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THE EFFECT OF CHITOSAN AND SALICYLIC ACID IN IMPROVING CERTAIN QUALITY CHARACTERISTICS AND REDUCING THE DETERIORATION OF STRAWBERRIES DURING COLD STORAGE

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Abstract. The strawberry (*Fragaria* × *Ananassa Duch.*) is among the most susceptible fruit crops to rapid post-harvest deterioration. This is due to high respiration and transpiration rates, the tenderness of the fruit tissues, and its susceptibility to microbial infection. This results in weight loss, reduced firmness, and deterioration in their physical and chemical properties, therefore shortening their shelf life and reducing their market value. Gradually, recent research has focused on the use of natural and environmentally safe treatments, including chitosan and salicylic acid, due to their role in preserving fruit quality, slowing down ageing processes and reducing post-harvest losses.

The objective of this study was to assessment of effect of chitosan and salicylic acid, and their interaction, on the preservation of certain quality attributes of strawberries during cold storage. The experiment was conducted using a factorial design to investigate three concentrations of chitosan (0, 0.5 and 1 per cent) and three levels of salicylic acid (0, 0.138 and 0.276 g L^{-1}), however assessing the effect of the treatments on weight loss rate, fruit firmness, total soluble solids (TSS), total acidity, vitamin C content, anthocyanins and total sugars.

The finding showed that chitosan, salicylic acid and their interaction had significant effects on all the characteristics studied. The use of chitosan reduced the rate of weight loss and maintained fruit firmness compared with the control treatment; it also contributed to improving the chemical characteristics by increasing total soluble solids, total acidity, vitamin C content, anthocyanins and total sugars. Similarly, the use of salicylic acid slowed down the maturing and ageing processes and reduced oxidative stress, which had a positive effect on preserving fruit quality during cold storage.

The results of the interaction analysis indicated that treatment with 1% chitosan combined with 0.276 g L^{-1} salicylic acid was the most effective, as it achieved the lowest rate of weight loss (14.18%) and the highest fruit firmness (6.84 N), as well as the highest total soluble solids content (9.28 per cent), the highest total acidity (0.71 per cent), the highest vitamin C content (52.30 mg/100 g fresh weight), the highest anthocyanin content (56.57 mg/100 g fresh weight) and the highest total sugar content (7.34%) compared with the control treatment, which

recorded the lowest values for most of the traits studied.
This development is attributed to the synergistic effect between chitosan and salicylic acid, as chitosan formed a semipermeable membrane that reduced the rates of respiration, transpiration and water loss, whilst salicylic acid helped to regulate physiological processes, reduce ethylene production, enhance the antioxidant system and maintain the integrity of cell membranes, thereby slowing down deterioration processes and preserving fruit quality during storage.
The study concludes that the use of chitosan at a concentration of 1 per cent combined with salicylic acid at a concentration of 0.276 g L^{-1} represents a promising and environmentally friendly treatment for preserving the quality characteristics of strawberries and extending their shelf life, and can be incorporated into post-harvest treatment programs to reduce wastage and improve the marketable and nutritional quality of the fruit.

Keywords: *Fragaria* × *Ananassa*, Chitosan, Salicylic acid, Cold storage, Shelf life, Bioactive compounds, Fruit firmness.

Introduction

Strawberries (*Fragaria* × *Ananasa Duch*) are among the most significant small fruit crops in the world, with a high nutritional and economic value. They are characterised by high levels of vitamin C, phenolic compounds, anthocyanins and antioxidants, which contribute to promoting human health and reducing the risk of many chronic diseases (Petriccione et al., 2015). However, strawberries are among the fruits most susceptible to post-harvest deterioration due to high respiration rates, water loss and rapid susceptibility to fungal diseases, which leads to a reduction in their marketable quality and a shortened storage life (Velikova et al., 2013). The post-harvest stage is one of the critical phases that determine the quality of fruit and its suitability for marketing and storage; therefore, many recent studies have focused on the use of safe and environmentally friendly treatments to minimise physiological deterioration and preserve the quality characteristics of fruit during cold storage (Bahmani et al., 2024). Among these agents, chitosan has emerged as a natural, biodegradable polymer; it is used as a thin food film that limits moisture loss, reduces respiration rates, and delays the chemical and physiological changes that occur during storage (Petriccione et al., 2015). Many studies have shown that treating strawberries with chitosan helped to preserve their firmness, reduce weight loss and delay the decline in acidity and ascorbic acid content, as well as improving antioxidant activity and extending the fruit's shelf life (Petriccione et al., 2015; Saleem et al., 2021). The findings of Velikova et al. (2013) also showed that chitosan-based coatings helped to extend the shelf life of strawberries and preserve their sensory characteristics during storage.

Salicylic acid is an important regulator of plant growth that plays a pivotal role in enhancing plant resistance to biotic and abiotic stresses, as well as in regulating physiological processes associated with ripening and ageing (Klesig & Malami, 1994). Studies have indicated that the post-harvest application of salicylic acid led to reduced ethylene production, a lower respiration rate, reduced mould development, and the preservation of fruit quality during cold storage (Babalar et al., 2007). The findings of Asghari (2006) also showed that treating strawberries with salicylic acid helped to preserve antioxidant activity and increase the content of bioactive compounds.

In recent years, research has focused on investigating the synergistic effect between chitosan and salicylic acid, given the differences in their respective mechanisms of action and the potential for a synergistic effect that improves post-harvest preservation efficiency. Sayyari et al. (2022) noted that the combination of chitosan and salicylic acid reduces microbial load and preserves fruit quality to a greater extent than when either is used alone. Zhang et al. (2022) also demonstrated that salicylic acid helps to reduce weight loss and preserve the quality attributes of strawberries during cold storage. A recent study also showed that treating strawberries with chitosan and salicylic acid helped to preserve vitamin C and antioxidant content and reduce specific degradation during storage (ISHS, 2022).

The aim of this study was therefore to evaluate the effect of chitosan and salicylic acid, and their interaction, on improving the quality characteristics and extending the shelf life of strawberries stored at 4 ± 1°C, and to determine the optimal concentrations capable of preserving the physical and chemical quality of the fruit during storage.

Materials and Methods

This study has been conducted at the Plant Physiology Laboratory, Department of Horticulture and Landscape Architecture, Faculty of Agriculture, University of Tikrit, during the 2025–2026 academic year to investigate the effect of chitosan and salicylic acid, and their interaction, on certain quality characteristics and the shelf life of strawberries (*Fragaria* × *Ananasa Duch*) during cold storage.

Plant samples:

(Ruby Gem) strawberries were collected at full market maturity from the greenhouses belonging to the Department of Horticulture and Landscape Architecture; fruits were selected that were uniform in size and colour and free from disease and mechanical damage. The fruit was then transported directly to the plant cryopreservation laboratory, washed with distilled water and left to air-dry at room temperature.

Experimental factors:

First factor: Chitosan: Three concentrations of chitosan were prepared as follows:

C0 = 0%

C1 = 0.5%

C2 = 1%

The chitosan solutions were prepared by dissolving the required amounts of chitosan powder in a 1% (v/v) acetic acid solution, with continuous stirring using a magnetic stirrer for 4–6 hours at room temperature until complete dissolution. The pH of the solution was then adjusted to 5.6 ± 0.1 using a 1N sodium hydroxide (NaOH) solution, after which the solution was filtered to remove undissolved impurities and used directly in the treatments.

Second Factor: Salicylic acid: Three concentrations of salicylic acid were used:

S0 = 0 g/l (control treatment)

S1 = 0.138 g/l

S2 = 0.276 g/l

Experimental design:

The experiment was conducted using a completely randomised design (CRD), comprising nine treatments resulting from the interaction between chitosan levels and salicylic acid levels, as follows: -

C0S0, C0S1, C0S2

C1S0, C1S1, C1S2

C2S0, C2S1, C2S2

Three replicates were used for each treatment, with each replicate comprising 15 fruits

Treatment procedure:

The fruits were first immersed in salicylic acid solutions for five minutes, then left to air-dry. The fruits were then immersed in chitosan solutions for three minutes, after which they were left to form a thin layer on the fruit surface.

Storage:

The fruits were placed in perforated plastic containers and stored in a refrigerator at a temperature of 4 ± 1 °C and a relative humidity of 80–85 % per cent. Measurements were taken at the start of storage (day 0) and again after 30 days of storage.

Traits studied:

1. **Rate of weight loss (%):**

Each fruit sample is weighed at the start of the experiment using a precision electronic balance, and the initial weight (W_1) is recorded. At the end of the storage period, the same fruits are weighed again and the final weight (W_2) is recorded.

The percentage of weight loss is then calculated using the following equation:

$$\text{Weight Loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

Where:

W_1= the initial weight of the fruit (g).

W_2= the final weight of the fruit after storage (g).

2. **Fruit firmness (N):** Fruit firmness was measured using a penetrometer fitted with a 5 mm diameter probe. Measurements were taken at two opposite points on the middle section of the fruit after removing a small portion of the skin, and the force required to penetrate the flesh was recorded. The average of the two readings for each fruit was calculated, and the results were expressed in newtons (N).

3. **Total Soluble Solids (TSS%):** Total soluble solids were measured using a hand-held refractometer.

4. **Total Acidity (%):** Total acidity (TA) was measured according to the AOAC International (2019) method and Jandal & Saeed (2025), then 10 ml of strawberry juice was taken and placed in a 250-ml round flask, subsequently diluted with 50 ml of distilled water. Added 2-3 drops of phenolphthalein indicator, and the sample was titrated with a 0.1 M sodium hydroxide (NaOH)

solution until a stable light pink colour persisted for 30 seconds. The total acidity was calculated and the findings expressed as a percentage of citric acid. The total acidity was calculated using the following equation:

TA (%) = (V × N × 0.064 × 100) / W

Where:

V = is the volume of sodium hydroxide consumed in the titration (ml).

N = is the standard concentration of sodium hydroxide.

0.064 = is the weight equivalent of citric acid.

W = is the volume or weight of the sample used.

5. **Vitamin C content (mg/100 g fresh weight):** The vitamin C content (ascorbic acid) was measured according to the AOAC International (2019) method and (Jandal & Saeed, 2025) by using 2,6-dichlorophenolindophenol (DCPIP) reagent. Ten grams of fresh strawberries were taken and crushed with 50 ml of a 3% oxalic acid solution; the extract was filtered using filter paper. Ten millilitres of the filtrate were taken and titrated with a standard DCPIP dye solution until a stable light pink colour persisted for 15 seconds. The vitamin C content was calculated based on the volume of dye consumed and the standard dye coefficient, and the findings were expressed in milligrams of ascorbic acid per 100 g of fresh fruit weight.
6. **Anthocyanin content mg per 100 g fresh weight:** The total anthocyanin content was investigated according to the methods of Giusti and Wrolstad (2001) and Mahdi & Jasim (2025). Five grams of strawberry fruit were ground with an extraction solution consisting of methanol acidified with 1% hydrochloric acid. The extract was filtered and stored away from light until measurements were taken. Two samples of the extract were prepared: the first in a buffer solution at pH = 1.0 and the second in a buffer solution at pH = 4.5. Light absorption was measured using a spectrophotometer at wavelengths of 520 and 700 nm. The total anthocyanin content was calculated based on the difference in absorbance between the two solutions, and the results were expressed in milligrams of cyanidin-3-glucoside per 100 g of fresh fruit weight. The equation used for the calculation is:

$$A = (A_{520} - A_{700})_{pH1.0} - (A_{520} - A_{700})_{pH4.5}$$

7. **Total sugars %:** The total sugar content was determined according to the methods of Dubois et al. (1956) and Mahdi & Jasim (2025). One gram of strawberry pulp was taken, crushed, and the sugars were extracted using distilled water. One millilitre of the extract was taken and 1 ml of a 5% phenol solution was added; 5 ml of concentrated sulphuric acid was then rapidly added. The tubes were shaken well and left for 30 minutes at room temperature to allow the colour to develop. Moreover, the optical absorbance of the solution was measured at a wavelength of 490 nm using a spectrophotometer. The total sugar concentration was determined using a standard curve prepared with glucose, and the results were expressed as a percentage of the fresh weight of the fruit (%).

Statistical analysis:

The data were analysed statistically using SAS software in accordance with the analysis of variance (ANOVA) for factorial experiments within a completely randomised design (CRD), and significant differences between means were tested using the Least Significant Difference (LSD) test at a significance level of 0.05.

Results and Discussion

1) The effect of chitosan and salicylic acid, and their interaction, on the rate of weight loss (%) in strawberries during cold storage.

The results in Table 1 indicate that there is a significant effect of both chitosan and salicylic acid, as well as their interaction, on the rate of weight loss in strawberries during cold storage. The control treatment (C_0S_0) recorded the highest rate of weight loss at 24.44%, whilst treatment C_1S_2 recorded the lowest rate of weight loss at 14.33%, which did not differ significantly from treatments C_2S_0 and C_2S_2, which recorded 14.18% and 14.87% respectively, indicating that the use of chitosan and salicylic acid, either alone or in combination, effectively contributed to reducing weight loss and preserving the fresh weight of the fruit during cold storage.

The results for the first factor (chitosan) also showed a statistically significant reduction in the average rate of weight loss as the chitosan concentration increased; the average was 21.48% in the control treatment (C_0), and fell to 17.01% at a concentration of 0.5% (C_1), then to 14.64% at a concentration of 1% (C_2), indicating that increasing the chitosan concentration helped improve the fruit's ability to retain moisture and reduce weight loss.

The results for the second factor showed that salicylic acid had a significant effect on reducing the rate of weight loss, with the mean falling from 19.59% in the control treatment (S_0) to 17.75% at a concentration of 0.138 g L^{-1} (S_1), and then to 16.15% at a concentration of 0.276 g L^{-1} (S_2), indicating that increasing the concentration of salicylic acid helped to reduce water loss and preserve fruit quality during storage.

Table 1. The effect of chitosan and salicylic acid, and their interaction, on the rate of weight loss (%) in strawberries during cold storage.

F2 / F1	Weight Loss (%)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0% (Control Treatment)	24.44 A	21.81 B	19.26 D	21.48 A
C1 = 0.5%	20.14 C	16.56 E	14.33 G	17.01 B
C2 = 1%	14.18 G	14.88 F	14.87 F	14.64 C
Mean of the Second Factor	19.59 A	17.75 B	16.15 C	

The means labelled with different letters within a treatment or interaction group are statistically different at the 0.05 significance level, according to Duncan's test.

The results indicate that the reduction in the rate of weight loss with increasing concentrations of chitosan and salicylic acid reflects the physiological role of both treatments in maintaining the water content of the fruit and minimising deterioration during cold storage, This can be explained by the fact that chitosan formed a semi-permeable film on the surface of the fruit, thereby limiting water loss through transpiration, reducing the respiration rate and slowing down the metabolic processes associated with ageing, which resulted in a lower rate of weight loss. Chitosan also reduces oxygen permeability and increases the concentration of carbon dioxide around the fruit, thereby helping to preserve the integrity of cell membranes and minimise moisture loss. These findings are consistent with those of Petriccione et al. (2015), who noted that chitosan coatings preserved the quality of strawberries and reduced the rate of weight loss during cold storage, as well as with Velikova et al. (2013), who demonstrated that chitosan-based coatings reduce water loss and extend the shelf life of fruit.

The positive effect of salicylic acid is attributed to its role in inhibiting ethylene production and reducing respiration rates, as well as enhancing the efficiency of antioxidant systems and maintaining the integrity of cell membranes, thereby reducing water loss and preserving the fruit’s moisture content. Babalar et al. (2007) andAsghari (2006) have noted that treating strawberries with salicylic acid reduced weight loss and preserved fruit quality during cold storage.

The results of the interaction analysis showed that the combination of chitosan and salicylic acid enhanced the effectiveness of preserving strawberry fruit quality compared with most single treatments, as it helped to maintain the fruit’s water content and reduce physiological deterioration during cold storage; This is attributed to the synergistic effect between the formation of a protective layer by chitosan, whilst salicylic acid helped to regulate physiological processes to limit oxidation and ageing, as confirmed by a study by Sayyari et al. (2022), which showed that the combination of the two substances improved the quality of strawberries and extended their shelf life compared with the use of each treatment individually.

2) The effect of chitosan and salicylic acid, and their interaction, on fruit firmness (N) in strawberries during cold storage. The results in Table (2) show that there is a significant effect of both chitosan and salicylic acid, as well as their interaction, on the firmness of strawberries during cold storage. Accordingly, the interaction between the two factors, the treatment comprising 1% chitosan and 0.276 g L^{-1} salicylic acid recorded the highest statistically significant firmness value of 6.84 newtons, while the control treatment (without chitosan or salicylic acid) noted the lowest statistically significant value of 3.14 N, indicating that the combined treatment of chitosan and salicylic acid was effective in maintaining fruit firmness and reducing softening during storage.

As for the main effect of chitosan, the results showed that the 1% concentration was superior, yielding the highest statistically significant average firmness of 6.12 newtons, followed by the 0.5% concentration with an average of 4.77 newtons, whilst the control treatment recorded the lowest mean of 3.82 Newtons. The results also indicated that salicylic acid had a significant effect on maintaining fruit firmness, with the 0.276 g L^{-1} concentration yielding the highest statistically significant mean of 5.31 Newtons, followed by the concentration of 0.138 g L^{-1} with an average of 4.76 N, whilst the control treatment recorded the lowest average of 4.64 N.

Table 2. Effect of chitosan and salicylic acid, and their interaction, on fruit firmness (N) in strawberries during cold storage.

F2 / F1	Fruit Firmness (N)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0%	3.14 H	3.47 G	4.86 E	3.82 C

F2 / F1	Fruit Firmness (N)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C1 = 0.5%	5.33 D	4.76 E	4.24 F	4.77 B
C2 = 1%	5.46 C	6.06 B	6.84 A	6.12 A
Mean of the Second Factor	4.64 C	4.76 B	5.31 A	

The means labelled with different letters within a treatment or interaction group are statistically significant at the 0.05 significance level, according to Duncan's test.

The increase in the firmness of fruits treated with chitosan can be explained by chitosan's ability to form a semi-permeable film around the fruit surface, thereby reducing water loss through transpiration and lowering the rate of respiration and ethylene production, as well as inhibiting the activity of cell wall-degrading enzymes such as polygalacturonase (PG) and pectin methylesterase (PME), thereby maintaining cell wall integrity, delaying pectin degradation and, consequently, limiting fruit softening during storage (Romanazzi et al., 2018; Petriccione et al., 2015).

The positive effect of salicylic acid is also attributed to its role in enhancing the antioxidant system, reducing oxidative stress and maintaining the integrity of cell membranes, as well as inhibiting ethylene production and slowing down the physiological processes associated with ripening and ageing, thereby preserving fruit firmness during storage (Asghari & Aghdam, 2010; Hayat et al., 2010).

It is believed that the synergistic effect between chitosan and salicylic acid stems from the fact that chitosan provides physical protection to the fruit, whilst salicylic acid regulates physiological and biochemical responses, resulting in better preservation of fruit quality compared to the use of each treatment individually (et al., 2021; Romanazzi et al., 2018; Salim).

3) The effect of chitosan and salicylic acid, and their interaction, on total soluble solids (TSS%) in strawberries during cold storage. The results in Table 3 showed that there was a significant effect of both chitosan and salicylic acid, as well as their interaction, on the total soluble solids (TSS%) of strawberry fruits during cold storage. The results of the interaction between chitosan at a concentration of 1% and salicylic acid at a concentration of 0.276 g L^{-1} showed the highest significant value of 9.28%, whilst the control treatment recorded the lowest value of 8.18%, indicating that the combined treatment was the most effective in preserving fruit quality during storage.

Table 3. Effect of chitosan, salicylic acid and their interaction on total soluble solids (TSS%) in strawberries during cold storage.

F2 / F1	total soluble solids (TSS%)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0%	8.18 I	8.38 H	8.62 F	8.39 C

F2 / F1	total soluble solids (TSS%)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C1 = 0.5%	8.48 G	8.71 E	8.92 C	8.70 B
C2 = 1%	8.81 D	9.02 B	9.28 A	9.03 A
Mean of the Second Factor	8.49 C	8.70 B	8.94 A	

The means labelled with different letters within a treatment or interaction group are statistically significant at the 0.05 significance level, according to Duncan's test.

The results also showed that an increase in chitosan concentration led to a significant increase in the total soluble solids content, which is attributed to the formation of a semi-permeable layer on the fruit surface that reduces the rate of respiration and transpiration and limits the consumption of sugars and organic acids in metabolic processes, thereby helping to preserve the soluble compounds within the fruit tissues during storage (Romanazzi et al., 2018).

Similarly, the use of salicylic acid led to an increase in the total soluble solids content compared with the control treatment, which is attributed to its role in delaying ripening processes, preserving the integrity of cell membranes and reducing carbohydrate consumption during storage, as well as enhancing the activity of antioxidant systems, thereby positively affecting fruit quality (Asghari & Aghdam, 2010).

The superiority of the combined treatment with chitosan and salicylic acid is attributed to their synergistic effect, as chitosan reduces water loss and lowers the respiration rate, whilst salicylic acid regulates the physiological processes associated with ripening and ageing, resulting in the maintenance of total soluble solids at higher levels compared with the use of each treatment individually (Petriccione et al., 2015; Romanazzi et al., 2018).

4) The effect of chitosan and salicylic acid, and their interaction, on the total acidity (%) of strawberries during cold storage. It can be seen from the results in Table (4) that there is a significant effect of both chitosan and salicylic acid, as well as their interaction, on the total acidity of strawberries during cold storage. The interaction treatment combining 1% chitosan and 0.276 g L^{-1} salicylic acid recorded the highest statistically significant total acidity value of 0.71%, whilst the control treatment (without chitosan or salicylic acid) recorded the lowest value of 0.52%, indicating that the combined treatment helped to reduce the consumption of organic acids as substrates for respiration and thus preserve total acidity during storage.

As for the main effect of chitosan, the 1% concentration yielded the highest statistically significant mean total acidity of 0.68%, followed by the 0.5% concentration with a mean of 0.61%, whilst the control treatment recorded the lowest mean of 0.55%. The results also showed that the salicylic acid treatment maintained higher levels of total acidity, with a mean of 0.64% at the highest concentration, compared with 0.62% and 0.58% for the lower concentrations and the control treatment, respectively.

Table 4. Effect of chitosan and salicylic acid, and their interaction, on total acidity (%) in strawberries during cold storage.

F2 / F1	total acidity (%)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0%	0.52 G	0.56 F	0.57 F	0.55 C
C1 = 0.5%	0.59 E	0.61 D	0.64 C	0.61 B
C2 = 1%	0.64 C	0.68 B	0.71 A	0.68 A
Mean of the Second Factor	0.58 C	0.62 B	0.64 A	

The means labelled with different letters within a treatment or interaction group are statistically significant at the 0.05 significance level, according to Duncan's test.

The preservation of total acidity in fruits treated with chitosan can be explained by the fact that chitosan forms a semi-permeable film on the fruit's surface, which reduces the rate of respiration and the consumption of organic acids used as substrates in metabolic processes, thereby slowing the decline in acidity and preserving fruit quality during storage (Priyadarshi et al., 2024; El-Araby et al., 2024). The positive effect of salicylic acid is also attributed to its role in inhibiting ripening processes and reducing ethylene production, as well as reducing the rate of respiration and maintaining the integrity of cell membranes, which leads to a reduction in the consumption of organic acids and delays their degradation during storage, thereby maintaining total acidity at higher levels compared with the control treatment (Almutairi et

al., 2024). The superior performance of the chitosan–salicylic acid combination treatment is explained by a synergistic effect between the two substances, as chitosan reduces gas exchange and water loss, whilst salicylic acid helps regulate the physiological processes associated with ripening and ageing, leading to the longer-term preservation of organic acids and improved fruit quality during storage (Priyadarshi et al., 2024; Almutairi et al., 2024).

The study findings are consistent with those reported by Almutairi et al. (2024), who found that treating strawberries with chitosan or salicylic acid preserved total acidity and slowed its decline during cold storage by reducing the respiration rate and delaying ripening processes. Furthermore, a recent review by Priyadarshi et al. (2024) confirmed that chitosan-based coatings are among the most effective techniques for preserving the chemical properties of strawberries, including total acidity, and for extending their shelf life.

5) The effect of chitosan and salicylic acid, and their interaction, on vitamin C content (mg/100 g fresh weight) in strawberries during cold storage. The results in Table (5) indicate that there is a significant effect of both chitosan and salicylic acid, as well as their interaction, on the vitamin C content of strawberries during cold storage. The interaction treatment combining 1% chitosan and 0.276 g L^{-1} salicylic acid achieved the highest statistically significant value of 52.30 mg/100 g fresh weight, whilst the control treatment (without chitosan or salicylic acid) recorded the lowest statistically significant value of 32.57 mg/100 g fresh weight, indicating that the combined treatment was the most effective in preserving the fruit's vitamin C content during storage.

As for the main effect of chitosan, the 1% concentration yielded the highest statistically significant mean of 48.84 mg/100 g fresh weight, followed by the 0.5% concentration with a mean of 41.42 mg/100 g fresh weight, whilst the control treatment recorded the lowest mean of 35.14 mg/100 g fresh weight. The results also showed that salicylic acid maintained higher levels of vitamin C, with the highest average of 44.83 mg/100 g fresh weight at a concentration of 0.276 g L^{-1}, compared with 41.76 and 38.81 mg/100 g fresh weight for the lower concentration and the control treatment, respectively.

This protective effect is attributed to chitosan's ability to form a semi-permeable protective film around the fruit, thereby reducing respiration rates and moisture loss and limiting the oxidative degradation of ascorbic acid, thus preserving vitamin C content during cold storage. Chitosan also possesses antioxidant and antimicrobial properties, which slow down ageing processes and preserve the fruit's nutritional components.

The maintenance of higher vitamin C levels in fruits treated with salicylic acid can also be explained by its role in activating the antioxidant defence system and reducing the accumulation of reactive oxygen species (ROS) and (ROS), as well as by inhibiting the activity of enzymes that oxidise ascorbic acid, thereby helping to preserve this vitamin and reduce its rate of degradation during storage. Recent studies have indicated that treating fruit with salicylic acid delays ripening processes and enhances the efficiency of the fruit's antioxidant defence system, which has a positive effect on its vitamin C content.

Table 5. Effect of chitosan and salicylic acid, and their interaction, on vitamin C content (mg/100 g fresh weight) in strawberries during cold storage.

F2 / F1	vitamin C content (mg/100 g fresh weight)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0%	32.57 I	35.42 H	37.42 G	35.14 C
C1 = 0.5%	38.28 F	41.22 E	44.75 D	41.42 B
C2 = 1%	45.58 C	48.63 B	52.30 A	48.84 A
Mean of the Second Factor	38.81 C	41.76 B	44.82 A	

The means labelled with different letters within a treatment or interaction group are statistically significant at the 0.05 significance level, according to Duncan's test.

The clear superiority of the combination treatment of chitosan and salicylic acid is attributed to the synergistic effect between the two substances; chitosan reduces water loss and slows down respiration, whilst salicylic acid enhances antioxidant activity and delays ageing, resulting in reduced oxidation of ascorbic acid and the preservation of the highest vitamin C content compared with the other treatments.

These results are consistent with those reported by Almutairi et al. (2024), who found that treating strawberries with chitosan and salicylic acid significantly preserved vitamin C content during refrigerated storage, Priyadarshi et al. (2024) also confirmed that chitosan-based coatings are among the most effective techniques for reducing the loss of oxidation-sensitive nutrients, including vitamin C, and for extending the shelf life of strawberries.

6) The effect of chitosan and salicylic acid, and their interaction, on the anthocyanin content (mg/100 g fresh weight) of strawberries during cold storage.

The results in Table (6) show that there is a significant effect of both chitosan and salicylic acid, as well as their interaction, on the anthocyanin content of strawberry fruits during cold storage. The interaction treatment combining 1% chitosan and 0.276 g L^{-1} salicylic acid recorded the highest significant value of 56.57 mg/100 g fresh weight, whilst the control treatment (without chitosan and without salicylic acid) recorded the lowest significant value of 41.13 mg/100 g fresh weight, indicating that the combined treatment was most effective at preserving anthocyanin content and enhancing the characteristic colour of strawberry fruits during storage.

As for the main effect of chitosan, the 1% concentration yielded the highest statistically significant mean of 54.06 mg/100 g fresh weight, followed by the 0.5% concentration with a mean of 48.46 mg/100 g fresh weight, while at 43.49 mg/100 g of fresh weight, the average control treatment was the lowest. The results also showed that salicylic acid led to a statistically significant increase in anthocyanin content, with the highest mean of 50.69 mg/100 g fresh weight at a concentration of 0.276 g L^{-1}, followed by a concentration of 0.138 g L^{-1} with an average of 48.77 mg/100 g fresh weight, whilst the control treatment recorded the lowest average of 46.55 mg/100 g fresh weight.

Table 6. Effect of chitosan and salicylic acid, and their interaction, on anthocyanin pigment (mg/100 g fresh weight) in strawberries during cold storage.

F2 / F1	anthocyanin pigment (mg/100 g fresh weight)			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0%	41.13 I	43.91 H	45.44 G	43.49 C
C1 = 0.5%	46.69 F	48.61 E	50.08 D	48.46 B
C2 = 1%	51.83 C	53.78 B	56.57 A	54.06 A
Mean of the Second Factor	46.55 C	48.77 B	50.69 A	

The means labelled with different letters within a treatment or interaction group are statistically significant at the 0.05 significance level, according to Duncan's test.

The increase in anthocyanin content in fruits treated with chitosan can be explained by its role in forming a semi-permeable biofilm that reduces respiration rates and oxidative stress, as well as stimulating the activity of enzymes involved in the biosynthesis of phenols and anthocyanins, thereby preserving the accumulation of these pigments and limiting their degradation during cold storage (Priyadarshi et al., 2024; El-Araby et al., 2024).

The positive effect of salicylic acid is also attributed to its role as a regulator of physiological responses; it enhances the antioxidant system and reduces the accumulation of reactive oxygen species (ROS), thereby reducing the oxidation of anthocyanins and maintaining their stability, in addition to stimulating the expression of genes associated with the biosynthesis of phenolic compounds, which is reflected in increased anthocyanin content and an enhanced characteristic red colour in strawberry fruits (Almutairi et al., 2024)

The clear superiority of the combined treatment with chitosan and salicylic acid is explained by a synergistic effect between the two substances; Chitosan reduces water loss and delays ageing processes, whilst salicylic acid enhances antioxidant defences and maintains the stability of natural pigments, resulting in the highest anthocyanin content recorded compared with the other treatments. The preservation of anthocyanins is considered an important indicator of the quality, nutritional value and marketability of strawberries (Priyadarshi et al., 2024; Almutairi et al., 2024).

The recent findings are in agreement with those of Almutairi et al. (2024), who found that the use of chitosan and salicylic acid led to the preservation of phenolic compounds and anthocyanins, improved colour, and reduced oxidative deterioration in strawberries during cold storage. Moreover, a review by Priyadarshi et al. (2024) described that chitosan-based bio-coatings are among the most effective techniques for preserving natural pigments and bioactive compounds in strawberries and extending their shelf life.

7) The effect of chitosan and salicylic acid, and their interaction, on the total sugar content of strawberries during cold storage.

The results in Table (7) showed that there was a significant effect of both chitosan and salicylic acid, as well as their interaction, on the total sugar content of strawberries during cold storage. The interaction treatment combining 1% chitosan and 0.276 g L^{-1} salicylic acid recorded the highest significant value of 7.34%, whilst the control treatment (without chitosan and without salicylic acid) recorded the lowest statistically significant value of 5.78%, indicating that the combined treatment was the most effective in preserving total sugar content during storage.

Regarding the baseline effect of chitosan, the mean control treatment had the lowest effect at 5.94%, while the mean concentration of 1% had the highest statistically significant effect at 7.12%, followed by the 0.5% concentration with a mean of 6.64%. The results also showed that salicylic acid had a significant effect on increasing the total sugar content, with the concentration of 0.276 g L^{-1} yielding the highest mean of 6.71%, followed by the 0.138 g L^{-1} concentration with an average of 6.66 per cent, whilst the control treatment recorded the lowest average of 6.33 per cent.

Table 6. Effect of chitosan and salicylic acid, and their interaction, on the total sugar content of strawberries during cold storage.

F2 / F1	total sugar content			Mean of the First Factor
	0 g/L (Control Treatment)	S1 = 0.138 g/L	S2 = 0.276 g/L	
C0 = 0%	5.78 H	6.15 F	5.90 G	5.94 C
C1 = 0.5%	6.29 E	6.75 D	6.89 C	6.64 B
C2 = 1%	6.92 C	7.09 B	7.34 A	7.12 A
Mean of the Second Factor	6.33 B	6.66 A	6.71 A	

The means labelled with different letters within a treatment or interaction group are statistically significant at the 0.05 significance level, according to Duncan's test.

The increase in total sugar content in fruits treated with chitosan can be explained by the fact that chitosan forms a semi-permeable film on the surface of the fruits, which reduces the rate of respiration and water loss, thereby limiting the consumption of sugars in metabolic processes and preserving their accumulation within the fruit tissues, in addition to its role in slowing down ageing processes and maintaining the integrity of cell membranes, which has a positive effect on fruit quality during storage (Jandal & Saeed, 2025; Priyadarshi et al., 2024; El-Araby et al., 2024).

The positive effect of salicylic acid is also attributed to its role in regulating physiological processes associated with ripening, as it reduces the rate of respiration and ethylene production, and enhances the efficiency of the antioxidant system, leading to reduced sugar consumption and the preservation of sugar content during cold storage (Almutairi et al., 2024).

The superior performance of the combined treatment with chitosan and salicylic acid is explained by a synergistic effect between these two substances; chitosan reduces water loss and slows metabolic activity, while salicylic acid helps maintain physiological balance and reduces the enzymatic breakdown of carbohydrates. This results in the highest total sugar content recorded in comparison with the other treatments. The preservation of sugars is a significant indicator of strawberry fruit quality, given its direct impact on flavour, nutritional value and consumer acceptance (Priyadarshi et al., 2024). This study is consistent with the findings of Almutairi et al. (2024), who found that the use of chitosan and salicylic acid led to the preservation of total sugars and improved the chemical properties of strawberry fruit during cold storage. In addition, a review by Priyadarshi et al. (2024) indicated that the application of chitosan-based bio-coatings has a potential to reduce sugar loss, preserve fruit quality and extend shelf life.

Conclusions

Based on our findings, the following conclusions can be titled:

1. Chitosan, salicylic acid and their interaction had a significant effect on all the physical and chemical characteristics studied in strawberries through cold storage, indicating the efficacy of these two substances in preserving fruit quality after harvest.
2. Using of chitosan, particularly at a concentration of 1%, reduced the rate of weight loss and maintained fruit firmness, in addition to improving chemical properties like total soluble solids (TSS), total acidity, vitamin C content, anthocyanins and total sugars.
3. Salicylic acid, especially at a concentration of 0.276 g L^{-1}, prevent to slow down ripening and maturing processes and reduce oxidative stress, which had an effect on preserving fruit quality during cold storage.
4. The combination treatment of 1% chitosan and 0.276 g L^{-1} salicylic acid showed the best overall performance for most of the physical and chemical properties studied, whilst the treatment comprising 0.5% chitosan and 0.276 g L^{-1} salicylic acid noted the lowest statistically significant rate of weight loss.
5. The development in the quality characteristics of the strawberries is attributed

to the synergistic effect between chitosan and salicylic acid, as chitosan acted as a biofilm to reduce moisture loss and respiration rates, while salicylic acid helped to regulate physiological processes and enhance the antioxidant system, while delaying fruit deterioration and extending their shelf life.

6. The findings confirm the potential for using chitosan and salicylic acid as safe and environmentally friendly alternatives to conventional preservatives in post-harvest treatment programs, to reduce wastage and improve the marketable and nutritional quality of strawberries.

Recommendations

Based on the results, the following is recommended:

1) It is recommended to use chitosan at a concentration of 1% in combination with salicylic acid at a concentration of 0.276 g L^{-1} in post-harvest treatments for strawberries, given the high efficacy demonstrated by this treatment in preserving quality attributes and extending shelf life.
2) Future studies should be conducted to evaluate the effect of higher or lower concentrations of chitosan and salicylic acid, with the aim of determining the optimum concentration according to variety and storage conditions.
3) To investigate the effect of combining chitosan and salicylic acid with other preservation techniques, such as Modified Atmosphere Packaging (MAP) or other bio-coatings, to enhance fruit quality and extend shelf life.
4) To assess the impact of these treatments on the sensory characteristics of the fruit, such as taste, aroma, colour and consumer acceptance, alongside an evaluation of the economic feasibility of their commercial application.
5) To conduct studies on different strawberry varieties and under various storage conditions and temperatures to verify the consistency of these treatments' efficacy across diverse production and marketing conditions.

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