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Chitosan–Zinc Oxide Nanoparticle Composite Coatings Preserve Postharvest Quality of 'Rosada' Cherry Tomato

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Abstract. **The postharvest quality of cherry tomato (*Solanum lycopersicum* L. var. *cerasiforme*) is often limited by rapid ripening and the early onset of senescence. Thus, there has been an increasing interest in exploring edible coatings to replace commercial wax-based and fungicides to preserve the postharvest quality of fresh produce. The current study assessed the effect of chitosan (CS) enriched with green-synthesized zinc oxide nanoparticles (ZnO-NPs) on preserving the postharvest quality of 'Rosada' cherry tomato fruit. The ZnO-NPs were synthesized using cancer bush (*Lessertia frutescens* L.) leaf extract and incorporated into CS (1.5% w/v) at 0%, 0.3%, 0.6%, and 0.9% to form the CS, CS + ZnO-NP 0.3%, CS + ZnO-NP 0.6%, and CS + ZnO-NP 0.9% composite coatings, respectively. Uniform fruit without any visible defect were gently dipped for 1 minute in the respective coatings, and the uncoated fruit were used as the control. Thereafter, fruit were air-dried at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity) for 1 hour. Fruit were then packed in open-top commercial boxes to assess postharvest quality during the 25 days of shelf life at room temperature. Incorporation of ZnO-NPs in CS coating effectively preserved postharvest quality of cherry tomato during shelf life compared with the postharvest quality of CS alone and the control. Chery tomato coated with ZnO-NPs had higher fruit texture and lower total sugars, thus reducing the sugar content, titratable acidity (TA), and ripening index (RI) during shelf life compared with those of cherry tomato coated with CS alone and the control. At the end of shelf life, fruit coated with 0.9% ZnO-NP and 0.6% ZnO-NP had a lower respiration rate, mass loss, total carotenoids, malondialdehyde, and hydrogen peroxide as well as high TA, ascorbic acid, total phenolic content, antioxidant activity, and antioxidant enzymes compared those of fruit coated with ZnO-NP 0.3%, CS, and control. Therefore, enriching the CS coating with ZnO-NPs using a range of 0.6% to 0.9% is recommended for preserving postharvest quality and extending the shelf life of cherry tomato at ambient conditions.**

Cherry tomato (*Solanum lycopersicum* L. var. *cerasiforme*) is rich in phytochemicals such as lycopene, β-carotene, and natural antioxidant compounds, including phenolic compounds and vitamins B, C, and E (Thitipramote et al. 2023; Yang et al. 2023). These bioactive compounds are associated with the reduced risk of cancer and cardiac diseases (Fibiani et al. 2022). Cherry tomato is highly perishable and has a relatively short postharvest life of approximately 5 to 7 d under ambient conditions (Akhtar et al. 2023). The postharvest quality of cherry tomato is mainly restricted by a high respiration rate that may accelerate the ripening and senescence processes and susceptibility to postharvest diseases, leading to fruit quality deterioration and economic loses (Buendía et al. 2019; Guo et al. 2020).

Accordingly, several postharvest techniques such as cold storage, fungicides, modified atmosphere (MA) packaging, and plastic film packaging have been effectively used to maintain the quality and prolong shelf life of horticultural produce (Liu et al. 2024; Vischetti et al. 2023). However, chilling injury may affect the quality of fruit if storage occurs below 12.5 °C for most fresh produce (Maghoumi et al. 2023). Synthetic fungicides are associated with environmental pollution, human health risks, and the proliferation of fungicide-resistant strains of the pathogens; these factors have led to the restrictions and bans of many synthetic fungicides (Ding et al. 2023). Thus, the use of the aforementioned postharvest technologies demonstrates the need to develop and explore cost-effective and environmentally friendly technologies to enhance quality and shelf life of fresh produce.

Among cost-effective postharvest technologies, preharvest bagging has the potential to accelerate maturity and improve postharvest quality fruit (Begum et al. 2023; Sohag et al. 2023). Previous studies have demonstrated that although preharvest bagging has the potential to improve the postharvest quality of horticultural produce, it reduces the shelf life of produce because of accelerated fruit maturity or ripening (Buthelezi et al. 2023; Sohag et al. 2023). In addition, the majority of the preharvest bagging materials are petroleum-based; therefore, they contribute to environmental pollution because they resist natural decomposition (Chand et al. 2020; Sohag et al. 2023). Thus, edible coatings are a cost-effective and eco-friendly alternative for preserving the postharvest quality of fresh produce.

Edible coatings generate a MA by creating a semipermeable barrier against O_2, CO_2, moisture, and solute movement, thus reducing respiration, water loss, and oxidation reaction rates (Pham et al. 2023). Edible coatings are based on natural biodegradable products such as polysaccharides, proteins, and lipids (Pham et al. 2023). Chitosan (CS) is a biodegradable biocompatible polymer that is obtained by the alkaline deacetylation of chitin, and it is a linear cationic polysaccharide with numerous applications in various fields, such as that focused on edible films and coatings (Gasilova et al. 2024; Wang et al. 2022). Additionally, CS is nontoxic and has antibacterial and antifungal or antimicrobial properties that are beneficial for food preservation (Gasilova et al. 2024). Previous studies have reported that chitosan-based edible coating improved postharvest quality and shelf life of various horticultural produce such as strawberries (*Fragaria ×ananassa* Duch.) (Saleem et al. 2021), black mulberry (*Morus nigra* L.) (Ojeda et al. 2021), pineapple (*Ananus comosus* L.) (Basumatary et al. 2021), mango (*Mangifera indica* L.) (Parvin et al. 2023), khasi mandarin (*Citrus reticulate* Blanco) (Goswami et al. 2024), apricot (*Prunus armeniaca* L.) (Algarni et al. 2022) and sweet cherry (*Prunus avium* L.) (Mujtaba et al. 2023). However, the restricted mechanical properties and gas and water vapor permeability of CS limit its application (Goswami et al. 2024). In addition, single chitosan-based coating has limited inhibition against microorganism and unsatisfactory barrier characteristics (Parvin et al. 2023). Consequently, functional properties such as antimicrobial activity and stability of CS can be enhanced by incorporating it with nano-materials such as metal oxides (Zafar and Iqbal 2024).

Nanoparticles have unique physical and chemical characteristics in addition to their antioxidant and antimicrobial activities (Zafar and Iqbal 2024). Among the metal oxides, zinc oxide nanoparticle (ZnO-NP) is a well-known inorganic nano-material that has attracted extensive attention because of its unique and excellent mechanical properties, barrier capacities, biocompatibility, and broad-spectrum antimicrobial performances (Lavinia et al. 2020). The ZnO-NPs have been

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recognized as safe coating materials by the US Food and Drug Administrations without potential threats to human health (Wu et al. 2019). Furthermore, techniques that use green-synthesized ZnO-NPs are considered cost-effective, environmentally friendly, and safe techniques that can be used instead of physical and chemical methods because they do not require toxic chemicals, high temperature, pressure, and energy (Anean et al. 2023; Ijaz et al. 2020). In addition, green-synthesized ZnO-NPs are promoted because of their antibacterial and antimicrobial characteristics because they comprise plant extracts such as cancer bush (*Lessertia frutescens* L.) (Ijaz et al. 2020; Zafar and Iqbal 2024). Cancer bush is rich in phytochemicals such as antioxidants, phenols, flavonoids, ascorbic acid (AA), and amino acids that act as capping and reducing agents and are capable of reducing metal salts into metal NPs (Buthelezi et al. 2023; Joshy et al. 2020). The application of CS as a fruit coating material has been widely explored, whereas using green-synthesized ZnO-NPs as a filter to reinforce the properties of CS has not been thoroughly investigated. Little is known about the effects of the application of green-synthesized ZnO-NPs to the CS matrix on postharvest quality of cherry tomato. Therefore, the current study evaluated the effects of CS-ZnO-NP composite coatings on preserving the postharvest quality and prolonging shelf life of 'Rosada' cherry tomato.

Materials and Methods

Plant materials. Cancer bush was used to green-synthesize ZnO-NPs. The plant material was obtained from Lavender Gardens Nursery, Pretoria, South Africa (lat. 25°39′43.1″S, long. 28°11′32.8″E, elevation 1339 m above sea level). The leaves were oven-dried (UTD-1295; LabTech, Johannesburg, South Africa) at 50 °C for 72 h and ground into a fine powder using a blender (RSH-080359 B; Game, Pretoria, South Africa) (Zafar and Iqbal 2024) and stored in clear low-density polyethylene resealable bags (thickness, 40 µm; width, 150 mm; length, 180 mm; West Pack Lifestyle, Pretoria, South Africa) until further use.

Biosynthesis of zinc oxide nanoparticles. The green synthesis of ZnO-NPs was performed following the method of Lakshmi et al. (2018), with minor modifications. Briefly, 10 g of dried cancer bush leaves was mixed with 200 mL of distilled water in a 500-mL beaker and then boiled at 60 °C for 10 min. The mixture was cooled at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity) and filtered through Miracloth®. The filtrate was stored in a refrigerator at 4 °C until further use.

Biologically synthesized ZnO-NPs was obtained by zinc acetate dihydrate [Zn $(CH_3CO_2)_2{\cdot}2H_2O$] and leaf extract of dry cancer bush leaves. Briefly, zinc nitrate dihydrate (2 M) was prepared in 100 mL of deionized water under constant agitation for 1 h at 80 °C using a hot plate magnetic stirrer (LC-MSB-HD; ThermoFisher Scientific, Randburg, South Africa). For pH maintenance, an aqueous solution of 0.05 M NaOH was slowly added during continuous agitation. After 1 h, 25 mL of cancer bush plant extract was gently added under continuous stirring for 2 h using a magnetic stirrer until a yellow–white precipitate was formed because of the reduction of zinc ions into ZnO-NPs caused by the excitation of surface plasmon vibrations (Lavinia et al. 2020). Then, a pale white solid pellet was obtained through centrifugation at 6000 rpm at 35 °C for 30 min, washed thrice with distilled water and once with ethanol, and oven-dried at 100 °C for 12 h. Thereafter, the pale white solid material was heated at 400 °C for 3 h in a muffle furnace using a digitally operated hot plate. The obtained powder material was ground and stored in an airtight container at ambient temperature for further use.

Fruit sampling. Matured (green stage) 'Rosada' cherry tomato fruit were obtained from ZZ2 commercial farm in Moeketsi, Limpopo, South Africa (lat. 23°53′10″S, long. 29°44′15″E, elevation 699 m above sea level). Thereafter, the harvested fruit were immediately transported in a well-ventilated vehicle to the Postharvest Laboratory of the University of Limpopo (lat. 25°36′54″S, long, 28°0′59.76″E, elevation 1310 m above sea level); later, the fruit were transported to the Botany Laboratory of the Sefako Makgatho Health Science University, Pretoria, South Africa (lat. 25°39′50.6″S, long. 28°08′01.1″E, elevation 1276 m above sea level) for further analysis. Fruit without any visible defects and with uniform color and size were selected for the experiment and disinfected by gently dipping in calcium hypochlorite solution (0.25 g/L distilled water) for 1 min and air-dried using a fan (Hi-Vel GHF001; Builders, Pretoria, South Africa) at ambient temperature for 30 min.

Preparation of coating treatments. Sequentially, CS (1.5% w/v) was mixed with canola oil (1% v/v) as a surfactant to improve adhesion to the fruit surface, Tween 20 (1% v/v) as an emulsifying agent, glycerol (1%) as a plasticizing agent, and ZnO-NP (0.3%, 0.6%, and 0.9%). A total of 1200 'Rosada' cherry tomato fruit without any visible defects were randomly selected and divided into four groups representing each composite coating and the control group. The control treatment was only washed in water containing calcium hypochlorite, while the three groups were further slowly dipped separately in CS, CS + ZnO-NP 0.3%, CS + ZnO-NP 0.6%, and CS ZnO-NP 0.9% for 1 min, followed by air drying at ambient temperature for 1 h. Generally, each treatment consisted of three replicates of 100 fruit per replicate packed in 6-kg (38.60 × 24.20 × 11.80 cm) open-top commercial boxes. Fruit postharvest quality data were collected at 5-d intervals during the 25 d of shelf life at ambient temperature.

Respiration rate. Five 'Rosada' cherry tomato fruit per treatment were placed separately in an airtight 352-mL consol jar for 20 min at ambient conditions to measure the respiration rate. A gas sample was measured for O_2 and CO_2 analyses using a portable gas analyzer (YESAIR 8-Channel IAQ Monitor; Gasonic, Calgary, Canada). The respiration rate was calculated according to Tesfay and Magwaza (2017) and expressed as nmol $CO_2\ kg^{-1}{\cdot}s^{-1}$.

Mass loss. The initial mass of individual fruit was determined using an electronic scale (Mettler Toledo, Model ML3002E; United Scientific, Johannesburg, South Africa). The fruit were weighed at harvest and 5-d intervals of sampling. Mass loss was calculated according to the method of De Bruno et al. (2023) using Eq. [1].

$$\text{Mass loss (\%)} = \frac{\text{Initial fruit mass} - \text{Final fruit mass}}{\text{Initial fruit mass}} \times 100 \quad [1]$$

Fruit texture. Cherry tomato fruit texture was assessed according to the method of López-Ramírez and Duarte-Sierra (2020) using a texture meter (Agrosta® texture analyzer; Selectech, Pretoria, South Africa) fitted with a 35-mm compression probe. Five fruits per treatment were used, and the test was run per fruit aligned horizontally on the compression platform. The textural profile was interpreted using force (N) and distance (mm) as the fundamental variables. The operating settings of the instrument were as follows: 1 mm/s probe speed and 0.30 N force.

Determination of the total sugar content. The total sugar content was determined according to the phenol–sulfuric acid method (Mandal et al. 2018). Chery tomato fruit samples (0.3 g) were homogenized in 20 mL of 70% ethanol (Sigma-Aldrich, St. Louis, MO, USA), and 1 mL of the ethanolic extract was treated with 1 mL of 5% phenol (w/v) (Steri OL PTY. Ltd., Johannesburg, South Africa) and 5 mL of 98% sulfuric acid (Shalom Laboratory Supplies C.C., Durban, South Africa). The absorbance of the developed color was read at 490 nm with a spectrophotometer (ultraviolet 1600 PC; Shimadzu, Milan, Italy), and the total sugar content was calculated based on a standard curve generated using a pure glucose solution. Results were expressed as mg glucose equivalent per gram of fruit fresh weight (FW).

Reducing sugar content. The reducing sugar content was determined following the method of La et al. (2021) using the dinitrosalicylic acid (DNS) method. The DNS reagent was prepared by dissolving 1.0 g of DNS (Sigma-Aldrich), 0.2 g of crystalline phenol (Steri OL PTY. Ltd.), and 0.1 g of sodium sulfate (Sigma-Aldrich) in 100 mL of 1% NaOH (Merck PTY. Ltd., Modderfontein, South Africa) by stirring at ambient temperature. Then, 1 mL of the alcohol extract was added in a test tube containing 3 mL of DNS reagent. Afterward, the mixture was heated in a boiling water bath for 5 min and cooled at room temperature. Thereafter, a total of 1 mL of 40% Rochelle salt (sodium–potassium tartrate salt) (Sigma-Aldrich) solution was added after the color had developed. The final absorbance of the set color was read at 575 nm using a spectrophotometer (ultraviolet 1600 PC; Shimadzu).

The reducing sugar content results were expressed as mg glucose equivalent per g of FW.

Titratable acidity and ripening index. Titratable acidity (TA) was assessed according to the method of Magri et al. (2024), with minor modifications. The TA content was determined using a TA meter (Orion-Star T910 pH Titrator; ThermoFisher Scientific, Johannesburg, South Africa). Briefly, 2 mL of cherry tomato juice was mixed with 90 mL of distilled water and titrated to pH 8.2 with 0.1 M NaOH (Steri OL PTY. Ltd.). The results were expressed as citric acid (%) equivalent. The ripening index (RI) of cherry tomato fruit was determined as a ratio of total soluble solids and TA (Grande Tovar et al. 2019).

Total carotenoid content. The total carotenoid content was assessed following the method of Mondal et al. (2022), with some changes. A total of 0.5 g of fruit tissue was homogenized in 20 mL of 80% acetone in a dark glass bottle at ambient temperature. The absorbance was recorded at 480 nm and 510 nm using the spectrophotometer (ultraviolet 1600 PC; Shimadzu). The total carotenoid content was calculated according to Hasan et al. (2022) and expressed as $\mu g \cdot g^{-1}$ of FW.

Ascorbic acid content. The AA content was assessed using the method of Castro-Cegrí et al. (2023), with minor modifications. Briefly, 2 g of the cherry tomato sample, 4 mL of metaphosphoric acid [8% (w/v)] and 4 mL of acetic acid [3% (v/v)] were homogenized and centrifuged (Hermle Labortechnik, Wehingen, Germany) at 8000 rpm for 5 min. Afterward, 2 mL of acetic acid was added and centrifuged again at 8000 rpm for 5 min. Thereafter, the absorbance of samples was measured at 245 nm using a spectrophotometer (ultraviolet-1600 PC; Shimadzu) under dim light. The AA concentration was calculated from a standard curve plotted using known concentrations of AA and expressed as mg/kg of FW.

Total phenol content. The total phenol content (TPC) was determined using the Folin–Ciocalteu colorimetric method reported by Castro-Cegrí et al. (2023), with minor modifications. A total of 1 g of cherry tomato fruit tissue was mixed with 10 mL of 80% methanol (v/v) and centrifuged for 10 min at 4000 g_n. A reaction mixture was prepared by adding 300 µL of methanolic extract to a solution prepared from 1.2 mL of sodium carbonate (7%) and 1.5 mL of Folin–Ciocalteu reagent (10%). Thereafter, the mixture was incubated in the dark at ambient temperature for 1 h. The supernatant absorbance was measured at 760 nm using a spectrophotometer (ultraviolet 1600 PC; Shimadzu). Gallic acid was used as the standard, and the results were expressed as mg gallic acid equivalent (GAE) 100 g^{-1} FW.

Free radical scavenging activity and ferric reducing antioxidant power. Free radical scavenging activity (RSA) was determined according to Dulta et al. (2022), with some modifications. Briefly, 1 g of the cherry tomato sample was mixed with 10 mL of 80% ethanol (v/v). After shaking (Orbital shaker 261; Labotec PTY. Ltd., Durban, South Africa) for 1 h and filtration using a Miracloth®, the reaction mixture was prepared from 1 mL of fruit ethanolic extract and 2 mL of DPPH (0.1 mM). Afterward, the solution was incubated in the dark at room temperature for 30 min (21 ± 1 °C). Thereafter, the absorbance of the reaction mixture was read at 520 nm using a spectrophotometer (ultraviolet 1600 PC; Shimadzu). Trolox was used as the standard, and free RSA was expressed as mM Trolox 100 g^{-1} FW.

Ferric reducing antioxidant power (FRAP) was quantified following the method of Hasan et al. (2022), with some modifications. The FRAP reagent was prepared by using acetate buffer (pH 3.6), 20 mM iron (III) chloride solution, and 10 mM TPTZ [2,4,6-Tris(2-pyridyl)-s-triazine] solution in 40 mM HCl in a ratio of 10:1:1 (v/v), respectively. Then, 100 µL of cherry tomato extract was allowed to react with 500 µL of FRAP working solution freshly prepared by mixing 300 mM acetate buffer (pH 3.6), 20 mM $FeCl3 \cdot 6H_2O$ solution, and 10 mM TPTZ solution in a ratio of 10:1:1 (v/v/v) and 2 mL distilled water for 1 h in the dark at ambient temperature. The results were expressed as mM Trolox 100 g^{-1} FW.

Malondialdehyde content. The malondialdehyde (MDA) content was determined based on the method described by Rasouli et al. (2019), with minor changes. A total of 3 g of the cherry tomato sample was mixed with 15 mL of 10% trichloroacetic acid and centrifuged for 20 min at 10,000 g_n for 20 min. Afterward, 2 mL of supernatant was mixed with 2 mL of 2-thiobarbituric acid (0.6% w/v). Then, the reaction mixture was heated for 20 min at 100 °C in a thermostatic water bath (DK-2000-IIIL; HINOTEK, Ningbo, China). The mixture was immediately allowed to cool on ice for 15 min and then centrifuged at 10,000 g_n for 20 min. The absorbance was recorded at 450 nm, 532 nm, and 600 nm using a spectrophotometer (ultraviolet 1600 PC; Shimadzu). The MDA content was calculated according to a calibration curve and expressed as $\mu mol \cdot kg^{-1}$ FW.

Hydrogen peroxide content. The hydrogen peroxide (H_2O_2) content was assessed following the method of Jacomassi et al. (2022), with some modifications. A total of 1 g of cherry tomato fruit tissue was mixed with 0.1% (w/v) trichloroacetic acid (1:4, w/v) and centrifuged at 10,000 g_n for 20 min. Subsequently, the supernatant (0.5 mL) was mixed with 0.5 mL of phosphate buffer (10 mM, pH 7.0) and 1 mL of potassium iodide (1 M). The absorbance was read at 390 nm using a spectrophotometer (ultraviolet 1600 PC; Shimadzu), and the concentration of H_2O_2 was expressed as $\mu mol \cdot kg^{-1}$ FW.

Antioxidant enzyme activities. Enzymes activities were assessed according to the method used by Castro-Cegrí et al. (2023). Frozen fruit tissue (1 g) was ground with 2 mL of phosphate buffer (100 mM, pH 7.2). Then, the homogenate was centrifuged at 10,000 g_n for 15 min. Thereafter, the supernatant obtained from the centrifuge was used for enzyme analyses.

Catalase activity. Catalase (CAT) activity was assessed according to Badawy et al. (2017), with some changes. Briefly, 100 µL of enzyme extract, 2.4 mL of phosphate buffer (50 mM, pH 5.0), and 500 µL of H_2O_2 (20 mM) was added in a cuvette. Thereafter, the change of absorbance at 240 nm was read using a spectrophotometer (ultraviolet 1600 PC; Shimadzu), and mean values were used to calculate CAT activity (extinction coefficient, 39.4 $mM^{-1} \cdot cm^{-1}$). The CAT activity was expressed as $U \cdot mg^{-1}$ protein.

Superoxide dismutase activity. Superoxide dismutase (SOD) activity was determined following the method of Das et al. (2022), with minor changes. Briefly, 100 µL of enzyme extract, 1 mL of distilled water, 500 µL of phosphate buffer (50 mM, pH 5.0), 100 µL of nitro blue tetrazolium (NBT) (20 µM), 200 µL of methionine (22 µM), 200 µL of Triton-X (0.1 µM), and 100 µL of riboflavin (0.60 µM) were added in a test tube that was exposed to a ultraviolet-light lamp for 10 min. Afterward, the absorbance was recorded at 560 nm using a spectrophotometer (ultraviolet 1600 PC; Shimadzu). One unit of SOD activity was determined as the amount of enzyme causing 50% inhibition of NBT photoreduction, and SOD activity was expressed as $U \cdot mg^{-1}$ protein.

Statistical analysis. The experiment was performed using a complete randomized design with three replicates. The collected data were subjected to an analysis of variance using GenStat statistical software (GenStat®, 18.1 edition; VSN International, Hemel, Hempstead, UK). Mean separation was performed using Fisher's least significant difference at a 5% level of significance.

Results and Discussion

Respiration rate. The respiration rate of both coated and uncoated 'Rosada' cherry tomato fruit gradually ($P < 0.001$) increased during shelf life of 25 d at ambient temperature (Fig. 1), which indicated an increase in the fruit metabolic activity (Formiga et al. 2022). Increasing the concentration of ZnO-NPs in the CS matrix resulted in a decreased respiration rate. Uncoated fruit had the highest respiration rate at the end of shelf life (22.21 $nmol \cdot kg^{-1} \cdot s^{-1}$), followed by CS (11.25 $nmol \cdot kg^{-1} \cdot s^{-1}$), CS + ZnO-NP 0.3% (9.25 $nmol \cdot kg^{-1} \cdot s^{-1}$), CS + ZnO-NP 0.6% (7.25 $nmol \cdot kg^{-1} \cdot s^{-1}$), and CS + ZnO-NP 0.9% (the lowest respiration rate of 5.01 $nmol \cdot kg^{-1} \cdot s^{-1}$). This can be attributed to the ability of polysaccharide-based edible coatings to generate a MA by creating a semipermeable barrier against O_2, CO_2, moisture, and solute movement (Perez-Vazquez et al. 2023); therefore, the coated 'Rosada' cherry tomato fruit had a significantly lower respiration rate compared with that of uncoated fruit (Fig. 1). The improved effectiveness of ZnO-NPs in the CS matrix to decrease the respiration rate compared with the CS coating treatment alone could be attributed to the composite coating being

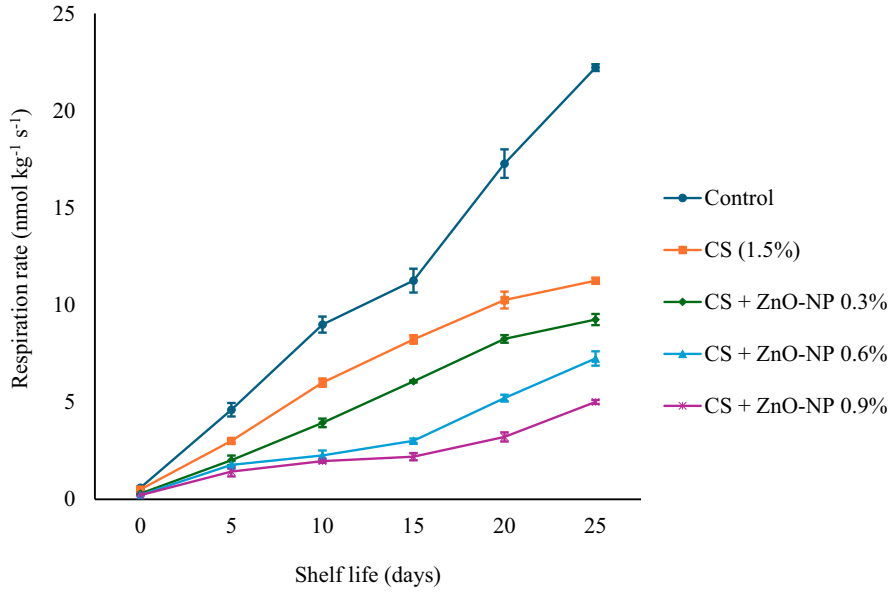

Fig. 1. Changes in the respiration rate of 'Rosada' cherry tomato fruit treated with chitosan (CS) and CS + nanoparticle (NP) coatings during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity). ZnO-NP = zinc oxide nanoparticle. Vertical bars represent the standard error of the mean value (n = 3).

able to more efficiently cover the lenticels and limit gaseous exchange because of improved gas permeability properties and higher membrane integrity (Dulta et al. 2022). The addition of ZnO-NPs into polysaccharide-based edible coatings can efficiently reinforce mechanical properties, barrier capacities, and anti-bio-contamination of the composite coating (Anean et al. 2023). Our results are similar to those of Hmmam et al. (2023), who reported that 0.5% of alginate-based ZnO-NPs effectively inhibited the respiration rate of 'Kiett' mango fruit during the 28 d of cold storage (13 °C) and 7 d of shelf life at room temperature compared with alginate-based coating alone and uncoated fruit.

Mass loss. Mass loss for both coated and uncoated 'Rosada' cherry tomato fruit gradually ($P < 0.001$) increased as the shelf life increased (Table 1). Typically, mass loss occurs in climacteric fruit during postharvest storage because of its respiration and transpiration processes, transference of humidity, and oxidation processes (Buendía et al. 2019). However, the application of edible coatings effectively reduced mass loss of cherry tomato fruit compared with the control. The uncoated fruit had the highest mass loss of 30.10%, whereas fruit coated with CS had reduced mass loss of 14.25%, followed by CS + ZnO-NP 0.3% (11.25%), CS + ZnO-NP 0.6% (6.91%), and CS + ZnO-NP 0.9% (the lowest wight loss of 4.29%) (Table 1). This reduction in mass loss could be attributed to the effects of the coatings as a semipermeable barrier against O_2, CO_2, moisture, and solute movement, thus reducing the respiration rate, water loss, and oxidation reaction rate (Akhtar et al. 2023; Goswami et al. 2024). Álvarez et al. (2021) reported that mass loss higher than 5% may restrict the storability of cherry tomato. In our study, CS + ZnO-NP treatments further decreased mass loss; the CS + ZnO-NP 0.9% treatment had the lowest mass loss (less than 4.29%) compared with that of other treatments and the control. The reduction of mass loss with the addition of ZnO-NPs to the CS coating could be attributed to the antimicrobial properties of ZnO, which reduced the loss of carbon atoms caused by the respiration process (Dulta et al. 2022). The low mass loss in coated fruit is correlated with a decrease in water loss caused by a reduction in transpiration and respiration rates (Akhtar et al. 2023, 2024). This is further supported by the results of this study that showed that coated fruit, and especially fruit coated with CS + ZnO treatments, experienced a reduced respiration rate compared with that of fruit with the CS coating alone and that of the control (Fig. 1).

Fruit texture. Fruit texture of both coated and uncoated 'Rosada' cherry tomato fruit significantly ($P < 0.001$) declined with increasing shelf life (Table 1). However, it was observed that fruit texture decreased more slowly with all treatments compared with the control. At the end of shelf life, 'Rosada' cherry tomato fruit coated with CS + ZnO-NP 0.9% showed an optimum effect of retaining fruit texture compared with other treatments. Hence, the highest fruit texture (19.92 N) was observed for cherry tomato coated with CS + ZnO-NP 0.9%, followed by cherry tomato coated with CS + ZnO-NP 0.6% (17.92 N), CS + ZnO-NP 0.3% (17.89 N), and CS (14.91 N); the lowest fruit texture (6.92 N) was noted in uncoated fruit. Fruit softening is caused by the deterioration of the cell structure, cell wall composition, and intracellular materials (Akhtar et al. 2024). The degradation of the cell wall leads to the deterioration of the physical structure within the cells, rupturing of the cell membrane, and leakage of its content, thus accelerating fruit tissue damage (Formiga et al. 2022). The maintenance of fruit texture could be attributed to the reduced respiration and other ripening processes during storage (Kathirvelu et al. 2024). This is further supported by the results of this study that showed that coated fruit had a reduced respiration rate during shelf life of 25 d compared with that of the control (Fig. 1). Furthermore, reduced fruit texture of coated fruit could be attributed to the ability of the coatings to limit the availability of O_2 and high level of CO_2, resulting in reduced activity of cell wall degradation enzymes such as polygalacturonase, pectin methylesterase, galactosidase, and cellulose (Álvarez et al. 2021; Ruelas-Chacon et al. 2017). The reduction of cell wall-degrading enzymes results in increased levels of pectin, which is an essential substance involved in the mechanical strength of the cell wall (Akhtar et al. 2024). The retention of cherry tomato texture in coated fruit can be related to the ability of the coating treatments to control mass loss (Álvarez et al. 2021), which is consistent with the results of this study, because coated fruit had significantly lower mass loss compared with uncoated fruit (Table 1). Moreover, the maintenance of cherry tomato fruit texture coated with CS + ZnO-NPs during shelf life compared with CS alone could be attributed the influence of ZnO-NPs on the barrier ability of the coating material, resulting in firmer fruit during the shelf life (La et al. 2021).

Total and reducing sugar contents. Changes in the total and reducing sugar contents of 'Rosada' cherry tomato fruit during 25 d of shelf life at ambient temperature are shown in Table 1. The total and reducing sugar contents of both coated and uncoated cherry tomato significantly ($P < 0.001$) increased during shelf life. This increase of sugars could be attributed to fruit ripening caused by the hydrolysis of polysaccharides leading to the production of soluble sugars during shelf life (Álvarez et al. 2021; Tchouala Tazo et al. 2023). Significant slow increases of the total and reducing sugar contents were observed in coated cherry tomato fruit, whereas a rapid increase was noted in uncoated fruit during shelf life. Although the CS + ZnO coatings were not statistically significant from each other, they had the lowest total and reducing sugar contents, respectively, at the end of shelf life compared with CS (109.22 and 80.27 mg·g^{-1} FW) and the control (159.99 and 99.79 mg·g^{-1} FW): CS + ZnO-NP 0.9%, 86.99 and 65.57 mg·g^{-1} FW; CS + ZnO-NP 0.6%, 88.91 and 67.25 mg·g^{-1} FW; and CS + ZnO-NP 0.3%, 90.99 and 69.91 mg·g^{-1} FW. The faster accumulation of sugars in control fruit during shelf life (Table 1) could be attributed to faster metabolic processes such as respiration and transpiration, which accelerate ripening of fresh produce (Tchouala Tazo et al. 2023). This is further supported by the results of this study that showed that untreated fruit had a higher respiration rate (Fig. 1), which may have promoted mass loss and firmness loss (Table 1) during shelf life compared with treated fruit. The reduced sugar contents of coated fruit could be attributable to the coating

Table 1. The effect of chitosan-zinc oxide nanoparticles composite coating on the physico-chemical properties of 'Rosada' cherry tomato fruit during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% RH).

Shelf life (days)	Treatments	Mass loss (%)	Texture (N)	Total sugars ($mg \cdot g^{-1}$ FW)	Reduced sugars ($mg \cdot g^{-1}$ FW)	Titratable acidity (citric acid %)	Ripening index (TSS/TA)
0	Control	0.00 ± 0.00 a	29.91 ± 0.12 lm	30.11 ± 0.12 a	30.08 ± 0.36 a	1.91 ± 0.53 o	0.40 ± 0.02 a
0	CS (1.5%)	0.00 ± 0.00 a	29.94 ± 0.10 lm	30.22 ± 0.06 a	30.05 ± 0.02 a	1.89 ± 0.06 no	0.39 ± 0.00 a
0	CS + ZnO-NP 0.3%	0.00 ± 0.00 a	29.99 ± 0.15 lm	30.21 ± 0.04 a	30.04 ± 0.03 a	1.84 ± 0.05 mno	0.38 ± 0.01 a
0	CS + ZnO-NP 0.6%	0.00 ± 0.00 a	30.05 ± 0.10 m	30.19 ± 0.02 a	30.03 ± 0.02 a	1.84 ± 0.01 mno	0.38 ± 0.01 a
0	CS + ZnO-NP 0.9%	0.00 ± 0.00 a	30.10 ± 0.25 m	30.19 ± 0.01 a	30.01 ± 0.01 a	1.82 ± 0.01 lmno	0.38 ± 0.01 a
5	Control	13.92 ± 0.44 k	27.55 ± 0.52 j	50.99 ± 1.10 e	45.99 ± 0.69 g	1.52 ± 0.05 ijkl	1.19 ± 0.06 cde
5	CS (1.5%)	3.82 ± 0.12 de	29.23 ± 0.42 klm	40.99 ± 0.16 c	40.98 ± 0.07 f	1.22 ± 0.01 fghi	0.91 ± 0.03 bcde
5	CS + ZnO-NP 0.3%	2.91 ± 0.10 cd	29.18 ± 0.24 klm	38.01 ± 0.54 bc	35.51 ± 0.38 bc	1.62 ± 0.02 jklmno	0.50 ± 0.02 ab
5	CS + ZnO-NP 0.6%	2.23 ± 0.18 c	29.01 ± 0.28 kl	37.04 ± 0.06 b	34.01 ± 0.19 b	1.64 ± 1.64 jklmno	0.49 ± 0.01 ab
5	CS + ZnO-NP 0.9%	1.05 ± 0.10 ab	28.25 ± 0.51 jk	37.01 ± 0.09 b	33.91 ± 0.10 b	1.74 ± 0.01 klmno	0.45 ± 0.03 ab
10	Control	15.93 ± 0.54 l	21.36 ± 0.20 f	79.99 ± 0.46 h	59.98 ± 0.07 kl	1.20 ± 0.06 efgh	3.92 ± 0.47 i
10	CS (1.5%)	4.81 ± 0.20 ef	24.93 ± 0.61 h	60.22 ± 0.32 f	48.01 ± 0.21 gh	1.43 ± 0.11 ghij	1.91 ± 0.10 f
10	CS + ZnO-NP 0.3%	3.05 ± 0.05 cd	26.08 ± 0.15 i	47.21 ± 0.23 d	39.91 ± 0.56 ef	1.57 ± 0.06 jklm	0.91 ± 0.02 bcde
10	CS + ZnO-NP 0.6%	2.90 ± 0.08 cd	26.01 ± 0.18 i	45.25 ± 0.14 d	38.25 ± 0.37 de	1.59 ± 0.01 jklmn	0.89 ± 0.06 bcd
10	CS + ZnO-NP 0.9%	1.99 ± 0.04 bc	27.25 ± 0.43 j	44.29 ± 0.31 d	37.21 ± 0.37 cd	1.61 ± 0.02 jklmn	0.84 ± 0.02 abc
15	Control	20.21 ± 0.33 m	17.87 ± 0.78 d	99.99 ± 0.26 k	77.81 ± 0.52 o	0.84 ± 0.01 bcd	7.21 ± 0.41 l
15	CS (1.5%)	7.54 ± 0.23 h	21.25 ± 0.35 f	80.26 ± 0.51 h	60.22 ± 0.46 l	1.10 ± 0.01 def	3.09 ± 0.09 h
15	CS + ZnO-NP 0.3%	5.02 ± 0.32 fg	24.25 ± 0.48 h	70.22 ± 0.27 g	50.22 ± 0.41 i	1.42 ± 0.12 ghij	1.91 ± 0.09 f
15	CS + ZnO-NP 0.6%	3.85 ± 0.12 de	24.99 ± 0.22 h	69.27 ± 0.48 g	49.91 ± 0.17 hi	1.50 ± 0.01 hijk	1.38 ± 0.04 e
15	CS + ZnO-NP 0.9%	2.39 ± 0.27 c	24.92 ± 0.16 h	68.45 ± 0.26 g	48.29 ± 0.15 hi	1.54 ± 0.04 jklm	1.33 ± 0.05 de
20	Control	24.29 ± 0.56 n	13.65 ± 0.51 b	150.27 ± 2.89 m	93.75 ± 2.69 q	0.64 ± 0.03 ab	8.92 ± 0.06 m
20	CS (1.5%)	10.15 ± 0.19 i	17.35 ± 0.33 d	100.01 ± 0.15 k	74.29 ± 0.46 n	0.88 ± 0.02 bcd	5.01 ± 0.03 j
20	CS + ZnO-NP 0.3%	8.01 ± 0.51 h	20.03 ± 0.21 e	79.21 ± 0.54 h	60.25 ± 0.40 l	0.90 ± 0.01 bcde	2.99 ± 0.11 h
20	CS + ZnO-NP 0.6%	6.01 ± 0.13 g	20.91 ± 0.19 ef	78.22 ± 0.14 h	57.91 ± 0.60 jk	1.19 ± 0.04 efg	2.42 ± 0.30 g
20	CS + ZnO-NP 0.9%	4.01 ± 0.16 def	22.93 ± 0.46 g	77.99 ± 0.02 h	56.79 ± 0.12 j	1.20 ± 0.02 efgh	2.09 ± 0.12 fg
25	Control	30.01 ± 1.16 o	6.92 ± 0.57 a	159.90 ± 1.14 n	99.79 ± 0.43 r	0.42 ± 0.06 a	9.94 ± 0.10 n
25	CS (1.5%)	14.52 ± 1.23 k	14.91 ± 0.17 c	109.22 ± 5.34 l	80.27 ± 0.41 p	0.64 ± 0.03 ab	6.71 ± 0.36 k
25	CS + ZnO-NP 0.3%	12.01 ± 0.52 j	17.89 ± 0.47 d	90.99 ± 0.54 j	66.91 ± 2.54 m	0.75 ± 0.03 bc	4.31 ± 0.36 i
25	CS + ZnO-NP 0.6%	9.62 ± 0.31 i	17.92 ± 0.13 d	88.91 ± 0.41 ij	67.25 ± 0.50 m	0.81 ± 0.05 bcd	4.11 ± 0.08 i
25	CS + ZnO-NP 0.9%	6.01 ± 0.14 g	19.92 ± 0.54 e	86.99 ± 0.54 i	65.57 ± 0.66 m	1.01 ± 0.02 cdef	4.09 ± 0.09 i

Mean values with different letters in the same column are statistically significant according to Fisher's least significant difference test at $P < 0.05$ (mean values ± standard error; $n = 3$).

CS = chitosan; RH = relative humidity; TA = titratable acidity; TSS = total soluble solids; ZnO-NP = zinc oxide nanoparticle.

film inhibiting the transition of complex carbohydrates into simple sugars (Akhtar et al. 2023). Similar results were also reported by Hmmam et al. (2023), who observed a decrease in both total and reducing sugars in mango fruit coated with alginate-ZnO-NPs during 28 d of storage at ambient temperature compared with control.

Titratable acidity. A gradual ($P < 0.001$) decrease of TA was observed in both coated and uncoated cherry tomato fruit during shelf life (Table 1). However, coated fruit showed a delayed degradation of TA with CS + ZnO-NP 0.9% treatment, showing a decline of 1.82% to 1.01%, followed by CS + ZnO-NP 0.6% (1.84% to 0.81%), CS + ZnO-NP 0.3% (1.84% to 0.75%), CS (1.89% to 0.64%), and control (1.91% to 0.42%) during shelf life. The decline in cherry tomato acidity could be attributed to ripening and is associated with a reduction in organic acids, which are primary substrates for the respiration process of climacteric fruits (Al-Hilifi et al. 2024; Saleem et al. 2021). A delay in TA decline in coated fruit could be attributable to the coating treatments reducing the amount of organic acid in cherry tomato fruit by inhibiting enzyme activity linked to organic acid metabolism and slowing the rate of acid degradation in cherry tomato during shelf life (Magri et al. 2024; Saleem et al. 2021).

Citric, malic, and oxalic acids are the three main organic acids of cherry tomato (Álvarez et al. 2021). Although TA declined during shelf life for all treatments, CS + ZnO-NPs coating had a higher TA value throughout the storage days because of slower organic acids consumption (Anean et al. 2023; Formiga et al. 2022). Our results are in agreement with those of Li et al. (2019), who reported that banana (*Musa paradisiaca* L.) fruit coated with soybean (*Glycine max* L.) protein isolate + plant-sourced cinnamaldehyde + ZnO-NPs had higher TA values during 7 d of shelf life at room temperature compared with those of uncoated fruit. This could be attributed to the effectiveness of the coating film to slow the fruit respiration rate to some extent, thus inhibiting the consumption of TA (Li et al. 2019).

Ripening index. The RI of all treatments gradually ($P < 0.001$) increased with increasing shelf life days (Table 1). Although all treatments showed a delayed increase of RI compared with control, a nonsignificant statistical difference was observed between CS + ZnO-NPs coatings during shelf life compared with the CS treatment and control. Among treatments, CS + ZnO-NP 0.9% had a lower RI of 4.09, followed by CS + ZnO-NP 0.6% (4.11), CS + ZnO-NP 0.3% (4.31), and CS (6.71) at the end of shelf life. This could be attributable to the semipermeable coating film that formed on the surface of the fruit, causing the modification of internal atmosphere and the endogenous CO_2 and O_2 concentrations of the fruit, thus slowing ripening (Magri et al. 2024). Uncoated fruit showed a rapid increase of RI during shelf life and at day 25 of shelf life, and the control had a higher RI (9.94) compared to that of coated fruit. This indicates the increased fruit ripening rate of control fruit (Al-Hilifi et al. 2024). The ratio of total soluble solids to TA is known to be an indicator of fruit quality; the sweet taste is the result of increased hydrolysis of polysaccharides (primarily starch), reduced acidity, and accumulation of sugars, resulting in an excellent sugar-to-acid ratio (Buthelezi et al. 2023).

Total carotenoid content. Carotenoids give the tomato fruit its characteristic red color (Tzortzakis et al. 2019). During ripening, the color of tomato changes from green to red because of the loss of chlorophyll and synthesis of carotenoids (Flores-López et al. 2023; Tzortzakis et al. 2019). In all treatments, the total carotenoids contents significantly ($P < 0.001$) increased during shelf life (Table 2). However, this increase was slower in coated cherry tomato fruit compared with that in the control. The total carotenoids content was significantly ($P < 0.001$) lower in fruit coated with CS + ZnO-NP 0.9% (57.89 $\mu g \cdot g^{-1}$ FW) and CS + ZnO-NP 0.6% (58.91 $\mu g \cdot g^{-1}$ FW), followed by CS + ZnO-NP 0.3% (68.01 $\mu g \cdot g^{-1}$ FW) and CS (75.92 $\mu g \cdot g^{-1}$ FW). Therefore, CS + ZnO-NP coatings effectively delayed the accumulation of total carotenoids at the end of shelf life compared with CS treatment alone. The uncoated cherry tomato fruit had higher total carotenoids contents during shelf life compared with those

Table 2. Effects of the chitosan-zinc oxide nanoparticle composite coatings on the phytochemical traits of 'Rosada' cherry tomato fruit during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% RH).

Shelf life (days)	Treatments	Total carotenoids (ug·g^{-1} FW)	Ascorbic acid (mg/kg FW)	Total phenolic content (mg GAE 100 g^{-1} FW)	RSA (mM Trolox 100 g^{-1} FW)	FRAP (Mm Trolox 100 g^{-1} FW)
0	Control	44.21 ± 1.56 a	13.02 ± 0.01 d	240.91 ± 1.13 e	153.24 ± 0.21 h	101.94 ± 0.06 g
0	CS (1.5%)	44.20 ± 0.38 a	13.04 ± 0.01 d	240.92 ± 0.54 e	153.24 ± 0.21 h	101.94 ± 0.07 g
0	CS + ZnO-NP 0.3%	44.21 ± 0.47 a	13.04 ± 0.01 d	240.90 ± 0.53 e	153.26 ± 0.20 h	101.95 ± 0.07 g
0	CS + ZnO-NP 0.6%	44.18 ± 0.61 a	13.04 ± 0.01 d	240.90 ± 0.53 e	153.25 ± 0.20 h	101.96 ± 0.09 g
0	CS + ZnO-NP 0.9%	44.21 ± 0.42 a	13.04 ± 0.01 d	240.90 ± 0.53 e	153.25 ± 0.20 h	101.96 ± 0.05 g
5	Control	64.99 ± 0.36 k	22.43 ± 0.39 k	260.97 ± 0.53 g	148.03 ± 0.14 g	109.29 ± 0.55 h
5	CS (1.5%)	55.29 ± 0.20 g	18.99 ± 0.25 j	279.91 ± 0.43 h	166.91 ± 0.11 j	119.94 ± 0.67 i
5	CS + ZnO-NP 0.3%	49.25 ± 0.42 de	16.93 ± 0.07 h	289.21 ± 0.42 i	173.91 ± 0.56 m	128.92 ± 0.26 j
5	CS + ZnO-NP 0.6%	46.91 ± 0.05 bc	15.28 ± 0.47 fg	290.92 ± 0.58 i	179.91 ± 0.13 o	135.39 ± 0.65 l
5	CS + ZnO-NP 0.9%	46.02 ± 0.56 ab	15.01 ± 0.01 f	300.01 ± 0.19 j	179.99 ± 0.14 o	140.41 ± 0.27 n
10	Control	68.09 ± 1.14 l	25.95 ± 0.04 m	238.91 ± 0.52 e	140.31 ± 0.34 f	100.04 ± 0.35 f
10	CS (1.5%)	62.91 ± 0.47 j	21.92 ± 0.50 k	290.41 ± 0.28 i	171.28 ± 0.23 l	129.09 ± 0.62 j
10	CS + ZnO-NP 0.3%	53.02 ± 0.27 f	19.03 ± 0.11 j	299.91 ± 0.25 j	184.91 ± 0.14 q	131.98 ± 0.18 k
10	CS + ZnO-NP 0.6%	49.92 ± 0.06 de	17.91 ± 0.10 i	312.92 ± 1.56 k	186.25 ± 0.62 r	145.25 ± 0.40 op
10	CS + ZnO-NP 0.9%	48.22 ± 0.43 cd	17.09 ± 0.35 h	329.95 ± 8.52 l	187.01 ± 0.62 rs	145.92 ± 0.62 p
15	Control	74.22 ± 2.29 n	29.99 ± 0.08 n	229.95 ± 0.46 d	124.21 ± 0.61 d	91.08 ± 0.56 e
15	CS (1.5%)	68.26 ± 0.63 l	24.95 ± 0.05 l	300.01 ± 0.21 j	179.91 ± 0.15 o	102.21 ± 0.45 g
15	CS + ZnO-NP 0.3%	57.92 ± 0.95 hi	21.91 ± 0.18 k	312.02 ± 0.82 k	187.77 ± 0.46 s	138.29 ± 0.72 m
15	CS + ZnO-NP 0.6%	50.98 ± 0.12 e	19.03 ± 0.51 j	330.21 ± 0.42 l	191.22 ± 0.43 t	150.22 ± 0.43 q
15	CS + ZnO-NP 0.9%	50.97 ± 0.48 e	18.99 ± 0.46 j	339.92 ± 0.45 m	192.91 ± 0.32 u	151.92 ± 0.58 r
20	Control	80.92 ± 0.47 o	12.99 ± 0.08 d	209.26 ± 0.38 b	101.02 ± 0.07 b	71.02 ± 0.52 b
20	CS (1.5%)	72.21 ± 0.78 m	14.07 ± 0.37 e	250.13 ± 0.12 f	154.22 ± 0.62 i	89.09 ± 0.62 d
20	CS + ZnO-NP 0.3%	65.21 ± 0.30 k	16.91 ± 0.13 h	330.02 ± 0.91 l	178.01 ± 0.05 n	144.21 ± 1.13 o
20	CS + ZnO-NP 0.6%	56.01 ± 0.46 gh	15.06 ± 0.14 f	359.92 ± 0.53 n	180.07 ± 0.42 o	159.11 ± 0.46 s
20	CS + ZnO-NP 0.9%	55.12 ± 0.14 g	15.92 ± 0.08 g	361.02 ± 0.58 no	181.71 ± 0.52 p	160.91 ± 0.12 t
25	Control	86.02 ± 0.05 p	3.22 ± 0.36 a	156.91 ± 0.54 a	81.21 ± 0.42 a	40.21 ± 0.24 a
25	CS (1.5%)	75.92 ± 0.62 n	8.01 ± 0.10 b	220.05 ± 0.13 c	102.25 ± 0.56 c	80.01 ± 0.58 c
25	CS + ZnO-NP 0.3%	68.01 ± 0.28 l	10.55 ± 0.26 c	339.01 ± 0.57 m	130.07 ± 0.49 e	100.12 ± 0.12 f
25	CS + ZnO-NP 0.6%	58.91 ± 0.33 i	12.95 ± 0.16 d	364.91 ± 0.15 op	167.21 ± 0.21 j	119.95 ± 0.43 i
25	CS + ZnO-NP 0.9%	57.89 ± 0.55 hi	13.01 ± 0.10 d	366.93 ± 0.07 p	168.91 ± 0.27 k	120.94 ± 0.57 i

Mean values with different letters in the same column are statistically significant according to Fisher's least significant difference test at $P < 0.05$ (mean values ± standard error; $n = 3$).

CS = chitosan; FRAP = ferric reducing antioxidant power; FW = fresh weight; GAE = gallic acid equivalent; RH = relative humidity; RSA = free radical scavenging activity; ZnO-NP = zinc oxide nanoparticle.

of the coating treatments. At the end of shelf life, control fruit had the highest carotenoids contents (86.02 μg·g^{-1} FW) compared with those of the coating treatments. The increase in total carotenoids contents in all samples during shelf life could be attributed to the fact that cherry tomatoes are a great source of carotenoids that vary with different ripening stages (Álvarez et al. 2021; Tzortzakis et al. 2019). Akhtar et al. (2024) stated that approximately 3 to 5 g of carotenoids is present in 100 g of tomato. The low contents of total carotenoids, which indicates a delay in ripening and color change, can be attributed to the inhibited respiration rate of coated fruit, which decreases chlorophyll degradation or carotenoid synthesis (Akhtar et al. 2024; da Silva et al. 2024). This is further supported by Fig. 1, which shows that coated fruit had a lower respiration rate during shelf life compared with that of uncoated fruit. Therefore, the application of coatings, especially CS + ZnO-NPs, demonstrated the ability to suppress the accumulation of total carotenoids and delay ripening and senescence (Akhtar et al. 2024). Table 1 shows that coating treatments reduced weight and texture loss in cherry tomato fruit during shelf life compared with the control. Also, the greater contents of total carotenoids in control fruit could be attributable to the enhanced ripening activity (Tsouvaltzis et al. 2023).

Ascorbic acid content. The AA content of coated and uncoated 'Rosada' cherry tomato significantly ($P < 0.001$) increased to a maximum after day 15 of shelf life; thereafter, it decreased after day 20 of shelf life (Table 2). Coated fruit showed a delayed increase in AA from days 0 to 15; afterward, it slowly decreased from days 20 to 25 of shelf life compared with the control. At the end of storage, fruit coated with CS + ZnO-NP 0.9% and CS + ZnO-NP 0.6% had the highest AA contents of 13.01 mg/kg and 12.95 mg/kg FW, respectively, followed by CS + ZnO-NP 0.3% (10.55 mg/kg FW), CS (8.01 mg/kg FW); the lowest AA contents (3.22 mg/kg FW) were observed in control fruit. This increase in the AA content was consistent with the increase in total carotenoids (Table 2), which was low in coated fruit and higher in control fruit, indicating a delay in the fruit ripening rate (Flores-López et al. 2023). In tomato fruit, the AA content increases with maturity and ripening stage; when the fruit reach the full ripe stage, the AA content starts to decline (Akhtar et al. 2024). The high reduction of AA in control fruit at days 20 to 25 of shelf life could be attributed to the fact that AA is reduced with storage time because of the ripening and senescence of fresh produce (Flores-López et al. 2023). Also, this decrease could be attributed to the conversion of AA to dehydroascorbic acid caused by the action of AA oxidase (Dulta et al. 2022). Oxygen availability to respiring fruit tissues negatively affects the AA concentration (Flores-López et al. 2023). Therefore, the lower AA content in control fruit during shelf life could be caused by the presence of O_2; additionally, because AA is extremely sensitive to chemical and enzymatic oxidation, it is also susceptible to degradation by temperature and light, which accelerate fruit quality deterioration (Tsouvaltzis et al. 2023). Furthermore, water loss in fruit promotes the loss of AA (Panahirad et al. 2020). This is further supported by the results of the present study that showed that control fruit had high mass loss and firmness loss compared with treated fruit (Table 1).

The AA is a potent free radical scavenger that inhibits fruit degradation during ripening (Tsouvaltzis et al. 2023). The results of the current study showed that incorporating ZnO-NPs into the CS matrix further decreased oxidation of AA by inhibiting the production of free radicals on the surface of cherry tomato fruit, thus reducing the degradation of the AA concentration in the fruit (Panahirad et al. 2020). Moreover, the high content of AA in coated fruit during shelf life could be caused by low O_2 availability, which delays the ripening rate, onset of senescence, and AA oxidation (Duguma 2022; Tsouvaltzis et al. 2023). In addition, the further retention of AA in fruit coated with CS + ZnO-NPs probably occurred because ZnO-NP coatings

further inhibit the O_2 supply, reducing the respiration rate and subsequently maintaining higher AA contents (Duguma 2022). Similar results were observed by Dulta et al. (2022), who reported that coating orange (*Citrus sinensis* L.) fruit with CS + ZnO-NPs reduced the O_2 permeability and activity of enzymes, resulting in inhibition of the oxidative deterioration of AA during 25 d of storage at 4 °C.

Total phenol content. The TPCs of coated and uncoated fruit during shelf life are presented in Table 2. The TPC of fruit coated with CS + ZnO-NPs significantly ($P < 0.001$) increased during shelf life, whereas the TPC of fruit treated with CS alone increased from days 0 to 15 and declined from days 15 to 25 of shelf life. The TPCs of untreated fruit significantly ($P < 0.001$) increased from days 0 to 5; thereafter, TPCs gradually ($P < 0.001$) declined from days 5 to 25 of shelf life. At the end of shelf life, coated fruit maintained a higher TPC compared with that of the control. Higher TPCs were observed in fruit coated with CS + ZnO-NP 0.9% (366.93 mg GAE 100 g^{-1} FW) and CS + ZnO-NP 0.6% (364.91 mg GAE 100 g^{-1} FW), followed by CS + ZnO-NP 0.3% (331.01 mg GAE 100 g^{-1} FW) and CS (220.05 mg GAE 100 g^{-1} FW); the lowest TPC (156.91 mg GAE 100 g^{-1} FW) was noted in control fruit at the end of shelf life. The TPC scavenges reactive oxygen species (ROS) in fresh produce, thus decreasing oxidative cell damage (Yin et al. 2019). Extended storage results in oxidative damage, which leads to the degradation of TPC in fresh produce (Kumar et al. 2021; Yin et al. 2019). In addition, senescence causes the breakdown of cell wall constituents, resulting in the degradation of TPC in fresh produce (Kumar et al. 2021). In the current study, coating treatments, especially CS + ZnO-NP coatings, effectively preserved TPC of cherry tomato, which could be attributable to the coatings forming a MA around the fruit surface and restraining the respiration and oxidation rates of TPC by suppressing the activity of polyphenol oxidase (López-Palestina et al. 2018). Incorporation of ZnO-NPs in the CS matrix further preserved TPC by effectively delaying fruit ripening because edible coatings reduce gas exchange, thereby slowing degradation of phenols (Lakshmi et al. 2018). The rapid decrease of TPC in control fruit after day 5 of shelf life could be ascribed to a higher respiration rate, which accelerated the decrease of TPC in cherry tomato fruit because of the degradation of certain phenolic compounds (Panahirad et al. 2020). This is further supported by the results of the current study that showed that uncoated fruit had higher respiration compared with that of coated fruit (Fig. 1).

Free radical scavenging activity and ferric reducing antioxidant power. The antioxidant activity of both coated and uncoated 'Rosada' cherry tomato fruit are presented in Table 2. The RSA of coated fruit significantly ($P < 0.001$) increased from days 0 to 15 and slightly decreased from days 15 to 25, whereas the RSA of uncoated fruit gradually deceased during shelf life. The FRAP of fruit treated with CS + ZnO-NPs significantly ($P < 0.001$) increased from days 0 to 20 and declined from days 20 to 25, whereas the FRAP of cherry tomato coated with CS alone increased from days 0 to 10, and thereafter declined until the end of shelf life. The FRAP of uncoated fruit gradually ($P < 0.001$) decreased during shelf life (Table 2). At the end of shelf life, the highest antioxidant activities (RSA and FRAP, respectively) were observed in fruit coated with CS + ZnO-NP 0.9% (168.91 and 120.4 mM Trolox 100 g^{-1} FW) and CS + ZnO-NP 0.6% (167.21 and 119.95 mM Trolox 100 g^{-1} FW), followed by CS + ZnO-NP 0.3% (130.07 and 100.12 mM Trolox 100 g^{-1} FW) and CS alone (102.25 and 80.01 mM Trolox 100 g^{-1} FW); the lowest concentrations (81.21 and 40.21 mM Trolox 100 g^{-1} FW) were observed in control fruit. Therefore, incorporating ZnO-NPs into the CS matrix maintained higher antioxidant activity of cherry tomato during shelf life. The gradual increase in antioxidant activity of the treated fruit from days 0 to 20 could be ascribed to the delay in ripening compared with that of the control fruit (Hasan et al. 2022). The higher RSA and FRAP in fruit coated with CS + ZnO-NPs could be ascribed to the improved antioxidant enzyme activity induced by ZnO-NPs, thus enhancing the fruit's overall antioxidant capacity and scavenging ability (Magri et al. 2024; Mwelase et al. 2022). The coating controlled the oxidation of free radicals, thus maintaining higher RSA and FRAP compared with those of uncoated fruit (Mwelase et al. 2022). In addition, coatings were able to act as effective barriers against O_2 transmission, thereby limiting phenolic compounds degradation and maintaining higher concentrations of antioxidants during shelf life. This is further supported by the results of the current study that showed that enriching CS with ZnO-NPs resulted in higher AA and TPC (Table 2) in coated cherry tomato during shelf life compared with those of the control fruit (Hasan et al. 2022). The gradual decrease of RSA and FRAP in control fruit during shelf life could be attributable to the decrease in the total phenolic content because some phenolic compounds are degraded during the respiration process (Saleem et al. 2021). Our study showed that uncoated fruit had a high respiration rate, which could have led to the rapid degradation of AA, TPC, and antioxidant activity (Table 2).

Malondialdehyde content. The MDA content significantly ($P < 0.001$) increased with increasing shelf life days in all the treatments (Fig. 2). This increase was slow in coated cherry tomato fruit, whereas the control showed a rapid accumulation of MDA during shelf life. At the end of shelf life, fruit coated with ZnO-NP 0.9% and ZnO-NP 0.6% had the lowest MDA content (3.91 and 4.01 μmol·kg^{-1} FW, respectively), followed by ZnO-NP 0.3% (5.92 μmol·kg^{-1} FW), and CS (8.99 μmol·kg^{-1} FW); the highest content of MDA content (12.75 μmol·kg^{-1} FW) was observed in the control fruit (Fig. 2).

The MDA content is a stress indicator because it is the end product of the peroxidation of unsaturated fatty acids and is used for the measurement of membrane stability in plant tissues (Castro-Cegrí et al. 2023). A change in the MDA level is regarded as a marker of membrane lipid peroxidation of fruits subjected to senescence or stress (Das et al. 2022). The rapid increase of MDA in control fruit during shelf life could be attributed to the higher production of ROS in fruits (Duong et al. 2022). Coating treatments effectively inhibited the overproduction of ROS by activating the antioxidant mechanism, which reduces the accumulation of the MDA concentration in coated fruits (Ricelli et al. 2020). This is further supported by the results of the present study that showed that coated fruit had higher antioxidant activity (DPPH and RSA) during shelf compared with that of uncoated fruit (Table 2). In addition, enriching CS with ZnO-NP coatings further improved the resistance of the cherry tomato cell membrane to ROS, preserved the membrane integrity, and reduced the accumulation of MDA during shelf life. This could be attributed to the antioxidant activity of ZnO-NPs, which further suppressed the oxidative stress, thus reducing the accumulation of MDA in fruit coated with CS + ZnO-NPs (Li et al. 2019).

Hydrogen peroxide content. Similar to the trend of the MDA content (Fig. 2), the H_2O_2 content of both coated and uncoated cherry tomato fruit gradually ($P < 0.001$) increased during shelf life (Fig. 3). This increase was more pronounced in the control compared with the coated fruit. At the end of shelf life, both CS + ZnO-NP 0.9% and CS + ZnO-NP 0.6% treatments had the lowest H_2O_2 contents (15.88 and 16.07 μmol·kg^{-1} FW), followed by CS + ZnO-NP 0.3% (20.03 μmol·kg^{-1} FW) and CS (26.98 μmol·kg^{-1} FW); the highest H_2O_2 content (32.93 μmol·kg^{-1} FW) was noted in control fruit.

The H_2O_2 is a strong ROS that is associated with quality degradation and reduced shelf life of fresh produce (Vincent et al. 2023). The rapid increase of H_2O_2 is associated with accelerated MDA accumulation and deterioration of membrane integrity in control fruit compared with treated fruit. Figure 2 shows that compared with treated fruit, uncoated fruit had rapid accumulation and high MDA contents during shelf life. Coated fruit had a delayed increase and lower H_2O_2 content during shelf life, which might be attributable to the activation of the antioxidant defense mechanism and restriction of the gaseous exchange that alleviates oxidative stress (Mahmoudi et al. 2022). Similar results were observed by Nxumalo et al. (2022), who stated that coating mandarin (*Citrus reticulata* Blanco) fruit with GA + ZnO-NPs reduced oxidation stress by decreasing rind electrolyte leakage, thus maintaining the cell membrane of coated fruit stored at 5 °C for 40 d compared with uncoated fruit.

Antioxidant enzyme activities. Antioxidant enzymes are essential for the prevention of oxidative stress in fresh produce (Panahirad et al. 2019). Antioxidative enzymes such as SOD converts superoxide into H_2O_2, whereas CAT suppresses the detrimental effect of H_2O_2

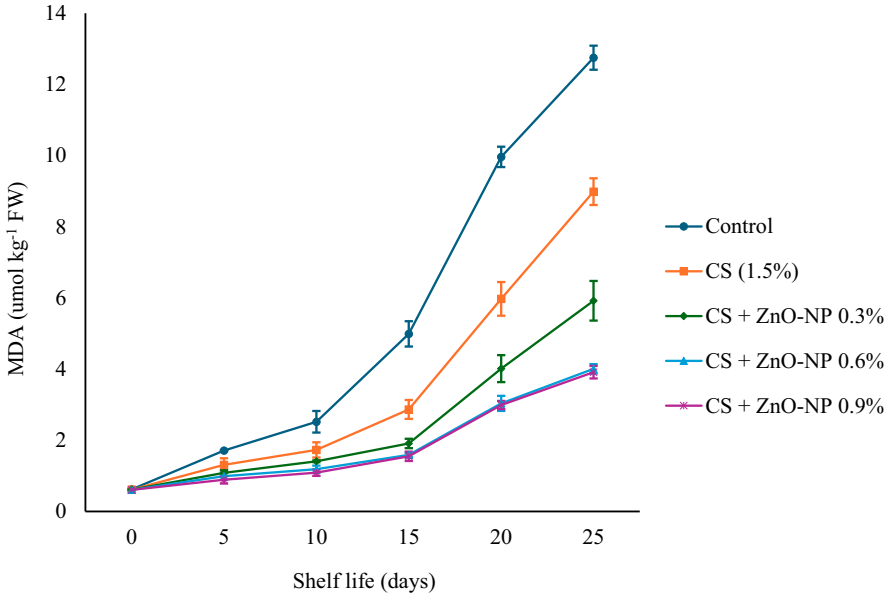

Fig. 2. Changes in the malondialdehyde content of 'Rosada' cherry tomato fruit treated with chitosan (CS) and CS + nanoparticle (NP) coatings during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity). CS = chitosan; ZnO-NP = zinc oxide nanoparticle. Vertical bars represent the standard error of the mean value (n = 3).

(Das et al. 2022). Although CAT activity in both coated and uncoated cherry tomato fruit gradually ($P < 0.001$) declined during shelf life, this decrease was more rapid in control than in coated fruits (Fig. 4). It was noted that the CAT activity of coated fruit was higher than that of control fruit during the shelf life period. At the end of shelf life, fruit coated with ZnO-NP 0.9%, ZnO-NP 0.6% had higher CAT activity (90.01 and 89.07 U·mg^{-1} protein, respectively), followed by ZnO-NP 0.3% (79.07 U·mg^{-1} protein) and CS (60.09 U·mg^{-1} protein); the lowest CAT activity (53.05 U·mg^{-1} protein) was observed in control fruit.

Antioxidative enzymes including CAT activity can scavenge excessive ROS in fruit, delay peroxidation of membrane lipids, slow the loss of membrane function, and mitigate oxidative stress, thus delaying senescence of fruit during storage to some extent (Das et al. 2022). Consequently, coating cherry tomato with CS improved its ability to restrict overproduction of H_2O_2. Moreover, enriching CS coating with ZnO-NPs further improved the properties of the coating to maintain high CAT antioxidant activity against ROS. Additionally, CS is a cationic marine polysaccharide with unique biological properties, such as biodegradation, immunological, antioxidant,

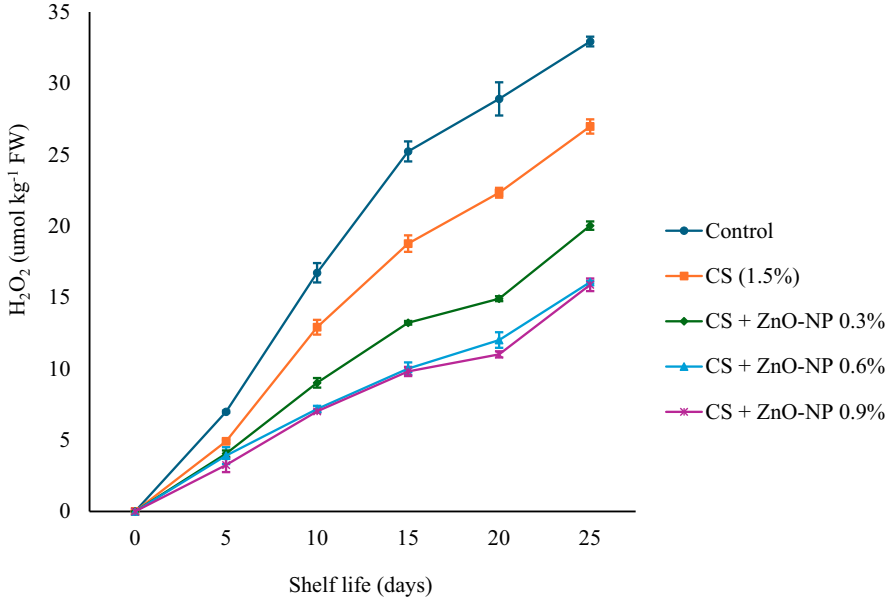

Fig. 3. Changes in the hydrogen peroxide content of 'Rosada' cherry tomato fruit treated with chitosan (CS) and CS + nanoparticle (NP) coatings during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity). ZnO-NP = zinc oxide nanoparticle. Vertical bars represent the standard error of the mean value (n = 3).

and antibacterial activities, that make it an effective scavenger of ROS (Hu et al. 2022). The scavenging mechanism of chitosan is associated with its structure, which features large numbers of hydroxyl and amino groups available to react with ROS, leading to extended shelf life of coated fruit compared with uncoated fruit (Chen et al. 2023). Enriching the CS coating with ZnO-NPs further modulated exposure of cherry tomato fruit to O_2, thus decreasing the increase of H_2O_2 and eventually slowing senescence of the fruit during shelf life. In addition, the lower CAT activity in control fruit could be attributed to ROS accumulation, which causes oxidative injury, thus accelerating senescence progression and various senescence-associated disorders during shelf life (Chen et al. 2023; Hu et al. 2022). This is further supported by the results of this study that showed that control fruit had higher contents of MDA (Fig. 2) and H_2O_2 (Fig. 3) during shelf life compared with those of treated fruit.

Similar to the trend of CAT, SOD activity of coated fruit significantly ($P < 0.001$) increased from days 0 to 15, and thereafter declined until the end of shelf life, whereas the SOD activity of control fruit gradually ($P < 0.001$) deceased during shelf life (Fig. 5). Coated cherry tomato fruit had high SOD activity during shelf life compared with that of control fruit. In addition, incorporating ZnO-NPs into the CS matrix further ($P < 0.001$) enhanced the SOD activity during shelf life compared with CS coating alone. Higher SOD activity was preserved with increased ZnO-NPs in the CS matrix. Thus, at the end of shelf life, the highest SOD activity was observed in cherry tomato treated with CS + ZnO-NP 0.9% and CS + ZnO-NP 0.6% (47.25 and 46.71 60.09 U·mg^{-1} protein, respectively), followed by CS + ZnO-NP 0.3% (40.22 60.09 U·mg^{-1} protein) and CS (35.24 60.09 U·mg^{-1} protein); the lowest SOD activity (15.71 60.09 U·mg^{-1} protein) was noted in control fruit. Therefore, CS + ZnO-NP coatings restricted oxidative stress and overproduction of ROS by particularly maintaining high antioxidative enzyme activity in coated cherry tomato fruit during shelf life. Also, the mode of action of ZnO-NPs involves the induction of oxidative stress, membrane disorganization of bacterial cell walls, and release of zinc ions that bind to the membrane of microorganisms, thus slowing the accumulation of ROS in the presence of moisture. Therefore, enriching the CS coating with ZnO-NPs promoted antioxidant enzymes activity and prolonged the shelf life of coated fruit.

Conclusion

The application of CS coating enriched with green-synthesized ZnO-NPs may be regarded as an effective technique to preserve postharvest quality and extend shelf life of cherry tomato at ambient conditions. The current study showed that incorporating ZnO-NPs (0.3%, 0.6%, and 0.9%) in CS (1.5%) coating delayed ripening and prolonged shelf life of

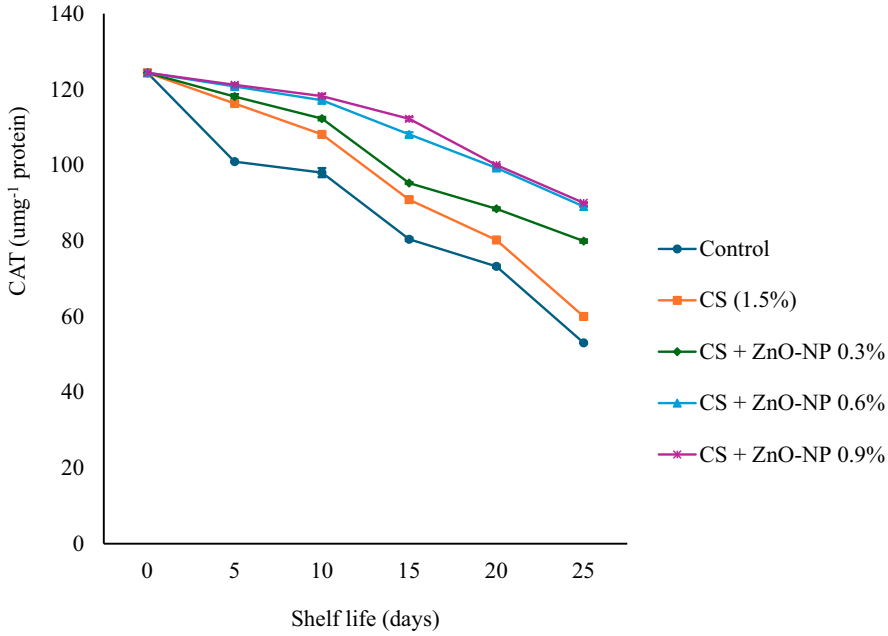

Fig. 4. Changes in the catalase activity of 'Rosada' cherry tomato fruit treated with chitosan (CS) and CS + nanoparticle (NP) coatings during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity). ZnO-NP = zinc oxide nanoparticle. Vertical bars represent the standard error of the mean value (n = 3).

cherry tomato compared with CS alone and the control. In addition, CS + ZnO-NPs (0.6% and 0.9%) further inhibited ripening indices and lipid oxidation and enhanced both antioxidant activity and antioxidant enzymes of cherry tomato during shelf life compared with other treatments. Therefore, incorporating ZnO-NPs at concentrations between 0.6% to 0.9% in the CS (1.5%) coating is recommended to maintain the quality of cherry tomato during shelf life. The results of this study may be applied to enhance the postharvest quality, shelf life, and marketing of cherry tomato fruit, which could lead to an increase in the export market. Future studies should investigate the incorporation of different inorganic nanoparticles into various edible coating materials in combination with biodegradable packaging films, which can possibly lead to further enhancement of postharvest quality and shelf life of fresh produce.

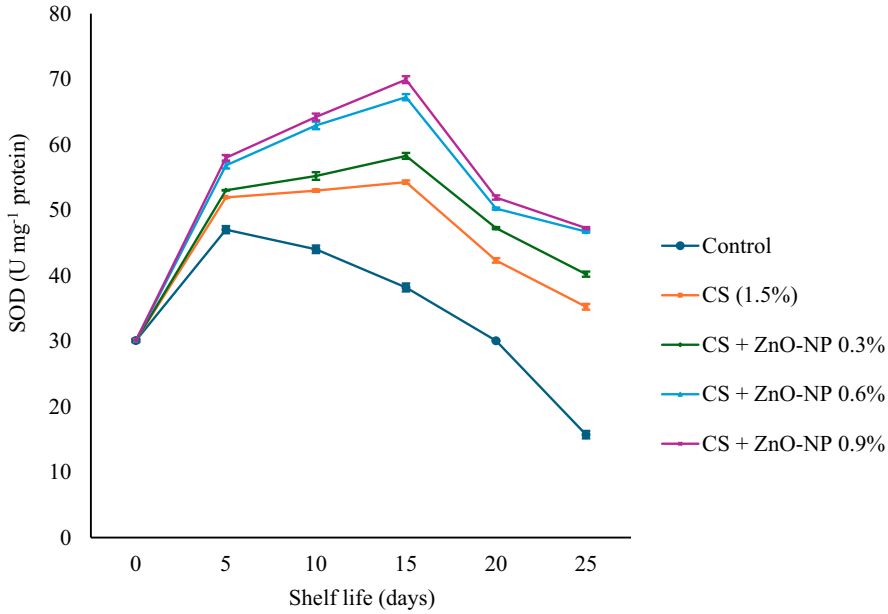

Fig. 5. Changes in superoxide dismutase activity of 'Rosada' cherry tomato fruit treated with chitosan (CS) and CS + nanoparticle (NP) coatings during 25 d of shelf life at ambient temperature (21 ± 1 °C and 60.0 ± 5% relative humidity). ZnO-NP = zinc oxide nanoparticle. Vertical bars represent the standard error of the mean value (n = 3).

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