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RESEARCH PAPER

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EVALUATION OF THE EFFECT OF SODIUM ALGINATE COMBINED WITH THYME ESSENTIAL OIL ON THE POSTHARVEST SHELF LIFE OF WASHINGTON NAVEL ORANGE (*Citrus sinensis* cv. Washington Navel)

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ABSTRACT

Citrus fruits, belonging to the Rutaceae family, are among the most widely cultivated fruits worldwide. However, oranges are highly susceptible to postharvest quality deterioration during storage. Weight loss, firmness reduction, and biochemical changes are among the major factors limiting the shelf life of citrus fruits. This study aimed to evaluate the effects of sodium alginate edible coatings enriched with thyme essential oil on the postharvest quality of Washington navel oranges. Fruits were treated with sodium alginate alone or in combination with thyme essential oil and stored at 20 ±2°C and 65 ±5% relative humidity for 60 days. The results demonstrated that coated fruits exhibited significantly lower weight loss and better firmness retention compared with untreated fruits. In addition, the coatings maintained higher levels of titratable acidity, total soluble solids, total phenolic content, flavonoids, and ascorbic acid throughout storage, leading to enhanced antioxidant capacity. Furthermore, the combined application of sodium alginate and thyme essential oil effectively preserved cellular membrane integrity, as indicated by reduced ion leakage. Overall, sodium alginate coatings enriched with thyme essential oil can be considered a safe and effective strategy to delay physiological senescence and improve the postharvest quality of Washington navel oranges.

Keywords: alginate, thyme, preservation, antioxidants, oranges

INTRODUCTION

Citrus fruits (*Citrus* spp.), belonging to the Rutaceae family, are among the most widely cultivated fruits worldwide [Suri et al. 2022]. They are rich in various bioactive compounds, including flavonoids, essential oils, carotenoids, limonoids, and synephrine, which provide protection against various diseases such as cancer, inflammatory conditions, digestive disorders, and cardiovascular diseases [Lu et al. 2023]. Orange has gained significant importance due to its wide range of applications, including juice production, jam, confectionery, and extracts. Its consumption provides numerous nutritional benefits, including flavonoids, vitamin C, potassium, beta-carotene, and dietary fiber [Saini et al. 2022]. Washington navel orange (*Citrus sinensis* cv. Washington Navel) is one of the most important sweet orange varieties and is highly valued for its delicious taste, nutritional properties, and seedless nature [El-Khalifa et al. 2022]. This cultivar originates from the Bahia orange (Bahia), which was selected and cultivated in Brazil. Washington navel oranges are large, weighing between 200 and 500 grams, and have a thick peel

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[El-Gioushy and Eissa 2019]. Despite the high production volume of oranges, significant postharvest losses occur due to improper handling and storage methods [Barsha et al. 2021]. Preserving the quality and quantity of fruits and vegetables after harvest is crucial for economic sustainability.

A recent approach to extending shelf life, maintaining nutritional benefits, and preventing physical and textural deterioration of fruits involves the application of edible coatings [Ali et al. 2025]. These coatings form a thin, consumable layer on the fruit's surface, creating a barrier against moisture loss, oxygen exchange, and nutrient depletion [Wang et al. 2020, Kaur et al. 2024]. Edible coatings are an environmentally friendly innovation designed to maximize fruit quality and longevity [Prakash et al. 2020, Kaur et al. 2024].

Sodium alginate-based edible coatings have demonstrated significant potential in fruit preservation [Wang et al. 2019]. Sodium alginate and its derivatives exhibit several biological activities, including antioxidants, coagulating, antimicrobial, biocompatibility, wound healing, low toxicity, and tissue engineering effects [Nkede et al. 2024]. Additionally, sodium alginate is considered an ideal edible coating due to its biocompatibility, biodegradability, non-toxicity, physicochemical properties, rheological behavior, and film-forming ability. Dulta et al. [2022] examined the effect of sodium alginate (1%) and chitosan (0.5%) coatings enriched with nano-zinc oxide (0.5 g/L) on orange quality and found that the coatings significantly improved quality parameters compared to uncoated oranges [Dulta et al. 2022]. The coated samples exhibited lower rates of pH change, total soluble solids variation, and titratable acidity reduction. In another study, cherries coated with 3% sodium alginate demonstrated delayed weight loss, acidity reduction, softening, and color change [Chiabrando and Giacalone 2015]. Similarly, an experiment on strawberries revealed that a sodium alginate-calcium chloride edible coating effectively reduced respiration rate and transpiration while delaying pH increase and soluble solids accumulation. Additionally, the coating preserved the sensory properties of sliced strawberries, such as color and texture [Alharaty and Ramaswamy 2020].

Garden thyme (*Thymus vulgaris*), belonging to the Lamiaceae family, is widely recognized in traditional medicine for its expectorant, antitussive, bronchodilatory, antispasmodic, carminative, and diuretic properties [Borugă et al. 2014]. Thyme essential oil contains over 40% phenolic compounds, primarily thymol and carvacrol, which possess strong antimicrobial properties. Key components of thyme essential oil include thymol, carvacrol, linalool, γ-terpinene, p-cymene, β-myrcene, and terpinen-4-ol [Nadi et al. 2023]. In a study examining the effects of a sodium alginate (SA) and thyme essential oil (TEO) coating on fresh pistachios, treated samples exhibited lower weight loss and superior quality indices compared to untreated samples, with the highest sensory scores observed in the SA-TEO coated pistachios [Shakerardekani et al. 2021]. Fatemi et al. [2011] investigated the impact of natural essential oils, including thyme and peppermint, on controlling green mold and improving postharvest orange quality. Their results indicated that thyme essential oil exhibited strong antifungal properties against citrus fungal diseases. Similarly, Akbari et al. [2024] evaluated the effects of thyme essential oil on the microbial and physiological quality of green bell peppers, finding that it minimized peroxidase activity and respiration rate without adversely affecting texture, total phenolic content, antioxidant activity, pH, or soluble solids. This treatment contributed to the extended shelf life and improved postharvest quality of bell peppers.

Despite extensive research on sodium alginate and thyme essential oil-based edible coatings in postharvest fruit preservation, no study has specifically investigated the combined effect of sodium alginate and thyme essential oil coatings on the postharvest shelf life of Washington navel oranges. Therefore, this study aims to evaluate the application of a sodium alginate-thyme essential oil edible coating on the postharvest quality and shelf life of Washington navel oranges.

MATERIALS AND METHODS

Experimental design. This study was conducted as a factorial experiment based on a completely randomized design during the 2023–2024 period in the Plant Physiology Laboratory of the Department of Agriculture, Hormozgan University. The experimental treatments consisted of sodium alginate at two concentrations (1% and 2%) and thyme essential oil at two concentrations (150 and 300 mg L^{-1}), applied individually and in combination, along with an uncoated control. Each treatment was performed in three biological replicates, with three fruits per replicate. Measurements were carried out at three storage times (0, 30, and 60 days).

Fruit material and maturity. Washington navel oranges (*Citrus sinensis* L.) were harvested at commercial maturity from an orchard located in Kerman province, Iran. Fruits were selected based on uniform peel color, similar size and weight, and absence of visible defects or mechanical damage. To ensure homogeneity of fruit maturity, initial total soluble solids (TSS) and titratable acidity (TA) were measured at harvest (day 0), and only fruits with comparable initial quality attributes were used in the experiment.

Preparation and application of edible coatings. Sodium alginate (chemical formula: $C_6H_9NaO_7$) was purchased from Sigma-Aldrich (St. Louis, MO, USA). Thyme essential oil (*Thymus vulgaris* L.) was obtained from Ayat Essences Company (Tehran, Iran). Edible coating solutions were prepared by dissolving sodium alginate in distilled water at concentrations of 1% and 2% (w/v) with continuous stirring until complete dissolution. Thyme essential oil was added to the alginate solutions at concentrations of 150 and 300 mg L^{-1} and homogenized thoroughly.

Prior to coating, fruits were washed with distilled water and air-dried at room temperature. Fruits were then immersed in the coating solutions for 2 min, allowed to drain, and dried at room temperature before storage.

Storage conditions. Coated and uncoated fruits were stored at 20 ±2 °C and 65 ±5% relative humidity for 60 days. Analyses were performed at the beginning of storage (day 0) and after 30 and 60 days of storage.

Measured traits. At the beginning of the experiment (T0), the following parameters were measured: fruit firmness, total soluble solids (TSS), ascorbic acid, titratable acidity (TA), total phenolic content, flavonoids, antioxidant capacity, and ion leakage. After 30 (T1) and 60 (T2) days, in addition to the mentioned traits, fruit decay and weight loss percentage were also evaluated.

Weight loss percentage. To determine the percentage of weight loss, the weight of all fruits in each container (three fruits together) was measured at the beginning of the experiment and again at 30 and 60 days using a digital scale with an accuracy of 0.01 g. Finally, weight loss percentage was calculated using Equation (1).

Equation 1:

$$\text{Weight loss (\%)} = [(\text{initial weight} - \text{final weight}) / \text{initial weight}] \times 100$$

Firmness. Fruit firmness was measured using a Lutron FS-1001 penetrometer equipped with an 8 mm cylindrical probe (Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan). Measurements were conducted on unpeeled fruits at two opposite equatorial positions, and the average value was recorded for each fruit. Firmness values were expressed in Newtons (N).

Total soluble solids (TSS). TSS content was determined using a digital refractometer (Prismatech PTRP100, Iran). A single drop of orange juice was placed on the device's prism, and the TSS value was recorded in Brix degrees [Ayala-Zavala et al. 2007].

Titratable acidity (TA). Titratable acidity was determined using the Ayala-Zavala method with slight modifications, and its value was calculated using Equation 2 [Ayala-Zavala et al. 2007].

Equation 2:

$$\mathrm{TA} = \left(\frac{\text{volume of NaOH consumed} \times \text{ normality of acid equivalent}}{\text{sample volume}}\right) \times 100$$

Ascorbic acid. Ascorbic acid (Vitamin C) was determined using the Etemadipoor method. A 100 µL sample of orange juice was added to a test tube containing 10 mL of 1% metaphosphoric acid and vortexed for 10 seconds. Then, 1000 µL (1 mL) of this mixture was transferred to 9 mL of indophenol solution and vortexed again for 10 seconds. The absorbance of the samples was read at 515 nm using an ELISA reader (BioTek Epoch 2TC Take3, BioTek Instruments, Inc., Winooski, VT, USA). In this experiment, 1% metaphosphoric acid was used as a blank [Etemadipoor et al. 2019].

Antioxidant capacity. To prepare the methanolic extract of the juice, a 1 : 3 ratio of orange juice to 85% methanol was used. Antioxidant capacity was measured using the DPPH free radical scavenging assay. In this experiment, 85% methanol was used as a blank, and the DPPH solution served as the control [Sheng et al. 2018]. The percentage of free radical inhibition was calculated using Equation (3).

Equation 3:

$$\text{Antioxidant capacity} = [(\mathrm{AC} - \mathrm{OD}) / \mathrm{AC}] \times 100$$

where AC represents the absorbance of the control and OD represents the absorbance of the samples.

Total phenols. Total phenolic content was determined using the Folin-Ciocalteu reagent. A 150 µL sample of methanolic extract was transferred to a 2 mL microtube, and 750 µL of 10% Folin-Ciocalteu reagent (Merck KGaA, Darmstadt, Germany) was added. After 5 minutes, 600 µL of 7% sodium carbonate was added. The samples were incubated for 90 minutes in the dark on a shaker (SHAKER-M model, Noorsanat Azma Ferdows Co., Iran). The total phenolic content was then measured at 760 nm using an ELISA reader (BioTek Epoch 2TC Take3, BioTek Instruments, Inc., Winooski, VT, USA) [Singleton and Rossi 1965].

Flavonoids. Flavonoid content was measured using the aluminum chloride ($AlCl_3$) colorimetric method. A 100 µL methanolic extract was placed in a 2 mL microtube, and 300 µL of 85% methanol was added. Then, 20 µL of 10% aluminum chloride and 20 µL of 1 M potassium acetate were added. Finally, 560 µL of distilled water was added, and the mixture was shaken for 30 minutes in the dark. The absorbance was then measured at 415 nm using an ELISA reader [Chang et al. 2002].

Ion leakage. Ion leakage was measured using the method described by Masoumi et al. [2010]. A 0.5 g sample of orange peel was placed in a 50 mL Falcon tube with 20 mL of distilled water and left for 24 hours. After 24 hours, the initial electrical conductivity (EC1) was measured using an EC meter (AD3000 model, ADWA Instruments, Szeged, Hungary). The samples were then incubated in a water bath at 100°C for one hour. After cooling to 25°C, the final electrical conductivity (EC2) was recorded. Ion leakage percentage was calculated using Equation (4).

Equation 4:

$$\text{Ion leakage} = (EC1 / EC2) \times 100$$

Sensory evaluation. Sensory evaluation was conducted as a preliminary descriptive assessment to compare the overall sensory quality of the samples during storage. The evaluation was performed by three trained evaluators from the Department of Food Science, who were familiar with the sensory attributes of citrus fruits. Before the evaluation, the assessors received training sessions focused on the identification and scoring of key sensory attributes, including appearance, color, aroma, texture, and overall acceptability. The training involved discussion of attribute definitions, use of reference samples, and calibration to ensure consistency among evaluators. Samples were coded with random three-digit numbers and presented in a randomized order under controlled laboratory conditions (ambient temperature and neutral lighting). The evaluators scored each attribute using a five-point hedonic scale, where 1 indicated very poor quality and 5 indicated excellent quality. The mean scores of the evaluators were used for statistical analysis.

Statistical analysis

All experimental data were analyzed using SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA). Prior to statistical analysis, data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test.

The effects of treatments, storage time, and their interactions were evaluated using factorial analysis of variance (ANOVA). When significant differences were detected, mean comparisons were performed using the least significant difference (LSD) test at a 5% probability level ($p \le 0.05$). Graphs were prepared using appropriate statistical software.

RESULTS AND DISCUSSION

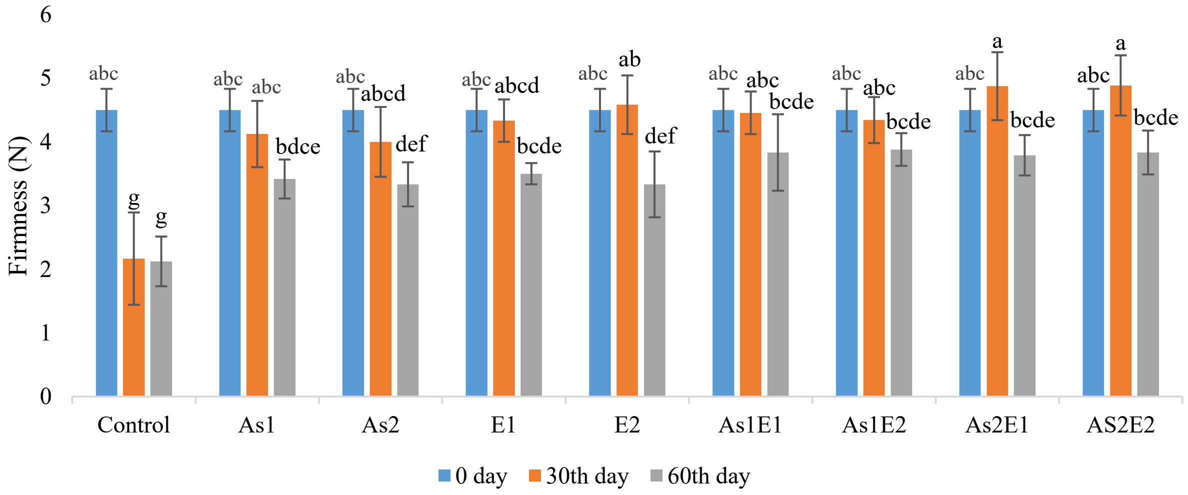
Effect of treatments on fruit skin firmness. Variance analysis of the data indicated that the effect of sodium alginate, garden thyme essential oil, storage time, and their interaction was significant at the 1% level (Table 1). The results of mean comparisons showed that after 30 days, the lowest firmness was observed in the control group, and the highest firmness at this time was observed in the As1E1 treatment. After 60 days of storage, the lowest firmness was seen in the control treatment, and the highest firmness was also observed in the As1E1 treatment (Figure 1). It appears that the treatments had a positive effect on the percentage of weight loss, which may be due to the role of sodium alginate in stabilizing the cell membrane. Sodium alginate enriched with essential oils significantly increases the shelf life of fruits. Sodium alginate containing essential oils acts as a barrier to reduce gas exchange, thus preventing tissue softening by slowing down respiration [Díaz-Mula et al. 2012]. A study found that grapes treated with a combination of sodium alginate and essential oils showed higher firmness compared to untreated samples [Wang et al. 2020]. In pineapple, fruit coated with sodium alginate along with lemongrass essential oil and sodium alginate enriched with antioxidants and olive oil showed higher firmness compared to the control group [Azarakhsh et al. 2014, Ramana Rao et al. 2016]. In some treatments, fruit firmness measured after 30 days of storage was slightly higher than that at harvest. This phenomenon, while seemingly counterintuitive, has been previously observed in edible coating studies [Rojas-Graü et al. 2008, Zhang et al. 2024]. The apparent increase can be attributed to reduced moisture loss from the peel surface, leading to a drier and more rigid outer layer, as well as structural changes induced by the alginate-calcium crosslinking network that increase the peel's resistance to penetration [Zhang et al. 2024]. Importantly, this reflects changes in peel physical properties rather than an actual increase in flesh firmness. Similar observations have been reported in other fruits coated with hydrocolloid-based edible coatings, where surface drying and coating matrix formation resulted in higher penetrometer resistance during early storage [Adjouman et al. 2018].

Table 1. Analysis of variance for some traits evaluated in the study

Source of variation	df	Firmness	Ion leakage	Weight loss	TSS	TA
Treatments	8	9.90**	268.56**	55.73**	1.11**	0.23**
Time	2	812.57**	3024.54**	123967.26**	150.57**	0.93**
Treatment × time	16	3.11**	160.79**	53.59**	0.64*	0.11**
Error	54	0.49	21.28	2.5	0.32	0.16
Total error	80	–	–	–	–	–
CV (%)	–	3.15	6.42	1.99	3.85	16.89

*significant at 5% level, **significant at 1% level

Figure 1. Effects of sodium alginate and thyme essential oil treatments on fruit firmness during storage (0, 30, and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



Effect of treatments on ion leakage. According to the results in the analysis of variance table, the effect of the experimental treatments and their interaction on the ion leakage trait was significant at the 1% level (Table 1). The results of mean comparisons showed that the highest ion leakage was observed in the control treatment at 60 days of storage, with significant differences compared to all other treatments at 30 days of storage, except for the control. The lowest ion leakage was observed in the As2E2 treatment (Figure 2). Ion leakage is an indicator used to assess the integrity of the cell membrane and its permeability. Maintaining the structural integrity of cells during the fruit ripening process is crucial for cell survival. Increased ion leakage is mainly due to cell degradation and increased membrane permeability [Sinha et al. 2022]. However, the sodium alginate coating with garden thyme essential oil, both individually and in combination, was effective in reducing ion leakage. Similar results were observed in peaches coated with sodium alginate along with rhubarb extract [Li et al. 2019].

Effect of treatments on weight loss. According to the analysis of variance table, the effect of sodium alginate, garden thyme essential oil, storage time, and their interactions on the percentage of weight loss in oranges was significant at the 1% level (Table 1). The results of mean comparisons also showed that after 30 days of storage, the control sample had the highest weight loss, and the lowest percentage of weight loss was observed in the As2E1 treatment. In the samples after 60 days of storage, the highest weight loss was observed in the control, and the lowest weight loss was observed in the As2E2 treatment (Figure 3). The edible coating of sodium alginate acts as a semi-permeable barrier to limit water exchange. This reduces moisture loss, respiration rate, oxidative reactions, and delays the physiological aging of fruits [Wang et al. 2020]. Garden thyme essential oil was added to sodium alginate to delay moisture loss and preserve other sensory characteristics. Adding essential oils and surfactants improves the water retention ability of the coating [Shakerardekani et al. 2021]. The results of this study are consistent with the findings of Shakerardekani et al. [2021] on pistachio (*Pistacia vera*), Utami et al. [2023] on strawberries (*Fragaria* sp.), Linh et al. [2024] on Darabi (*Citrus maxima*), and Dulta et al. [2022] on oranges (*Citrus sinensis* L.).

Figure 2. Effects of sodium alginate and thyme essential oil treatments on ion leakage during storage (0, 30, and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test

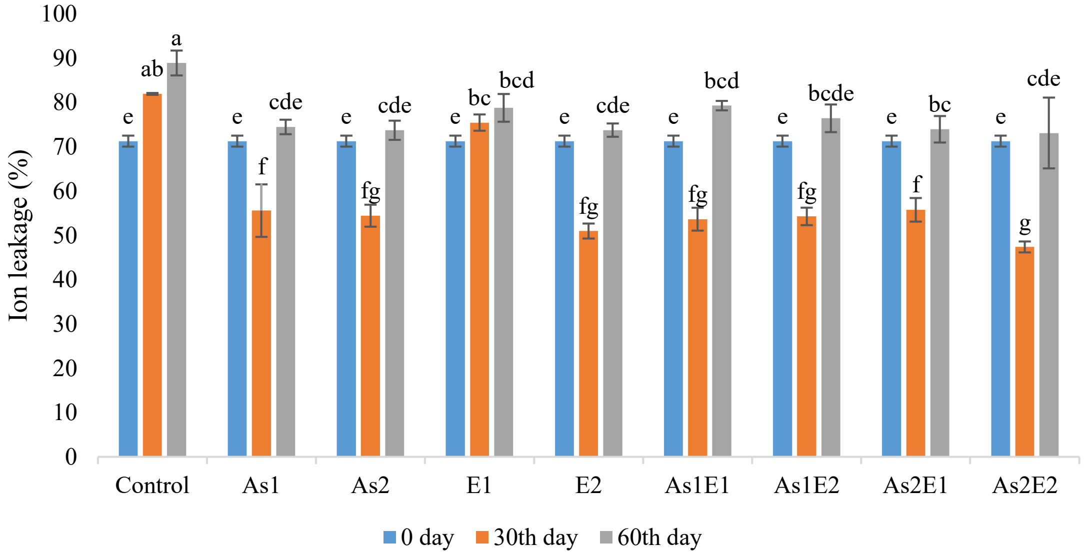
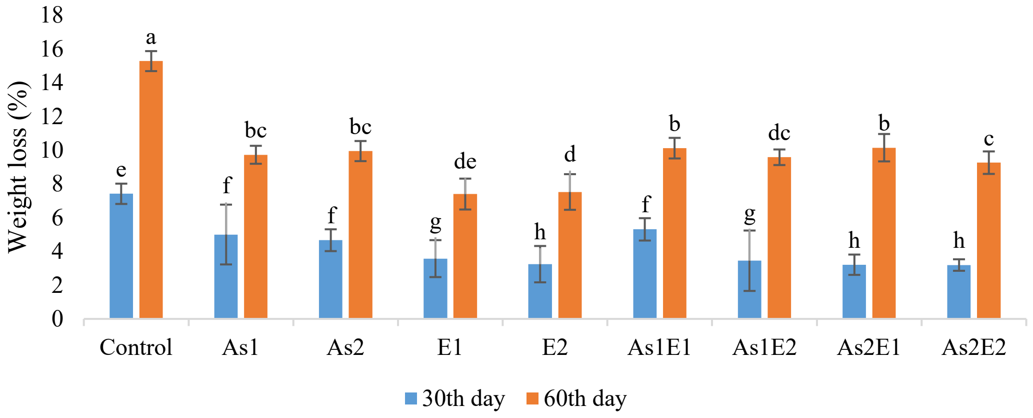


Figure 3. Effects of sodium alginate and thyme essential oil treatments on weight loss percentage during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



Effect of treatments on total soluble solids (TSS). Based on the results shown in the analysis of variance table, the effect of sodium alginate, garden thyme, and storage time was significant at the 1% level, while their interactions were significant at the 5% level on the total soluble solids (TSS) content (Table 1). The results of mean comparisons indicated that the control treatment at 60 days of storage had the highest TSS, while the lowest TSS was observed in the As1E1 treatment. In the 30-day storage samples, the control also had the highest TSS (Figure 4). The treatments showed a slight increase in TSS compared to the control, which might be due to the formation of a physical barrier by the coating materials, reducing transpiration losses. The highest TSS in the control may be attributed to faster metabolic activities through respiration and transpiration in the control compared to the other treatments. Similar observations have been reported by Rokaya et al. [2016] for different mandarin orange varieties and Thapa et al. [2020] for sweet oranges.

Figure 4. Effects of sodium alginate and thyme essential oil treatments on total soluble solids during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test

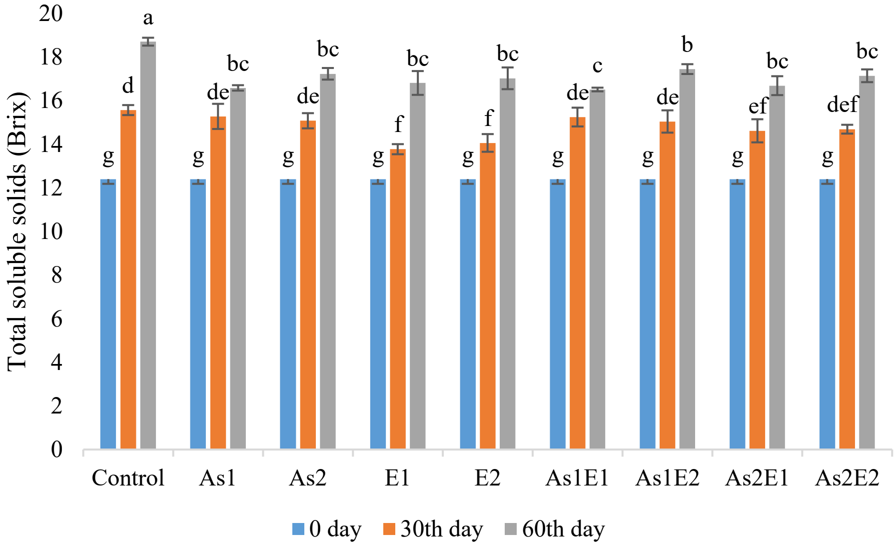
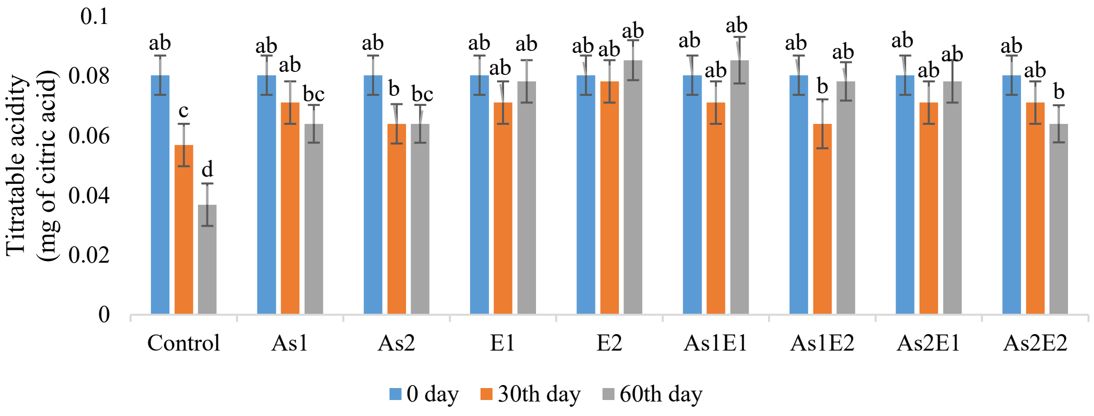


Figure 5. Effects of sodium alginate and thyme essential oil treatments on TA during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



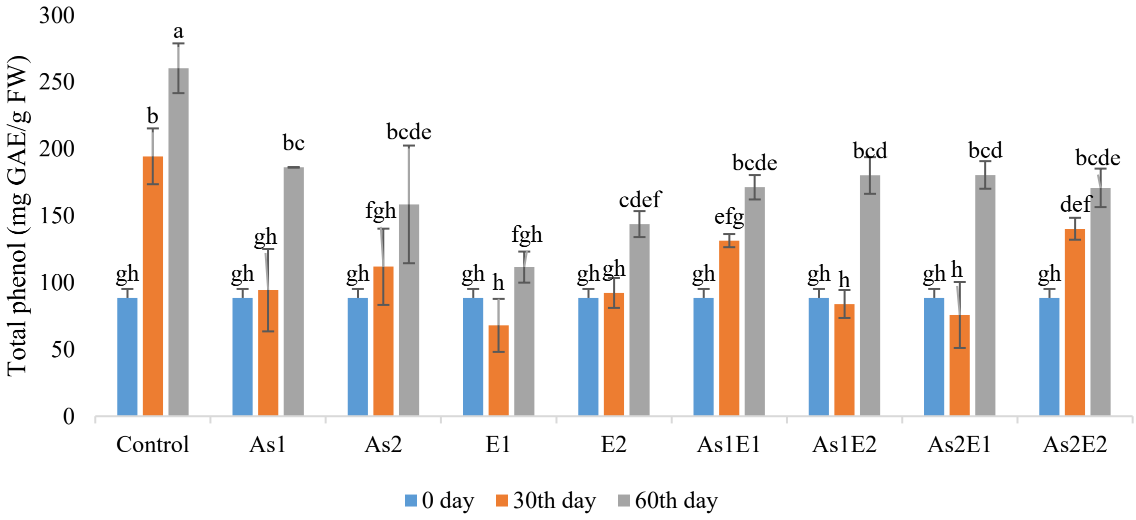
Effect of treatments on titratable acidity (TA). According to the results from the analysis of variance, the effect of sodium alginate, garden thyme essential oil, storage time, and the interaction between the treatments and time were significant at the 1% level on titratable acidity (TA) – as shown in Table 1. Based on the results of mean comparisons, the highest titratable acidity was observed in the E2 and As1E1 treatments, which showed a significant difference compared to the control at both 30 and 60 days of storage (Figure 5). In this study, the titratable acidity in all coated treatments was lower than in the control. This might be due to reduced acid utilization during respiration in fruits treated with sodium alginate and garden thyme essential oil, while faster acid utilization during respiration was observed in the control fruits during storage. Rokaya et al. [2016] and Khorram et al. [2017] reported the highest TA in the control compared to fruits treated with different coating materials in mandarin and Kinnow mandarin, respectively [Rokaya et al. 2016, Khorram et al. 2017]. Although titratable acidity (TA) values at 60 days of storage were higher in some treatments compared to the initial harvest, this increase should not be attributed to heterogeneity of fruit maturity at harvest. All fruits were harvested at the same commercial maturity stage. The observed retention or increase in TA during storage can be explained by the reduced respiration rate and delayed organic acid degradation in coated fruits. Similar behavior has been reported in previous studies, where edible coatings slowed metabolic processes and preserved organic acids during storage [Diaz-Mula et al. 2012, Chiabrando and Giacalone 2015].

Table 2. Analysis of variance for some evaluated traits in the study

Source of variation	df	Sensory evaluation	Total phenols	Flavonoids	Antioxidant capacity	Ascorbic acid
Treatments	8	0.76*	1627.59**	0.23**	18.71**	11.43**
Time	2	6.02**	70370.73**	7.96**	6296.11**	1631.38**
Treatment × time	16	0.52**	1700.03**	0.14**	11.29**	10.23**
Experimental Error	54	0.47	780.02	0.22	0.4	3.54
Total error	80	–	–	–	–	–
CV (%)	–	16.8	22.49	19.41	1.82	1.99

*significant at 5% level,**significant at 1% level

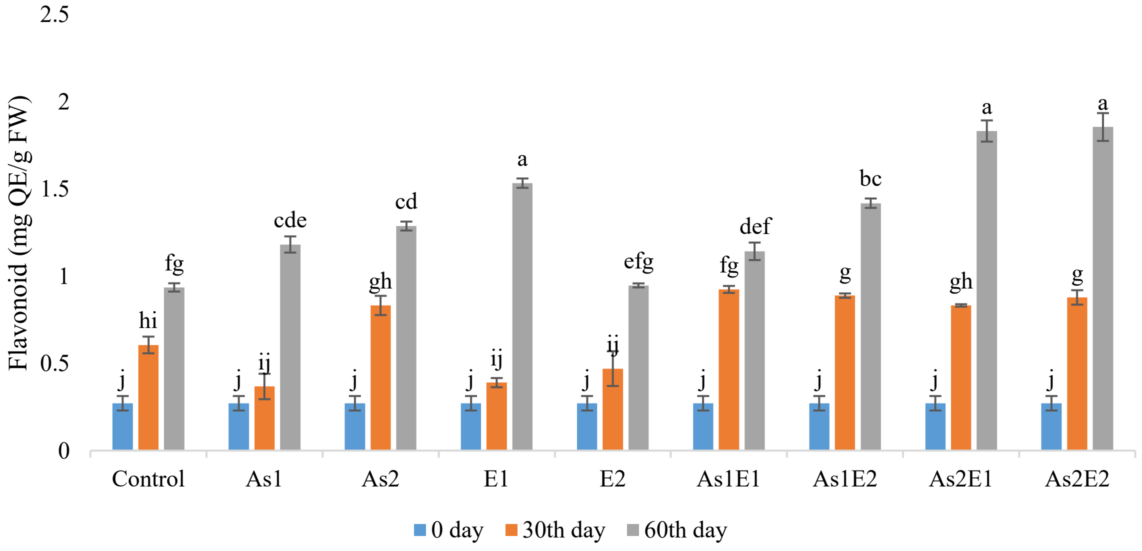
Figure 6. Effects of sodium alginate and thyme essential oil treatments on total phenol during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



Effect of treatments on total phenol content. The results of the analysis of variance showed that the effect of sodium alginate and garden thyme at the 5% level, as well as storage time and the interaction of time and treatments, was significant at the 1% level for total phenol content (Table 2). The mean comparison results indicated that in the samples after 30 days of storage, the highest phenol content was observed in the control treatment, and the lowest phenol content was in the E1 treatment. In the samples after 60 days, the highest total phenol content was observed in the control, while the lowest total phenol content was observed in the garden thyme treatment with a concentration of 150 mg/L (Figure 6). Edible coatings reduce the loss of polyphenols and maintain a higher antioxidant capacity during post-harvest storage of cherries [Díaz-Mula et al. 2012]. Studies on plums and apricots have reported that coatings reduce the ripening rate, thereby delaying the onset of aging and reducing cellular structural degradation. Additionally, coatings reduce respiration, decrease the available oxygen for metabolic activities in the fruit, and consequently reduce the activity of phenol oxidase and peroxidase [Ghasemnezhad et al. 2010, Kumar et al. 2017, Thakur et al. 2018]. A continuous increase in phenolic compounds was observed in cherries coated with alginate during cold storage. Thus, the coating allows for the accumulation of phenolic compounds throughout storage without any reduction [Díaz-Mula et al. 2012].

Effect of treatments on total flavonoids. According to the results of the analysis of variance, the effect of sodium alginate, garden thyme, storage duration, and their interaction was significant at the 1% level for flavonoid content (Table 2). The mean comparison results showed that in the samples after 30 days of storage, the highest flavonoid content was observed in the As1E1 treatment, while the lowest flavonoid content was in the As1 treatment. In the samples after 60 days of storage, the highest flavonoid content was observed in the As2E2 treatment, and the lowest flavonoid content was in the E2 treatment (Figure 7). Research has shown that flavonoid content can be influenced by fruit ripening, post-harvest treatments, and extraction processes [Tai et al. 2014, Addi et al. 2022]. In the present study, the results showed that flavonoid content increased over time. This might be due to the increase in flavonoid levels during storage, which enhances antioxidant properties and helps combat oxidative stress. Additionally, sodium alginate coating combined with garden thyme essential oil maintains flavonoid content by controlling the activity of the mentioned enzymes. These results align with studies on flavonoids in citrus fruits [Díaz-Mula et al. 2012, Thakur et al. 2018, Riva et al. 2020, Addi et al. 2022].

Figure 7. Effects of sodium alginate and thyme essential oil treatments on total flavonoid during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



Effect of treatments on antioxidant capacity and ascorbic acid content. The results from the analysis of variance indicated that the effect of sodium alginate, garden thyme essential oil, storage duration, and their interaction on the antioxidant capacity of the fruits was significant at the 1% level (Table 2). The mean comparison results showed that with the increase in storage time, the antioxidant capacity also increased, and at each time point, the control sample differed significantly from the other treatments (Figure 8). According to the variance table, the effect of sodium alginate, garden thyme essential oil, storage duration, and their interaction on ascorbic acid (vitamin C) content in oranges was significant at the 1% level (Table 2). The mean comparison results indicated that after 60 days, the highest ascorbic acid content was observed in the As2E2 treatment, while the lowest content was in the control sample. For the 30-day storage samples, no significant differences were observed among the treatments (Figure 9).

Figure 8. Effects of sodium alginate and thyme essential oil treatments antioxidant capacity during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test

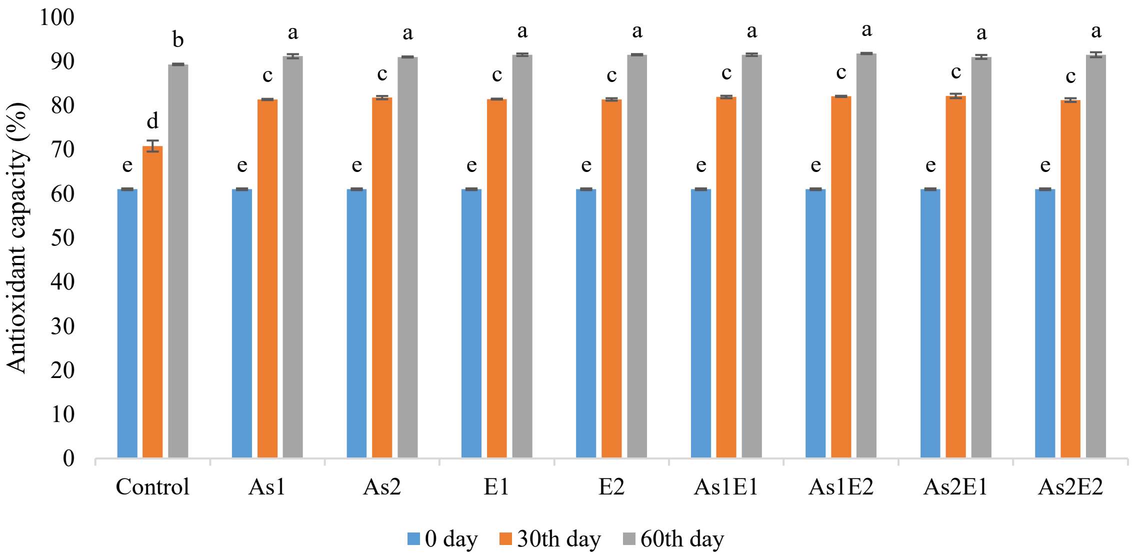
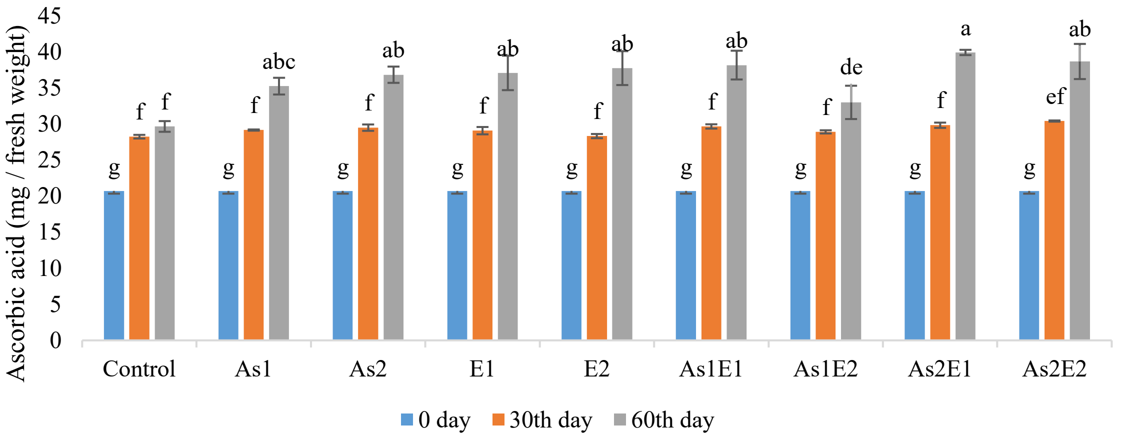
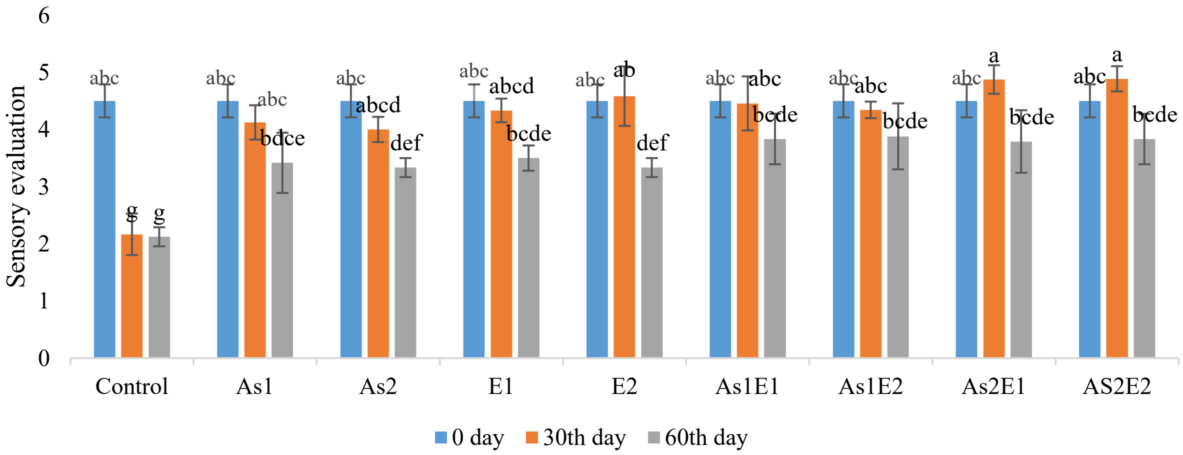


Figure 9. Effects of sodium alginate and thyme essential oil treatments on ascorbic acid during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



Fruits are rich in minerals, vitamins, and antioxidants that protect against cancer and cardiovascular diseases. However, improper storage of fruits has adverse effects on their quality, such as browning, off-flavors, loss of soluble solids, and decreased antioxidant activity [Barzegar et al. 2018]. Rahemi et al. [2023] reported that during storage, ascorbic acid is highly susceptible to degradation due to oxidation compared to other nutrients. By maintaining membrane stability, the binding of free radicals and reactive oxygen species to the membrane surface can be prevented, thereby preserving antioxidants such as ascorbic acid. The reduction in antioxidant capacity of the fruits during storage can be explained by the fact that ascorbic acid is converted by the enzyme ascorbate oxidase into dehydroascorbate, and by phenol oxidase [Linh et al. 2024]. A study on cherries showed that sodium alginate coating was effective in preserving antioxidants in cherries, with an increase in anthocyanins, phenolics, delayed loss of titratable acidity, and ascorbic acid content during 21 days of storage at 4°C. It was also reported that sodium alginate coating significantly reduced active oxygen levels, decreased the activity of defense enzymes, and preserved total soluble solids, titratable acidity, and ascorbic acid content, which resulted in increased antioxidant activity [Chiabrando and Giacalone 2015]. It was also reported that sodium alginate edible coatings combined with essential oils exhibited higher antioxidant activity. Similarly, sodium alginate coatings enriched with citral and eugenol helped preserve antioxidant activity, anthocyanins, and phenolics in raspberries and fresh apples during refrigeration storage. Sodium alginate, by creating a semi-permeable barrier around the fruit and inhibiting ethylene production, helps preserve the antioxidant activity of fruits [Guerreiro et al. 2016, Wang et al. 2020].

Figure 10. Effects of sodium alginate and thyme essential oil treatments on sensory evaluation during storage (30 and 60 days). Values represent mean ± standard error (SE; n = 3). Means followed by the same letters are not significantly different at p ≤ 0.05 according to the LSD test



Effect of treatments on sensory evaluation. The results from the analysis of variance table indicated that the treatments of sodium alginate, garden thyme, and their combination were significant at the 5% level, while storage time and their interaction were significant at the 1% level for sensory evaluation (Table 2). The results of mean comparisons showed that the lowest score was observed in the control treatment at both 30 and 60 days of storage, while the highest score was observed in the As2E2 treatment at 30 days of storage, with a significant difference compared to the control (Figure 10). The agricultural and food sectors are required to evaluate the organoleptic properties of oranges through sensory analysis. This type of analysis is related to consumer perception, as food is evaluated through the senses using organoleptic properties such as appearance, smell, aroma, texture, and taste [Villaseñor-Aguilar et al. 2024]. In this experiment, the sensory properties of the oranges were evaluated using a panel test. The results showed that sensory scores decreased over time, and the application of treatments at all levels improved the overall quality of the samples. Furthermore, the results indicated that the combined treatments of sodium alginate and garden thyme essential oil were the most effective. These results are consistent with findings from research by Megha et al. [2023] on pears, Fatemi et al. [2011] on oranges, and Shabanian et al. [2015] on oranges.

CONCLUSIONS

Washington navel oranges, although a non-climacteric fruit, have a high rate of perishability. One of the strategies to increase shelf life in postharvest processes is treating fruits with edible coatings. In the present study, sodium alginate coatings combined with garden thyme essential oil effectively preserved the physicochemical and antioxidant quality of Washington navel oranges during storage. The treatments reduced quality deterioration, as evidenced by lower firmness loss, reduced ion leakage, and better retention of total soluble solids, titratable acidity, phenolic compounds, flavonoids, and ascorbic acid.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

DATA AVAILABILITY

The data generated or analyzed during this study are included in this published article.

AUTHORS' CONTRIBUTIONS

H.H.: conducting laboratory work, providing fruits. R.E.: selecting the topic, leading and guiding the team, analyzing the data. M.B.: writing the article.

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