Delaying Ripening and Preserved Quality Characteristics of Tomato Fruits by Using Some Postharvest Treatments During Cold Storage.

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ABSTRACT

This research was conducted through the 2024 and 2025 seasons on Tomato (*Solanum lycopersicum var.* Staffy 409*).* Tomato fruits were harvested at the turning stage (20–30% red coloration) to study the effect of postharvest treatments, chitosan (CS, 125 ppm), potassium permanganate (7.5 ppm), salicylic acid (SA, 0.4 mM), pomegranate peel extract + chitosan (PPE-CS, 125 ppm each), liquorice root extract + chitosan (LRE - CS, 125 ppm each), and zeolite + chitosan (ZE-CS, 125 ppm each), in addition to an untreated control, on delaying ripening and maintaining quality attributes, and extending storability during cold storage at 10°C and 90–95% relative humidity for 30 days. The obtained results revealed that the application of a zeolite composite solution at 125 ppm and salicylic acid at 0.4 mM was notably effective in reducing weight loss and lycopene accumulation, as well as changes in color, with no signs of decay. In addition to retention and maintained firmness, titratable acidity, ascorbic acid, antioxidant content and lightness. Moreover, after 30 days of storage at 10°C, SA treatment yields an excellent appearance, while Ze-CS treatment achieves a good appearance during the same period.

Keywords: Tomatoes- chitosan- potassium permanganate- salicylic acid- pomegranate peel extract.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is ranked among the most important horticultural fruits worldwide, prized for its nutritional value and economic significance. However, its postharvest shelf life is severely limited by its highly perishable nature. As a climacteric fruit, tomato continues to ripen after harvest through a burst of ethylene production and respiratory activity, leading to rapid tissue softening, pigment changes, and quality degradation (Zapata et al., 2008). These physiological changes, combined with high transpiration rates and susceptibility to pathogenic fungi, result in significant losses through shriveling, decay, and senescence during storage, distribution, and marketing (El-Ramady et al., 2015; Chrysargyris et al., 2016). In order to mitigate these issues, most postharvest storage methods focus on regulating respiration and ethylene activity to slow down these changes (Martínez-Romero et al., 2007). Therefore, the development of effective and sustainable postharvest strategies to mitigate these issues is crucial for reducing losses and extending the marketability of products.

A primary focus of postharvest technology is controlling the action of ethylene and regulating respiration rates. A promising strategy to achieve this is the application of edible coatings and bioactive compounds that can modify the internal atmosphere, scavenge ethylene, and bolster the fruit's innate defense mechanisms. Among these, chitosan (CS), a biodegradable and non-toxic polysaccharide, has emerged as a leading material. CS-based coatings form semi-permeable barriers that reduce respiration, minimize water loss, and delay ripening, thereby preserving firmness and weight in tomatoes and other fruits (Wang et al., 2022). Furthermore, its antimicrobial and antifungal properties enhance its role in postharvest management (Gasilova et al., 2024). Several reports

confirm that CS-based edible films extend the shelf life and maintain the quality of various horticultural commodities, including cherry tomatoes **(**Buthelezi et al., 2023) and strawberries (Saleem et al., 2021).

The efficacy of chitosan can be significantly enhanced by integrating it with other functional materials. Zeolites, crystalline aluminosilicates with high porosity and cation-exchange capacity, are excellent adsorbents for ethylene. Their incorporation into chitosan matrices creates composite coatings that actively remove ripening hormones from the storage environment, further delaying senescence (de-Bruijn et al., 2020). Their abundance, low cost, nontoxicity, and environmental safety make them excellent sorbents for ethylene removal in the agro-food sector (Hosseinnia et al., 2024). Tomato fruits treated with zeolite at 3% (w/w, based on chitosan) exhibited improved coating properties, thereby delaying the ripening of the tomatoes. Zeolite is utilized due to its high porosity and large surface area, which enable effective adsorption of ethylene, carbon dioxide, and oxygen gases (García et al., 2014). Similarly, potassium permanganate ($KMnO_4$) acts as a potent ethylene oxidizer, converting it to carbon dioxide and water, a technology proven to reduce respiration and extend the shelf life of various climacteric fruits (Atala and El-Gendy, 2020).

Beyond physical barriers and adsorbents, the use of plant-derived bioactive compounds offers a biological strategy to delay ripening and enhance resistance. Salicylic acid (SA), a natural phenolic compound, acts as a signaling molecule that suppresses endogenous ethylene biosynthesis and respiration, thereby delaying senescence and softening. SA treatment also enhances the antioxidant system, helping to maintain ascorbic acid levels and reduce oxidative stress in fruits such as tomatoes and kiwis (Aghdam et al., 2014).

Furthermore, agro-industrial waste extracts represent a sustainable and potent source of antimicrobial and antioxidant agents. Pomegranate peel extract (PPE), rich in phenolic compounds, provides potent antioxidant and antimicrobial activities that can reduce microbial burden and slow oxidative degradation when incorporated into coatings (Nicosia et al., 2016). Furthermore, liquorice root extract possesses well-documented antifungal, antioxidant, and anti-inflammatory properties, showing great potential as a natural bio-preservative to control postharvest diseases and maintain quality (Madanipour et al., 2019).

Therefore, this study aims to evaluate and compare the effectiveness of several postharvest treatments, including chitosan coatings functionalized with pomegranate peel extract, liquorice root extract, and zeolite, as well as applications of potassium permanganate and salicylic acid delaying ripening, maintaining quality attributes, and extending the storability of tomato fruits during 30 days of storage at 10°C and 90-95% relative humidity.

MATERIALS AND METHODS

Tomato fruits (*Solanum lycopersicum* var. Staffy 409) were harvested at the turning stage (20-30%) of surface in the aggregate shows a definite change in colour from green to tarnish yellow, pink, red or orange from a private farm in Fayoum Governorate, Egypt, on April 3rd and 5th during the 2024 and 2025 seasons, respectively. Immediately after harvest, the fruits were transported to the Vegetable Handling Research Department laboratory at the Horticultural Research Institute, Agricultural Research Center, Giza.

For the storage experiment, only tomatoes that were free from physiological defects and fungal diseases, and that exhibited uniform size (diameter: 4-5 cm) and weight (100-110 g), were selected. The fruits were washed in a 0.05% sodium hypochlorite solution for 5 minutes to ensure surface sanitation before applying the coating treatments, then rinsed with distilled

water, and air-dried at room temperature, as described by Chrysargyris et al. (2016).

Preparation of pomegranate peel extract (PPE) and liquorice root extract (LRE): Pomegranates (*Punica granatum* L.) were obtained from a local market (Giza, Egypt). The fruits were thoroughly washed with distilled water, and the seeds were removed. Liquorice roots (*Glycyrrhiza glabra*) were purchased from the local market, Cairo, Egypt and washed with distilled water. Both dried pomegranate peels and liquorice roots were dried in a hot air oven (D-63450 Heraeus, Germany) at 50 °C. After drying, the samples were ground into a fine powder before extraction of the bioactive compounds. Ethanolic extracts were obtained using a previous methodology (Babu et al., 2003). Preparation of solutions for PPE and LRE: A 0.25% chitosan solution with 0.25% PPE or LRE, respectively, was prepared separately.

Preparation of Zeolite solutions: The zeolite-chitosan composite, a 3% zeolite suspension (relative to 0.5% chitosan), was prepared according to Xu et al. (2006). A 0.25% chitosan solution was prepared by dissolving chitosan in 0.5% acetic acid at 45°C under continuous magnetic stirring until complete dissolution. Zeolite powder was dispersed in 2 L of 1% acetic acid and stirred vigorously for 24 hours. Then, 8 L of the 0.25% chitosan solution was gradually added to the zeolite suspension, followed by 24 h of continuous stirring.

Table (1). Bioactive compound of PPE-CS, LRE-CS extracts, and ZE-CS composite:

Treatments	Bioactive compounds		
	Total phenolic content (mg GAE/g)	Total flavonoid content (mg QC/g)	Antioxidant activity (%)
Pomegranate peel extract (PPE)	112.73±0.24[a]	73.61±0.25[a]	83.49±0.49[a]
Liquorice root extract (LRE)	44.96±0.27[b]	26.11±0.26[b]	58.13±0.30[b]
Zeolite composite (ZE)	1.09±0.02[c]	3.23±0.01[c]	4.71±0.23[c]

Table (2): Mineral composition of zeolite:

Component	Fe_2O_3	MnO	CaO	K_2O	P_2O_5	SiO_2	MgO
%	12.89	0.15	10.97	1.63	0.90	39.27	9.23

Analytical methods: Proximate analysis of minerals was determined according to the standard methods of the **A.O.A.C. (2016).**

Coating treatments: Tomato fruits were dipped for 5 minutes in the following solutions:

- Chitosan (CS) at 125 ppm.
- Pomegranate peel extract (PPE) at 125 ppm + chitosan at 125 ppm (PPE-CS).
- Liquorice root extract (LRE) at 125 ppm + chitosan at 125 ppm (LRE-CS)
- Zeolite composite (ZE) at 125 ppm + chitosan at 125ppm (ZE-CS)
- Potassium permanganate ($KMnO_4$) at 7.5 ppm.
- Salicylic acid (SA) at 0.4 mM.
- Untreated fruits (control).

After treatment, all samples were air-dried and packed into carton boxes (25 cm × 15 cm × 10 cm), each containing approximately 1000 g of fruit, to constitute an experimental unit (EU). Each treatment consists of twenty experimental units. The samples were stored at 10°C and 90–95% relative humidity under a completely randomized design. For each treatment and time point, three experimental units were randomly selected and analyzed

immediately after treatments as well as after 7, 14, 21, and 30 days of storage.

Postharvest Quality Assessments

Weight loss: This was measured using the following equation: $[(W_a-W_b)/W_a]$ x 100.Where: W_a= Initial fruit weight, W_b = fruit weight at the sampling period

General appearance (score): was evaluated using a scale of 9 to 1, where 9 = excellent, 7 = good, 5 = fair, 3 = poor, and 1 = unsalable. Fruits with a rating of 5 or lower were considered unmarketable, following the criteria established by Kader (2002).

Decay: Tomato decay and disorder severity were assessed using a subjective scoring system based on (1 = none, 2 = slight, 3 = moderate, 4 = severe, 5 = extreme), following the description by Wang and Qi (1997).

Color: Tomato color was measured using a Minolta CR-400 Chroma Meter, recording the a* value (red-green intensity: $a^* > 0$ = red, $a^* < 0$ = green) and lightness (L^* value).

Firmness: was evaluated with a hand pressure tester (Italian model) featuring an 8 mm plunger, and the results were recorded in kg/cm^2 (Abbott, 1999).

Titratable acidity (%): This was measured through titration with 0.1 N NaOH using phenolphthalein as an indicator outlined by A.O.A.C. (1990).

Ascorbic acid (vitamin C) content: (mg/100g fresh weight) was measured using the iodometric titration method (Satria et al., 2021).

Lycopene content (mg/g fresh weight): was assessed according to the method outlined by Anthon and Barrett (2006).

Antioxidant activity using DPPH: was assessed using the DPPH radical scavenging assay (Brand-Williams et al., 1995).

Total phenolic content "in extract": was determined following a method described by Wolfe et al. (2003).

Total flavonoid content "in extract": was assessed according to the method described by Zhishen et al. (1999).

Statistical Analysis: Duncan's multiple range test method was applied for comparing means, as described by Waller and Duncan (1969). Data were statistically analyzed using the analysis of variance described by Snedecor and Cochran (1980).

RESULTS AND DISCUSSION

Weight Loss: Water loss is a major factor in crop deterioration, leading to a reduction in marketable weight and resulting in quantitative crop losses. Additionally, it negatively impacts quality by causing wilting, shriveling, and tissue softening (Hasan et al., 2024). The data in **Table (3)** indicate a gradual increase in weight loss percentage with prolonged storage periods. These results are in agreement with Álvarez-Pérez et al. (2025). They may be due to nutrient consumption during respiration and the exchange of water caused by differences in the water vapor pressure gradient between the tissue and the ambient air during the storage period (Al-Dairi et al., 2021).

Among both seasons, all postharvest treatments reduced weight loss relative to the control. However, tomatoes treated with salicylic acid (SA) and zeolite with chitosan (ZE-CS) were the most effective in reducing weight-loss percentages, with no significant difference between them. At the same time, the other treatments were less effective in this regard, consistent with prior reports in tomatoes (García et al., 2014, and Baninaiem et al., 2016).

Weight loss during storage results from the combined effects of substrate utilization through respiration and water loss through transpiration. Salicylic acid can curb both: it interferes with mitochondrial electron

transport (acting as an inhibitor/uncoupler) to lower O_2 uptake, and it can promote stomatal closure in many contexts, reducing transpiration and thus water loss (Hanaei et al., 2022). Moreover, zeolite adsorbs headspace ethylene, thereby delaying ripening and respiration, improving visual quality, and reducing weight loss. Formulation-dependent tuning of gas permeation and adsorption (O_2/CO_2/ethylene) further helps control degradative changes and support mass retention during storage (Hosseinnia et al., 2024).

After 30 days of storage, the lowest weight loss was recorded for SA-treated tomato fruits, followed by ZE-CS treatment, with a significant difference between the two. The highest weight loss was observed in the untreated (control) group.

General Appearance score (GA):

The general appearance score of tomato fruits was significantly influenced by postharvest treatments, storage durations, and their interactions in the two seasons, as illustrated in **Table (4).** Showed a significant decline in general appearance with prolonged storage periods, these are confirmed by Mohammed et al. (2021). This decline may be attributed to wilting, shriveling, decay, color changes, and overall deterioration (Zhang et al., 2020), as well as delayed ripening (Wakene and Sharew, 2024). Shrinkage is a key indicator of deterioration, resulting in a deterioration of quality and a reduction in quantity (Bapary et al., 2024). However, tomato fruits treated with all postharvest treatments had significantly higher appearance than untreated fruits. SA maintained an excellent appearance with no noticeable changes over 30 days of storage. ZE-CS maintained good visual quality. Meanwhile, ZE-CS exhibited good appearance during the same period. These results also support the view of Baninaiem et al. (2016) on SA and de-Bruijna et al., (2019) on ZE, who reported that the application of SA and ZE-CS prolonged the storage life of tomato fruits, as measured by a delay in the accumulation of lycopene and a decrease in decay development, exhibited longer storage life, and reduced spoilage.

Salicylic acid (SA) inhibits ethylene biosynthesis and transpiration, as well as delaying some fruit ripening processes during postharvest storage **(**Ennab et al., 2020). Senescent changes, which result in losses of physicochemical properties and nutritional qualities, can also be inhibited. Consequently, fruit storage life could be markedly prolonged. Exogenous SA could be effective in reducing the rate of respiration and ethylene production (Wang et al., 2024) and delaying the senescence. On the other hand, SA treatment reduces cellular metabolic activities, such as respiration and ethylene production, thereby maintaining the membranes and cell walls and preventing an abnormal increase in soluble solids (Şahin et al., 2025). Additionally, it also inhibits the spread of fungal contamination (Xu et al., 2023).

Zeolite with chitosan coatings was assessed for extending tomato shelf life by tracking fungal decay, respiration, core quality metrics, and visual appearance. Zeolite delays ripening by scavenging ethylene in the package headspace, dampening the signal that accelerates softening and red color development. When integrated into a chitosan–zeolite coating, performance improves: the composite adsorbs ethylene and carbon dioxide while moderating oxygen, forms a semi-permeable barrier that curbs water loss, and suppresses microbes through chitosan's antimicrobial action and a mildly acidified microenvironment. As a result, tomatoes retain their firmness and surface integrity, exhibit reduced decay, and maintain their taste and color over a longer marketable period (do-Nascimento et al., 2020).

Deacy (score):

As presented in **Table (5),** the data reveal that postharvest applications, storage durations, and their interaction significantly impact decay (score) in both seasons. The

decay score of tomato fruits increased significantly with prolonged storage period, which aligns with Mohammed et al. (2021). This was attributed to physiological changes that occurred in the fruits through storage, including increased respiration rates, enhanced enzyme activity, and cell wall degradation. These factors led to fruit softening and ripening, resulting in greater moisture condensation on the fruit's surface, reduced firmness, and increased susceptibility to fungal infections (Silva et al., 2021). Furthermore, all postharvest treatments had a significantly greater effect in minimizing the decay score compared to untreated fruits. Additionally, the SA and ZE-CS treatments showed no signs of decay throughout the storage period. In contrast, the untreated fruits recorded the highest decay score. These findings are consistent with Baninaiem et al. (2016).

SA contributes to fungal activity and redox modulation, enhancing peroxidase while suppressing PPO enzyme (Yao and Tian, 2005), while ZE -CS lowers headspace ethylene, jointly preserving firmness and limiting infection. (Davarynejad et al., 2015). Also, zeolite possesses antimicrobial, anti-inflammatory, and antioxidant properties. In packaging applications, zeolite reduces headspace ethylene through adsorption, which delays ripening and reduces disease susceptibility. Accordingly, some studies report no visible fungal decay in stored tomato fruits treated with ZE-CS during storage (Kordala and Wyszkowski, 2024).

There was a significant interaction between all treatments and all storage times for both seasons. The control fruit (untreated) showed the highest decay scores, which began to exhibit signs of decay after ten days of storage and recorded the highest decay score after 30 days of cold storage at 10°C for both seasons. This could be due to elevated respiration and ethylene emission, which accelerate ripening and increase susceptibility to infection. On the other hand, tomato fruits dipped in SA or ZE-CS treatments do not show any decay throughout all storage times for both seasons. The other treatments recorded significantly lower decay compared to those obtained from the control treatment, consistent with delayed ripening.

Table (3). Effect of some postharvest treatments and storage period on the weight loss (%) of tomato fruits during storage in the 2024 and 2025 seasons.

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	0.00^{q}	3.16^{ijk}	6.30^{c}	10.47^{b}	14.58^{a}	$\mathbf{6.90^{A}}$
PPE-CS 125ppm each	0.00^{q}	1.95^{m-p}	3.35^{ik}	4.52^{e-g}	5.06^{ef}	$\mathbf{2.98^{B}}$
LRE-CS 125ppm each	0.00^{q}	1.64^{p}	2.71^{j-m}	3.51^{h-j}	4.27^{fh}	$\mathbf{2.42^{C}}$
ZE-CS 125 ppm each	0.00^{q}	1.77^{op}	2.06^{l-p}	2.64^{k-n}	3.16^{ik}	$\mathbf{1.93^{D}}$
Salicylic acid 0.4mM	0.00^{q}	1.65^{p}	1.92^{m-p}	2.29^{l-p}	2.81^{jl}	$\mathbf{1.73^{D}}$
Chitosan 125 ppm	0.00^{q}	1.90^{m-p}	2.72^{j-m}	$4.63e^{-g}$	6.04^{cd}	$\mathbf{3.06^{B}}$
Potassium permanganate 7ppm	0.00^{q}	1.86^{n-p}	2.55^{k-o}	3.87^{g-i}	5.26^{de}	$\mathbf{2.71^{BC}}$
Mean	$\mathbf{0.00^{E}}$	$\mathbf{1.99^{D}}$	$\mathbf{3.09^{C}}$	$\mathbf{4.56^{B}}$	$\mathbf{5.88^{A}}$	
	Season 2025					
Control	0.00^{l}	3.28^{fg}	6.42^{c}	10.59^{b}	14.70^{a}	$\mathbf{7.00^{A}}$
PPE-CS 125ppm each	0.00^{l}	1.84^{i-k}	3.24^{fg}	4.41^{d}	4.95^{d}	$\mathbf{2.89^{B}}$
LRE-CS 125ppm each	0.00^{l}	1.73^{jk}	2.60^{g-i}	3.40^{ef}	4.19^{de}	$\mathbf{2.38^{C}}$
ZE-CS 125 ppm each	0.00l	1.56^{k}	1.84^{i-k}	2.50^{g-j}	3.02^{f-h}	$\mathbf{1.79^{D}}$
Salicylic acid 0.4mM	0.00^{l}	1.64^{k}	1.91^{i-k}	2.35^{h-k}	2.98^{f-h}	$\mathbf{1.78^{D}}$
Chitosan 125 ppm	0.00^{l}	1.82^{i-k}	2.51^{g-j}	4.42^{d}	6.07^{c}	$\mathbf{2.96^{B}}$
Potassium permanganate 7ppm	0.00^{l}	1.72^{jk}	2.11^{i-k}	3.26^{fg}	4.71^{d}	$\mathbf{2.36^{C}}$
Mean	$\mathbf{0.00^{E}}$	$\mathbf{1.94^{D}}$	$\mathbf{2.95^{C}}$	$\mathbf{4.42^{B}}$	$\mathbf{5.80^{A}}$	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Table (4): Effect of postharvest treatments and storage duration on the general appearance (score) of tomato fruits during storage in the 2024 and 2025 seasons

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	9.00^{a}	8.33^{ab}	7.00^{cd}	5.00^{f}	2.33^{g}	**6.33^{C}**
PPE-CS 125 ppm each	9.00^{a}	9.00^{a}	7.00^{cd}	6.33^{de}	5.67^{ef}	**7.40^{B}**
LRE-CS 125 ppm each	9.00^{a}	9.00^{a}	7.67^{bc}	7.00^{cd}	6.33^{de}	**7.80^{B}**
ZE-CS 125 ppm each	9.00^{a}	9.00^{a}	9.00^{a}	8.33^{ab}	7.67^{bc}	**8.60^{A}**
Salicylic acid 0.4 mM	9.00^{a}	9.00^{a}	9.00^{a}	9.00^{a}	8.33^{ab}	**8.87^{A}**
Chitosan 125 ppm	9.00^{a}	9.00^{a}	8.33^{ab}	5.67^{ef}	5.00^{f}	**7.40^{B}**
Potassium permanganate 7ppm	9.00^{a}	9.00^{a}	8.33^{ab}	7.00^{cd}	5.67^{ef}	**7.80^{B}**
Mean	**9.00^{A}**	**8.91^{A}**	**8.05^{B}**	**6.91^{C}**	**5.86^{D}**	
	season 2025					
Control	9.00^{a}	7.67^{bc}	6.33^{de}	5.67^{ef}	2.33^{g}	**6.20^{D}**
PPE-CS 125 ppm each	9.00^{a}	9.00^{a}	7.67^{bc}	6.33^{de}	5.00^{f}	**7.40^{C}**
LRE-CS 125 ppm each	9.00^{a}	9.00^{a}	7.67^{bc}	7.00^{cd}	5.67^{ef}	**7.67^{BC}**
ZE-CS 125 ppm each	9.00^{a}	9.00^{a}	9.00^{a}	9.00^{a}	8.33^{ab}	**8.87^{A}**
Salicylic acid 0.4 mM	9.00^{a}	9.00^{a}	9.00^{a}	9.00^{a}	8.33^{ab}	**8.87^{A}**
Chitosan 125 ppm	9.00^{a}	9.00^{a}	8.33^{ab}	5.67^{ef}	5.00^{f}	**7.40^{C}**
Potassium permanganate 7ppm	9.00^{a}	9.00^{a}	9.00^{a}	7.00^{cd}	5.67^{ef}	**7.93^{B}**
Mean	**9.00^{A}**	**8.81^{A}**	**8.14^{B}**	**7.10^{C}**	**5.76^{D}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Table (5): Effect of some postharvest treatments and storage period on decay (score) of tomato fruits during storage in the 2024 and 2025 seasons.

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	1.00^{c}	1.00^{c}	1.00^{c}	2.33^{b}	3.67^{a}	**1.80^{A}**
PPE-CS 125 ppm each	1.00^{c}	1.00^{c}	1.00^{c}	1.33^{c}	2.33^{b}	**1.33^{B}**
LRE-CS 125 ppm each	1.00^{c}	1.00^{c}	1.00^{c}	1.00^{c}	1.33^{c}	**1.07^{BC}**
ZE-CS 125 ppm each	1.00^{c}	1.00^{c}	1.00^{c}	1.00^{c}	1.00^{c}	**1.00^{C}**
Salicylic acid 0.4 mM	1.00^{c}	1.00^{c}	1.00^{c}	1.00^{c}	1.00^{c}	**1.00^{C}**
Chitosan 125 ppm	1.00^{c}	1.00^{c}	1.00^{c}	2.33^{b}	3.33^{a}	**1.73^{A}**
Potassium permanganate 7ppm	1.00^{c}	1.00^{c}	1.00^{c}	1.00^{c}	2.33^{b}	**1.27^{BC}**
Mean	**1.00^{C}**	**1.00^{C}**	**1.00^{C}**	**1.43^{B}**	**2.14^{A}**	
	Season 2025					
Control	1.00^{e}	1.00^{e}	1.33^{e}	2.33^{cd}	4.00^{a}	**1.93^{A}**
PPE-CS 125ppm each	1.00^{e}	1.00^{e}	1.00^{e}	1.33^{e}	2.67^{bc}	**1.40^{BC}**
LRE-CS 125ppm each	1.00^{e}	1.00^{e}	1.00^{e}	1.00^{e}	2.00^{d}	**1.20^{CD}**
ZE-CS 125 ppm each	1.00^{e}	1.00^{e}	1.00^{e}	1.00^{e}	1.00^{e}	**1.00^{D}**
Salicylic acid 0.4mM	1.00^{e}	1.00^{e}	1.00^{e}	1.00^{e}	1.00^{e}	**1.00^{D}**
Chitosan 125 ppm	1.00^{e}	1.00^{e}	1.00^{e}	2.00^{d}	3.00^{b}	**1.60^{B}**
Potassium permanganate 7ppm	1.00^{e}	1.00^{e}	1.00^{e}	1.00^{e}	2.00^{d}	**1.20^{CD}**
Mean	**1.00^{C}**	**1.00^{C}**	**1.05^{C}**	**1.38^{B}**	**2.24^{A}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Firmness:

A significant problem with postharvest tomatoes is their susceptibility to damage, including ripening and softening, during storage, distribution, and marketing **(**Sophea et al., 2024). As presented in **Table (6)**, fruit firmness had significantly declined as the storage period extended; this aligns with Gharezi et al. (2012).

Fruit softening occurs as a result of the breakdown of cell wall components, deterioration of the cell structure, and changes in turgor pressure. This process is driven by the depolymerization of cell wall polysaccharides, particularly through polygalacturonase-mediated pectin degradation, which is tightly integrated with ethylene-regulated ripening programs (Qin and Zhou, 2025). Softening is thus a coordinated process involving cell wall remodeling enzymes, ethylene-driven transcriptional control, and biophysical factors. The level of polygalacturonase activity has been positively correlated with fruit ripening and softening in tomato fruits. This is closely related to ethylene production, ultimately leading to fruit softening (Vicente et al., 2007).

All postharvest treatments in the present study preserved firmness compared to controls, by tempering ethylene-induced delay in cell wall weakening and limiting cell wall disassembly (Aprilyanto et al., 2025). However, tomatoes treated with salicylic acid (SA) and zeolite with chitosan (ZE-CS) were the most efficient treatment in preserving firmness, with no significant difference between them.

The physiological basis for the effect of salicylic acid (SA) involves multiple mechanisms. SA inhibits tissue softening in fruit by reducing the activity of cell wall hydrolases and maintaining membrane integrity (Chen et al., 2023). It downregulates metabolic activity, including respiration and ethylene production, which slows ripening and helps maintain cell wall structure (Tipu and Sherif, 2024). Wei et al. (2011) reported that the exogenous application of SA enhances defense mechanisms and the production of antioxidants in fruits during storage, leading to a decrease in lipid peroxidation of the cell membrane and a maintained cell membrane structure.

The application of zeolite-chitosan composite (ZE-CS) coatings significantly extended the postharvest shelf life of tomatoes by mitigating the ripening process. This effect is primarily attributed to the high adsorption capacity of the zeolite for ethylene gas, a volatile plant hormone that triggers and accelerates ripening and senescence (Siangyai et al., 2024).

After 30 days of storage, SA treatment exhibited the highest fruit firmness retention, making it the most efficient treatment, followed by ZE-CS treatment, with no significant difference observed between them across both seasons. Meanwhile, untreated fruits recorded the lowest value of fruit firmness levels.

Table (6): Effect of some postharvest treatments and storage period on firmness (kg/cm^2) of tomato fruits during storage in the 2024 and 2025 seasons

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	0	21	0	Mean
Control	6.47^{a}	6.00^{a-e}	5.03^{a-i}	4.13^{ij}	3.18^{j}	**4.96^{D}**
PPE-CS 125 ppm each	6.47^{a}	6.29^{a-d}	6.10^{a-e}	5.28^{a-i}	4.78^{e-i}	**5.79^{A-C}**
LRE-CS 125 ppm each	6.47^{a}	6.43^{a-c}	5.64^{a-h}	5.02^{a-i}	4.29^{h-j}	**5.57^{B-D}**
ZE-CS 125 ppm each	6.47^{a}	6.32^{a-d}	6.13^{a-e}	5.92^{a-e}	5.89^{a-f}	**6.15^{AB}**
Salicylic acid 0.4 mM	6.47^{a}	6.39^{a-d}	6.43^{a-c}	6.45^{ab}	6.26^{a-d}	**6.40^{A}**
Chitosan 125 ppm	6.47^{a}	6.05^{a-e}	5.52^{a-i}	4.94^{d-i}	4.43^{f-j}	**5.48^{CD}**
Potassium permanganate 7ppm	6.47^{a}	5.78^{a-g}	4.97^{c-i}	5.00^{b-i}	4.33^{g-j}	**5.31^{CD}**
Mean	**6.47^{A}**	**6.18^{AB}**	**5.69^{BC}**	**5.25^{CD}**	**4.74^{D}**	
	Season 2025					
Control	5.46^{a}	5.00^{a-c}	4.03^{b-f}	3.13^{fg}	2.18^{g}	**3.96^{C}**
PPE-CS 125 ppm each	5.46^{a}	5.31^{a}	5.10^{ab}	4.53^{a-e}	3.78^{c-f}	**4.84^{AB}**
LRE-CS 125 ppm each	5.46^{a}	5.27^{a}	4.64^{a-d}	4.02^{b-f}	3.29^{e-g}	**4.54^{B}**
ZE-CS 125 ppm each	5.46^{a}	5.43^{a}	5.33^{a}	5.14^{ab}	4.89^{a-c}	**5.25^{A}**
Salicylic acid 0.4 mM	5.46^{a}	5.39^{a}	5.28^{a}	5.07^{ab}	4.85^{a-c}	**5.21^{A}**
Chitosan 125 ppm	5.46^{a}	5.05^{ab}	4.80^{a-c}	4.31^{a-f}	3.43^{d-f}	**4.61^{B}**
Potassium permanganate 7ppm	5.46^{a}	5.11^{ab}	4.37^{a-f}	4.41^{a-e}	3.48^{d-f}	**4.57^{B}**
Mean	**5.46^{A}**	**5.22^{AB}**	**4.79^{BC}**	**4.37^{C}**	**3.70^{D}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Color "Lightness (*L value)":**

To quantify the visual impact of the coating, the surface color of the tomatoes was evaluated throughout the storage period. A significant decrease in lightness (*L** value) was observed over time in both experimental seasons **Table (7)**, indicating a progressive darkening of the fruit. These results are consistent with the findings of Park et al. (2018). The observed reduction in *L** value is likely due to surface dehydration, which diminishes the fruit's glossiness and results in a darker appearance (Sumonsiri et al., 2022).

After 30 days of storage, significant differences in lightness (*L** value) were observed among postharvest treatments. All postharvest treatments significantly maintained higher *L** values compared to the untreated control. Meanwhile, at the end of the storage period, both salicylic acid (SA) and ZE-CS treatments were the most effective at preserving lightness (high *L** values), with no significant difference between them. SA-treated fruits exhibited a statistically higher mean *L** value, followed by the other treatments, while the untreated control consistently resulted in the lowest *L** values, indicating fruit darkening. These findings are consistent with those of Abou-Zaid et al. (2020). The superior preservation of *L** values by SA and ZE-CS is likely related to their role in mitigating fruit water loss, a key factor in surface darkening. The pronounced darkening of the untreated control fruits aligns with the results of Dehestani-Ardakani and Mostofi (2019). The higher loss of peel luminosity in the untreated control was possibly related to the higher water loss in the control fruit. In contrast, SA treatment exhibited a higher *L** value, resulting in a darker peel and

maintaining the skin brightness of the pomegranate compared to control samples **(**Koyuncu *et al*., 2019). Additionally, Fischer *et al*. (2018) demonstrated that ZE-CS application reduced water loss in passion fruit by absorbing degradative gases, such as ethylene and oxygen, and by forming a barrier that minimizes water evaporation, thereby preserving the taste and color. Zeolite, along with other additives such as chitosan, can have a more significant effect on enhancing the properties of the polymer (Hosseinnia *et al*., 2024). The use of CS as an edible coating on the fruit surface could provide an additional gloss, which increases and conserves the *L** value during storage (Jurić et al., 2023).

Color (*a value):**

The surface color of tomatoes is a critical visual indicator of ripeness, directly influencing their marketability and consumer preference (Umeohia and Olapade, 2024). The *a** value is a critical visual indicator for assessing color change and, thus, the degree of ripening in tomatoes. It is one of the key factors influencing consumer perception of the quality of fresh tomatoes (Thole et al., 2020).

As shown in **Table (8)**, the *a** values significantly increased with prolonged storage periods, indicating more red and ripe fruits, a finding consistent with Park et al. (2018). This color shift is driven by the natural ripening process, where a climacteric peak in ethylene production accelerates the transformation of chloroplasts into chromoplasts. This transformation is associated with the degradation of chlorophyll and the accumulation of lycopene, the pigment responsible for the characteristic red hue of ripe tomatoes (Zhang et al., 2020). Ethylene stimulates chlorophyll degradation and enhances lycopene biosynthesis; therefore, inhibiting or removing ethylene can slow color changes and prolong shelf life (Kumaran *et al*., 2025).

All postharvest treatments resulted in significantly lower *a** values compared to the untreated control. After 30 days of storage, tomato fruits treated with salicylic acid (SA) or ZE-CS exhibited lower *a** values (indicating less skin redness), with no significant difference observed between them. In contrast, untreated tomatoes had higher *a** values (greater skin redness) throughout storage.

The mechanism for this delay is treatment-specific: Salicylic acid (SA) acts by directly inhibiting ethylene biosynthesis, thereby delaying senescence. Zeolite (ZE), functioning as an ethylene absorber, delays color development by removing the ethylene gas from the storage environment. This slows senescence, thereby retarding chlorophyll breakdown and lycopene accumulation. Zeolite was used as an antioxidant, neuroprotective, and cardioprotective agent, and it was observed to reduce various degradation parameters, including color change and browning index **(**Jiang et al., 2024).

Table (7): Effect of some postharvest treatments and storage period on the color (L^* value) of tomato fruits during storage in the 2024 and 2025 seasons

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	51.03^{a}	43.47^{h-k}	38.281^{m}	34.82^{mn}	31.36^{n}	**39.79^{C}**
PPE-CS 125 ppm each	51.03^{a}	44.38^{g-j}	43.36^{h-k}	43.58^{g-k}	43.80^{g-j}	**45.23^{B}**
LRE-CS 125 ppm each	51.03^{a}	46.41^{c-h}	44.52^{f-j}	43.75^{g-j}	42.99^{h-k}	**45.74^{B}**
ZE-CS 125 ppm each	51.03^{a}	49.44^{a-c}	48.85^{a-e}	47.95^{a-f}	47.09^{b-g}	**48.87^{A}**
Salicylic acid 0.4 mM	51.03^{a}	50.38^{ab}	49.52^{a-c}	45.83^{d-j}	48.21^{a-e}	**48.99^{A}**
Chitosan 125 ppm	51.03^{a}	47.11^{b-g}	45.43^{e-j}	42.32^{jk}	40.17^{kl}	**45.21^{B}**
Potassium permanganate 7ppm	51.03^{a}	49.36^{a-d}	48.17^{a-e}	46.08^{c-i}	42.69^{ijk}	**47.46^{A}**
Mean	**51.03^{A}**	**47.22^{B}**	**45.45^{C}**	**43.48^{D}**	**42.33^{D}**	
	Season 2025					
Control	50.94^{a}	43.38^{h-j}	38.19^{l}	34.09^{m}	31.27^{m}	**39.57^{D}**
PPE-CS 125 ppm each	50.94^{a}	44.29^{g-j}	43.27^{h-j}	43.49^{h-j}	43.71^{h-j}	**45.14^{C}**
LRE-CS 125 ppm each	50.94^{a}	46.32^{d-h}	44.43^{g-j}	43.66^{h-j}	42.90^{i-k}	**45.65^{C}**
ZE-CS 125 ppm each	50.94^{a}	49.70^{a-c}	48.76^{a-e}	48.11^{a-f}	47.00^{c-g}	**48.90^{A}**
Salicylic acid 0.4 mM	50.94^{a}	50.29^{ab}	49.38^{a-d}	48.95^{a-e}	48.12^{a-f}	**49.53^{A}**
Chitosan 125 ppm	50.94^{a}	47.02^{c-g}	45.34^{f-j}	42.23^{jk}	39.95^{kl}	**45.10^{C}**
Potassium permanganate 7ppm	50.94^{a}	49.27^{a-d}	47.74^{b-f}	45.99^{e-i}	42.60^{jk}	**47.31^{B}**
Mean	**50.94^{A}**	**47.18^{B}**	**45.30^{C}**	**43.79^{D}**	**42.22^{E}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Table (8): Effect of some postharvest treatments and storage period on the color (a^* value) of tomato fruits during storage in the 2024 and 2025 seasons

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	4.60^{l}	8.44^{h}	18.97^{cd}	21.99^{b}	29.49^{a}	**16.70^{A}**
PPE-CS 125 ppm each	4.60^{l}	6.94^{h-k}	10.87^{fg}	13.41^{e}	17.49^{d}	**10.66^{C}**
LRE-CS 125 ppm each	4.60^{l}	7.64^{hi}	11.32^{fg}	14.20^{e}	20.57^{bc}	**11.67^{B}**
ZE-CS 125 ppm each	4.60^{l}	5.24^{kl}	6.13^{i-l}	6.80^{h-k}	7.50^{h-j}	**6.05^{D}**
Salicylic acid 0.4 mM	4.60^{l}	5.04^{kl}	5.69^{j-l}	6.26^{i-l}	6.82^{h-k}	**5.68^{D}**
Chitosan 125 ppm	4.60^{l}	5.53^{kl}	12.54^{ef}	17.87^{d}	21.46^{b}	**12.40^{B}**
Potassium permanganate 7ppm	4.60^{l}	6.33^{i-l}	10.51^{g}	14.15^{e}	17.09^{d}	**10.53^{C}**
Mean	**4.60^{E}**	**6.45^{D}**	**10.86^{C}**	**13.53^{B}**	**17.20^{A}**	
	Season 2025					
Control	5.50^{mn}	9.02^{i}	19.87^{cd}	22.89^{b}	30.39^{a}	**17.54^{A}**
PPE-CS 125 ppm each	5.50^{mn}	7.92^{ijk}	11.77^{gh}	14.31^{f}	18.39^{de}	**11.58^{C}**
LRE-CS 125 ppm each	5.50^{mn}	8.38^{ij}	12.22^{gh}	15.10^{f}	21.47^{bc}	**12.53^{B}**
ZE-CS 125 ppm each	5.50^{mn}	5.26^{n}	6.78^{j-n}	7.50^{i-l}	8.07^{i-k}	**6.62^{D}**
Salicylic acid 0.4 mM	5.50^{mn}	5.64^{l-n}	6.28^{k-n}	6.83^{j-n}	7.72^{i-k}	**6.39^{D}**
Chitosan 125 ppm	5.50^{mn}	6.43^{k-n}	13.44^{fg}	18.77^{de}	22.36^{b}	**13.30^{B}**
Potassium permanganate 7ppm	5.50^{mn}	7.23^{i-m}	$11.^{41h}$	15.05^{f}	17.99^{e}	**11.43^{C}**
Mean	**5.50^{E}**	**7.13^{D}**	**11.68^{C}**	**14.35^{B}**	**18.05^{A}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Titratable acidity:

The data shown in **Table (9)** indicate that as storage time increased, all postharvest applications significantly slowed the degradation of titratable acidity (TA) during storage compared to the control, aligning with the findings of Mohammed et al. (2021). The reduction in TA through storage duration occurs because organic acids serve as substrates in respiratory processes throughout ripening (Atoo et al., 2022). However, all postharvest applications significantly slowed the degradation of titratable acidity (TA) throughout storage in comparison to the control.

After 30 days, among the treatments, tomato fruits treated with SA showed the highest TA levels, followed by those treated with ZE-CS, with no significant differences between them. In contrast, the control treatment recorded the lowest TA levels at the end of the storage duration.

Furthermore, the slight differences in TA values observed during storage between treated and untreated tomatoes could be attributed to the loss of water by the samples, as TA is expressed as a percentage of citric acid per tomato wet weight (Antala et al., 2025). The efficiency of SA and ZE-CS treatments in maintaining TA levels can be attributed to their roles in slowing down respiration, reducing ethylene production, and delaying ripening, which in turn slows the decrease in TA (Changwal *et al*., 2021, and Jiang et al., 2024).

Vitamin C content:

Tomato fruits commonly exhibit progressive loss of vitamin C during storage due to oxidative and senescence-related processes that convert ascorbic acid to less stable forms, thereby accelerating its degradation. As revealed in **Table (10)**, all postharvest treatments were significantly more effective in preserving vitamin C content during storage as compared with control treatments. Among the treatments, salicylic acid (SA) and ZE-CS were the most effective, recording the highest vitamin C values with no significant difference between them, while the lowest values were observed in untreated fruits across both seasons, which is consistent with previous studies on tomato postharvest physiology (Elkelish et al., 2020). Vitamin C loss occurs primarily through enzymatic and oxidative pathways. The enzyme ascorbic acid oxidase converts ascorbic acid to dehydroascorbic acid, while general oxidative degradation is accelerated by respiratory metabolism during senescence. Additionally, the rate of sugar consumption through respiration often exceeds water loss via transpiration, leading to a concentration effect that further reduces vitamin C levels (Cao et al., 2023).

On the other hand, a significant interaction was observed between postharvest treatments and storage duration. After 30 days of storage at 10°C, SA and ZE-CS treatments were the most effective at maintaining vitamin C content and reducing its loss, confirming their role in delaying postharvest senescence and preserving nutritional quality. Salicylic acid (SA) preserves vitamin C by enhancing the activity of antioxidant enzymes, which inhibit ascorbic acid oxidase (AAO) and slow down ascorbic acid oxidation. Additionally, SA reduces respiration and ethylene production, thereby delaying senescence and conserving vitamin C as dehydroascorbic acid (Mwelase *et al*., 2024). Meanwhile, ZE-CS is associated with the preservation of vitamin C, potentially through the gradual release of beneficial compounds or by modifying the storage microenvironment to slow metabolic decay (Zeinalipour and Saadati, 2024).

Table (9): Effect of some postharvest treatments and storage period on titratable acidity (%) of tomato fruits during storage in the 2024 and 2025 seasons.

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	1.03^{a}	0.99^{ab}	0.85^{c-h}	0.72^{i}	0.56^{j}	**0.83^{C}**
PPE-CS 125 ppm each	1.03^{a}	0.96^{a-c}	0.90^{b-f}	0.90^{b-f}	0.78^{g-i}	**0.91^{AB}**
LRE-CS 125 ppm each	1.03^{a}	0.95^{a-c}	0.89^{b-f}	0.83^{e-i}	0.82^{e-i}	**0.91^{AB}**
ZE-CS 125 ppm each	1.03^{a}	0.96^{a-c}	0.95^{a-c}	0.94^{a-d}	0.87^{c-h}	**0.95^{A}**
Salicylic acid 0.4 mM	1.03^{a}	0.93^{a-f}	0.94^{a-e}	0.90^{b-f}	0.82^{f-i}	**0.92^{AB}**
Chitosan 125 ppm	1.03^{a}	0.96^{a-c}	0.87^{b-g}	0.82^{f-i}	0.75^{hi}	**0.89^{B}**
Potassium permanganate 7ppm	1.03^{a}	0.93^{a-f}	0.93^{a-f}	0.85^{c-h}	0.83^{d-i}	**0.91^{AB}**
Mean	**1.03^{A}**	**0.95^{B}**	**0.90^{C}**	**0.85^{D}**	**0.78^{E}**	
	Season 2025					
Control	1.04^{a}	0.96^{a-c}	0.85^{d-h}	0.72^{i}	0.56^{j}	**0.83^{C}**
PPE-CS 125 ppm each	1.04^{a}	0.97^{ab}	0.91^{b-f}	0.91^{b-f}	0.79^{g-i}	**0.92^{AB}**
LRE-CS 125 ppm each	1.04^{a}	0.96^{ab}	0.90^{b-f}	0.84^{fgh}	0.83^{f-h}	**0.92^{AB}**
ZE-CS 125 ppm each	1.04^{a}	0.97^{ab}	0.96^{ab}	0.95^{a-d}	0.88^{b-g}	**0.96^{A}**
Salicylic acid 0.4 mM	1.04^{a}	0.94^{a-d}	0.95^{a-d}	0.91^{b-f}	0.83^{f-h}	**0.93^{AB}**
Chitosan 125 ppm	1.04^{a}	0.96^{a-c}	0.88^{b-g}	0.83^{f-h}	0.76^{hi}	**0.90^{B}**
Potassium permanganate 7ppm	1.04^{a}	0.93^{b-f}	0.94^{a-e}	0.86^{c-h}	0.84^{e-h}	**0.92^{AB}**
Mean	**1.04^{A}**	**0.96^{B}**	**0.91^{C}**	**0.86^{D}**	**0.78^{E}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Table (10): Effect of some postharvest treatments and storage period on the ascorbic acid (mg/ 100g F.W.) of tomato fruits during storage in the 2024 and 2025 seasons.

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	25.40^{a}	21.15^{g-i}	16.45^{o}	11.59^{p}	6.40^{q}	**16.20^{E}**
PPE-CS 125 ppm each	25.40^{a}	22.31^{e-h}	21.51^{f-i}	19.22^{k-m}	16.92^{no}	**21.07^{D}**
LRE-CS 125 ppm each	25.40^{a}	22.71^{d-f}	21.03^{hi}	21.14^{g-i}	21.25^{g-i}	**22.31^{C}**
ZE-CS 125 ppm each	25.40^{a}	24.25^{a-c}	23.72^{b-d}	22.34^{e-g}	20.96^{i}	**23.33^{B}**
Salicylic acid 0.4 mM	25.40^{a}	24.67^{ab}	23.70^{b-d}	23.18^{c-e}	22.65^{d-f}	**23.92^{A}**
Chitosan 125 ppm	25.40^{a}	23.43^{b-e}	21.70^{f-i}	20.53^{ij}	19.35^{j-l}	**22.08^{C}**
Potassium permanganate 7ppm	25.40^{a}	22.41^{e-g}	20.44^{i-k}	19.02^{lm}	18.05^{mn}	**21.06^{D}**
Mean	**25.40^{A}**	**22.99^{B}**	**21.22^{C}**	**19.57^{D}**	**17.94^{E}**	
	Season 2025					
Control	25.50^{a}	21.32^{h-k}	16.55^{p}	11.69^{q}	6.50r	**16.31^{D}**
PPE-CS 125 ppm each	25.50^{a}	22.41^{e-i}	21.61^{f-j}	19.32^{l-n}	17.02^{op}	**21.17^{C}**
LRE-CS 125 ppm each	25.50^{a}	22.81^{d-f}	21.13^{i-k}	21.24^{h-k}	21.35^{g-k}	**22.41^{B}**
ZE-CS 125 ppm each	25.50^{a}	24.35^{a-c}	23.79^{b-d}	22.67^{d-g}	21.47^{f-j}	**23.56^{A}**
Salicylic acid 0.4 mM	25.50^{a}	24.82^{ab}	23.80^{b-d}	23.40^{c-e}	22.75^{d-f}	**24.05^{A}**
Chitosan 125 ppm	25.50^{a}	23.53^{b-e}	21.15^{i-k}	20.10^{k-m}	18.85^{mn}	**21.83^{B}**
Potassium permanganate 7ppm	25.50^{a}	22.51^{d-h}	20.54^{j-l}	$19.^{12mn}$	18.15^{no}	**21.16^{C}**
Mean	**25.50^{A}**	**23.11^{B}**	**21.22^{C}**	**19.65^{D}**	**18.01^{E}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Lycopene content:

The postharvest ripening of tomato fruit is characterized by complex biochemical changes, most notably the rapid synthesis and accumulation of lycopene, a compound valued for both its visual and nutritional properties. Data presented in **Table (11)** indicate that the lycopene content of tomato fruits increased significantly during storage at 10ºC in both seasons. This result is consistent with the well-documented pattern of lycopene accumulation during postharvest ripening, as reported by Abou-Zaid et al. (2020). However, significant differences in lycopene accumulation were observed among the postharvest treatments. All treatments effectively slowed lycopene synthesis compared to the untreated control. Fruits treated with salicylic acid (SA) or zeolite (ZE-CS) were the most effective, resulting in the lowest lycopene content by the end of the storage period in both seasons, with no significant difference between them. In contrast, untreated control fruits exhibited the highest accumulation of lycopene.

The effectiveness of SA and ZE-CS in delaying lycopene accumulation is attributed to their distinct mechanisms of ripening inhibition. SA acts internally, suppressing ethylene biosynthesis and reducing respiration rates (Kumar et al., 2021), thereby delaying chlorophyll degradation and carotenoid accumulation. In contrast, ZE functions externally by adsorbing ethylene from the storage environment, consequently dampening the ethylene signaling that triggers lycopene synthesis (de-Bruijna et al., 2019).

At the end of the storage period in twoseasons, tomato fruits dipped in SA or ZE-CS were the superior treatment in reducing lycopene accumulation, resulting in the lowest lycopene content, with no significant differences observed between them. In contrast, the highest lycopene content was observed in untreated fruits.

Antioxidant content:

The degradation of antioxidant compounds is a significant factor contributing to the deterioration of tomato quality during storage. The antioxidant activity (%) in tomato fruits decreased significantly with prolonged storage in both seasons **Table (12)**, a finding consistent with that of Singh et al. (2025). This decline is attributed to the oxidation of polyphenols and ascorbic acid, which reduces DPPH scavenging activity. Additionally, antioxidant levels diminish as they scavenge reactive oxygen species (ROS) produced under postharvest stress conditions (Lecholocholo et al., 2022).

In addition, all postharvest treatments effectively mitigated this decline compared to the untreated control. Pomegranate peel extract+chitosan (PPE-CS) at 125 ppm was the most effective treatment, followed by zeolite chitosan composite (ZE-CS) at 125 ppm and salicylic acid (SA), with no significant differences between them in the second season. These results align with those of Mohlamonyane et al. (2024), who reported minimal degradation of antioxidant compounds in treated tomatoes. Furthermore, after 30 days, PPE-CS and ZE-CS were most effective in reducing antioxidant decline, with no significant difference between them, followed by SA compared to control samples.

The protective effect of these treatments is attributed to PPE-CS, which protects against oxidative stress by reducing gaseous exchange, thereby slowing oxidation and senescence processes. PPE-CS treated fruits exhibit a higher antioxidant capacity due to the presence of bioactive compounds in the extract (Parsa et al., 2021). At the same time, ZE-CS adsorbs ethylene and modifies the storage atmosphere, thereby reducing respiration and oxidative stress. The efficacy of zeolite treatment can be attributed to multiple mechanisms. Zeolites are known to act as elicitors, activating secondary metabolic pathways and defense systems within plant cells, thereby enhancing the

synthesis and retention of phytochemicals, including phenolics. Additionally, its function as an ethylene scavenger reduces senescence, a key driver of phenolic degradation, resulting in a higher preserved phenol content and antioxidant activity compared to control fruits (de-Bruijna et al., 2019).

SA delays ripening by inhibiting ethylene biosynthesis and respiration rates. It enhances antioxidant production, decreases lipid peroxidation, and maintains cell membrane integrity, thereby preserving antioxidant content and extending the storage period (Kumar et al., 2021).

The interaction between postharvest treatments and storage periods was significant during the two seasons of this study after 30 days of storage at 10°C. Tomato fruits treated with Pomegranate peel extract 125ppm and zeolite composite at solution 125 ppm were most effective in reducing the decline of antioxidant content, with non-significant differences between them, followed by SA. In contrast, the lowest antioxidant was observed in untreated fruits.

Conclusion:

The use of SA and ZE-CS treatments reduced ethylene production, slowed the ripening process, and helped maintain the quality attributes of the fruits during storage. After 30 days of storage at 10°C, tomato fruits treated by SA retained an excellent appearance with no signs of decay, while ZE-CS treatment gave a good appearance with no signs of decay during the same period.

Table (11): Effect of some postharvest treatments and storage period on the content of lycopene (mg/g F.W.) of tomato fruits during storage in the 2024 and 2025 seasons.

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	23.33^{p}	36.00^{e-i}	37.89^{d-f}	49.62^{b}	65.54^{a}	**42.48^{A}**
PPE-CS 125 ppm each	23.33^{p}	29.65^{l-o}	32.58^{h-m}	34.95^{f-j}	39.59^{c-e}	**32.02^{C}**
LRE-CS 125 ppm each	23.33^{p}	30.10^{k-o}	35.44^{f-i}	37.33^{d-g}	43.36^{c}	**33.91^{B}**
ZE-CS 125 ppm each	23.33^{p}	27.30^{op}	29.37^{l-o}	31.29^{j-o}	32.03^{i-n}	**28.66^{E}**
Salicylic acid 0.4 mM	23.33^{p}	27.59^{o}	29.66^{l-o}	31.97^{i-n}	33.99^{f-k}	**29.31^{DE}**
Chitosan 125 ppm	23.33^{p}	27.96^{no}	31.26^{j-o}	33.36^{g-l}	40.63^{cd}	**31.31^{C}**
Potassium permanganate 7ppm	23.33^{p}	28.99^{m-o}	31.00^{j-o}	34.23^{f-j}	36.58^{d-h}	**30.83^{CD}**
Mean	**23.33^{E}**	**29.66^{D}**	**32.46^{C}**	**36.11^{B}**	**41.68^{A}**	
	2025 season					
Control	24.11^{q}	36.78^{f-i}	40.77^{c-e}	50.40^{b}	66.32^{a}	**43.68^{A}**
PPE-CS 125 ppm each	24.11^{q}	30.43^{m-p}	33.36^{i-n}	35.73^{g-k}	40.37^{c-f}	**32.80^{C}**
LRE-CS 125 ppm each	24.11^{q}	30.88^{l-p}	36.22^{g-j}	38.11^{d-g}	44.14^{c}	**34.69^{B}**
ZE-CS 125 ppm each	24.11^{q}	28.08^{p}	29.89^{n-p}	32.07^{k-o}	32.81^{j-n}	**29.39^{E}**
Salicylic acid 0.4 mM	24.11^{q}	28.37^{op}	30.44^{m-p}	32.75^{j-n}	34.77^{g-l}	**30.09^{DE}**
Chitosan 125 ppm	24.11^{q}	28.74^{op}	32.04^{k-o}	34.14^{h-m}	41.41^{cd}	**32.09^{C}**
Potassium permanganate 7ppm	24.11^{q}	29.77^{n-p}	30.88^{l-op}	34.75^{g-l}	37.36^{e-h}	**31.38^{CD}**
Mean	**24.11^{E}**	**30.44^{D}**	**33.37^{C}**	**36.85^{B}**	**42.46^{A}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

Table (12): Effect of some postharvest treatments and storage period on the antioxidant activity (%) of tomato fruits during storage in the 2024 and 2025 seasons.

Treatments*	Storage periods (days)					
	Season 2024					
	0	7	14	21	30	Mean
Control	41.27^{a}	35.90^{de}	32.31^{g-j}	27.75^{l}	24.89^{m}	**32.43^{C}**
PPE-CS 125 ppm each	41.27^{a}	40.20^{ab}	37.27^{cd}	35.71^{d-f}	37.23^{cd}	**38.34^{A}**
LRE-CS 125 ppm each	41.27^{a}	38.78^{bc}	35.19^{d-f}	33.63^{e-g}	29.98^{j-l}	**35.77^{B}**
ZE-CS 125 ppm each	41.27^{a}	$39.00a^{-c}$	37.07^{cd}	35.51^{d-f}	35.07^{d-f}	**37.59^{A}**
Salicylic acid 0.4 mM	41.27^{a}	38.39^{bc}	35.80^{de}	34.57^{e-g}	32.43^{g-i}	**36.49^{B}**
Chitosan 125 ppm	41.27^{a}	33.34^{fg}	30.09^{i-l}	28.53^{kl}	27.89^{l}	**32.22^{C}**
Potassium permanganate 7ppm	41.27^{a}	32.54^{gh}	30.62^{h-k}	30.06^{i-l}	28.76^{kl}	**32.65^{C}**
Mean	**41.27^{A}**	**36.88^{B}**	**34.05^{C}**	**32.25^{D}**	**30.89^{E}**	
	Season 2025					
Control	41.39^{a}	35.61^{c-e}	31.76^{g-i}	27.68^{kl}	26.15^{l}	**32.52^{D}**
PPE-CS 125 ppm each	41.39^{a}	39.33^{ab}	37.39^{bc}	35.83^{cd}	37.35^{bc}	**38.26^{A}**
LRE-CS 125 ppm each	41.39^{a}	38.90^{b}	35.31^{c-e}	35.64^{c-e}	30.10^{ij}	**36.27^{C}**
Zeolite composite 125 ppm	41.39^{a}	39.12^{ab}	37.19^{bc}	35.63^{c-e}	35.19^{c-e}	**37.71^{AB}**
Salicylic acid 0.4mm	41.39^{a}	38.51^{b}	37.28^{bc}	34.69^{d-f}	32.55^{f-h}	**36.88^{BC}**
Chitosan 125ppm	41.39^{a}	33.46^{e-g}	30.21^{ij}	29.61^{i-k}	27.6^{kl}	**32.47^{D}**
Potassium permanganate 7ppm	41.39^{a}	32.66^{f-h}	30.74^{h-j}	28.76^{jk}	28.5^{zjk}	**32.42^{D}**
Mean	**41.39^{A}**	**36.80^{B}**	**34.27^{C}**	**32.55^{D}**	**31.08^{E}**	

The values that contain the same capital or small letters in the same columns and rows indicate that there are no significant variations between each other at the level of 0.05.

*Control (untreated), PPE-CS 125ppm (pomegranate peel extract + chitosan (PPE-CS, 125ppm each), liquorice root extract+chitosan (LRE-CS, 125ppm each), zeolite+chitosan (ZE-CS, 125ppm each).

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الملخص العربي

تأخير النضج والحفاظ على صفات الجودة لثمار الطماطم باستخدام بعض معاملات ما بعد الحصاد أثناء التخزين المبرد

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أجري البحث خلال موسمي 2024 و2025 على الطماطم صنف (*Solanum lycopersicum* var. Staffy 409)، حيث تم حصاد ثمار الطماطم فى مرحلة التحول اللوني (20-30% نسبة اللون الاحمر من سطح الثمرة)،لدراسة تأثير بعض معاملات ما بعد الحصاد باستخدام كل من: الكيتوزان تركيز 125جزء في المليون، برمنجنات البوتاسيوم7.5 جزء في المليون، حمض الساليسيليك(SA) بتركيز 0.4 ملمول، مستخلص قشر الرمان تركيز 125 جزء فى المليون، ومستخلص جذور العرقسوس بتركيز 125 جزء فى المليون، مركب الزيوليت بتركيز 125 جزء في المليون بالإضافة إلى معاملة المقارنة (الكنترول)، على تأخير النضج والحفاظ على صفاتالجودة وإطالة فترة التخزين لثمار الطماطم بعد الحصاد وأثناء التخزين المبرد على درجة حرارة 10°م ورطوبة نسبية 90–95% لمدة 30 يومًا.وأظهرت النتائج أن معاملة الزيوليت بتركيز 125 جزءًا في المليون، وكذلك معاملة حمض الساليسيليك بتركيز 0.4 ملي مولكانتاالأكثر فاعلية في تقليل الفقد في الوزن وتأخيرتراكم الليكوبين، والتغيرات اللونية للثمار، مع عدم ظهور أي إصابةبالاعفان. كما أدت إلى الحفاظ على الصلابة، والحموضة، وفيتامين جومضادات الاكسدة، وكذلك درجة اللمعان. وعلاوة على ذلك، بعد 30 يوم من التخزين على درجة عشرة مئوية أعطت معاملة حمض الساليسيليك مظهر ممتاز، في حين أعطت معاملة مركب الزيوليت مظهرًا جيدًا بعد نفس المدة.