International Journal of Horticultural Science and Technology
Journal homepage: http://ijhst.ut.ac.ir

Selenium Nanoparticle Treatments Alleviate Chilling Injury and Preserve the Quality of Valencia Orange Fruit in Cold Storage

Zahra Sadat Amiri[1], Zahra Pakkish[1], Fatemeh Nasibi[2]*

1 Department of Horticultural Sciences, Faculty of Agriculture, Shahid Bahonar University of Kerman, Kerman, Iran
2 Department of Biology, Faculty of Sciences, Shahid Bahonar University of Kerman, Kerman, Iran

ARTICLE INFO

Article history:

Received: 8 May 2023,
Received in revised form: 27 September 2023,
Accepted: 30 September 2023

Article type:

Research paper

Keywords:

Chilling injury,
Lipid peroxidation,
Orange,
Oxidative stress,
Selenium nanoparticle

ABSTRACT

In this study, we evaluated the effects of selenium nanoparticles on chilling injury and improving the shelf life of Valencia orange (*Citrus sinensis*) fruit. Treatments included 0.5 and 1 mg L^{-1} selenium nanoparticles, with three replicates per treatment and six replicates in total. Statistical analyses were performed using SPSS, with data analyzed by one-way ANOVA and mean separations by Duncan's new multiple-range test. Results showed that samples treated with selenium at 0.5 and 1 mg L^{-1} significantly decreased lipid peroxidation (55 and 62%, respectively) compared to control samples. Selenium treatments also in creased the activity of antioxidant enzymes, including CAT (twice and four times), peroxidase (2.5 and 4 times), APX (about 0.5 and 2.5 times) , and SOD (by 4 and 6 times), with consistent results in DPPH radical scavenging (by 2.5 and 3.5 times) in the orange fruits. Selenium at both concentrations effectively reduced the incidence of chilling injury in Valencia orange fruits during six months of storage at 3 °C. Chilling injury was best reduced at 1 mg L^{-1}. This study proved that selenium can enhance orange fruit quality and increase its tolerance to cold storage conditions, potentially leading to selenium-enriched fruits with health benefits for consumption.

Abbreviation: Ascorbate peroxidase (APX), Catalas (CAT), Chilling injur y (CI), 2,2-dihenyl-1-picrylydrazyl (DPPH), Glutathion reductase (GR), M alondialdehyde (MDA), Peroxidase (POD), Reactive oxygen species (RO S), Se (Selenium), Superoxide dismutase (SOD)

Introduction

Chilling injury (CI) is a primary postharvest problem for orange (*Citrus sinensis* L.) and many other horticulture crops in storage (Salcini and Massantini, 2005; Wang, 1993; Manners et al., 2003; Zhang and Tian, 2010). Washington Navel orange fruits are susceptible to CI during storage below 5 °C (Syvertsen, 1982). Their main CI symptoms are surface pitting, browning, discoloration, and decay (Schirra et al., 2005; Gualanduzzi, 2009). Several promising methods have been developed to alleviate CI symptoms in orange fruits. These include postharvest physical treatments with UV-C (Odriozola-Serrano et al., 2007; Slaughter et al., 2008), modified atmosphere packaging (Manners et al., 2003),

*Corresponding author's email: nasibi.f@uk.ac.ir

temperature conditioning (Obenland et al., 2012), and chemical treatments with plant growth regulators (Montesinos-Herrero and Palou, 2010; Schirra et al., 2005).

Oxidative stress from excess reactive oxygen species (ROS) has associations with the appearance of chilling damage in fruits (Hodges et al., 2004). ROS changes by reactions with numerous cell components, coursing a cascade of oxidative reactions and inactivating enzymes, lipid peroxidation, protein degradation, and DNA damage (Nadarajah, 2020). Aerobic organisms have developed defense systems to establish a fine-tuned balance between ROS production and removal. Plants are protected against ROS effects by a complex antioxidant system. This involved both lipid-soluble antioxidant (α- tocopherol and carotenoids) and water-soluble reductants (glutathione and ascorbate) and enzymes, such as catalase (CAT), glutathione reductase (GR), ascorbate peroxidase (APX), Superoxide dismutase (SOD) and peroxidase (POD) (Apel and Hirt, 2004; Hasanuzzaman et al., 2020). Oxidative damage only ensues when these complex systems fail to limit ROS accumulation. Previous studies have shown a positive relationship between the activity of antioxidant enzymes and the chilling tolerance in harvested fruits (Sala, 1998; Wang, 1995). These results suggest that enhanced antioxidant enzyme systems and reduced membrane lipid peroxidation may be involved in chilling tolerance in harvested fruit.

Selenium (Se) is an essential trace element with fundamental importance to human health and antioxidant properties for humans and animals (Jezek et al., 2012). Selenium is present in trace amounts in both organic and inorganic forms in soil and environment, which can be uptake and translocated in various parts of plants (Kikkert and Berkelaar, 2013). Selenium is also an essential constituent of selenoproteins that play a vital role in many biological functions with antioxidant properties, such as antioxidant defense, formation of thyroid hormones, DNA synthesis, fertility and reproduction, HIV treatment, free radical-induced diseases, and protection from toxic heavy metals (Fairweather-Tait et al., 2011).

Selenium is reportedly beneficial to crops. It mainly exists in four different oxidation states: selenide (SeO^{-2}), selenium (SeO), selenite (SeO_3^{-2}), and selenate (SeO_4^{-2}). Se nanoparticles have less toxicity than other forms of selenium due to their high reactivity, wide specific surface area, and good adsorption capability (Deng et al., 2019; Li et al., 2020; Zhao et al., 2020; Poldma et al., 2011). Researchers found that the function of selenium nanoparticles in plant growth and metabolism is much more effective than its usual forms, such as selenate and selenite. However, using these nanoparticles at high concentrations causes toxicity (Hu et al., 2018; Babajani et al., 2019; Zahedi et al., 2019).

Se increases plant growth and protects crops against specific biotic and abiotic stresses such as drought, salinity, heavy metals, etc. The physiological and antioxidant properties of Se have raised the curiosity of biologists in the recent past. It plays a beneficial role in plants by enhancing plant growth (Cartes et al., 2010; Hasanuzzaman et al., 2010), reducing damage caused by UV-induced oxidative stress (Yao et al., 2013), increasing chlorophyll and carotenoids in plant leaves (Dong et al., 2013), stimulating enzymatic and non-enzymatic antioxidant system against cadmium-toxicity (Kumar et al., 2012; Lin et al., 2012) and improving plant tolerance to drought stress by regulating water status (Yao et al., 2009). Low levels of Se stimulate the antioxidant machinery in plants, but it acts as a prooxidant at high levels (Feng et al., 2013). Selenium can regulate reactive oxidative species (ROS) levels in stressed plants through three pathways. These include stimulating the spontaneous dismutation of O^{2-} into H_2O_2, prompting a direct reaction between selenium-containing compounds and ROS, and reducing excess ROS generation in plants exposed to different environmental stresses while regulating antioxidative enzymes. ROS regulation by selenium may be a key mechanism for preventing plant stress (Cartes et al., 2010). Selenium nanoparticles reportedly alleviated various abiotic stresses caused by metals, drought, and temperature (Ikram et al., 2020; Zahedi et al., 2019).

Improving productivity and reducing postharvest losses in the fruit industry is crucial, and scientific studies have shown that techniques like biotechnology and nanotechnology could be the solution. Nanotechnology is especially promising, potentially enhancing agricultural productivity through nano fertilizers, efficient herbicides, pesticides, soil feature regulation, wastewater management, and pathogen detection. It also offers benefits for industrial food processing, including improved production, market value, nutrition, safety, and antimicrobial protection. Additionally, nanotechnology can increase the shelf life of fruits and reduce post-farming losses. However, like all technologies, it is essential to consider any unintended effects that could harm the environment or human health before implementing them broadly. While nanoparticles

may have unique properties that could impact toxicity, it is essential to note that not all engineered nanoparticles are more toxic than fine-size particles of the same chemical composition. With careful consideration and research efforts, nanotechnology can benefit the fruit industry and relevant industries (Upadhyay et al., 2022; Fadiji et al., 2022; Neme et al., 2021). This study aimed to assess the effects of selenium nanoparticles on postharvest quality and shelf life of Valencia orange (*Citrus sinensis* L.) fruits in cold storage (3 °C).

Materials and Methods

Valencia orange fruit and treatments

Valencia orange (*Citrus sinensis* L.) fruits were harvested at commercial maturity from a commercial orchard in Kerman, Iran, and transported to Shahid Bahonar University, Kerman, 2021. On the same day, orange fruits without wounds or rot were selected based on uniformity of size and absence of physical injury or disease. The harvested fruits were disinfected with 1% sodium hypochlorite (v/v) for 2 min, washed, and air-dried. Subsequently, they were randomly divided into 3 groups. Two groups were immersed in aqueous solution containing 0.5 and 1 mg L^{-1} Se nanoparticles for 5 min according to preliminary experiments. Selenium nanoparticles were purchased from Pishgaman Company, Mashhad, Iran. A third group was immersed in distilled water for 5 min and was considered the control group. All fruits were enclosed in plastic boxes with polyethylene film bags to maintain relative humidity at about 95% and were stored at 3 °C.

Evaluation of chilling injury (CI)

Chilling injury (%) was calculated by the following formula (Obenland et al., 2009):

$$Chilling\ injury\ (\%) = (Total\ number\ of\ fruits\ in\ each\ treatment - number\ of\ fruits\ with\ no\ chilling\ injury)/(total\ number\ of\ fruits\ in\ the\ treatment) \times 100$$

Measurement of lipid peroxidation content

Lipid peroxidation content was determined and expressed as malondialdehyde (MDA) equivalents, according to a method by Rajinder et al. (1981), with slight modifications. Pulp and peel tissues (4.0 g) from orange fruits were homogenized with 20 mL of 10% trichloroacetic acid and then centrifuged for 10 min at 5000 × g. One ml of the supernatant was mixed with 3 mL of 0.5% thiobarbituric acid (TBA) dissolved previously in 10% trichloroacetic acid. The reaction mixture was heat-treated for 20 min at 95 °C, cooled immediately, and then centrifuged for 10 min at 10,000 × g to clarify precipitation. Absorbance at 532 nm was measured and subtracted from the non-specific absorbance at 600 nm. The amount of MDA was calculated using an extinction coefficient of 155 mM^{-1} cm^{-1} and expressed as mM g^{-1} FW.

Hydrogen peroxide assay

An assay for H_2O_2 content was carried out by the procedure described by Prassad (1996). Fresh tissues (2 g) were homogenized with 10 mL of acetone at 0 °C. The supernatant phase was collected after centrifugation for 15 min at 6000 g at 4 °C. The supernatant (1 mL) was mixed with 0.1 mL of 5% titanium sulphate and 0.2 mL ammonia and then centrifuged for 10 min at 6000 g and 4 °C. The pellets were dissolved in 3 mL of 10% (v/v) H_2SO_4 and centrifuged for 10 min at 5000 g. The absorbance of the supernatant phase was measured at 410 nm. H_2O_2 content was calculated using H_2O_2 as standard. The results were expressed as µg g^{-1} FW (Prassad, 1996).

Antioxidant enzyme assay (catalase and peroxidase activity)

Catalase and peroxidase activity was analyzed according to Xing et al. (2011), with slight modifications. The reaction mixture consisted of 2 mL sodium phosphate buffer (50 mM, pH 7.0), 0.5 mL H_2O_2 (40 mM) and 0.5 mL enzyme extract. The decomposition of H_2O_2 was measured by absorbance decline (A) at 240 nm. CAT activity was expressed as U kg-1 of FW, where U = Δ-A at 240 nm per second. Regarding POD determination, 0.5 mL enzyme extract was incubated in 2 mL buffered substrate (100 mM sodium phosphate, pH 6.4 and 8 mM guaiacol) for 5 min at 30 °C, and the increasing absorbance was measured at 460 nm every 30 s for 120 s after adding 1 mL of H_2O_2 (24 mM). POD and CAT activity was expressed as U mg^{-1} protein.

Superoxide dismutase

Superoxide dismutase activity was assayed according to Misra and Fridovich (1972). About 200 mg fresh tissues were homogenized in 5 mL of 100 mM K-phosphate buffer (pH 7.8) containing 0.1 mM EDTA, 0.1% (v/v) Triton X-100, and 2% (w/v) polyvinyl pyrrolidone (PVP). The extract was filtered through muslin cloth and centrifuged at 10000 g for 10 min at 4-8 °C. The supernatant was dialyzed in cellophane membrane tubing against a cold extraction buffer for 4 h with carbonate/bicarbonate buffer and

then was used in assaying. The assay mixture in a total volume of 3 mL contained 50 mM sodium carbonate/bicarbonate buffer (pH 9.8), 0.1 mM EDTA, 0.6 mM epinephrine and enzyme. Epinephrine was the last component to be added. Four minutes later, the adrenochrome formation was recorded at 475 nm in a UV-Vis spectrophotometer. One unit of SOD activity was expressed as an enzyme required to cause 50% inhibition of epinephrine oxidation under experimental conditions. The specific activity of the enzyme is expressed as U mg^{-1} protein.

Ascorbate peroxidase

Ascorbate peroxidase was assayed according to Nakano and Asada (1981). The reaction mixture in a total volume of 1 mL contained 50 mM K-phosphate buffer (pH 7.0), 0.2 mM ascorbic acid, 0.2 mM EDTA, 20 mM H_2O_2 and enzyme. H_2O_2 was the last component to be added, and the decrease in absorbance was recorded at 290 nm (extinction coefficient of 2.8 Mm cm^{-1}) using a UV-Vis spectrophotometer. A correction was illustrated for low, non-enzymatic oxidation of ascorbic acid by H_2O_2. Specific enzymatic activity was expressed as U mg^{-1} protein.

DPPH radical scavenging activity

DPPH (2,2-dihenyl-1-picrylydrazyl) radical scavenging activity was done according to Oliveira et al. (2009) with some modifications. Each treatment on fresh tissue sample (0.5 g) was homogenized in 4 mL absolute methanol at 4 °C. After centrifugation, an aliquot (0.3 mL) of the methanol extract was mixed with 2.7 mL of methanolic solution containing DPPH radicals (0.1 mmol L^{-1}). The reaction mixture was shaken and incubated for 120 min at room temperature, and the absorbance was read at 517 nm against a blank. The scavenging ability was calculated using the following equation:

$$\text{scavenging activity} = \frac{\text{A517 of control-A517 of sample0}}{\text{A517 of control}} \times 100$$

α-tocopherol was used as a standard antioxidant analyzed at the same time. The final results were calculated and expressed as α-tocopherol equivalents per gram on a fresh weight basis.

Selenium analysis

After harvesting, 0.5 g of fruit tissue was homogenized for selenium analysis. The samples were acid-digested with 10 mL of concentrated H_2SO_4 (Wolf, 1982) and digestion tubes were incubated overnight at room temperature. Then, 0.5 mL of H_2O_2 (35%) was added to the tubes and heated at 350 °C in a digestion block until fumes were produced. They were further heated for 30 min. Then, 0.5 mL of H_2O_2 was slowly added in cooled tubes and placed back into the digestion block. The above step was repeated until the cooled digested material turned colorless. Extract volume was maintained up to 50 mL in volumetric flasks. Whatman No. 40 filter paper was used for filtering the extract to determine selenium contents in the fruit tissue.

Data analysis

All statistical analyses were performed with SPSS version 13.0 (SPSS Inc., Chicago, IL, USA). Data at each time point were analyzed by one-way ANOVA, and mean separations were performed by Duncan's new multiple range test. Differences at $p<0.05$ were considered significant. Each treatment consisted of three replicates and the experiment was repeated six times.

Results

Effect of Se on CI of orange fruit

Data showed that untreated control orange fruits displayed signs of CI symptoms, such as surface pitting and browning, after a month of storage. Furthermore, the CI index in control oranges was found to be as high as 49.29% after 6 months. However, orange fruits treated with 0.5 and 1 mg L^{-1} Se showed CI symptoms only after 60 days of storage. It was also observed that the Se treatment decreased 50% and 70% in the CI index in 0.5 and 1 mg L^{-1}, respectively (Fig. 1).

Lipid peroxidation and H_2O_2 content

MDA content as a lipid peroxidation index can be used as direct indicators of membrane injury, which is often associated with CI. We observed a continuous increase in lipid peroxidation in both control and treated orange fruits stored at 3 °C. However, the Se treatment significantly delayed the increase in lipid peroxidation during storage. It was also noted that at the end of the storage period (Day 180), the lipid peroxidation of samples that were treated with Se at 0.5 and 1 mg L^{-1} decreased significantly (55 and 62%, respectively) compared to the control samples (Fig. 2).

The findings showed that the initial H_2O_2 content in the orange fruit pulp was low, ranging from 7.1 to 7.25 μg g^{-1} FW. Through storage time, the H2O2 content increased as well. At the end of the 180-day storage period, the control samples had an

H_2O_2 content of 29.10 µg g^{-1} FW in pulp flesh, while the Se-treated samples showed an H_2O_2 content of 18 and 12 µg g^{-1} FW in response to 0.5 and 1 mg L^{-1} Se nanoparticles, respectively (Fig. 3).

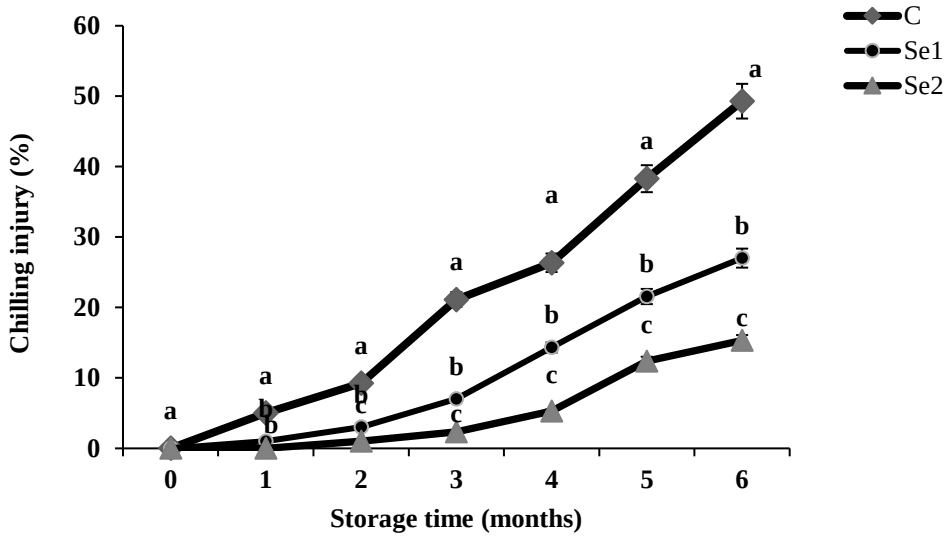

Fig. 1. Effect of selenium (Se) on chilling injury of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Mean values followed by similar letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviations of mean values.

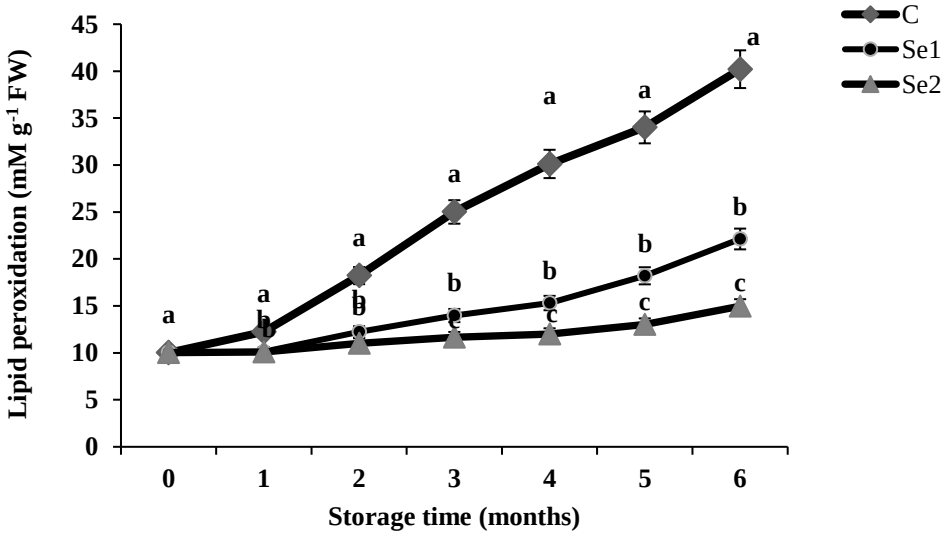

Fig. 2. Effect of selenium (Se) on lipid peroxidation of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0. 5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

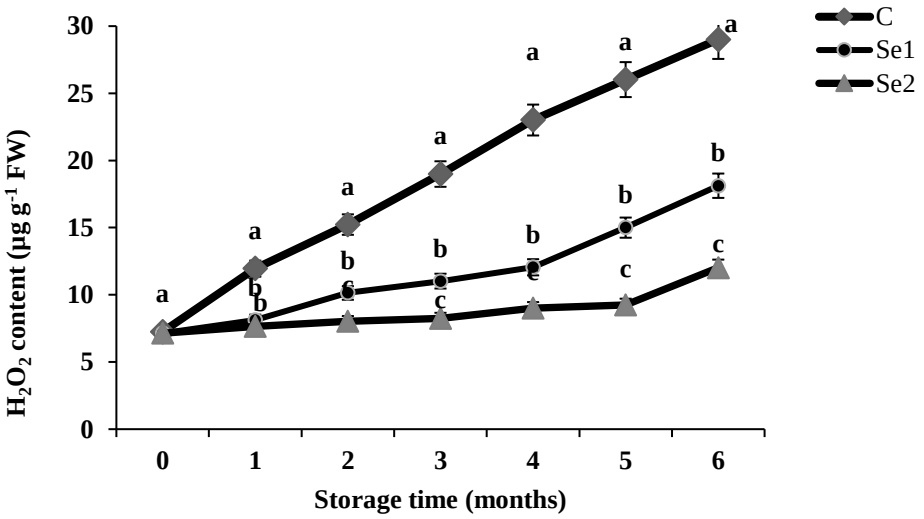

Fig. 3. Effect of selenium (Se) on H_2O_2 content of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

Effect of Se on induction of antioxidant enzymes

Se treatments at both 0.5 and 1 mg L^{-1} led to an increase in the activity of antioxidant enzymes in orange fruit pulp. The CAT, POD, SOD, and PAX enzymes all demonstrated a similar pattern, with the highest activity levels occurring in the fourth month and decreasing over time. However, samples treated with Se showed a more significant increase in activity compared to control samples. At the end of the experiment, CAT enzyme activity increased by two and four times, respectively, with Se pretreatment at 0.5 and 1 mg L^{-1} (Fig. 4). Peroxidase enzyme activity also increased by 2.5 and 4 times under the treatment of Se 0.5 and 1 mg L^{-1}, respectively in orange fruit on the 180th day of treatment (Fig. 5). Additionally, the APX enzyme activity increased about 2.5 times in response to 1 mg L^{-1} Se at the end of the experiment (Fig. 6). Finally, the activity of the SOD enzyme increased by 4 and 6 times in these fruits in response to 0.5 and 1 mg L^{-1} Se, respectively (Fig. 7).

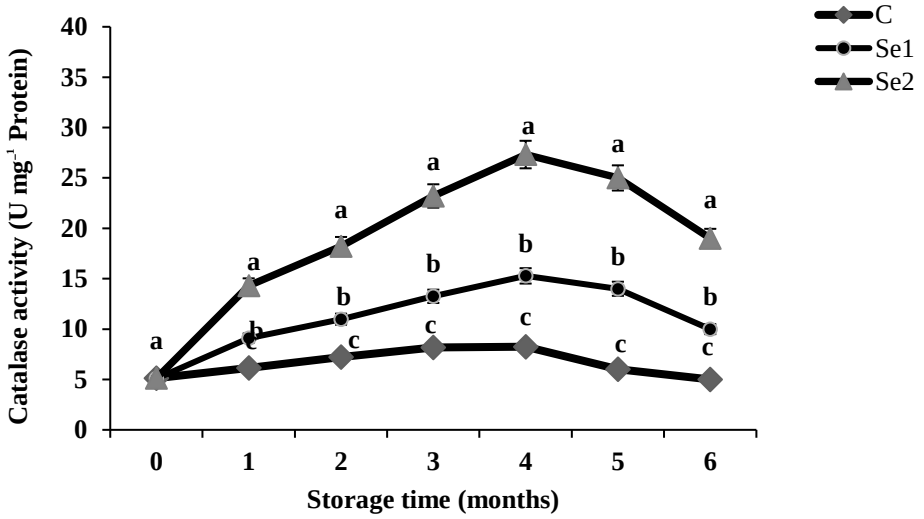

Fig. 4. Effect of selenium (Se) on catalase activity enzyme of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

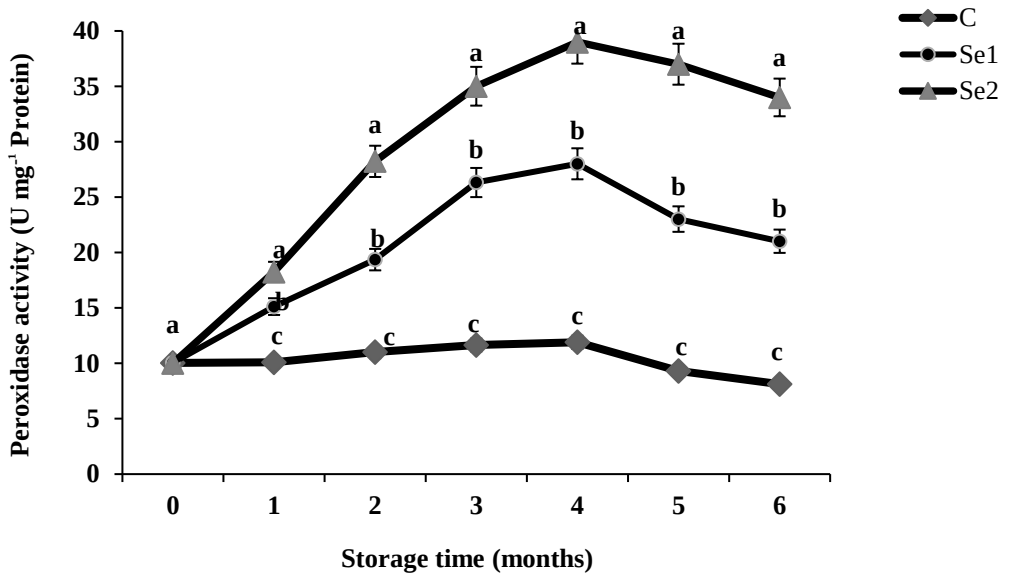

Fig. 5. Effect of selenium (Se) on peroxidase activity enzyme of Valencia orange fruit during storage under low temperature (C: control fruit; Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

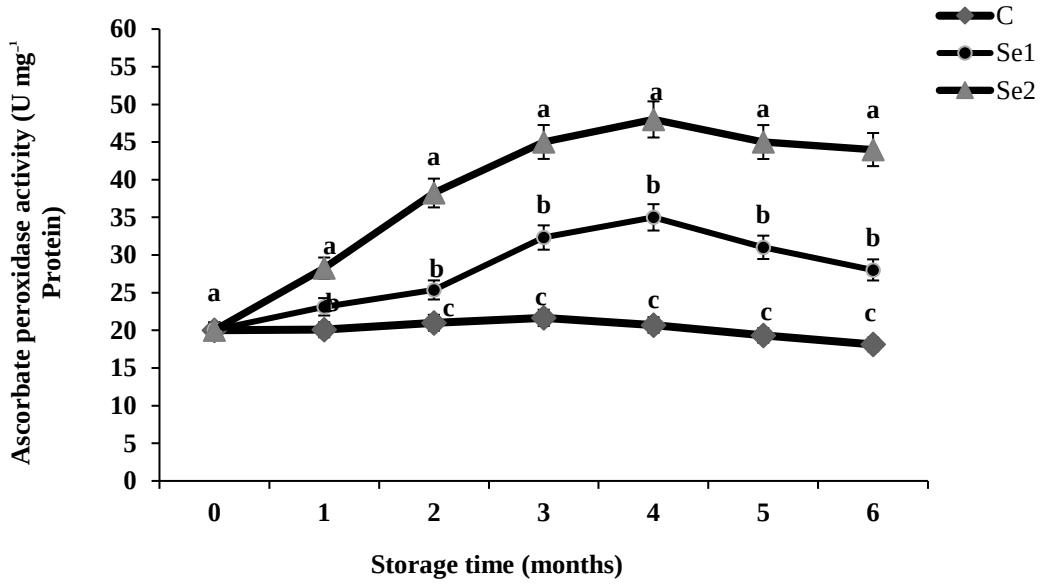

Fig. 6. Effects of selenium (Se) on ascorbate peroxidase activity enzyme of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

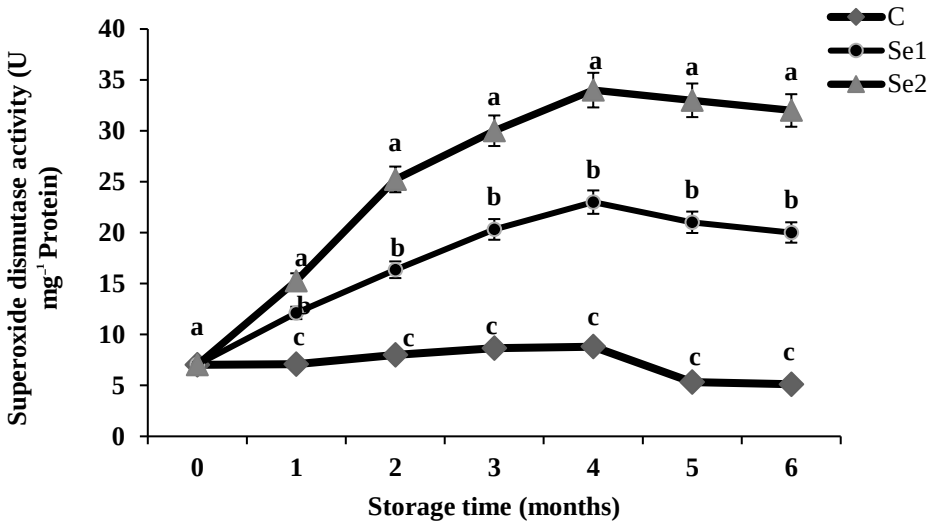

Fig. 7. Effects of selenium (Se) on superoxide dismutase activity enzyme of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

Effect of Se on DPPH radical scavenging activity

Enzyme activities showed that after treating fruits with Se for four months, the DPPH radical scavenging activity in orange fruit stored at 3 °C increased significantly. In response to concentrations of 0.5 and 1 mg L^{-1} Se, the activity increased by 2.5 and 3.5 times, respectively, before showing a decrease. However, even at the end of the experiment, the treated samples still showed higher DPPH activity than the control samples (Fig. 8).

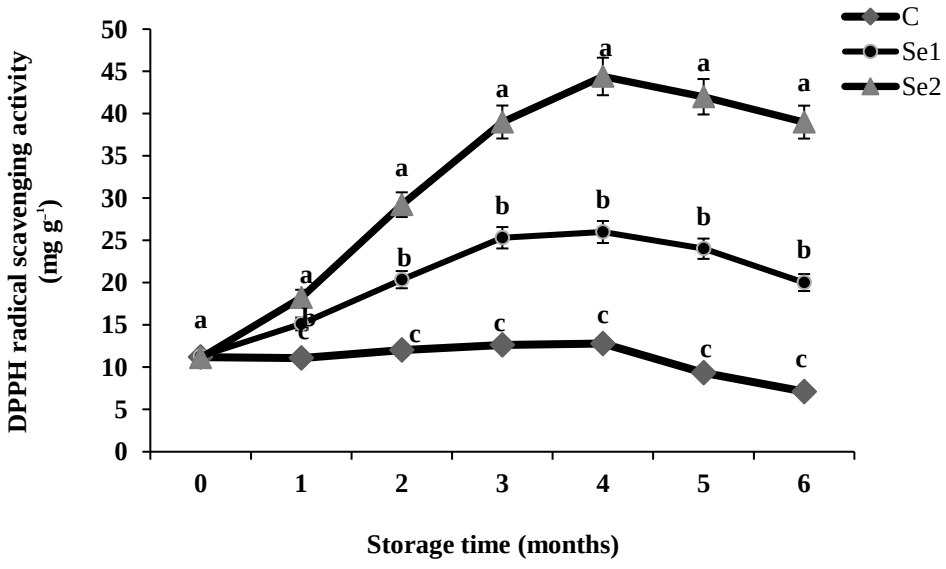

Fig. 8. Effects of selenium (Se) on DPPH radical scavenging activity of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

Effect of Se treatment on selenium concentration of Valencia orange fruit

Based on the measurements, it was found that the amount of Se in fruits significantly increased after treating orange fruits with selenium for 180 days. The increase was 2 to 3 times greater than the control samples (Fig. 9). These findings suggest that incorporating selenium into fruit production may have potential benefits for enhancing the nutritional value of oranges.

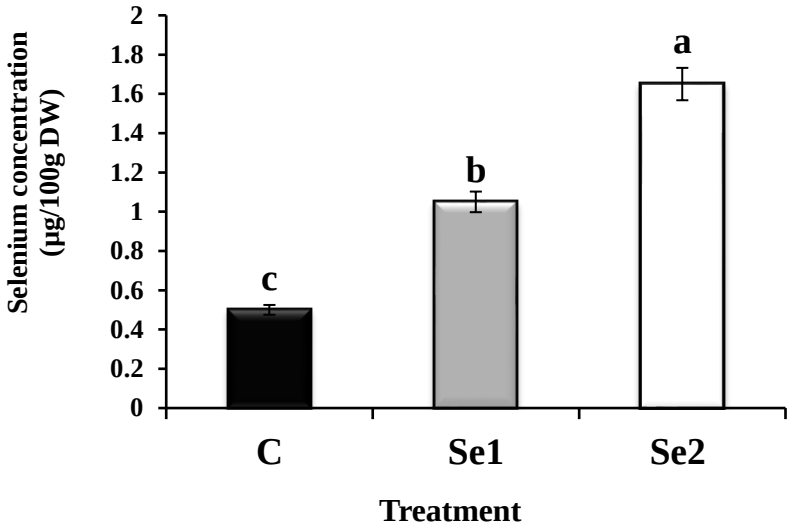

Fig. 9. Effects of selenium (Se) on selenium concentration of Valencia orange fruit during storage under low temperature (C: control fruit, Se1: selenium 0.5 mg L^{-1}, Se2: selenium 1 mg L^{-1}). Means followed by same letters are not significantly different at $p<0.05$ according to Duncan's multiple range test. Vertical bars represent standard deviation of the mean.

Discussion

Researchers have found that selenium is an essential element for animals and humans. It can also benefit plants in nutritional ways. When applied at lower concentrations, it protects plants by conferring tolerance to specific abiotic and biotic stresses. However, higher concentrations can lead to phytotoxicity (Hasanuzzaman et al., 2010; Kikkert and Berkelaar, 2013). Studies have shown that selenium can increase the vase life of *Lilium longiflorum* cut flowers (Lu et al., 2020), enhance the shelf life of tomatoes and olive fruit (Neysanian et al., 2020) and olive fruit (Regni et al., 2021), and control postharvest gray mold in tomatoes (Wu et al., 2014; Wu et al., 2016). Nanotechnology has provided a promising solution to improve crop productivity and protection. Selenium nanoparticles are more effective than their usual forms, such as selenate and selenite (Hu et al., 2018; Babajani et al., 2019; Zahedi et al., 2019; Zhou et al., 2020). However, it is essential to note that high concentrations of these nanoparticles can be toxic, so the optimal concentration should be carefully determined. In this research, we aimed to evaluate the impact of Se nanoparticles on the occurrence of oxidative stress, activation of the antioxidant defense system, and storage life of Valencia orange fruits.

By monitoring H_2O_2 and MDA content as an oxidative index in the cell membrane of orange fruits, we observed that Se-treated fruits showed a decrease in MDA and H_2O_2 content, which improved fruit quality. This finding indicates the antioxidant properties of Se nanoparticles. Several studies have also demonstrated the protective role of selenium against oxidative stress in plants. For instance, Jozwiak and Politycka (2019) reported that Se increased the activities of SOD, POD, and CAT in cucumber roots under drought stress. Tognon et al. (2016) found that Se increased postharvest performance and vase life in snapdragon cut flowers by decreasing lipid peroxidation and alleviating oxidative damage. In our study, the high activity of antioxidant enzymes such as SOD, CAT, GPX, and APX, along with the increased shelf life of oranges in the Se-supplemented fruits, can be attributed to the higher efficiency of Se in enhancing the antioxidant system compared to non-treated fruits. Recent studies have also shown that Se improves the ability of many plants to scavenge ROS through the enzymatic system (Chi et al., 2017; Pereira et al., 2018). Wu et al. (2017) reported that Se enhanced the activities of SOD and CAT in the roots and leaves of Chinese cabbage exposed to cadmium stress. Overall, our

research findings agree with previous studies that have reported the beneficial effects of Se nanoparticle treatment in activating the antioxidant system and improving fruit quality. Neysanian et al. (2020) reported that tomato plants treated with Se nanoparticles improved enzymatic antioxidants in tomato and showed that Se nanoparticles are more effective than selenate in activating the antioxidant system.
It is interesting to note that the consumption of selenium-enriched products has become increasingly important due to the role of selenium on human health. Recent data from a study on Se measurement evaluating Valencia orange fruits showed that Se increased in fruits treated with Se nanoparticles while using a safe concentration. The estimated value for Se daily intake is 55 µg (Nysanian et al., 2020). Based on the results of this research, treating fruits such as oranges with Se nanoparticle solution can increase the quality and longevity of shelf life. It can assist in producing Se-enriched oranges. Consuming these fruits can benefit human health in response to selenium.

Acknowledgments
This study was supported by Shahid Bahonar University, Kerman, Iran.

Conflict of Interest
The authors indicate no conflict of interest for this work.

References
Apel K, Hirt H. 2004. Reactive oxygen species: metabolism oxidative stress, and signal transduction. Annual Review Plant Biology 55, 373-399.

Babajani A, Iranbakhsh A, Ardebili Z, Eslami B. 2019. Differential growth, nutrition, physiology, and gene expression in *Melissa officinalis* mediated by zinc oxide and elemental selenium nanoparticles. Environmental Science and Pollution Research 26(24), 24430–24444.

Cartes P, Jara AA, Pinilla L, Rosas A, Mora ML. 2010. Selenium improves the antioxidant ability against aluminum induced oxidative stress in ryegrass roots. Annals of Applied Biology 156 (2), 297–307.

Deng W, Wang H, Wu B, Zhang X. 2019. Selenium-layered nanoparticles serving for oral delivery of phytomedicines with hypoglycemic activity to synergistically potentiate the antidiabetic effect. Acta Pharmaceutica Sinica B 9 (1), 74-86.

Dong JZ, Wang Y, Wang SH, Yin LP, Xu GJ, Zheng C, Lei C, Zhang MZ. 2013. Selenium increase chlorogenic acid, chlorophyll and carotenoids of *Lycium chinense* leaves. Journal of Science of Food and Agriculture 93, 310–315.

Fadiji AE, Mthiyane MN, Onwudiwe DC, Babalola OO. 2022. Harnessing the known and unknown impact of nanotechnology on enhancing food security and reducing postharvest losses: constraints and future prospects. Agronomy 12, 1657.

Fairweather-Tait SJ, Bao Y, Broadley MR, Collings R, Ford D, Hesketh JE, Hurst R. 2011. Selenium in human health and disease. Antioxidant and Redox Signaling 14 (7), 1337–1383.

Feng RW, Wei CY, Tu SX. 2013. Roles of selenium in protecting plants against abiotic stresses. Environmental and Experimental Botany 87, 8–68.

Gualanduzzi S, Baraldi E, Braschi I, Carnevali F, Gessa CE, De Santis A. 2009. Respiration, hydrogen peroxide levels and antioxidant enzyme activities during cold storage of zucchini squash fruit. Postharvest Biology and Technology 52, 16–23.

Hasanuzzaman M, Bhuyan MHM, Zulfiqar F, Raza A, Mohsin SM, Mahmud JA. 2020. Reactive oxygen species and antioxidant defense in plants under abiotic stress: revisiting the crucial role of a universal defense regulator. Antioxidants 9 (8), 681.

Hasanuzzaman M, Hossain MA, Fujita M. 2010. Selenium in higher plants: physiological role, antioxidant metabolism and abiotic stress tolerance. Journal of Plant Sciences 5, 354–375.

Hodges DM, Lester GE, Munro KD, Toivonen PM. 2004. Oxidative stress: importance for postharvest quality. Horticultural Science 39, 924-929.

Hu T, Li H, Li J, Zhao G, Wu W, Liu L. 2018. Absorption and bio-transformation of selenium nanoparticles by wheat seedlings (*Triticum aestivum* L). Frontiers in Plant Science 9, 597.

Ikram M. Raja NI, Javed B, Hussain M, Hussain M, Ehsan M, Akram A. 2020. Foliar applications of bio-fabricated selenium nanoparticles to improve the growth of wheat plants under drought stress. Green Processing and Synthesis 9 (1), 706–714.

Ježek P, Škarpa P, Lošák T, Hlušek J, Jůzl M, ElznerJezek P. 2012. Selenium–an important antioxidant in crops biofortification. From the edited volume of antioxidant enzyme book. Edited by Mohammed Amr El-Missiry. Published October 3rd, ISBN978-953-51-0789.

Jozwiak W, Politycka B. 2019. Effect of selenium on alleviating oxidative stress caused by a water deficit in cucumber roots. Plants 8, 217.

Kikkert J, Berkelaar B. 2013. Plant uptake and translocation of inorganic and organic forms of selenium. Archives of Environmental Contamination and Toxicology 65, 458–465.

Kumar M, BijoA J, Baghel RS, Reddy CRK, Jha B. 2012. Selenium and spermine alleviate cadmium induced toxicity in the red sea weed *Gracilaria dura* by regulating antioxidant system and DNA methylation. Plant Physiology and Biochemistry 51, 129–138.

Li H, Liu X, Wessie M, Chen L. 2020. Selenium supplementation alleviates cadmium-induced damages in tall fescue through modulating antioxidant system, photosynthesis efficiency, and gene expression.

Environmental Science and Pollution Research 1-3.

Lin L, Zhou W, Dai H, Cao F, Zhang G, Wu F. 2012. Selenium reduces cadmium uptake and mitigates cadmium toxicity in rice. Journal of Hazardous Materials 343–351.

Lu N, Wu L, Shi M. 2020. Selenium enhances the vase life of *Lilium longiflorum* cut flower by regulating postharvest physiological characteristics. Scientia Horticulturae 264, 109172.

Manners GD, Breksa AP, Schoch TK, Hidalgo MB. 2003. Analysis of bitter limonoids in citrus juices by atmospheric pressure chemical ionization and electrospray ionization liquid chromatography-mass spectrometry. Journal of Agriculture and Food Chemistry 51, 3709–3714.

Misra HP, Fridovich I. 1972. Role of superoxide anion in the auto-oxidation of epinephrine and a simple assay for superoxide dismutase. Journal of Biology and Chemistry 247, 3170-3175.

Montesinos-Herrero C, Palou L. 2010. Combination of physical and low-toxicity chemical postharvest treatments for the management of citrus fruit: a review. Stewart Postharvest Review 1, 1.

Nadarajah KK. 2020. ROS homeostasis in abiotic stress tolerance in plants. International Journal of Molecular Sciences 21, 5208.

Nakona Y, Asada K. 1981. Hydrogen peroxide scavenged by ascorbate-specific peroxidase in spinach chloroplast. Plant Cell Physiology 22, 867-880.

Neme K, Nafady A, Uddin S, Tola Y. 2021. Application of nanotechnology in agriculture, postharvest loss reduction and food processing: food security implication and challenges. Heliyon 7, e08539.

Neysanian M, Iranbakhsh A, Ahmadvand R, OraghiArdebili Z, Ebadi M. 2020. Comparative efficacy of selenate and selenium nanoparticles for improving growth, productivity, fruit quality, and postharvest longevity through modifying nutrition, metabolism, and gene expression in tomato: potential benefits and risk assessment. PLoS One 15(12), e0244207.

Obenland D, Collin S, Mackey B, Sievert J, Fjeld K, Arpaia ML. 2009. Determinants of flavor acceptability during the maturation of navel oranges. Postharvest Biology and Technology 52, 156–163.

Obenland D, Collin S, Sievert J, Arpaia ML. 2012. Impact of high-temperature forced-air heating of navel oranges on quality attributes, sensory parameters, and flavor volatiles. Horticultural Sciences 47, 386–390.

Odriozola-Serrano I, Hernndez-Jover T, Martn-Belloso O. 2007. Comparative evaluation of UV–HPLC methods and reducing agents to determine vitamin C in fruits. Food Chemistry 105, 1151–1158.

Oliveira I, Sousa A, Ferreira IC, Bento A, Estevinho L, Pereira JA. 2009. Total phenols, antioxidant potential and antimicrobial activity of walnut (*Juglan sregia* L.) green husks. Food Chemical Toxicology 46, 2326-2331.

Pereira AS, Dorneles AOS, Bernardy K, Sasso VM, Bernardy D, Possebom G, Rossato LV, Dressler VL, Tabaldi LA. 2018. Selenium and silicon reduce cadmium uptake and mitigate cadmium toxicity in *Pfaffia glomerata* (Spreng.) Pedersen plants by activation antioxidant enzyme system. Environmental Science and Pollution Research 25, 18548–18558.

Poldma P, Tonutare T, Viitak A, Luik A, Moor U. 2011. Effect of selenium treatment on mineral nutrition, bulb size, and antioxidant properties of garlic (*Allium sativum* L.). Journal of Agriculture and Food Chemistry 26, 549-555.

Prassad TK. 1996. Mechanisms of chilling-induced oxidative stress injury and tolerance in developing maize seedlings: changes in antioxidant system, oxidation of proteins and lipids, and protease activities. The Plant Journal 10, 1017-1026.

Rajinder SD, Dhindsa PP, Thorpe TA. 1981. Leaf senescence: correlated with increased levels of membrane permeability and lipid peroxidation, and decreased levels of superoxide dismutase and catalase. Journal of Experimental Botany 32, 93-101.

Regni L, Micheli M, Marco Del Pino A, Palmerini CA, D'Amato R, Lucia Facchin S, Famiani F, Peruzzi A, Mairech H, Proietti P. 2021. First evidence of the beneficial effects of Se-supplementation on in vitro cultivated olive tree explants. Plants 10(8), 1630.

Sala JM, Lafuente M. 2000. Catalase enzymes activity is related to tolerance of mandarin fruits to chilling. Postharvest Biology and Technology 20, 81-89.

Salcini MC, Massantini R. 2005. Minimally processed fruits: an update on browning control. Stewart Postharvest Review 1, 7.

Schirra M, Mulas M, Fadda A, Mignani I, Lurie S. 2005. Chemical and quality traits of 'Olinda' and 'Campbell' oranges after heat treatment at 44 or 46°C for fruit fly disinfestations. LWT-Food Science and Technology 38, 519-527.

Slaughter DC, Obenland DM, Thompson JF, Arpaia ML, Margosan DA. 2008. Non-destructive freeze damage detection in oranges using machine vision and ultraviolet fluorescence. Postharvest Biology and Technology 48, 341–346.

Syvertsen JP. 1982. Dehydration of freeze-damaged oranges. Horticultural Sciences 17, 803–804.

Tognon GB, Sanmartín C, Alcolea V, Cuquel FL, Goicoechea N. 2016. Mycorrhizal inoculation and/or selenium application affect post-harvest performance of snapdragon flowers. Plant Growth Regulation 78, 389–400.

Upadhyay TK, Kumar SV, Sharangi AB, Upadhye VJ, Khan F, Pandey P, Kamal MA, Baba AY, Khalid RH. 2022. Nanotechnology-based advancements in postharvest management of horticultural crops. Phyton 91(3), 471-87.

Wang CY. 1993. Approaches to reduce chilling injury of fruits and vegetables. Horticultural Review 15, 63–132.

Wang CY. 1995. Effect of temperature preconditioning on catalase, peroxidase, and superoxide dismutase in chilled zucchini squash. Postharvest Biology and Technology 5, 67-76.

Wolf B.1982. A comprehensive system of leaf analysis and its use for diagnosing crop nutrient status. Communications in Soil Science and Plant Analysis 13, 1035–1059.

Wu Z, Yin X, Bañuelos GS, Lin ZQ, Zhu Z, Liu Y, Yuan L, Li M. 2016. Effect of selenium on control of postharvest gray mold of tomato fruit and the possible mechanisms involved. Frontiers in Microbiology (6), 1-11.

Wu ZC, Liu S, Zhao J, Wang FH, Du YQ, Zou SM, Li HM, Wen D, Huang YD. 2017. Comparative responses to silicon and selenium in relation to antioxidant enzyme system and the glutathione-ascorbate cycle in flowering Chinese cabbage (*Brassica campestris* L. ssp chinensis var. utilis) under cadmium stress. Environmental and Experimental Botany 133, 1-11.

Wu ZL, Yin XB, Lin ZQ, Bañuelos GS, Yuan LX, Liu Y. 2014. Inhibitory effect of selenium against *Penicillium expansum* and its possible mechanisms of action. Current Microbiology 69, 192–201.

Xing Y, Li X, Xu Q, Yun J, Lu Y, Tang Y. 2011. Effects of chitosan coating enriched with cinnamon oil on qualitative properties of sweet pepper (*Capsicum annuum* L.). Food Chemistry 124, 1443–1450.

Yao X, Chu J, Wang G. 2009. Effects of selenium on wheat seedlings under drought stress. Biological Trace Element Research 130, 283–290.

Yao X, Jianzhou C, Xueli H, Binbin L, Jingmin L, Zhaowei Y. 2013. Effects of selenium on agronomical characters of winter wheat exposed to enhanced ultraviolet-B. Ecotoxicology and Environmental Safety 92, 320–326.

Zahedi SM, Abdelrahman M, Hosseini MS, Hoveizeh NF, Tran LSP. 2019. Alleviation of the effect of salinity on growth and yield of strawberry by foliar spray of selenium-nanoparticles. Environmental Pollution 253, 246–258.

Zhang CF, Tian SP. 2010. Peach fruit acquired tolerance to low temperature stress by accumulation of linolenic acid and N-acyl phosphatidylethanolamine in plasma membrane. Food Chemistry 120, 864–872.

Zhou N, Long H, Wang C, Yu L, Zhao M, Liu X. 2020. Research progress on the biological activities of selenium polysaccharides. Food and Function Journal 11, 4834.