

	Journal of Horticulture and Postharvest Research Journal Homepage: https://www.jhpr.birjand.ac.ir	 University of Birjand
---	---	--

Development of antimicrobial peppermint essential oil sachet for active packaging of strawberry: effects on antioxidant, microbial and physicochemical quality

Azam Amiri^{1,2,*} , Mohammad Mahmoodi Sourestani¹, Seyed Mohammad Hassan Mortazavi³, Ali Reza Kiasat⁴ and Zahra Ramezani^{4,5}

¹. Department of Horticultural Science, Faculty of Agriculture, Shahid Chamran University of Ahvaz, Ahvaz, Iran

². Date Palm and Tropical Fruits Research Center, Horticultural Science Research Institute, Agricultural Research Education and Extension Organization (AREEO), Ahvaz, Iran

³. Chemistry Department, Faculty of Science, Shahid Chamran University of Ahvaz, Ahvaz, Iran

⁴. Toxicology Research Center, Medical Basic Sciences Institute, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

⁵. Medicinal Chemistry Department, Faculty of Pharmacy, Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran

ARTICLE INFO

Original Article

Article history:

Received 20 January 2026

Revised 15 April 2026

Accepted 18 April 2026

DOI: 10.22077/jhpr.2026.10624.1643

P-ISSN: 2588-4883

E-ISSN: 2588-6169

*Corresponding author:

Date Palm and Tropical Fruits Research Center, Horticultural Science Research Institute, Agricultural Research Education and Extension Organization (AREEO), Ahvaz, Iran.

Email: amiriazam23@gmail.com

© This article is open access and licensed under the terms of the Creative Commons Attribution License <http://creativecommons.org/licenses/by/4.0/> which permits unrestricted, use, distribution and reproduction in any medium, or format for any purpose, even commercially provided the work is properly cited.

A B S T R A C T

Purpose: The strawberry, known for its delightful flavor and significant nutritional benefits, suffers from a limited shelf life after harvest. Consequently, the proper handling and storage of this delicate fruit are essential. Antimicrobial packaging is recognized as a key application of active packaging. Thus, this study aimed to explore the impact of antimicrobial packaging on the postharvest quality of strawberries. **Research Method:** This investigation consisted of two experiments. The first experiment involved the use of silica mesoporous particles (SMP) derived from rice husk to create antimicrobial sachets. The loading capacity and release of essential oil (EO) from the substrate were evaluated through gas chromatography analysis. In the second experiment, active packaging for the strawberry cultivar Camarosa was implemented using sachets produced in the first phase, which were infused with peppermint essential oil (PEO). Various qualitative and biochemical characteristics were assessed. **Findings:** The results revealed that at the conclusion of the storage period, the highest total antioxidant activity (31.72 iron II Mmol g⁻¹) was observed in the fruits packaged with sachets, while the control group exhibited the highest anthocyanin content (83.5mg 100grFW⁻¹). At the end of storage, the treated fruits demonstrated enhanced catalase (198 U g⁻¹) and phenylalanine ammonia-lyase (1660 U kg⁻¹) activities. The packaged fruits with sachets showed a reduced microbial load, with total mesophilic bacteria counts of 3.7 and 0.5 Log CFU g⁻¹ in the control and treated samples, respectively, at the end of storage. It has been proven that by encapsulating long-term effectiveness is ensured by controlled release hydrocarbon monoterpene such menthol and easy handling, with positive effects for its antifungal activity. **Research limitations:** No limitations were found. **Originality/Value:** The findings suggest that the increased enzyme activity and reduced levels of malondialdehyde positively influence the shelf life of strawberry fruits.

Keywords:

Active packaging, Antioxidant enzymes, Mesoporous silica particles, Strawberry

INTRODUCTION

Active packaging serves as an alternative approach to prolonging the post-harvest lifespan of fruits, accomplished by the release or absorption of active substances from the packaging system. This method is extensively utilized for antimicrobial purposes. Antimicrobial packaging systems effectively eradicate contaminants and pathogenic microorganisms responsible for food spoilage. The antimicrobial system inhibits microbial growth by extending the lag phase during the growth of microorganisms and by reducing the population of viable microorganisms (Otoni et al., 2016). Strawberry (*Fragaria × ananassa* Duch.) is one of the most popular fruits belonging to the Rosaceae family. It is cultivated and consumed worldwide due to its special taste, attractive color, distinctive sweetness, and nutritional value, including minerals, vitamins, phenolics, anthocyanins, amino acids, and antioxidant properties (Meighani & Salehi Sarbijan, 2025). These bioactive compounds can reduce the risk of chronic diseases such as heart disease, type II diabetes, obesity, cancer, and neurodegenerative diseases. In addition, the shelf life of strawberry fruit is very limited due to its susceptibility to mechanical injury, physiological deterioration, water loss, and microbial decay (Colussi et al., 2021).

Essential oil (EO) components have antimicrobial activity that can be a suitable alternative to synthetic pesticides and the preservatives of food. However, due to high hydrophobicity and volatility, they can lose this activity before acting as a fungicide. Encapsulation in microcapsules has been developed for the protection and preservation of the effectiveness of bioactive substances (Amiri et al., 2021). Silica mesoporous supports (SMPS) have been used as inorganic scaffolds for the storage and release of drugs and organic molecules. Mesoporous silica supports for EO delivery in food applications have been reported elsewhere, Park et al. (2011) found that MCM-41 and SBA-15 loaded with natural antimicrobial allyl isothiocyanate were antimicrobially active against *Escherichia coli*, *Bacillus cereus*, and *Pichia anomola*. A study by Ruiz-Rico et al. (2017) reported a significant reduction in the concentration of *Listeria innocua* in pasteurized skimmed milk using vanillin grafted onto the surface of MCM-41. The shelf life of strawberries can be prolonged through the use of different active antimicrobial packaging systems, including pullulan/bacterial cellulose packaging film loaded with *Citrus* extracts (Xu et al. 2024), active packaging films that incorporate microcapsules of oregano essential oil (Li et al., 2020), and encapsulated oregano oil: extending strawberry shelf life (Taheri et al., 2026). Many studies have revealed extensive interests in sachets with functional properties such as avocado (Bill et al., 2018) and strawberry (Sangsuwan et al., 2016). A microencapsulated antifungal sachet of clove essential oil was developed, and its efficacy was assessed as an antimicrobial packaging solution for peach fruit rot (Irshad et al., 2024). Encapsulated thyme essential oil in zein nanofiber film to prevent *Botrytis cinerea*, and their use in the packaging system for strawberries was investigated (Ansarifar & Moradinezhad, 2021). The type of material used as an anti-microbial carrier plays an important role in loading and releasing the capacity of the anti-microbial sachet. The elevated expense and restricted availability of raw materials, along with their chemical properties, may restrict the utilization of these sachets. Therefore, innovative strategies are necessary to maintain the quality of fruit. As a result, this research aimed to create an anti-microbial sachet within a sealed package to investigate its potential application as an anti-microbial packaging solution for strawberries during storage.

MATERIALS AND METHODS

Plant material and treatment

Strawberry fruits (cv. Camarosa) were collected at commercial maturity (level 3/4 red) from a local greenhouse situated in Dezful, Khuzestan Province, and were subsequently transported to the laboratory of Shahid Chamran University of Ahvaz in 2023. Initially, the fruits were disinfected using a 0.1% sodium hypochlorite solution for 2 minutes and then carefully rinsed with distilled water. Following this, a spore suspension containing 10^6 spores mL^{-1} of *B. cinerea* was injected at two longitudinal points on the fruits using a sampler. Finally, the fruits were packaged in triplicate using clamshells made of polystyrene, with dimensions of 8 cm in width, 11 cm in length, and 7 cm in depth. They were stored at a temperature of $4 \pm 1^\circ\text{C}$ and a relative humidity (RH) of $90 \pm 5\%$. Each replication consisted of eight fruits, which were analyzed on days 1, 3, 5, 7, 9, and 11 of their storage periods.

Synthesis of silica mesoporous supports loaded with essential oil components

Silica mesoporous synthesized from rice husk, infused with peppermint essential oil (sourced from Kashan Barij Essential Oil Co.), was produced through vapor adsorption by combining 40 mg of peppermint essential oil with 40 mg of MCM-41 silica in a securely sealed 8 mL vial. The resulting mixture was incubated for 24 hours while being continuously agitated (Davarpanah & Kiasat, 2013). Sachets measuring 3×5 cm were positioned a top the container for use in fruit packaging.

N₂ adsorption–desorption isotherms

The equilibrium adsorption isotherms of nitrogen were determined at 77 K utilizing static volumetric adsorption systems (ASAP 2020 analyser; Micromeritic, Atlanta, GA, USA). The adsorption isotherms were fitted to calculate the Brunauer-Emmett-Teller (BET) surface area; the micropore volume was obtained using the t-plot method, and the pore size distribution was assessed through the Barrett-Joyner-Halenda (BJH) method. Prior to conducting the adsorption measurements, the sample was maintained at 60°C for 33 hours under vacuum.

Release of essential oil from mesoporous silica particles

The quantity of PEO residue in the sachets was assessed after 1, 4, 8, and 12 days. The PEO was extracted using 5 mL of methanol (Ades et al., 2012). Following centrifugation for 10 minutes, the supernatant was analyzed with an Agilent 5975 gas chromatography system from Japan, utilizing a BP-5MS column that measures 30 m in length and 0.25 mm in diameter. The stationary phase layer thickness was 0.25 mm. additionally; the column temperature was programmed to increase from 60°C (for the first minute) to a final temperature of 250°C at a rate of 5°C per minute. The temperatures for the injection chamber and detector were set at 280°C and 300°C , respectively. The helium carrier gas flowed at a rate of $1 \text{ mL} \cdot \text{min}^{-1}$ through the column, the scan time was set to 1 minute, and the ionization energy was maintained at 70 eV.

Quality assessment

The weight loss was calculated during the storage through weighing polystyrene boxes including arils at the initial stage (W1) over different removing times (W2) with the use of following equation (1) (Amiri et al., 2021a).

$$\text{Weight loss (\%)} = \frac{w_1 - w_2}{w_1} \times 100 \quad (1)$$

To assess the firmness of the fruit, a Lutron digital hardness tester (Model FG-5020) was utilized, and the penetration of the fruit flesh was conducted twice with a diameter of five mm from both sides of the fruit's surface, with the results being expressed in Newtons (N). Four fruits were taken into account for each replication.

Bioactive parameters

The concentrations of Vitamin C were measured in the fruit juice using the 2, 6-dichlorophenol indophenol method (AOAC, 2005). The pH differential method was used to determine the total anthocyanin concentrations (TAC). A spectrophotometer (UV-2100, New Jersey) was used to measure the absorbance at 520nm and 700nm in the buffers at pH 1.0 and 4.5, which were expressed as mg (cyanidine-3-glucoside) /g FW (Lee et al., 2005). The mixture of 80% methanol was applied as a solvent, which was added to 1g fruit flesh homogenate in a falcon tube. Then, it was shaken at 200 rpm for 3 h, and was centrifuged at 6,000rpm for 15min. The supernatant was used to measure total antioxidant activity and the total phenolic compounds (TPC). Thereafter, 200 µl of methanolic extract was added to a tube with 1.5ml of Folin-Ciocalteu reagent (10% V/V) to react in 5min, and then 1.5 ml of 6% sodium carbonate was added and homogenized. The absorbance was recorded at 725 nm after the incubation of the mixture in the dark for 90 min, which was resulted in Gallic acid and were presented in Gallic acid equivalent (GAE) mg / 100g FW (Slinkard and Singleton, 1977). The Benzie and Strain (1996) method was used to determine AC through slight modifications. Initially, 10mM of TPTZ (2,4,6-tripyridyltriazine) solution in 40mM of HCl, 20mM of FeCl₃.6H₂O, and 0.3 M of sodium acetate buffer was mixed to freshly prepare FRAP reagent. Then, 3.6mL was mixed with 80µl of supernatant of that reagent, which was incubated for 50min at 37°C. The absorbance was recorded at 593nm against a FRAP blank. The calibration curve was set by aqueous solution of known Fe (II) concentrations (FeSO₄.7H₂O), and the results were presented in mmol /g FW.

MDA content and Hydrogen peroxide (H₂O₂)

Membrane lipid peroxidation was measured by thiobarbituric acid (TBA) test to measure malondialdehyde (MDA) (Velikova et al., 2000). The absorption rate was determined at a wavelength of 532 nm, from which the nonspecific adsorption at 600 nm was deducted. Malondialdehyde concentration (MDA) was calculated using a correction factor (µmol⁻¹ cm⁻¹) as 0.1155 and expressed in µmol / g FW. The hydrogen peroxide amount was measured based on the reaction of hydrogen peroxide with potassium iodide. The absorbance of the samples was measured at a wavelength of 390 nm (Reference).

Defense-related enzyme (CAT, APX, PPO, PAL) activities of the strawberry

For enzyme activity assays, 2 g of pulp tissue was homogenized with 8 mL of ice-cold 100 mmol L⁻¹ sodium phosphate buffer (pH 7.0) containing 1% (w/v) polyvinyl polypyrrolidone (PVPP). The homogenate was centrifuged at 10,000 rpm for 15 min at 4 °C, and the supernatant was used for enzymatic analysis. Catalase activity (CAT) was determined according to Wang et al. (2004). The reaction mixture contained 2 mL of sodium phosphate buffer, 0.4 mL of H₂O₂, and 1 mL of crude enzyme extract. The decomposition of H₂O₂ was monitored spectrophotometrically at 240 nm. A change in absorbance of 0.001 per minute was defined as one unit of enzyme activity (U min⁻¹g⁻¹ FW). Ascorbate peroxidase (APX) activity was assayed following Nakano and Asada (1981). The oxidation of ascorbate was monitored at 290 nm. Enzyme activity was calculated (U min⁻¹g⁻¹ FW). For phenylalanine ammonia-Lyase (PAL) Activity 2 g of pulp tissue was homogenized with 8 mL of ice-cold 100 mmol L⁻¹ sodium phosphate buffer (pH 8.7) containing 1% (w/v) PVPP, and centrifuged at 10,000 rpm

for 15 min at 4 °C. The enzyme activity was determined according to Assis et al. (2001) by monitoring the increase in absorbance at 290 nm. A change of 0.001 absorbance unit per minute was defined as one enzyme unit, and the specific activity was expressed as $\text{U g}^{-1} \text{FW}$. For polyphenol Oxidase (PPO) assay, 2 g of pulp tissue was homogenized with 8 mL of ice-cold 200 mmol L citric acid buffer (pH 6.8) containing 1% (w/v) PVPP. The homogenate was centrifuged at 10,000 rpm for 15 min at 4 °C. The reaction mixture contained 2 mL of citric acid buffer (pH 6.8), 1 mL of 100 mmol L¹ 4-methylcatechol, and 2 mL of enzyme extract. The increase in absorbance at 398 nm at 25 °C was recorded for 2 min. The specific activity was expressed ($\text{U min}^{-1} \text{g}^{-1} \text{FW}$).

Sensory evaluation

The sensory evaluation of the fruits was conducted with a test panel consisting of 10 trained panelists. These panelists assessed quality parameters including taste, color, aroma, and overall acceptance, utilizing a 5-point scale (ranging from 5 to 1). In this scale, a score of 5 indicated extreme liking (very characteristic of the fruit), 4 represented moderate liking, 3 denoted neutralities (neither liked nor disliked), 2 indicated moderate disliking, and 1 signified extreme disliking (Moradinezhad et al., 2018). The entire process was carried out at ambient temperature and under standard lighting conditions.

Microbiological evaluations

Ten grams of fruit were homogenized and diluted in a series with saline solution (NaCl 0.9%) in triplicate for each treatment. Subsequently, 1 mL of this solution was diluted with 9 mL of sterile saline solution (10⁻²). The Lawn plate method was employed to cultivate microbial colonies on Plate Count Agar (PCA, Sigma Aldrich) for mesophilic aerobic bacteria. Incubation occurred at 30 °C for 48 hours, while Rosbengal-Chloramphenicol Agar for molds and yeast was incubated at 25 °C for 72 hours. Finally, the microbial colonies were counted two times and the results were reported as log CFU/g (Amiri et al., 2021a).

Data analysis

A factorial design experiment was applied in this research based on a completely randomized design; with four replications. Moreover, the LSD (least significant difference) was applied to determine the specific differences among the means at $P=0.01$. The data were analyzed using MSTATC software (v. 9.1).

RESULTS AND DISCUSSION

Release of EO in the silica mesoporous

The evaluation of EO release in SMP (Table 1) showed that on the first day in SMP-PEO, all compounds were released, leading to the identification of gas chromatographic peaks of these compounds by the end of the fourth day of storage. However, the peak of menthol release continued until the end of the 12th day. Mesoporous silica contains small molecules (especially non-polar molecules of flavor and aroma compounds) that can form a complex and thus enhance the flavor of the food by minimizing evaporation and regulating its release during storage and application. This complex is the non-covalent binding of small molecules to silica. Silica encapsulation modulates the terpene release, which allows the selection of the most appropriate oil composition or application time to achieve a specific terpene profile (Sousa et al., 2014).

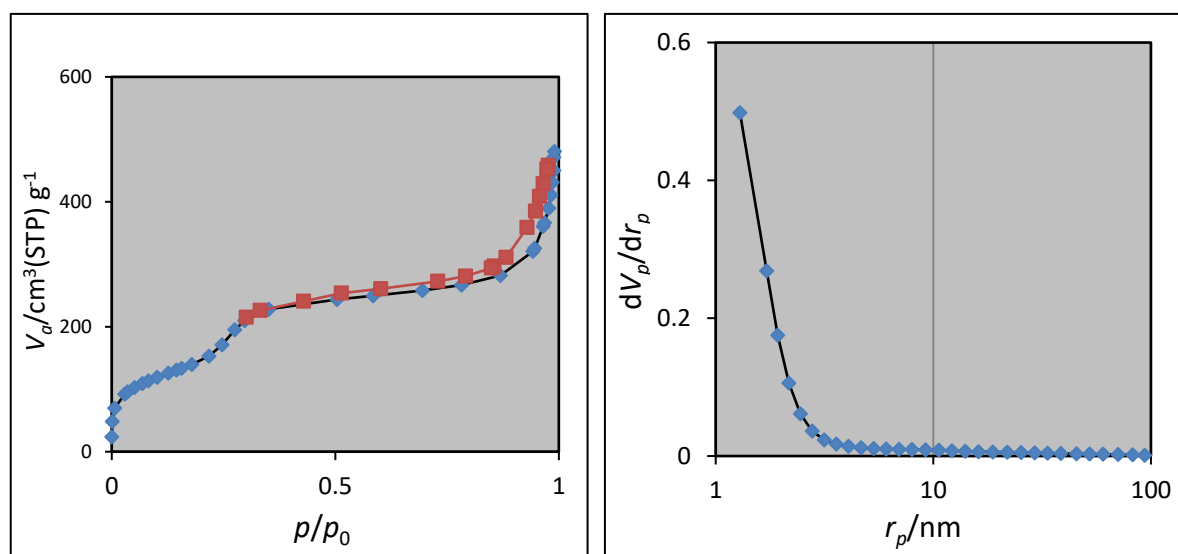


Fig. 1. BJH diagram of silica mesoporous synthesised of rice husk.

Table 1. Identified compounds of peppermint essential oil contained in Silica mesoporous.

	1	4	8	12
Isomenthone	+	+	-	-
Menthol	+	+	+	+
Menthone	+	+	-	-
Pulgon	+	+	-	-

-: not detected, + detected

N₂ adsorption–desorption isotherms

The nitrogen adsorption-desorption diagram at 77°K and the BJH diagram for MCM41 is shown in [Figure 1](#). These diagrams have a type IV isotherm with a steep adsorption-desorption loop in the range of relative pressure (P/P_0) 0.4 to 0.8, which is characteristic of regular mesopore compounds. The coincidence of the cycle in adsorption and desorption indicates the cylindrical structure of the channels of these mesopores. Based on the BJH diagram, a very high order in this structure is also clearly evident.

Firmness and weight loss (WL)

The least amount of WL was observed in fruit treated with SMP sachet ([Fig 2. A](#)). The greatest reduction in WL was observed in the control fruits. The changes in WL of the fruit during the last days were due to the increased metabolic activity as well as rapid microbial growth along with the destruction of fruit tissue. These results are consistent with previous reports given by Peretto et al. (2014) concerning the reduction of strawberry fruit's weight in different cultivars during the storage. High respiration intensity caused by accelerating the maturation and aging processes consumes the fruit nutrients ([Gao et al., 2013](#)), which in turn reduces the fruit's weight during the storage. In similar results with this study, it was revealed that the EO vapor reduces the dehydration or weight loss process in peaches ([Montero-Prado et al., 2011](#)). Essential oil vapor in packaging system with chitosan beads could delay weight loss of the strawberry fruit than the control. EOs act as a barrier between the fruit and environment, which reduces the external exchanges and ultimately prevents the loss of fruit juices ([Sangsuwan et al., 2016](#)).

The results showed that the firmness of the fruit is decreased along with increasing the storage period; accordingly, the lowest amount of the firmness was related to the 11th day of the storage, which led to a maximum decrease of 59.69 % compared to the first day in control fruit. (Fig. 2B). The fruits packed with SMP- PEO sachet had the highest firmness during the storage period; while, the control fruits had the lowest firmness. The PEO treatment was able to maintain the firmness of the fruit tissue during the storage compared to the control treatment. Similar to the results of this study, the firmness of peach fruits (Montero-Prado et al., 2011) treated with cinnamon oil was appropriately maintained compared to the control fruits. Although the mechanism of plant's EOs action in firmness maintenance is not yet known (, adding these compounds to the fruit's package and maintaining the firmness can be attributed to a decrease in the activity of cell wall softening enzymes (Valero et al., 2006).

Membrane peroxidation and hydrogen peroxide content

The results showed that hydrogen peroxide increased during storage so that the highest amount was recorded in control, which increased by 39.14% compared to the SMP- PEO sachet. During the storage period, the highest amount of hydrogen peroxide was recorded in control on day 11 of storage, and the lowest was associated with the SMP- PEO sachet (Fig. 3A). Hydrogen peroxide is a powerful oxidant that peroxidizes membrane lipids (Xu et al., 2024). Therefore, an increase in hydrogen peroxide is associated with an increase in lipid peroxidation and ion leakage into the living cell. Lipid peroxidation begins with the attack of reactive oxygen radicals (Li et al., 2020). As was already, *B. cinerea* mycelium into the tissue is associated with oxidative stress, which causes an increase in hydrogen peroxide in the fruit tissue (Cai, et al, 2015). The results showed an increase in MDA amount with increasing the storage period. The lowest amount of MDA on 11th day was related to the SMP- PEO sachet, which showed a decrease of 42.92% compared to the control (Fig. 3B).

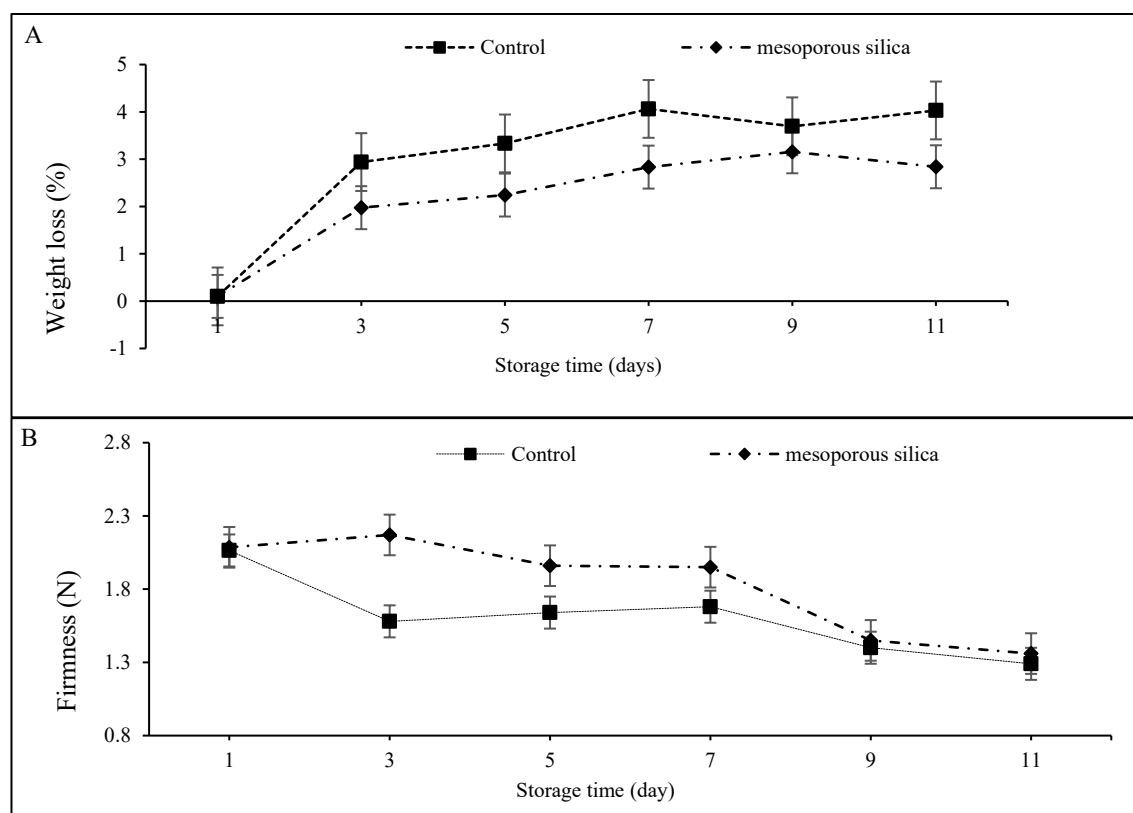


Fig. 2. Effect of antimicrobial sachet on weight loss (A), and firmness (B) of strawberry fruits during storage at 1°C and 90% relative humidity for 11 days.

In previous studies, was showed that using essential oils in the vapor phase can have a better effect than in the liquid phase. It is concluded that the EO mechanism against *B. cinerea* might be due to its effect on cell membrane permeability according to the electrolytes' leakage (Amiri et al., 2020). Accordingly, the film-loaded microcapsules of oregano EO slow the strawberry MDA, hydrogen peroxide and delay the aging process of the fruit (Li et al., 2020). The MDA is the product of fatty acid oxidation and considering an indicator of cell membrane lipid peroxidation by the production of reactive oxygen species (Cai et al., 2015). By reduction of MDA amount the damage to the membranes is reduced, thereby the peroxidation of the membrane lipids, which, in turn, preserves the integrity of the membrane and prevents tissue damage (Amiri et al., 2021).

Bioactive parameters

The highest amount of the ascorbic acid was obtained in the fruits packed with sachets and the least amount was accompanied by control fruits (Fig. 4A). Ascorbic acid is one of the important antioxidants, which its reduction is due to the use of this vitamin as an electron donor for oxidants to neutralize free radicals. In addition, the reduction of ascorbic acid during the storage is related to its consumption during the respiratory reaction ascorbic acid is an important antioxidant involved in aging resistance (Amiri et al., 2021a). The PEO treatment reduced the ascorbic acid content compared to untreated fruits with a lower slope rate during the storage.

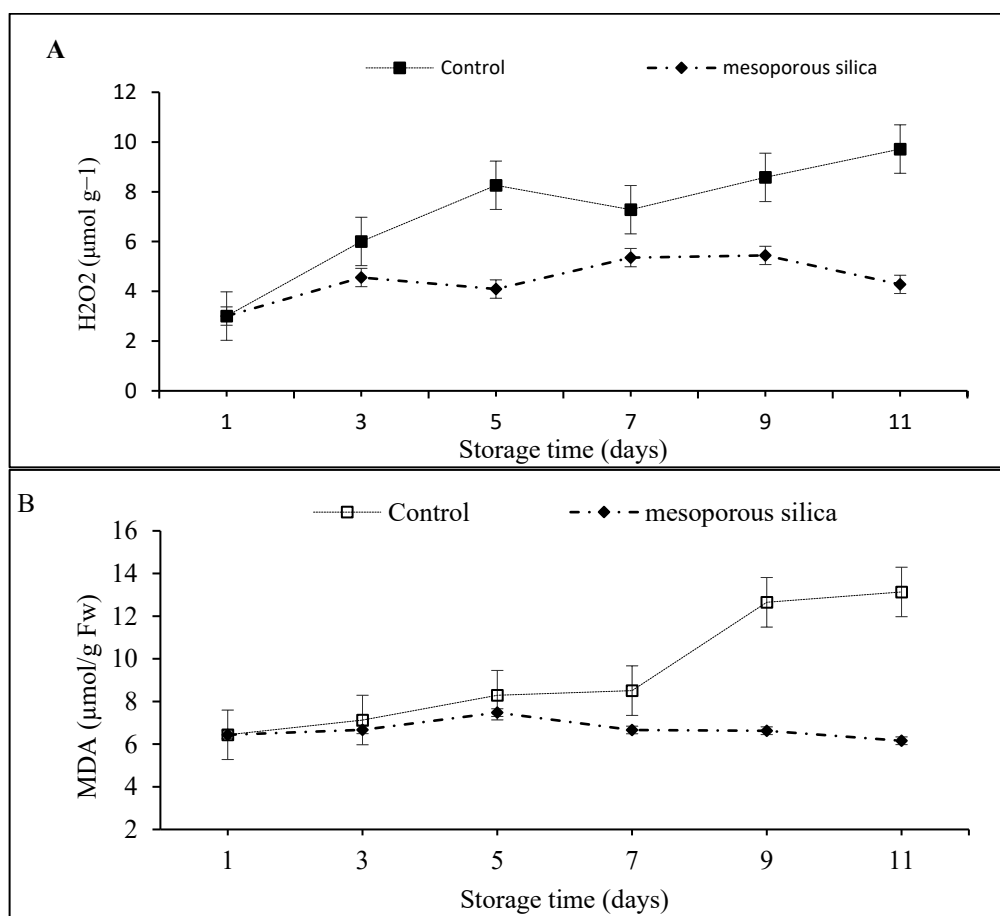


Fig. 3. Effect of antimicrobial sachet on the hydrogen peroxide (A), and membrane peroxidation (B) of strawberry fruits during storage at 1°C and 90% relative humidity for 11 days.

The results also showed that of phenolic substances initially increased until the 5th day and then decreased along with increasing the storage period. At the last day of the experiment, the fruits packed with SMP- PEO sachet had the highest number of phenolic substances (Fig. 4B). Also, it was revealed that lowest antioxidant capacity at 11th day of the control; while, the fruits packed with SMP- PEO sachet had the highest antioxidant capacity (Fig. 4C). As stated in the results, the change trend in antioxidant capacity had a two-stage pattern during the fruit storage in which incremental experiments and then decreasing trend were recorded from the first day up to day seven. According to the results of decay percentage indicators, the amount of hydrogen peroxide is a coherent mechanism. This means that along with increasing the hydrogen peroxide amount, the essential oil loads in this substrate with a slow total antioxidant activity release would happen which eventually result in fungal and controlled fungal growth enhancement, and produced hydrogen peroxide decrease. The EO seemed to maintain its total antioxidant activity by reducing the activity of free radicals and prevention of aging. The EO encapsulated in beta-cyclodextrin facilitated the antioxidant activity in lettuce. It should be noted that phenolic turpentine essential oil terpenes remain on the lettuce surface and increase the number of phenolic substances and antioxidant capacity (Viacava et al., 2018). The results of anthocyanin content displayed that its amount increased during the experimental period up to day seven, and then, decreased (Fig. 4D). Anthocyanins are a group of phenolic compounds that are involved in the red-blue color of many vegetables and fruits and play an important role in human health (Wang & Gao, 2013). Phenols and anthocyanins are among the substrates of polyphenol oxidase enzyme, which diminish along with increasing the activity of this enzyme and therefore, a decrease was observed in these compounds. The control during the storage period exposed a higher amount of anthocyanin than the treated fruit, which is due to the anthocyanin concentration occurred by the tissues' water loss in this treatment. Increasing the amount of anthocyanin during the harvesting period is associated with fruit's weight and moisture loss leading to anthocyanin concentration (Meighani et al., 2014).

Antioxidant enzyme activity

During the storage period, the highest amount of CAT and APX enzyme activity was observed in the fruits packed with SMP- PEO sachet. Significant changes in enzyme activity were seen in different treatments; while, no change was observed in the control treatment in CAT and APX during the maintenance period. The antioxidant enzymes activity such as catalase and ascorbate peroxidase increased with rising the fruit storage period, so that the fruits packed with SMP- PEO sachet. The fruits packed with SMP- PEO sachet disclosed the highest activity of the CAT and APX during the storage (Fig. 5A and B). Consistent with the results of this study, another research uncovered that the high level of antioxidant enzymes. activity such as catalase, peroxidase, superoxide dismutase, and ascorbate peroxidase and low level of malondialdehyde strengthen the antioxidant defense system and delay strawberry fruit's aging (Cai et al., 2015). It is important noting that thyme essential oil can act as a signal compound to create a defense function and to increase the activity of defense enzymes and intensify the antioxidant capacity (Khumalo et al., 2017). As part of the endogenous enzymatic defense system, antioxidant enzymes catalase, ascorbate peroxidase, are responsible for scavenging all kinds of oxygen radicals produced under different conditions (Wang and Gao, 2013). In general, the metabolism of reactive oxygen species is controlled by antioxidant enzymes including catalase, ascorbate peroxidase, and superoxide dismutase (Villarino et al., 2011). As mentioned earlier, the infiltration of *Botrytis cinerea* mycelium into the tissue is associated with oxidative stress, which causes hydrogen peroxide increase in the fruit tissue.

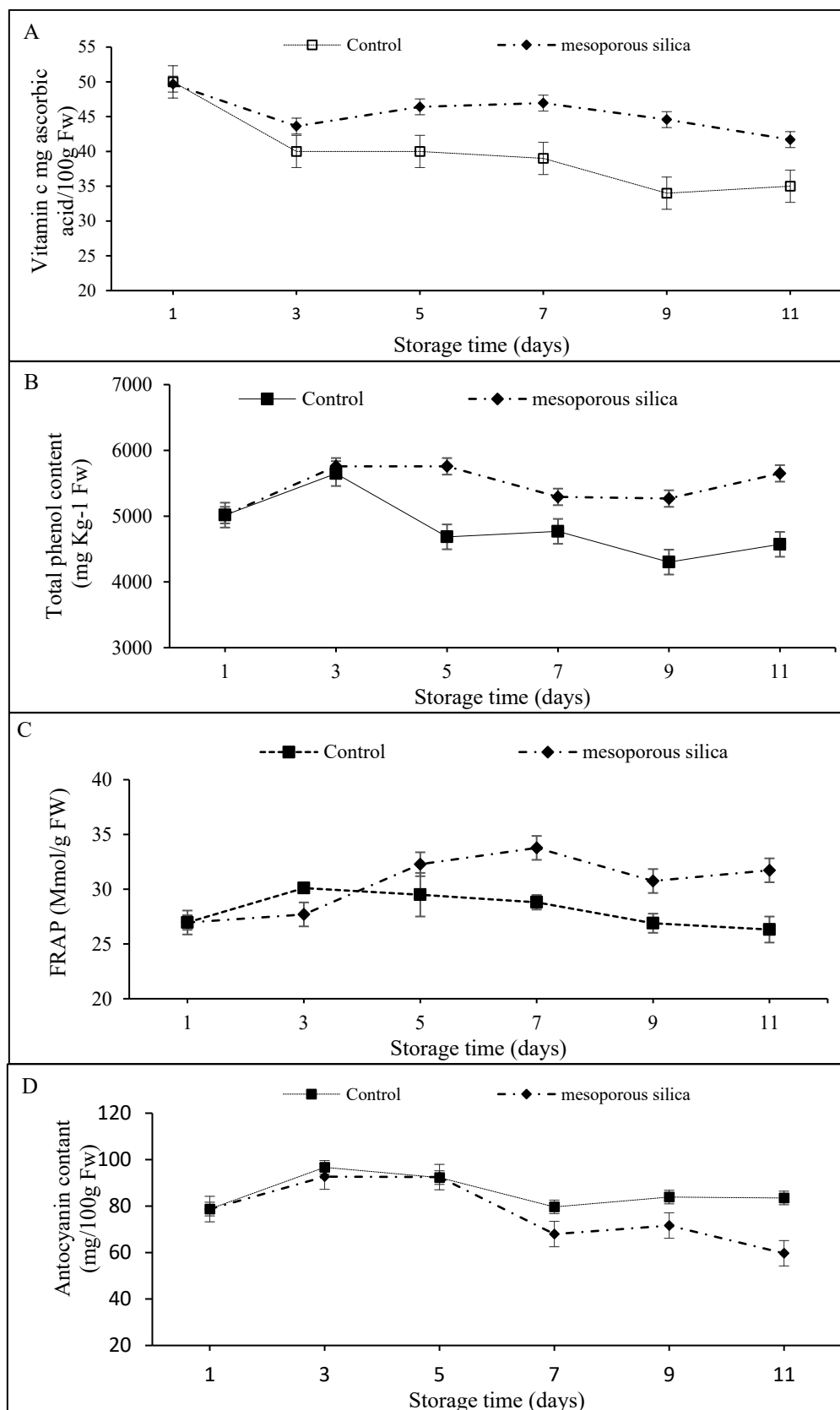


Fig. 4. Ascorbic acid (A), total phenol (B), antioxidant activity (C), and anthocyanin (D) of strawberry fruits packed during storage at 1°C and 90% relative humidity for up to 11 days.

The antioxidant enzymes activity is an indicator of the ability and efficiency of the internal antioxidant system in neutralization of free radicals and prevention of fruit rot. As reported in previous studies, increasing the antioxidant enzymes' activity is accompanied by increasing fruit pathogen's resistance with peach fruits (Montero-Prado et al., 2011), and avocado (Sellamuthu et al., 2013). The results also showed that of PAL activity increased until the 5th day and then decreased along with increasing the storage period (Fig. 5C). The PPO activity was increase during storage time (Fig. 5D). Thyme oil vapour significantly increased the PPO and PAL activities in 'Spring Princess' fruit (Cindi et al., 2016). In the strawberries infected with *Botrytis cinerea* and *Rhizopus stolonifer*, the tea tree's essential oil directly or indirectly reduced the fruit rot through activating antioxidant enzymes such as superoxide dismutase, PAL, and peroxidase. The researchers found out that the activity of superoxide dismutase is increased along with the hydrogen peroxide elevation during this period at the beginning of storage time, and this mechanism is considered as the secondary metabolites in the essential oil and a signal to stimulate resistance against the disease (Shao et al., 2013).

Microbiological evaluations

Total mesophilic aerobic by evaluating of yeast and mold populations were was counted during the storage period (Fig. 6A and Fig. 6B). A higher change was observed in the total mesophilic aerobic counted than in the yeast and mold populations. The SMP- PEO sachet exhibited a significantly lower microbial load during storage. Over time, the antimicrobial effect increased due to of SMP- PEO sachet acts as an EO adsorbent. They SMP contain PEO for porous structure, and the release of menthol in the strawberry packaging gradually increases, so reducing the microbial load on the last days. Incorporation involves the entrapment of EO within the polymer matrix, leading to its gradual release, which facilitates the development of an antimicrobial system while simultaneously activating an antimicrobial mechanism at the appropriate moment (Sangsuwan et al., 2016). GC analysis results showed that menthol release occurred gradually over the period. The rapid solubility of hydrocarbon monoterpenes in the cell membrane in the gaseous phase is due to the strong anti-microbial properties of this oil (Tyagi & Malik, 2011). Other study revealed that, even after 30 days, carvacrol and thymol encapsulated in mesoporous scaffolds were able to maintain antifungal activity and inhibit fungal growth, antifungal behavior of these EOs is enhanced via their entrapment in mesoporous supports (Bernardos, et al., 2014). It has been proven that by encapsulating volatiles, their long-term effectiveness is ensured by controlled release and easy handling, with positive effects for their antifungal activity (Janatova et al., 2015). EOs change the membrane fluidity to become abnormally permeable, leading to the leakage of radicals, cytochrome C, calcium ions, and proteins, which cause oxidative stress (Amiri, et al., 2021).

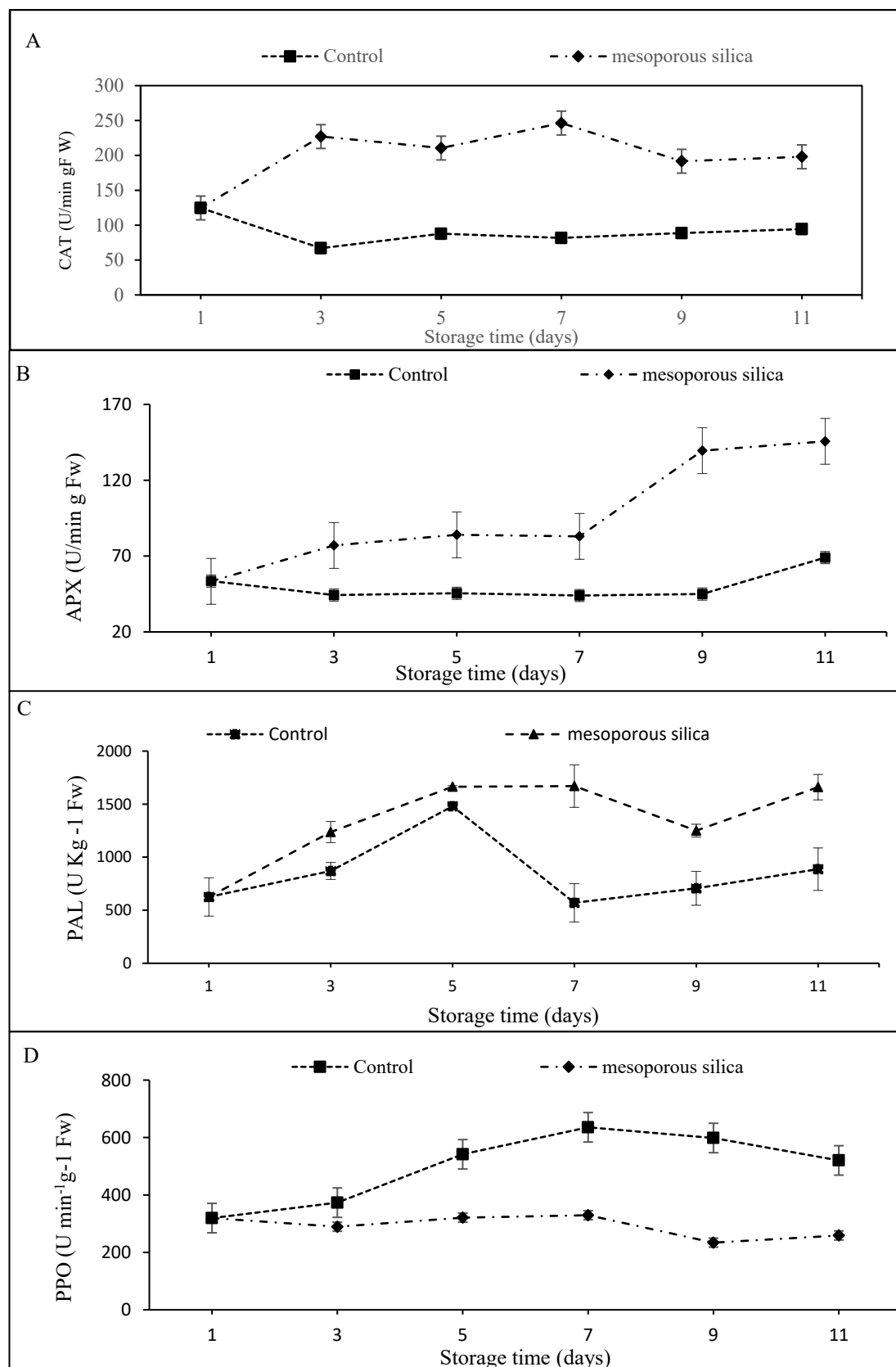


Fig. 5. Effect of antimicrobial sachet on APX (A), CAT activity (B), PAL activity(C), and PPO activity (D) of strawberry fruits packed during storage at 1°C and 90% relative humidity for up to 11 days.

Sensory evaluation

A quantitative descriptive analysis was used to evaluate the effect of SMP- PEO sachet on the sensory parameter of strawberries. Sensory attributes of the fruits (texture, odor, appearance, and overall acceptance) are presented in Figure 7. Compared to the control, SMP- PEO sachet could maintain a better appearance by decreasing the darkening process and improving anthocyanins content. The strawberries packed with SMP- PEO sachet retained their firmness well until the 11th day, in contrast to that of control that lost its texture score. Overall acceptability scores showed that all strawberries packed with SMP- PEO sachet had the highest scores. Sangsuwan et al. (2016) studied the sensory properties of strawberry packed with chitosan beads and reported that overall acceptance scores of control strawberry and the strawberry packed with chitosan beads did not change during storage while those packed with beads containing EOs decreased apparently on Day2. However, the scores of strawberry in the EO treatments were still acceptable until Day10. Perdones et al. (2012) studied the sensory properties of strawberry coated with chitosan-lemon EOs and reported that the typical strawberry aroma and flavour score of the coated sample decreased compared with non-coated sample and resulted in decreased sample acceptability. Packed fruit in zein nanofiber and Z/TEO nanofiber groups had acceptable overall appearance for marketing, as no obvious signs of decay were observed at 12th and 15th day of cold storage, respectively (Ansarifar, & Moradinezhad, 2021).

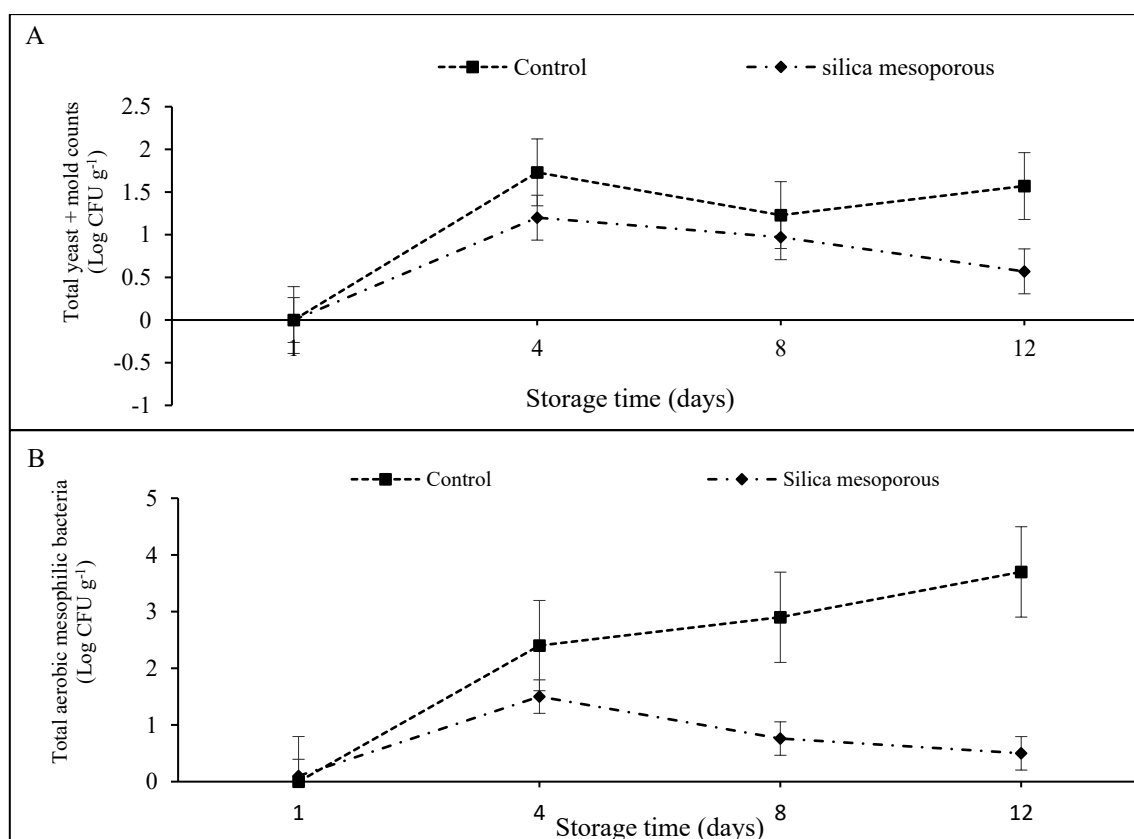


Fig. 6. Effect of antimicrobial sachet on Total yeast + mold counts (A) and total aerobic mesophilic bacteria (B) (Log CFU g⁻¹) of strawberry fruits packed during storage at 1°C and 90% relative humidity for up to 11 days.

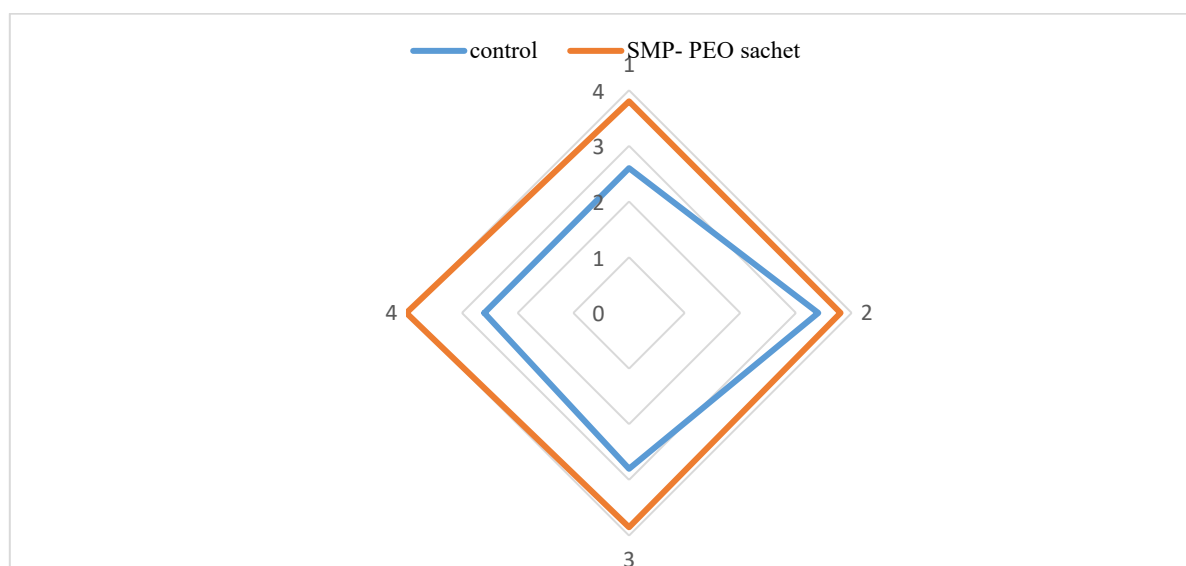


Fig. 7. Effect of antimicrobial sachet on sensory acceptance of strawberry fruits packed during storage at 1°C and 90% relative humidity for up to 11 days.

CONCLUSIONS

PEO sachets are utilized in the packaging of strawberry fruit. The shelf life of the strawberry fruit was positively affected by PEO sachets, which demonstrated higher levels of phytochemical content compared to the untreated fruit samples. It can be concluded that employing PEO sachets in the vapor phase represents a promising method for prolonging the shelf life of fruit and enhancing both microbial characteristics and biochemical parameters throughout the storage duration. The observed increase in antioxidant activity in fruits treated with PEO sachets may be attributed to the preservation of phenolic and ascorbic acid contents.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgments

We gratefully acknowledge the support of this work by the Shahid Chamran University of Ahvaz. (Grant no. SCU.AH98.212).

REFERENCES

- Ades, H., Kesselman, E., Ungar, Y., & Shimoni, E. (2012). Complexation with starch for encapsulation and controlled release of menthone and menthol. *LWT-Food Science and Technology*, 45(2), 277–288. <https://doi.org/10.1016/j.lwt.2011.08.008>.
- Amiri, A., Ramezani, A., Mortazavi, S. M. H., Hosseini, S. M. H., & Yahia, E. (2021) Shelf-life extension of pomegranate arils using chitosan nanoparticles loaded with *Satureja hortensis* essential oil. *Journal of the Science of Food and Agriculture*, 101(9), 3778-3786. <https://doi.org/10.1016/j.ultsonch.2020.105302>.
- Amiri, A., Mottaghipisheh, J., Jamshidi-Kia, F., Saeidi, K., Vitalini, S., & Iriti, M. (2020) Antimicrobial Potencies of Major Functional Foods' Essential Oils in Liquid and Vapor Phases: A Short Review. *Applied Sciences (Switzerland)*, 10, 8103. <https://doi.org/10.3390/app10228103>.

- Ansarifar, E., & Moradinezhad, F. (2021). Preservation of strawberry fruit quality via the use of active packaging with encapsulated thyme essential oil in zein nanofiber film. *International Journal of Food Science and Technology*, 56(9), 4239-4247. <https://doi.org/10.1111/ijfs.15130>.
- AOAC (2005). Vitamin C. Ascorbic acid in vitamin preparations and juices. In: Helrich K (ed) Official methods of analysis, 15th edn. AOAC, Arlington, pp, 1058–1059.
- Assis, J. S., Maldonado, R., Muñoz, T., Escribano, M. I., & Merodio, C. (2001). Effect of high carbon dioxide concentration on PAL activity and phenolic contents in ripening cherimoya fruit. *Postharvest Biology and Technology*, 23: 33–39 [https://doi.org/S0925-5214\(01\)00100-4](https://doi.org/S0925-5214(01)00100-4).
- Benzie, I. F. F., & Strain, J. J. (1996). The ferric reducing ability of plasma (FRAP) as a measure of 'antioxidant power': The FRAP assay. *Analytical Biochemistry*, 239, 70–76. <https://doi.org/10.1006/abio.1996.0292>.
- Bernardos, A., Marina, T., Žáček, P., Pérez-Esteve, É., Martínez-Mañez, R., Lhotka, M., Kouřimská, L., Pulkrábek, J., & Klouček, P. (2015). Antifungal effect of essential oil components against *Aspergillus niger* when loaded into silica mesoporous supports. *Journal of the Science of Food and Agriculture*, 95(14), 2824-2831. <https://doi.org/10.1002/jsfa.7022>. Epub 2014 Dec 19. PMID: 25428206.
- Bill, M., Pillai, S. K., Tinyane, P., Ray, S. S., & Sivakumar, D. (2018). The effect of thyme oil low-density polyethylene impregnated pellets in polylactic acid sachets on storage quality of ready-to-eat avocado. *Food and Bioprocess Technology*, 11(1), 141-151. <https://doi.org/10.1007/s11947-017-2001-5>.
- Cai, Z., Yang, R., Xiao, H., Qin, X., & Si, L. (2015). Effect of preharvest application of *Hanseniaspora uvarum* on postharvest diseases in strawberries. *Postharvest Biology and Technology*, 100, 52–58. <https://doi.org/10.1016/j.postharvbio.2014.09.004>.
- Cindi, M. D., Soundy, P., Romanazzi, G., & Sivakumar, D. (2016). Different defense responses and brown rot control in two *Prunus persica* cultivars to essential oil vapours after storage. *Postharvest Biology and Technology*, 119, 9-17.
- Colussi, R., Ferreira da Silva, W.M., Biduski, B., Mello El Halal, S. L., da Rosa Zavareze, E., & Guerra Dias, A. R. (2021). Postharvest quality and antioxidant activity extension of strawberry fruit using allyl isothiocyanate encapsulated by electrospun zein ultrafine fibers. *LWT* 143, 111087. <https://doi.org/https://doi.org/10.1016/j.lwt.2021.111087>.
- Davarpanah, J. & Kiasat, A. R. (2013). Catalytic application of silver nanoparticles immobilized to rice husk-SiO₂-aminopropylsilane composite as recyclable catalyst in the aqueous reduction of nitroarenes, *Catalysis Communication*, 41, 6-11. <https://doi.org/10.1016/j.catcom.2013.06.020>.
- Khumalo, K. N., Tinyane, P., Soundy, P., Romanazzi, G., Glowacz, M., & Sivakumar, D. (2017). Effect of thyme oil vapour exposure on the brown rot infection, phenylalanine ammonia-lyase (PAL) activity, phenolic content and antioxidant activity in red and yellow skin peach cultivars. *Scientia Horticulturae*, 214, 195–199. <https://doi.org/10.1016/j.scienta.2016.11.044>.
- Lee, J., Durst, R. W., & Wrolstad, R. E. (2005). Determination of total monomeric anthocyanin pigment content of fruit juices, beverages, natural colorants, and wines by the pH differential method: Collaborative study. *Journal of AOAC International*, 88, 1269–1278. <https://doi.org/10.1093/jaoac/88.5.1269>.
- Li, L., Song, W., Shen, C., Dong, Q., Wang, Y., & Zuo, S. (2020). Active packaging film containing oregano essential oil microcapsules and their application for strawberry preservation. *Journal of Food Processing and Preservation*, 44, e14799. <https://doi.org/10.1111/jfpp.14799>.
- Irshad Gull-e-laala, G., Naz, F. (2024). Suppression of *Fusarium sporotrichioides* initiating peach fruit rot with microencapsulated antifungal sachet of clove essential oil tablets. *European Journal of Plant Pathology*, 170, 851–865. <https://doi.org/10.1007/s10658-023-02771-3>.
- Janatova, A., Bernardos, A., Smid, J., Frankova, A., Lhotka, M., Kourimská, L., & Klouček, P. (2015). Long-term antifungal activity of volatile essential oil components released from mesoporous silica materials. *Industrial Crops and Products*, 67, 216-220.
- Meighani, H., Ghasemnezhad, M., & Bakhshi, D. (2014). Effect of different coatings on post-harvest quality and bioactive compounds of pomegranate (*Punica granatum* L.) fruits. *Journal of Food Science and Technology*, 52, 4507–4514. <https://doi.org/10.1007/s13197-014-1484-6>.

- Meighani, H., & Salehi Sarbijan, M. (2025). Influence of pre-harvest methyl jasmonate application on the fruit quality of strawberry cv. Paros at harvest and during cold storage. *Journal of Horticulture and Postharvest Research*, 8(3), 413-426. <https://doi.org/10.22077/jhpr.2025.9281.1506>.
- Montero-Prado, P., Rodriguez-Lafuente, A., & Nerin, C. (2011). Active label-based packaging to extend the shelf-life of “Calanda” peach fruit: Changes in fruit quality and enzymatic activity. *Postharvest Biology and Technology*, 60, 211–219. <https://doi.org/10.1016/j.postharvbio.2011.01.008>.
- Moradinezhad, F., Khayyat, M., Ranjbari, F., & Maraki, Z. (2018). Physiological and quality responses of Shishe-Kab pomegranates to short-term high CO₂ treatment and modified atmosphere packaging. *International Journal of Fruit Science*, 18(3), 287-299. <https://doi.org/10.1080/15538362.2017.1419399>
- Nakano, Y., & Asada, K. (1981) Hydrogen peroxide is scavenged by ascorbate-specific peroxidase in spinach chloroplasts. *Plant & Cell Physiology*, 22(5), 867–880. <https://doi.org/10.1093/oxfordjournals.pcp.a076232>.
- Otoni, C. G., Espitia, P. J. P., Avena-Bustillos, R. J., & McHugh, T. H. (2016). Trends in antimicrobial food packaging systems: Emitting sachets and absorbent pads. *Food Research International*, 83, 60–73. <https://doi.org/10.1016/j.foodres.2016.02.018>.
- Park, S.-Y.; Barton, M.; & Pendleton, P. (2011). Mesoporous silica as a natural antimicrobial carrier. *Colloids and Surfaces A*, 385, 256–261.
- Peretto, G., Du, W.X., Avena-Bustillos, R. J., Sarreal, S. B. L., Hua, S. S. T., Sambo, P., & McHugh, T. H. (2014). Increasing strawberry shelf-life with carvacrol and methyl cinnamate antimicrobial vapors released from edible films. *Postharvest Biology and Technology*, 89, 11–18. <https://doi.org/10.1016/j.postharvbio.2013.11.003>.
- Perdones, A., Sanchez-Gonzalez, L., Chiralt, A., & Vargas, M. (2012). Effect of chitosan-lemon essential oil coatings on storage-keeping quality of strawberry. *Postharvest Biology and Technology*, 70, 32e41. <http://dx.doi.org/10.1016/j.lwt.2016.07.021>
- Sangsuwan, J., Pongsapakworawat, T., Bangmo, P., & Sutthasupa, S. (2016). Effect of chitosan beads incorporated with lavender or red thyme essential oils in inhibiting *Botrytis cinerea* and their application in strawberry packaging system. *LWT*, 74, 14-20. <http://dx.doi.org/10.1016/j.lwt.2016.07.021>
- Sellamuthu, P. S., Mafune, M., Sivakumar, D., Soundy, P. (2013). Thyme oil vapour and modified atmosphere packaging reduce anthracnose incidence and maintain fruit quality in avocado. *Journal of the Science of Food and Agriculture*, 93, 3024–3031. <https://doi.org/10.1002/jsfa.6135>.
- Slinkard, K., & Singleton, V. L (1977). Total Phenol Analysis: Automation and Comparison with Manual Methods. *American Journal of Enology and Viticulture*, 28, 1-6. <https://doi.org/10.5344/ajev.1977.28.1.49>.
- Shao, X., Wang, H., Xu, F., & Cheng, S. (2013). Effects and possible mechanisms of tea tree oil vapor treatment on the main disease in postharvest strawberry fruit. *Postharvest Biology and Technology*, 77, 94–101. <https://doi.org/10.1016/j.postharvbio.2012.11.010>.
- Sousa, F.L., Santos, M., Rocha, S. M, & Trindade, T. (2014). Encapsulation of essential oils in SiO₂ microcapsules and release behaviour of volatile compounds. *Journal of Microencapsulation*. 31(7):627-35. <https://doi.org/10.3109/02652048.2014.911376>. Epub 2014 Apr 25. PMID: 24766205.
- Taheri, R. A., Dehghani, M., & Parastouei, K. (2026). Biodegradable packaging using hazelnut and walnut shells enriched with encapsulated oregano oil: Extending strawberry shelf life. *Journal of Stored Products Research*, 115, 102817. <https://doi.org/10.1016/j.jspr.2025.102817>.
- Tyagi, A.K.; & Malik, A. (2010). Liquid and vapour-phase antifungal activities of selected essential oils against *candida albicans*: Microscopic observations and chemical characterization of cymbopogon citratus. *BMC Complementary and Alternative Medicine*, 10(1), 65. <https://doi.org/10.1186/1472-6882-10-65>.
- Ruiz-Rico, M.; Pérez-Esteve, É.; Bernardos, A.; Sancenón, F.; Martínez-Máñez, R.; Marcos, M. D.; & Barat, J. M. (2017). Enhanced antimicrobial activity of essential oil components immobilized on silica particles. *Food Chemistry*, 233, 228–236. <https://doi.org/10.1016/j.foodchem.2017.04.118>.

- Velikova, V., Yordanov, I., & Edreva, A. (2000). Oxidative stress and some antioxidant systems in acid rain-treated bean plants: protective role of exogenous polyamines. *Plant Science*, 151, 59–66. [https://doi.org/10.1016/S0168-9452\(99\)00197-1](https://doi.org/10.1016/S0168-9452(99)00197-1).
- Villarino, M., Sandín-Espana, P., Melgarejo, P., & De Cal, A. (2011). High chlorogenic and neochlorogenic acid levels in immature peaches reduce *Monilinia laxa* infection by interfering with fungal melanin biosynthesis. *Journal of Agricultural and Food Chemistry*, 59, 3205–3213. <https://doi.org/10.1021/jf104251z>.
- Viacava, G. E., Ayala-Zavala, J. F., González-Aguilar, G. A., & Ansorena, M. R. (2018). Effect of free and microencapsulated thyme essential oil on quality attributes of minimally processed lettuce. *Postharvest Biology and Technology*, 145, 125–133. [10.1016/j.postharvbio.2018.07.004](https://doi.org/10.1016/j.postharvbio.2018.07.004).
- Wang, S.Y., & Gao, H. (2013). Effect of chitosan-based edible coating on antioxidants, antioxidant enzyme system, and postharvest fruit quality of strawberries (*Fragaria x aranassa* Duch.). *LWT-Food Science and Technology*, 52, 71–79. <https://doi.org/10.1016/j.lwt.2012.05.003>.
- Wang, Y. S., Tian, S. P., Xu, Y., Qin, G. Z., & Yao, H. (2004). Changes in the activities of pro-and anti-oxidant enzymes in peach fruit inoculated with *Cryptococcus laurentii* or *Penicillium expansum* at 0 or 20 C. *Postharvest Biology and Technology*, 34, 21–28. <https://doi.org/10.1016/j.lwt.2012.05.003>.
- Xu, J., Wang, Y., Chai, L., Yin, D., Lin, T., Tao, Y., Liu, S., Qi, H., Gao, X., & Jiang, J. (2024). Pre-harvest treatments: A different insight into preservation of strawberries. *Journal of Berry Research*, 14(2), 151-173. <https://doi.org/10.3233/JBR-240001>.