid, APX, SOD, CAT, GR activities	Wang et al. (2022)
Cherries (Cristalina' and 'Prime Giant')	1 mM	↑ SSC, ↓ TA, firmness loss	↑ total anthocyanins, TPC, H- TAA, L- TAA, ↓ total carotenoids	Valero et al. (2011)
Guava (Maamoura)	6 mM	↓ water loss, percent decay, TA, ↑ visual quality, firmness, SSC: TA ratio	↑ ascorbic acid	Abd El-Gawad (2021)
Grapes (Alphonse Lavallée)	2 mM	↑ visual quality, berry detachment force, chlorophyll content↓ percent decay, rachis browning	↓ TPC	Sabir and Sabir (2017)
Hemi melons (Xizhoumi 25 hao)	15 mM	↓ CI	↑ glutathione content, ascorbic acid, APX, GR, POD activities, Cm-APX, Cm-GR, Cm-POD gene expression	Jing et al. (2018)
Jujube (Dongzao)	5 mM	↑ chlorophyll content, internal oxalic acid content, ACC oxidase activity, ↓ reddening index, DI, ethanol content, ethylene production, respiration rate	-[a]	Wang et al. (2009)
Jamun (-[b])	2 mM	↓ shrivelling, SSC, TA, SSC:TA ratio	↑ TPC, CAT, POD activities	Aslam et al. (2020)
Litchi (Hong Huay)	15%	↑ colour values, ↓ BI	↑ anthocyanins, POD activity, ↓ PPO activity	Saengnil et al. (2006)
(Gola)	2 mM	↓ BI, decay incidence, ↑ SSC, TA, sensory quality	↑ anthocyanins, ascorbic acid, TPC, APX, SOD, POD, CAT, GR activities	Ali et al. (2021)
Longan (Daw)	5%	↓ BI, disease incidence, ↑ sensory attributes	↓ PPO activity	Whangchai et al. (2006)
Loquat (Hafif Çukurgöbek)	6 mM	↑ colour values, firmness, BI, TA, ↓ SSC:TA ratio, fructose, sorbitol	↑ TPC, TFC, organic acids	Öz et al. (2016)
Lotus (-[b])	10 mM	↓ BI, bacterial count, ↑ visual quality	↓ PPO, POD activities, ↑ TPC, ascorbic acid, APX, CAT, SOD activities	Ali et al. (2020)
Mango (Samar Bahisht Chaunsa)	5 mM	↓ fruit softening, ethylene production, respiration rate, pectin esterase activity, SSC, SSC:TA ratio, ↑ TA	↑ ascorbic acid, total antioxidants, TPC, SOD, POD, CAT activities	Razzaq et al. (2015)
(Zill)	5 mM	↑ SSC, TA, ↓ CI	↑ ascorbic acid, ascorbate redox state, APX, SOD, POD, CAT activities	Ding et al. (2007)
(Zill)	5 mM	↓ ethylene, decay index, ↑ firmness, TA	-[a]	Zheng et al. (2007b)
Peach (Bayuecui)	5 mM	↓ respiration, EL, ↑ firmness	↓ LOX, PPO, ↑ APX, CAT, SOD, POD activities	Zheng et al. (2007c)
Persimmons (Youhou)	5 mM	↓ ethylene production, ↑ firmness, soluble pectin, juice yield	↑ PPO, POD activities	Li et al. (2018)
Plums (Damili)	5 mM	↓ ethylene production, fruit softening, chlorophyll fluorescence ratio, ↑ flesh reddening, firmness	↑ anthocyanins, ↓ PAL activity	Wu et al. (2011)
Pomegranate (Hicazna)	6 mM	↑ colour values, TA, glucose, fructose	↑ TPC, total antioxidants	Koyuncu et al. (2019)
Rambutan (Anak Sekolah)	10%	↑ colour values, firmness, ↓ SSC, ○ TA	-[a]	Hafiz et al. (2017)
Rocket and baby spinach (-[b])	1 mM	↑ visual quality, ↓ respiration, yellowing, ammonia, chlorophyll degradation, mesophilic aerobic count	↑ TPC, total antioxidants	Cefola and Pace (2015)

Abbreviations: ACC oxidase = 1-aminocyclopropane-1-carboxylic acid, AI = acid invertase, APX = ascorbate peroxidase, BI = browning index, 4CL = 4-coumarate CoA ligase, CAT = catalase, CAD = cinnamyl alcohol dehydrogenase, CI = chilling injury, DI = diseases incidence, DPPH = 2,2-diphenyl-1-picryl-hydrazyl-hydrate, EL = electrolyte leakage, GR = glutathione reductase, H-TAA - Hydrophilic total antioxidant activity, L-TAA = Lipophilic total antioxidant activity, LOX = lipoxygenase, NI = neutral invertase, PAL = phenylalanine ammonia-lyase, POD = peroxidase, PPO = polyphenol oxidase, SSC = soluble solids content, SSC:TA = soluble solids content and titratable acidity ratio, SPS = sucrose phosphate synthase, SOD = superoxide dismutase, TA = titratable acidity, TFC = total flavonoid content, TPC = total phenolic content, SS-synthase = sucrose synthase synthesis activity, SS-cleavage = sucrose synthase cleavage activity, ↑ = increased, ↓ = decreased, ↔ = maintained, ○ = non-significant, - [a] = not investigated, - [b] = not mentioned

postharvest treatments, as these attributes are closely allied with the physiochemical quality of fruit and vegetables. OA treatment has been shown to be effective in retaining cosmetic appearance without impairing colour change and internal quality. This statement is aligned with earlier findings in which postharvest dip treatments of OA expressed better visual quality in guava (*Psidium guajava* L.) (Abd El-Gawad., 2021), grapes (Sabir and Sabir, 2017), lotus (Ali et al., 2020), and rocket (*Diplotaxis tenuifolia L.*) and baby spinach leaves (Cefola and Pace, 2015). Furthermore, the application of 2 mM OA to apricot trees at fruit set stage notably improved taste of fruit as compared to untreated control (Ahmed et al., 2021). Similarly, 'Mollar de Elche' pomegranate trees sprayed with an aqueous solution containing 10 mM OA showed better hedonic score for visual quality attributes such as size, brightness, colour uniformity and intensity, and firmness, and significantly improved sweetness and sourness which presents greater score for overall liking of the fruit. This is probably due to increased SSC, glucose, and a sharp increase in antioxidant profile (ascorbic acid, maleic acid, total phenolics, anthocyanins) of pomegranate fruit (García-Pastor et al., 2020) (Table 2). In addition to this, postharvest OA dip treatment also influenced the sensory attributes during storage as previously reported in longan (Whangchai et al., 2006) and litchi (Ali et al., 2021) fruit (Table 6).

7. Crosstalk of OA application with other postharvest treatments

Although, the effects of OA are promising when applied individually, however the combination treatment has certainly pronounced the results in several studies. OA dip treatment combined with food grade coating/ chemical treatments expressed significant results for reducing storage constraints such as enzymatic browning and CI and aided in extending storage life. Lo'ay and Dawood (2017) have reported that OA (20 mM) blended with chitosan/polyvinyl alcohol coating material showed significant results in delaying peel browning in 'Williams' bananas during 10 days of shelf period by inhibiting the activities of PAL and PPO and retaining higher phenolic concentrations in treated fruit. Similarly, OA dip treatment (5 mM) with chitosan-based coating

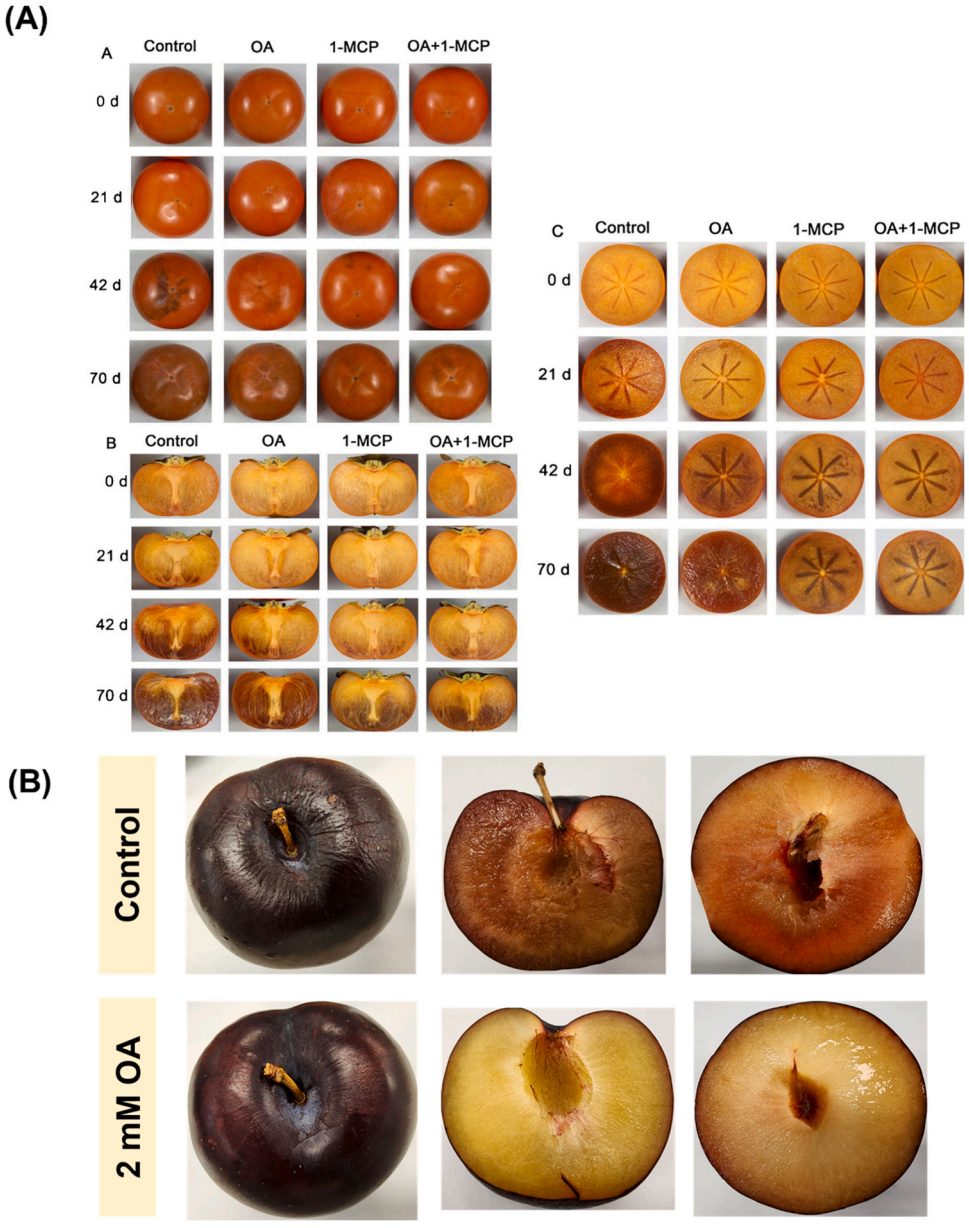


Fig. 4. OA dip treatment effects alone or in combination with other treatments on (A) chilling injury of 'Youhou' persimmons (Li et al., 2018). (B) Impact of postharvest 2 mM OA dip treatment on chilling injury in 'Black Amber' plums after 14 + 1 (cold + ambient) days of storage (unpublished data).

considerably attenuated browning in pomegranate cv. 'Rabbab-e--Neyriz' fruit by mitigating ROS induced oxidative stress, and reduced MDA and H_2O_2 contents during 120 days of cold storage (Ehteshami et al., 2019). In addition to that, combined application of OA and chitosan coating conserved higher anthocyanins, antioxidant activities, phenolic concentrations, and ascorbic acid levels in cold stored pomegranates (Ehteshami et al., 2020). In another study, OA (5 mM or 50 mM) blended in chitosan or carboxymethyl cellulose coatings were found effective in ameliorating CI in pomegranates and increased the unsaturated, and unsaturated/saturated fatty acids ratio during 120 days of cold storage following 3 days at ambient conditions (Ehteshami et al., 2019). Moreover, plums cv. 'Black Amber' treated with alginate edible coating blended with 1.0 mM OA exhibited reduced weight loss and delayed respiration during 40 days of cold storage (Bal, 2019). The pronounced effect of combined application can be evident from previous study of Li et al. (2018) who have reported that OA application in combination with 1-MCP treatment found more effective for lowering CI incidence in 'Youhou' persimmons stored at 1 °C, as compared to fruit treated with individual application of OA and 1-MCP respectively (Fig. 4A). Furthermore, the guavas cv. 'Maamoura' treated with 6 mM OA in combination with propolis extract (4%) coating exhibited higher texture quality, SSC, sugar acid ratio, and ascorbic acid during cold storage following shelf reconditioning (Abd El-Gawad., 2021). Likewise, the 'Valentia' oranges treated with combined application of sodium nitroprusside (SNP) (1 mM) and OA (10 mM) effectively reduced fruit decay, delayed the firmness loss, increased SSC, sugar acid ratio, maintained higher levels of ascorbic acid during 8 weeks of cold storage following one week of shelf period (Mohamed et al., 2016).

Besides OA combinations with postharvest chemical treatments, OA application with different non-chemical treatments have also been reported in various scientific reports. Hot water treatment (HWT) is usually employed as quarantine treatment for disinfestation of fruit fly and prerequisite for export of fruit and vegetables to international markets (Hasan et al., 2020). HWT also aids in reducing disease incidence during postharvest supply chain. Thabet (2019) reported that combined application of OA (10%) and short HWT (63 °C for 12 s) dipping markedly reduced spore germination and mycelial growth of *Botrytis cinerea* Pers. (gray mould) and *Rhizopus stolonifer* Vuillemin (rhizopus rot) thereby inhibited disease incidence in strawberries during 5 and 15 days of storage at 20 °C and 5 °C respectively. The combined application of HWT (55 °C for 12 min) and 10% OA dipping of 'Rose Scented' litchi fruit considerably retained pericarp colour, better eating quality, and high SSC and acidity during 10 days of cold storage (Marboh et al., 2012). Conversely, the combined application of 5 mM OA dipping in 0 °C ice-water mixture (designated as cold shock treatment) mitigated CI in 'Jin 3' green bell peppers during entire period of cold storage (Wang et al., 2022). It has also been reported in longan cv. 'Daw' for lowering pericarp browning subjected subsequent application of OA dipping treatment and ozone fumigation during cold storage. It also reduced disease incidence, delayed activity of PPO enzyme and expressed high score for sensory attributes in cold stored longans, as compared to control and individual OA treatment (Whangchai et al., 2006). Above all, OA dip treatment following storage in MAP bags and fruit stored under CA condition significantly extending storage periods with maintained quality (Ali et al., 2021; Hafiz et al., 2017; Koyuncu et al., 2019; Sabir and Sabir, 2017).

8. Role of OA in fruit and vegetables safety

Fruit and vegetables are abundantly consumed worldwide due to rich source of phytonutrients and to fulfill the dietary requirements. Though, several foodborne illnesses are closely associated with intake of fresh fruit and vegetables as they are carrying different contaminants including microbes and residues of pesticide sprays. Recent foodborne outbreaks have been reported due to *Salmonella, Escherichia coli,* and *Listeria monocytogenes* pathogens linked with fresh fruit and vegetables (Bhilwadikar et al., 2019). On the one hand, the contamination in fresh horticultural produce in production phase can happen through soil, irrigation water, contaminated seeds, inadequately composted manure, and pests (Bhilwadikar et al., 2019; Siddique and Malik, 2022). On the other hand, the fresh fruit and vegetables are also harbouring contaminants through improper harvest handling, unseemly storage conditions and unhygienic storage and supply chain facilities can result in higher incidence of microbes, which in turn triggers postharvest rot that renders a product unacceptable for market (Hasan et al., 2021). OA dip application has shown great potential in microbial and pesticidal decontamination of fresh fruit and vegetables. Previously, apples cv. 'Red Fuji' washed with oxalic acid solution exhibited significant reduction of microbial colonies, pesticidal residues, and heavy metals in cold stored fruit in addition to delayed senescence by lowering ethylene production, respiration, delaying acidity and soluble solids content, and maintaining higher antioxidant enzymes (Dong et al., 2009a; Dong et al., 2009b). Ruíz-Jiménez et al. (2014) have reported that artichoke dipped in 1 mM OA for 10 min reduced mesophilic aerobics and, yeast and moulds by 1.3- and 1.2-fold respectively during 3 days of shelf period. Likewise, oxalic acid dip treatment (7.5%) showed significant inhibition of microbial count in longan fruit cv. 'Long', delayed postharvest peel browning and expressed lower fruit decay during entire period of storage (Hai et al., 2014). Similarly, OA dip treatment substantially reduced total bacterial count and maintained overall quality in lotus root slices during five days of shelf period (Ali et al., 2020). Additionally, OA dip treatment has marked effects in decontamination of pesticides as previously revealed by Satpathy et al. (2012) who have claimed that washing with 0.1% OA solution showed considerable degradation (41–81%) of organophosphorus pesticide residues in different vegetables including okra, tomato, eggplant, cauliflower, capsicum, and beans. Accordingly, OA washing could be employed in fresh produce industry for delivering safe product to the consumers by avoiding cross-contamination in supply chain operations. Nevertheless, it warrants further research for optimizing its concentration and assessing the response of different commodities during postharvest period for commercial scale application.

9. Conclusions and prospects

This review presents a summary of numerous scientific reports about the novel organic acid 'oxalic acid', which ubiquitously occurs in plants and covers an intricate plethora of physiochemical processes and defence metabolism. The quantification of the OA compound has been reported in a wide range of edible fruit and vegetables, where it varies among plant species, cultivar, plant organ, growing conditions and location, and stage of harvest maturity. In recent years, the pre-and postharvest application of OA in fruit and vegetables has received significant attention from researchers due its role in enhancing crop yield, uniform colour development, increasing antioxidant capacity, and quality management during postharvest period. The preharvest application of OA at different stages, including days after full blossom, clearly elucidates its impact in improvement of fruit quality attributes including overall fruit size, juice yield and firmness, and delayed postharvest ripening by inhibiting ethylene production, respiration and restricting excessive water loss, as well as maintaining high antioxidant profiles during storage in different horticultural produce. Postharvest application of OA dip treatment shows impressive results in mitigating various postharvest constraints including loss of moisture and textural quality, CI, enzymatic browning, fruit softening and cell wall disassembly and decay incidence, as well as significantly reducing the loss of nutritional and sensory qualities during extended storage periods. Additionally, OA has been proven to induce systemic resistance against different pathogens and protect against postharvest storage rots. The application of OA delays postharvest ripening and extends storage life of fruit and vegetables, but an understanding of the mechanism underlying the exact mode of action is still at infancy stage, warrants future investigation at

the molecular level. Even though the concentration of OA for exogenous application is extremely low, further research is needed to unravel the change of endogenous OA content to negate health concerns. As OA is an organic food safe compound, it could be used as suitable alternative for postharvest quality management of horticultural crops.

CRediT authorship contribution statement

Mahmood Ul Hasan: Conceptualization, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Zora Singh:** Project administration, Resources, Supervision, Writing – review & editing. **Hafiz Muhammad Shoaib Shah:** Writing – review & editing, visualization **Jashanpreet Kaur:** Writing – review & editing. **Eben Afrifa-Yamoah:** Writing – review & editing, Supervision. **Andrew Woodward:** Writing – review & editing, Supervision. **Aman Ullah Malik:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Acknowledgments

The authors MU Hasan and HMS Shah are grateful to Edith Cowan University (ECU) Australia for providing higher degree by research (HDR) scholarship to pursue PhD in horticulture. The authors would like to thank Dr Michael Stein, ECU HDR Communication Adviser, for his support in language improvement of this review article.

References

Abd El-Gawad, M.G., 2021. Influence of propolis extract and oxalic acid on preserving quality of guava fruits during postharvest cold storage. Plant Arch. 21, 127–138. https://doi.org/10.51470/plantarchives.2021.v21.S1.024.

Ahmed, M., Ullah, S., Razzaq, K., Rajwana, I.A., Akhtar, G., Nazb, A., Aminc, M., Khalidd, M.S., Khalidd, S., 2021. Pre-harvest oxalic acid application improves fruit size at harvest, physico-chemical and sensory attributes of 'Red Flesh' apricot during fruit ripening. J. Hortic. Sci. Technol. https://doi.org/10.46653/jhst2142048.

Ali, M., LIU, M.-M., Wang, Z.E., Li, S.E., Jiang, T.J., Zheng, X.L., 2019. Pre-harvest spraying of oxalic acid improves postharvest quality associated with increase in ascorbic acid and regulation of ethanol fermentation in kiwifruit cv. Bruno during storage. J. Integ. Agric. 18, 2514–2520. https://doi.org/10.1016/S2095-3119(19)62791-7.

Ali, S., Khan, A.S., Anjum, M.A., Nawaz, A., Naz, S., Ejaz, S., Hussain, S., 2020. Effect of postharvest oxalic acid application on enzymatic browning and quality of lotus (*Nelumbo nucifera* Gaertn.) root slices. Food Chem. 312, 126051 https://doi.org/10.1016/j.foodchem.2019.126051.

Ali, S., Khan, A.S., Malik, A.U., Anwar, R., Anjum, M.A., Nawaz, A., Shafique, M., Naz, S., 2021. Combined application of ascorbic and oxalic acids delays postharvest browning of litchi fruits under controlled atmosphere conditions. Food Chem. 350, 129277 https://doi.org/10.1016/j.foodchem.2021.129277.

Aloni, B., Karni, L., Rylski, I., Zaidman, Z., 1994. The effect of nitrogen fertilization and shading on the incidence of "colour spots" in sweet pepper (*Capsicum annuum*) fruit. J. Hortic. Sci. 69, 767–773. https://doi.org/10.1080/14620316.1994.11516511.

Anwar, R., Gull, S., Nafees, M., Amin, M., Hussain, Z., Khan, A., Malik, A., 2018. Pre-harvest foliar application of oxalic acid improves strawberry plant growth and fruit quality. J. Hortic. Sci. Technol. 1, 35–41. https://doi.org/10.46653/jhst180101035.

Arif, A.B., Susanto, S., Widayanti, S.M., Matra, D.D., 2023. Pre-storage oxalic acid treatment inhibits postharvest browning symptoms and maintains quality of abiu (*Pouteria caimito*) fruit. Sci. Hortic. 311, 111795 https://doi.org/10.1016/j.scienta.2022.111795.

Aslam, M.M., Ullah, S., Razzaq, K., Rajwana, I.A., Akhtar, G., Nazar, H., Faried, M.A., Ullah, U.N., Khalil, U., 2020. Orchard locality and postharvest oxalic acid application influence fruit quality and shelf life of Jamun (*Syzygium cumini* L.) fruit. J. Pure Appl. Agric. 5, 34–41.

Attalla, K., De, S., Monga, M., 2014. Oxalate content of food: a tangled web. Urology 84, 555–560. https://doi.org/10.1016/j.urology.2014.03.053.

Awad, M.A., Al-Qurashi, A.D., Elsayed, M.I., 2013. Effect of pre-storage salicylic acid and oxalic acid dipping on chilling injury and quality of 'Taify' pomegranates during cold storage. J. Food Agric. Environ. 11, 117–122.

Azzu, Y.M., 2016. Modulation of fruit ripening, storage time and quality of fruits with emulsion of chitosan alone and loaded with salicylic acid or oxalic acid. Doctoral dissertation, Curtin University.

Bae, H., Yun, S.K., Yoon, I.K., Nam, E.Y., Kwon, J.H., Jun, J.H., 2014. Assessment of organic acid and sugar composition in apricot, plumcot, plum, and peach during fruit development. J. Appl. Bot. Food Qual. 87 https://doi.org/10.5073/JABFQ.2014.087.004.

Bal, E., 2019. Effects of alginate edible coating enriched with salicylic and oxalic acid on preserving plum fruit (*Prunus salicina* L. cv.'Black amber') quality during post-harvest storage. Acta Sci. Pol. -Hortoru 18, 35–46. https://doi.org/10.24326/asphc.2019.4.4.

Barberis, A., Cefola, M., Pace, B., Azara, E., Spissu, Y., Serra, P.A., Logrieco, A.F., D'hallewin, G., Fadda, A., 2019. Postharvest application of oxalic acid to preserve overall appearance and nutritional quality of fresh-cut green and purple asparagus during cold storage: A combined electrochemical and mass-spectrometry analysis approach. Postharvest Biol. Technol. 148, 158–167. https://doi.org/10.1016/j.postharvbio.2018.10.016.

Batool, M., Bashir, O., Amin, T., Wani, S.M., Masoodi, F., Jan, N., Bhat, S.A., Gul, A., 2022. Effect of oxalic acid and salicylic acid treatments on the post-harvest life of temperate grown apricot varieties (*Prunus armeniaca*) during controlled atmosphere storage. Food Sci. Technol. Inter. 28, 557–569. https://doi.org/10.1177/108201322110320.

Bhandari, M.R., Kawabata, J., 2004. Organic acid, phenolic content and antioxidant activity of wild yam (*Dioscorea* spp.) tubers of Nepal. Food Chem. 88, 163–168. https://doi.org/10.1016/j.foodchem.2003.12.027.

Bhilwadikar, T., Pounraj, S., Manivannan, S., Rastogi, N., Negi, P., 2019. Decontamination of microorganisms and pesticides from fresh fruits and vegetables: A comprehensive review from common household processes to modern techniques. Compr. Rev. Food Sci. Food Saf. 18, 1003–1038. https://doi.org/10.1111/1541-4337.12453.

Çalişkan, M., 2000. The metabolism of oxalic acid. Turk. J. Zool. 24, 103–106.

Cefola, M., Pace, B., 2015. Application of oxalic acid to preserve the overall quality of rocket and baby spinach leaves during storage. J. Food Process. Preser. 39, 2523–2532. https://doi.org/10.1111/jfpp.12502.

Davies, D.D., Asker, H., 1983. Synthesis of oxalic acid by enzymes from lettuce leaves. Plant Physiol. 72, 134–138. https://doi.org/10.1104/pp.72.1.134.

Deng, J., Bi, Y., Zhang, Z., Xie, D., Ge, Y., Li, W., Wang, J., Wang, Y., 2015. Postharvest oxalic acid treatment induces resistance against pink rot by priming in muskmelon (*Cucumis melo* L.) fruit. Postharvest Biol. Technol. 106, 53–61. https://doi.org/10.1016/j.postharvbio.2015.04.005.

Dias, C., Ribeiro, T., Rodrigues, A.C., Ferrante, A., Vasconcelos, M.W., Pintado, M., 2021. Improving the ripening process after 1-MCP application: Implications and strategies. Trends Food Sci. Technol. 113, 382–396. https://doi.org/10.1016/j.tifs.2021.05.012.

Ding, Z.S., Tian, S.P., Zheng, X.L., Zhou, Z.W., Xu, Y., 2007. Responses of reactive oxygen metabolism and quality in mango fruit to exogenous oxalic acid or salicylic acid under chilling temperature stress. Physiol. Plant. 130, 112–121. https://doi.org/10.1111/j.1399-3054.2007.00893.x.

Dong, X.Q., Rao, J.P., Tian, G.N., Zhang, J.Y., Liao, X.Y., 2009a. Effects of oxalic acid compound cleaning agent on storage quality of fruits of apple 'Red Fuji'. Acta Hortic. Sin. 36, 577–582.

Dong, X.Q., Rao, J.P., Tian, G.N., Zhang, J.Y., Zhang, X.R., 2009b. Effects of oxalic acid compound cleaning agent on washing efficiency and post-harvest physiology of apples. Acta Bot. Boreal. -Occid. Sin. 29, 1643–1648.

Ehteshami, S., Abdollahi, F., Ramezanian, A., Dastjerdi, A.M., Rahimzadeh, M., 2019. Enhanced chilling tolerance of pomegranate fruit by edible coatings combined with malic and oxalic acid treatments. Sci. Hortic. 250, 388–398. https://doi.org/10.1016/j.scienta.2019.02.075.

Ehteshami, S., Abdollahi, F., Ramezanian, A., Mirzaalian Dastjerdi, A., 2020. Maintenance of quality and bioactive compounds in pomegranate fruit (*Punica granatum* L.) by combined application of organic acids and chitosan edible coating. J. Food Biochem. 44, e13393 https://doi.org/10.1111/jfbc.13393.

El-Zaeddi, H., Calín-Sánchez, Á., Nowicka, P., Martínez-Tomé, J., Noguera-Artiaga, L., Burló, F., Wojdyło, A., Carbonell-Barrachina, Á.A., 2017. Preharvest treatments with malic, oxalic, and acetylsalicylic acids affect the phenolic composition and antioxidant capacity of coriander, dill and parsley. Food Chem. 226, 179–186. https://doi.org/10.1016/j.foodchem.2017.01.067.

Erbaş, D., 2023. Effect of oxalic acid treatments and modified atmosphere packaging on the quality attributes of rocket leaves during different storage temperatures. Horticulturae 9, 718. https://doi.org/10.3390/horticulturae9060718.

Ergönül, P.G., Nergiz, C., 2010. Determination of organic acids in olive fruit by HPLC. Czech J. Food Sci. 28, 202–205. https://doi.org/10.17221/1379-CJFS.

Foster, J., Luo, B., Nakata, P.A., 2016. An oxalyl-CoA dependent pathway of oxalate catabolism plays a role in regulating calcium oxalate crystal accumulation and defending against oxalate-secreting phytopathogens in *Medicago truncatula*. PLoS One 11, e0149850. https://doi.org/10.1371/journal.pone.0149850.

Franceschi, V.R., Horner, H.T., 1980. Calcium oxalate crystals in plants. Bot. Rev. 46, 361–427. https://doi.org/10.1007/BF02860532.

Franceschi, V.R., Loewus, F.A., 1995. Oxalate biosynthesis and function in plants and fungi. In: Khan, S. (Ed.), Calcium oxalate in biological systems. CRC press, Boca Raton, pp. 113–130. https://doi.org/10.1201/9781003068747.

García-Pastor, M.E., Giménez, M.J., Serna-Escolano, V., Guillén, F., Valero, D., Serrano, M., García-Martínez, S., Terry, L.A., Alamar, M.C., Zapata, P.J., 2021.

Oxalic acid preharvest treatment improves colour and quality of seedless table grape 'Magenta' upregulating on-vine abscisic acid metabolism, relative *VVNCED1* gene expression, and the antioxidant system in berries. Front. Plant Sci. 12 https://doi.org/10.3389/fpls.2021.740240.

García-Pastor, M.E., Giménez, M.J., Valverde, J.M., Guillén, F., Castillo, S., Martínez-Romero, D., Serrano, M., Valero, D., Zapata, P.J., 2020. Preharvest application of oxalic acid improved pomegranate fruit yield, quality, and bioactive compounds at harvest in a concentration-dependent manner. Agronomy 10, 1522. https://doi.org/10.3390/agronomy10101522.

Giménez, M., Martínez-Esplá, A., Castillo-Gironés, S., Valverde, J., Martínez-Romero, D., Castillo, S., 2017. Effect of preharvest application of methyl salicylate, oxalic acid and methyl jasmonate on yield and quality of 'Sweet Heart' cherries. Acta Hortic. 1256, 501–504. https://doi.org/10.17660/ActaHortic.2019.1256.71.

Hafiz, A.F.A., Keat, Y.W., Ali, A., 2017. Effect of integration of oxalic acid and hot water treatments on postharvest quality of rambutan (*Nephelium lappaceum* L. cv. Anak Sekolah) under modified atmosphere packaging. J. Food Sci. Technol. 54, 2181–2185. https://doi.org/10.1007/s13197-017-2645-1.

Hai, L., Joomwong, A., Chanbang, Y., Uthaibutra, J., 2014. Effects of oxalic acid dipping and wax coating on pericarp browning and storage life of fresh Vietnamese longan fruit cv. long. Int. J. Agric. Innov. Res. 3, 670–677.

Hasan, M.U., Malik, A.U., Khan, A.S., Anwar, R., Latif, M., Amjad, A., Shah, M.S., Amin, M., 2020. Impact of postharvest hot water treatment on two commercial mango cultivars of Pakistan under simulated air freight conditions for China. Pak. J. Agric. Sci. 57, 1381–1391. https://doi.org/10.21162/PAKJAS/20.9930.

Hasan, M.U., Riaz, R., Malik, A.U., Khan, A.S., Anwar, R., Rehman, R.N.U., Ali, S., 2021. Potential of *Aloe vera* gel coating for storage life extension and quality conservation of fruits and vegetables: An overview. J. Food Biochem. 45, e13640 https://doi.org/10.1111/jfbc.13640.

He, J., Deng, J., Zheng, Y., Gu, J., 2006. A synergistic effect on the production of S-adenosyl-l-methionine in *Pichia pastoris* by knocking in of S-adenosyl-l-methionine synthase and knocking out of cystathionine-β synthase. J. Biotechnol. 126, 519–527. https://doi.org/10.1016/j.jbiotec.2006.05.009.

Huang, H., Jing, G., Guo, L., Zhang, D., Yang, B., Duan, X., Ashraf, M., Jiang, Y., 2013a. Effect of oxalic acid on ripening attributes of banana fruit during storage. Postharvest Biol. Technol. 84, 22–27. https://doi.org/10.1016/j.postharvbio.2013.04.002.

Huang, H., Zhu, Q., Zhang, Z., Yang, B., Duan, X., Jiang, Y., 2013b. Effect of oxalic acid on antibrowning of banana (*Musa* spp., AAA group, cv. 'Brazil') fruit during storage. Sci. Hortic. 160, 208–212. https://doi.org/10.1016/j.scienta.2013.05.041.

Jin, P., Zhu, H., Wang, L., Shan, T., Zheng, Y., 2014. Oxalic acid alleviates chilling injury in peach fruit by regulating energy metabolism and fatty acid contents. Food Chem. 161, 87–93. https://doi.org/10.1016/j.foodchem.2014.03.103.

Jing, W., Mao, L.C., Li, X.W., Lv, Z., Liu, C.H., Huang, Y.Y., Li, D.D., 2018. Oxalic acid pretreatment reduces chilling injury in Hami melons (*Cucumis melo* var. reticulatus Naud.) by regulating enzymes involved in antioxidative pathways. Sci. Hortic. 241, 201–208. https://doi.org/10.1016/j.scienta.2018.06.084.

Kant, K., Arora, A., Singh, V., Kumar, R., 2013. Effect of exogenous application of salicylic acid and oxalic acid on post harvest shelf-life of tomato (*Solanum lycopersicon* L.). Indian J. Plant Physiol. 18, 15–21. https://doi.org/10.1007/s40502-013-0004-4.

Koyuncu, M.A., Erbas, D., Onursal, C.E., Secmen, T., Guneyli, A., Sevinc Uzumcu, S., 2019. Postharvest treatments of salicylic acid, oxalic acid and putrescine influences bioactive compounds and quality of pomegranate during controlled atmosphere storage. J. Food Sci. Technol. 56, 350–359. https://doi.org/10.1007/s13197-018-3495-1.

Koyuncu, M.A., Secmen, T., Onursal, C.E., Erbas, D., Guneylı, A., Uzumcu, S.S., Koyuncu, F., 2018. Effect of postharvest oxalic acid treatment on cold storage of apricot cv. 'Aprikoz'. Sci. Pap. -Ser. B, Hortic. 147–152.

Li, J., Han, Y., Hu, M., Jin, M., Rao, J., 2018. Oxalic acid and 1-methylcyclopropene alleviate chilling injury of 'Youhou' sweet persimmon during cold storage. Postharvest Biol. Technol. 137, 134–141. https://doi.org/10.1016/j.postharvbio.2017.11.021.

Li, P., Liu, C., Luo, Y., Shi, H., Li, Q., PinChu, C., Li, X., Yang, J., Fan, W., 2022. Oxalate in plants: metabolism, function, regulation, and application. J. Agric. Food Chem. 70, 16037–16049. https://doi.org/10.1021/acs.jafc.2c04787.

Li, P., Yin, F., Song, L., Zheng, X.L., 2016. Alleviation of chilling injury in tomato fruit by exogenous application of oxalic acid. Food Chem. 202, 125–132. https://doi.org/10.1016/j.foodchem.2016.01.142.

Li, P., Zheng, X.L., Chowdhury, M.G.F., Cordasco, K., Brecht, J.K., 2015. Prestorage application of oxalic acid to alleviate chilling injury in mango fruit. HortSci 50, 1795–1800. https://doi.org/10.21273/HORTSCI.50.12.1795.

Li, P., Zheng, X.L., Liu, Y., Zhu, Y., 2014. Pre-storage application of oxalic acid alleviates chilling injury in mango fruit by modulating proline metabolism and energy status under chilling stress. Food Chem. 142, 72–78. https://doi.org/10.1016/j.foodchem.2013.06.132.

Libert, B., Franceschi, V.R., 1987. Oxalate in crop plants. J. Agric. Food Chem. 35, 926–938. https://doi.org/10.1021/jf00078a019.

Lo'ay, A., Dawood, H., 2017. Minimize browning incidence of banana by postharvest active chitosan/PVA combines with oxalic acid treatment to during shelf-life. Sci. Hortic. 226, 208–215. https://doi.org/10.1016/j.scienta.2017.08.046.

Madebo, M.P., Ayalew, Y., Zheng, Y., Jin, P., 2022. Nitric oxide and its donor sodium-nitroprusside regulation of the postharvest quality and oxidative stress on fruits: A systematic review and meta-analysis. Food Rev. Int. 29, 1–29. https://doi.org/10.1080/87559129.2022.2122995.

Manjunatha, G., Lokesh, V., Neelwarne, B., Singh, Z., Gupta, K.J., 2014. Nitric oxide applications for quality enhancement of horticulture produce. In: Janick, J. (Ed.), Hortic. Rev. Wiley Online Library, New Jersey, United States of America, pp. 121–156. https://doi.org/10.1002/9781118916827.ch02.

Marboh, E., Lal, R., Mishra, D., Goswami, A., 2012. Effect of hot water treatment and oxalic acid on colour retention and storage quality of litchi fruit cv. Rose Scented. Indian J. Hortic. 69, 484–488.

Maringgal, B., Hashim, N., Tawakkal, I.S.M.A., Mohamed, M.T.M., 2020. Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality. Trends Food Sci. Technol. 96, 253–267. https://doi.org/10.1016/j.tifs.2019.12.024.

Martínez-Esplá, A., García-Pastor, M.E., Zapata, P.J., Guillén, F., Serrano, M., Valero, D., Gironés-Vilaplana, A., 2017. Preharvest application of oxalic acid improves quality and phytochemical content of artichoke (*Cynara scolymus* L.) at harvest and during storage. Food Chem. 230, 343–349. https://doi.org/10.1016/j.foodchem.2017.03.051.

Martinez-Espla, A., Zapata, P.J., Valero, D., Garcia-Viguera, C., Castillo, S., Serrano, M., 2014. Preharvest application of oxalic acid increased fruit size, bioactive compounds, and antioxidant capacity in sweet cherry cultivars (*Prunus avium* L.). J. Agric. Food Chem. 62, 3432–3437. https://doi.org/10.1021/jf500224g.

Martínez-Esplá, A., Serrano, M., Martínez-Romero, D., Valero, D., Zapata, P.J., 2019. Oxalic acid preharvest treatment increases antioxidant systems and improves plum quality at harvest and during postharvest storage. J. Sci. Food Agric. 99, 235–243. https://doi.org/10.1002/jsfa.9165.

Maryam, A., Anwar, R., Malik, A.U., Raheem, M.I.U., Khan, A.S., Hasan, M.U., Hussain, Z., Siddique, Z., 2021. Combined aqueous ozone and ultrasound application inhibits microbial spoilage, reduces pesticide residues and maintains storage quality of strawberry fruits. J. Food Meas. Charac. 15, 1437–1451. https://doi.org/10.1007/s11694-020-00735-3.

Melino, V.J., Soole, K.L., Ford, C.M., 2009. Ascorbate metabolism and the developmental demand for tartaric and oxalic acids in ripening grape berries. BMC Plant Biol. 9 (1), 14. https://doi.org/10.1186/1471-2229-9-145.

Mohamed, M., Abd El-khalek, A., Elmehrat, H., Mahmoud, G.A., 2016. Nitric oxide, oxalic acid and hydrogen peroxide treatments to reduce decay and maintain postharvest quality of 'Valencia' orange fruits during cold storage. Egypt. J. Hortic. 43, 137–161. https://doi.org/10.21608/ejoh.2016.2833.

Munir, E., Yoon, J.J., Tokimatsu, T., Hattori, T., Shimada, M., 2001. A physiological role for oxalic acid biosynthesis in the wood-rotting basidiomycete *Fomitopsis palustris*. Proc. Nat. Acad. Sci. 98, 11126–11130. https://doi.org/10.1073/pnas.191389598.

Nguyễn, H.V.H., Savage, G., 2013a. Oxalate content of New Zealand grown and imported fruits. J. Food Compos. Anal. 31, 180–184. https://doi.org/10.1016/j.jfca.2013.06.001.

Nguyễn, H.V.H., Savage, G.P., 2013b. Total, soluble and insoluble oxalate contents of ripe green and golden kiwifruit. Foods 2, 76–82. https://doi.org/10.3390/foods2010076.

Nisperos-Carriedo, M.O., Buslig, B.S., Shaw, P.E., 1992. Simultaneous detection of dehydroascorbic, ascorbic, and some organic acids in fruits and vegetables by HPLC. J. Agric. Food Chem. 40, 1127–1130. https://doi.org/10.1021/jf00019a007.

Öz, A.T., Kafkas, N.E., Bozdoğan, A., 2016. Combined effects of oxalic acid treatment and modified atmosphere packaging on postharvest quality of loquats during storage. Turk. J. Agric. For. 40, 433–440. https://doi.org/10.3906/tar-1509-12.

Özkaya, O., Şener, A., Saridaş, M.A., Ünal, Ü., Valizadeh, A., Dündar, Ö., 2015. Influence of fast cold chain and modified atmosphere packaging storage on postharvest quality of early season-harvested sweet cherries. J. Food Process. Preser. 39, 2119–2128. https://doi.org/10.1111/jfpp.12455.

Ozturk, A., Yildiz, K., Ozturk, B., Karakaya, O., Gun, S., Uzun, S., Gundogdu, M., 2019. Maintaining postharvest quality of medlar (*Mespilus germanica*) fruit using modified atmosphere packaging and methyl jasmonate. LWT-Food Sci. Technol. 111, 117–124. https://doi.org/10.1016/j.lwt.2019.05.033.

Palma, A., Muntoni, M., D'Aquino, S., 2023. Influence of modified atmosphere packaging on post-harvest physiology, overall quality, and bioactive compounds during cold storage and shelf-life of 'Tondo Nero' figs (*Ficus carica* L.). Food Packag. Shelf Life 35, 101030. https://doi.org/10.1016/j.fpsl.2023.101030.

Pereira, C., Barros, L., Carvalho, A.M., Ferreira, I.C., 2013. Use of UFLC-PDA for the analysis of organic acids in thirty-five species of food and medicinal plants. Food Anal. Methods 6, 1337–1344. https://doi.org/10.1007/s12161-012-9548-6.

Pinela, J., Barreira, J.C., Barros, L., Antonio, A.L., Carvalho, A.M., Oliveira, M.B.P., Ferreira, I.C., 2016. Postharvest quality changes in fresh-cut watercress stored under conventional and inert gas-enriched modified atmosphere packaging. Postharvest Biol. Technol. 112, 55–63. https://doi.org/10.1016/j.postharvbio.2015.10.004.

Porat, R., Lichter, A., Terry, L.A., Harker, R., Buzby, J., 2018. Postharvest losses of fruit and vegetables during retail and in consumers' homes: Quantifications, causes, and means of prevention. Postharvest Biol. Technol. 139, 135–149. https://doi.org/10.1016/j.postharvbio.2017.11.019.

Poyrazoğlu, E., Gökmen, V., Artık, N., 2002. Organic acids and phenolic compounds in pomegranates (*Punica granatum* L.) grown in Turkey. J. Food Compos. Anal. 15, 567–575. https://doi.org/10.1006/jfca.2002.1071.

Prasad, R., Shivay, Y.S., 2017. Oxalic acid/oxalates in plants: from self-defence to phytoremediation. Cur. Sci. 112, 1665–1667.

Razavi, F., Hajilou, J., 2016. Enhancement of postharvest nutritional quality and antioxidant capacity of peach fruits by preharvest oxalic acid treatment. Sci. Hortic. 200, 95–101. https://doi.org/10.1016/j.scienta.2016.01.011.

Razzaq, K., Khan, A.S., Malik, A.U., Shahid, M., Ullah, S., 2015. Effect of oxalic acid application on Samar Bahisht Chaunsa mango during ripening and postharvest. LWT-Food Sci. Technol. 63, 152–160. https://doi.org/10.1016/j.lwt.2015.03.069.

Retamal-Salgado, J., Adaos, G., Cedeño-García, G., Ospino-Olivella, S.C., Vergara-Retamales, R., Lopéz, M.D., Olivares, R., Hirzel, J., Olivares-Soto, H., Betancur, M., 2023. Preharvest applications of oxalic acid and salicylic acid increase fruit firmness

and polyphenolic content in blueberry (*Vaccinium corymbosum* L.). Horticulturae 9, 639. https://doi.org/10.3390/horticulturae9060639.
Ruíz-Jiménez, J.M., Zapata, P.J., Serrano, M., Valero, D., Martínez-Romero, D., Castillo, S., Guillén, F., 2014. Effect of oxalic acid on quality attributes of artichokes stored at ambient temperature. Postharvest Biol. Technol. 95, 60–63. https://doi.org/10.1016/j.postharvbio.2014.03.015.
Sabir, F.K., Sabir, A., 2017. Postharvest quality maintenance of table grapes cv.'Alphonse Lavallée' by exogenous applications of salicylic acid, oxalic acid and MAP. Erwerbs-Obstbau 59, 211–219. https://doi.org/10.1007/s10341-016-0314-6.
Saengnil, K., Lueangprasert, K., Uthaibutra, J., 2006. Control of enzymatic browning of harvested 'Hong Huay' litchi fruit with hot water and oxalic acid dips. Sci. Asia 32, 345–350. https://doi.org/10.2306/scienceasia1513-1874.2006.32.345.
Satpathy, G., Tyagi, Y.K., Gupta, R.K., 2012. Removal of organophosphorus (OP) pesticide residues from vegetables using washing solutions and boiling. J. Agric. Sci. 4, 69–78. https://doi.org/10.5539/jas.v4n2p69.
Sayyari, M., Valero, D., Babalar, M., Kalantari, S., Zapata, P.J., Serrano, M., 2010. Prestorage oxalic acid treatment maintained visual quality, bioactive compounds, and antioxidant potential of pomegranate after long-term storage at 2C. J. Agric. Food Chem. 58, 6804–6808. https://doi.org/10.1021/jf100196h.
Serna-Escolano, V., Giménez, M.J., Castillo, S., Valverde, J.M., Martínez-Romero, D., Guillén, F., Serrano, M., Valero, D., Zapata, P.J., 2021. Preharvest treatment with oxalic acid improves postharvest storage of lemon fruit by stimulation of the antioxidant system and phenolic content. Antioxidants 10, 963. https://doi.org/10.3390/antiox10060963.
Shah, H.M.S., Singh, Z., Afrifa-Yamoah, E., Hasan, M.U., Kaur, J., Woodward, A., 2023. Insight into the role of melatonin in mitigating chilling injury and maintaining the quality of cold-stored fruits and vegetables. Food Rev. Int. 1–27. https://doi.org/10.1080/87559129.2023.2212042.
Shimokawa, K., Ueda, Y., Kasai, Z., 1972. Decarboxylation of oxalic acid during ripening of banana fruit (*Musa sapientum* L.). Agric. Biol. Chem. 36, 2021–2024. https://doi.org/10.1080/00021369.1972.10860513.
Siddique, Z., Malik, A.U., 2022. Fruits and vegetables are the major source of food safety issues need to overcome at household level (traditional vs. green technologies): A comparative review. e13003 J. Food Saf. 42. https://doi.org/10.1111/jfs.13003.
Singh, Z., 2022. Interventions to minimise postharvest losses, ensure the quality and safety of tropical and subtropical fruits: an overview. Acta Hortic. (1340), 1–12. https://doi.org/10.17660/ActaHortic.2022.1340.1.
Thabet, M., 2019. Application of chitosan and oxalic acid combined with hot water to control postharvest decay of strawberry fruits caused by *Botrytis cinerea* and *Rhizopus stolonifer*. Middle East J. Appl. Sci. 9, 63–77.
Tian, S.P., Li, B.Q., Shi, X., Qin, G., Wang, Y., 2013. Postharvest disease control of mango fruit and the regulating mechanisms. Acta Hortic. (992), 493–498. https://doi.org/10.17660/ActaHortic.2013.992.60.
Tian, S.P., Wan, Y., Qin, G., Xu, Y., 2006. Induction of defense responses against *Alternaria rot* by different elicitors in harvested pear fruit. Appl. Microbiol. Biotechnol. 70, 729–734. https://doi.org/10.1007/s00253-005-0125-4.
Tong, C.B.S., Hicks, K.B., Osman, S.F., Hotchkiss Jr, A.T., Haines, R.M., 1995. Oxalic acid in commercial pectins inhibits browning of raw apple juice. J. Agric. Food Chem. 43, 592–597. https://doi.org/10.1021/jf00051a008.
UNO, 2019. World population prospects 2019 highlights. Department of Economic and Social Affairs, Population Division.
USDA, 2021. Information on the upcoming amendment to the varroacide, oxalic acid (API-Bioxal™). Agricultural Research Service, USDA.
Üzümcü, S.S., Koyuncu, M.A., Onursal, C.E., Güneylİ, A., Erbaş, D., 2020. Effect of pre-Harvest oxalic acid treatment on shelf-life of apricot cv. 'Roxana. Nev. B. Teknol. Der. 9, 73–80. https://doi.org/10.17100/nevbiltek.561704.
Valero, D., Diaz-Mula, H.M., Zapata, P.J., Castillo, S., Guillen, F., Martinez-Romero, D., Serrano, M., 2011. Postharvest treatments with salicylic acid, acetylsalicylic acid or oxalic acid delayed ripening and enhanced bioactive compounds and antioxidant capacity in sweet cherry. J. Agric. Food Chem. 59, 5483–5489. https://doi.org/10.1021/jf200873j.
Wagner, G.J., 1981. Vacuolar deposition of ascorbate-derived oxalic acid in barley. Plant Physiol. 67, 591–593. https://doi.org/10.1104/pp.67.3.591.
Walker, R.P., Famiani, F., 2018. Organic acids in fruits: metabolism, functions and contents. Hortic. Rev. 45, 371–430. https://doi.org/10.1002/9781119431077.ch8.
Wang, F., Yang, Q., Zhao, Q., Li, X., 2022. Cold shock treatment with oxalic acid could alleviate chilling injury in green bell pepper by enhancing antioxidant enzyme activity and regulating proline metabolism. Sci. Hortic. 295, 110783 https://doi.org/10.1016/j.scienta.2021.110783.
Wang, H., Huang, H., Huang, X., Hu, Z., 2006. Sugar and acid compositions in the arils of *Litchi chinensis* Sonn.: cultivar differences and evidence for the absence of succinic acid. J. Hortic. Sci. Biotechnol. 81, 57–62. https://doi.org/10.1080/14620316.2006.11512029.
Wang, Q., Lai, T., Qin, G., Tian, S.P., 2009. Response of jujube fruits to exogenous oxalic acid treatment based on proteomic analysis. Plant Cell Physiol. 50, 230–242. https://doi.org/10.1093/pcp/pcn191.
Wang, Z., Cao, J., Jiang, W., 2016. Changes in sugar metabolism caused by exogenous oxalic acid related to chilling tolerance of apricot fruit. Postharvest Biol. Technol. 114, 10–16. https://doi.org/10.1016/j.postharvbio.2015.11.015.
Whangchai, K., Saengnil, K., Uthaibutra, J., 2006. Effect of ozone in combination with some organic acids on the control of postharvest decay and pericarp browning of longan fruit. Crop Prot. 25, 821–825. https://doi.org/10.1016/j.cropro.2005.11.003.
Wu, F., Zhang, D., Zhang, H., Jiang, G., Su, X., Qu, H., Jiang, Y., Duan, X., 2011. Physiological and biochemical response of harvested plum fruit to oxalic acid during ripening or shelf-life. Food Res. Intern. 44, 1299–1305. https://doi.org/10.1016/j.foodres.2010.12.027.
Youryon, P., Chimphakdee, N., Supapvanich, S., 2017. Effects of preharvest salicylic acid or oxalic acid on quality of 'Queen' pineapple fruit harvested at different month stored at room temperature. Acta Hortic. 1256, 489–494. https://doi.org/10.17660/ActaHortic.2019.1256.69.
Yu, L., Jiang, J., Zhang, C., Jiang, L., Ye, N., Lu, Y., Yang, G., Liu, E., Peng, C., He, Z., 2010. Glyoxylate rather than ascorbate is an efficient precursor for oxalate biosynthesis in rice. J. Exp. Bot. 61, 1625–1634. https://doi.org/10.1093/jxb/erq028.
Zhang, W., Jiang, W., 2019. UV treatment improved the quality of postharvest fruits and vegetables by inducing resistance. Trends Food Sci. Technol. 92, 71–80. https://doi.org/10.1016/j.tifs.2019.08.012.
Zheng, J., Li, S., Xu, Y., Zheng, X., 2019. Effect of oxalic acid on edible quality of bamboo shoots (*Phyllostachys prominens*) without sheaths during cold storage. LWT - Food Sci. Technol. 109, 194–200. https://doi.org/10.1016/j.lwt.2019.04.014.
Zheng, X.L., Tian, S.P., 2006. Effect of oxalic acid on control of postharvest browning of litchi fruit. Food Chem. 96, 519–523. https://doi.org/10.1016/j.foodchem.2005.02.049.
Zheng, X.L., Tian, S.P., Gidley, M.J., Yue, H., Li, B.Q., Xu, Y., Zhou, Z.W., 2007a. Slowing the deterioration of mango fruit during cold storage by pre-storage application of oxalic acid. J. Hortic. Sci. Biotechnol. 82, 707–714. https://doi.org/10.1080/14620316.2007.11512294.
Zheng, X.L., Tian, S.P., Gidley, M.J., Yue, H., Li, B.Q., 2007b. Effects of exogenous oxalic acid on ripening and decay incidence in mango fruit during storage at room temperature. Postharvest Biol. Technol. 45, 281–284. https://doi.org/10.1016/j.postharvbio.2007.01.016.
Zheng, X.L., Tian, S.P., Meng, X., Li, B.Q., 2007c. Physiological and biochemical responses in peach fruit to oxalic acid treatment during storage at room temperature. Food Chem. 104, 156–162. https://doi.org/10.1016/j.foodchem.2006.11.015.
Zheng, X.L., Ye, L., Jiang, T., Jing, G., Li, J., 2012a. Limiting the deterioration of mango fruit during storage at room temperature by oxalate treatment. Food Chem. 130, 279–285. https://doi.org/10.1016/j.foodchem.2011.07.035.
Zheng, X.L., Jing, G., Liu, Y., Jiang, T., Jiang, Y., Li, J., 2012b. Expression of expansin gene, *MiExpA1*, and activity of galactosidase and polygalacturonase in mango fruit as affected by oxalic acid during storage at room temperature. Food Chem. 132, 849–854. https://doi.org/10.1016/j.foodchem.2011.11.049.
Zheng, X.L., Brecht, J.K., 2017. Oxalic acid treatments. In: Pareek, S. (Ed.), Novel Postharvest Treatments of Fresh Produce. CRC Press, Boca Raton, Florida, USA, pp. 35–50. https://doi.org/10.1201/9781315370149.
Zhu, Y., Yu, J., Brecht, J.K., Jiang, T.J., Zheng, X.L., 2016. Pre-harvest application of oxalic acid increases quality and resistance to *Penicillium expansum* in kiwifruit during postharvest storage. Food Chem. 190, 537–543. https://doi.org/10.1016/j.foodchem.2015.06.001.
Zhu, Z., Meng, X., Tian, S.P., 2010. Effect of preharvest oxalic acid sprays on calcium content and distribution in mango fruit cells. Chin. B. Bot. 45, 23.