



Enhancing Fig Fruit Storability Using Citric Acid and Transglutaminase-Modified Goat Whey Coatings Incorporated with Pomegranate Peel

Bnar Mohammed Sadiq ^{a *} , Jasim Mohammed Salih AL-Saadi ^b , Ali Muhi Aldeen Omar Aljabary ^c

^a Nursing Department, Darbandikhan Technical Institute, Sulaimani Polytechnic University, Sulaymaniyah, Iraq.

^b Department of Dairy Science, College of Food Sciences, Al-Qasim Green University, Baghdad, Iraq.

^c Food Science & Quality Control Department, Halabja Technical College, Sulaimani Polytechnic University, Sulaymaniyah, Iraq.

Submitted: 19 July 2026
Revised: 12 September 2026
Accepted: 25 September 2026

* Corresponding Author:
bnar.mohammed@spu.edu.iq

Keywords: Whey protein, Citric acid, Transglutaminase, Pomegranate peel, Crosslinking, Shelf life, Post-Harvest, Fig fruit.

How to cite this paper: B. M. Sadiq, J. M. AL- Saadi, A. M. Omer, "Enhancing Fig Fruit Storability Using Citric Acid and Transglutaminase-Modified Goat Whey Coatings Incorporated with Pomegranate Peel", KJAR, vol. 11, no. 2, pp. 102-120, December 2026, [doi: 10.24017/science.2026.2.5](https://doi.org/10.24017/science.2026.2.5)



Copyright: © 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY-NC-ND 4.0)

Abstract: The fig fruits (*Ficus carica* L.) can be easily damaged in post harvest periods because of moisture loss, softening, microbial decay, and oxidation. In this study, the efficacy of the edible coating formulation of goat milk casein mixed with citric acid (CA), microbial transglutaminase (TG) and pomegranate peel extract (PPE) to preserve the physicochemical and biochemical characteristics of fresh figs in refrigerated storage was investigated. The locally grown 'Raihane' figs were coated with the formulations of CA, TG and/or PPE, which were based on goat milk, and then stored for 12 and 24 days under 3 ± 1 °C, with 90–94% relative humidity. The structural changes and protein cross-linking caused by TG treatment were investigated by sodium dodecyl sulfate–polyacrylamide gel electrophoresis. The post harvest quality was evaluated in terms of weight loss, decay, ascorbic acid content, antioxidant activity, oxidative browning and other physicochemical and biochemical characteristics. The physicochemical and nutritional characteristics of the coated fruits were retained better and quality deterioration was found to be slower than the uncoated control as a result of the reduced oxidative browning. The CA-modified casein treatment had significantly lower weight loss (3.24%) and decay (6.82%) at day 24 compared to the control (30.29%). The coatings also proved to be effective in retaining ascorbic acid and antioxidant activity during storage. Coatings with CA and PPE had the best potential to preserve fruit quality and antioxidant properties among the treatments. In summary, goat milk-based edible coatings, especially when fortified with CA and PPE, appear to be environmentally friendly and potentially biodegradable postharvest treatments that extend the shelf life of fresh figs, lower postharvest losses, and preserve the nutritional and functional properties which contribute towards enhanced quality and marketability.

1. Introduction

Post-harvest quality care is an essential component of fruit and vegetable production, and the freshness, nutritional value, safety, marketability, and shelf life of fresh produce are all affected by postharvest physiological processes. Even after harvesting, fruits continue to respire, transpire, mature, senesce, and undergo metabolic changes. Firmness, color, flavor, nutritional content, and overall consumer appeal may gradually decrease as a result of these processes.

Increased deterioration and postharvest losses can also result from machine damage and microbial contamination during harvesting, handling, transportation, storage, and marketing [1-4]. Maintaining fruit quality, reducing food waste, increasing output, and improving the sustainability and effectiveness of the food supply chain all depend on improved postharvest management [5, 6].

The goal of contemporary postharvest technology is to develop methods that minimize microbial spoilage, delay physiological degradation, and preserve nutritional and sensory attributes. Among these methods, edible coatings have attracted considerable attention because they may affect oxidation, gas exchange, moisture transfer, and interactions between the fruit and bacteria [7-9]. The fig (*Ficus carica* L.) is a significant fruit crop in the *Moraceae* family, it is valuable economically, industrially, and nutritionally. Figs were first grown in antiquity and are now a popular fruit in the Middle East, Mediterranean, and other warm regions. In addition to being consumed fresh and dried, the fruit is processed into jams, preserves, pastes, drinks, candies, and other value-added products of interest. Figs are economically significant because they can be processed, used, and consumed with their byproducts. With almost 1.14 million tons produced worldwide, figs are the most significant fruits. Despite being extremely perishable and challenging to handle after harvest, fresh figs are essential for commercial and nutritional purposes [10]. They are vulnerable to physical damage, water loss, softening, biochemical deterioration, and microbiological decay because of their high moisture content, delicate texture, sensitive skin, and advanced physiological maturity at the time of harvest. Therefore, fresh figs can only sustain a high level of commercial quality for a limited amount of time after harvest. Fresh figs rapidly decay after harvest, which lowers their market value and the distance they can be shipped and sold for [11].

Previous studies have found that the main reasons for the deterioration of fig postharvest quality are decay, weight loss, softness, nutritional degradation, and microbial growth [9-11]. Therefore, postharvest fig care is crucial. The availability of fresh fruit may be improved, losses may be reduced, and opportunities for broader distribution and commercialization may be created by extending the fruit's storage and marketing periods [12]. The use of edible coatings is a promising method for enhancing the postharvest performance of fresh figs fruits. Edible coatings are thin layers of food-grade materials placed on the surfaces of food products to provide beneficial compounds and protective barriers [7, 8, 13]. Protein- and polysaccharide-based films are particularly interesting because their functional characteristics can be altered by cross-linking and adding active substances [14-16].

It has been demonstrated that the edible coverings on fresh figs reduce weight loss, retain firmness, limit microbiological deterioration, and preserve phenolic and antioxidant chemicals [10-12]. Citric acid (CA) was used as a chemical modifier because of its various carboxyl groups that can interact and cross-link in protein and polysaccharide matrices. Citric acid has been found to enhance the structural and mechanical characteristics of protein-based films, as well as decrease the water absorption and water-vapor transfer capacity [17-19]. The multiple carboxyl groups of CA have been studied as a natural cross-linking agent for protein- and biopolymer-based edible films and coatings because they can interact with polymer chains, and under the right conditions, they can lead to the formation of a more stable polymer network. The incorporation of CA can also be attributed to the extra beneficial properties related to food preservation, such as anti-browning, antibacterial, and antioxidant properties. However, the efficiency of CA as a cross-linking or functional agent is highly dependent on the type and structure of the protein matrix, concentration of CA, pH, temperature, and processing conditions. Hence, the effect of CA modification on goat milk casein coating and its capacity to preserve the quality and extend the storage life of fresh figs should be evaluated through experimentation [20-22].

Microbial transglutaminase (TG) is another method for altering protein structure. TG induces covalent cross-linking of glutamine and lysine residues in proteins, forming an intermolecular protein network. This enzymatic cross-linking has been extensively explored in food systems, protein-based materials, and other applications, as it has great potential to enhance structural stability, mechanical properties, and functional characteristics [23]. Enzymatic cross-linking of protein molecules by microbial TG can facilitate covalent bonding between protein molecules, enhancing the structural integrity and functional attributes of the protein coating layer [24]. Unlike enzymatic crosslinking by TG, CA can chemically interact with protein-based matrices and, under the right conditions, can

participate in crosslinking reactions by interacting with protein functional groups. Both modification techniques are effective, depending on the protein matrix, modifier concentration, pH, temperature, and processing. Thus, it is helpful to compare the coatings of TG- and CA-modified casein to assess which modification approach is better for preserving the physicochemical and bioactive properties of fresh figs during storage [24, 25].

Pomegranate peel extract (PPE) is a useful natural addition in the food sector due to its notable antimicrobial, antioxidant, preservation qualities, prolongs shelf life, improves sensory quality, and manages postharvest infections in a variety of food applications [26, 27].

PPE enhances mechanical strength, antioxidant activity, and film functioning when added to edible coatings, especially those composed of biopolymers like chitosan or gelatin, while it may marginally lower barrier qualities [28]. Given its high bioactive content and environmental sustainability, using pomegranate peel, a significant agro-industrial by-product, as a natural packaging material is a viable active food preservation approach [29].

PPE contains phenolics, flavonoids, and tannins that are beneficial for antioxidant activity, which also allows PPE to be used as a natural preservative in edible packaging [30]. Protein-based films and coatings are becoming increasingly prevalent in food packaging because of their exceptional gas barrier properties, outstanding film-forming ability, and biodegradability. The customers' quest for high-quality and sustainable products is driving this trend [4, 6]. Cross-linking, achieved through covalent or non-covalent bonds within or between protein molecules, is essential for enhancing the structural and functional characteristics of food systems and packaging materials, including meat products. This enhances the coating properties, water resistance, and mechanical durability [4].

Whey protein, a biopolymer derived from milk, is widely used in edible coatings and films. It has outstanding nutritional and functional characteristics and is biodegradable. Whey protein contains β -lactoglobulin, α -lactalbumin, bovine serum albumin, and immunoglobulins that help with film formation, emulsification, and gelling. Whey protein films are useful for food preservation because they are clear, flexible, and effective barriers against odor and oxygen [31, 32]. Thermal and enzymatic cross-linking improves the mechanical characteristics and longevity of whey protein films by creating intermolecular bonds between the protein molecules. Whey protein films are hydrophilic and have weak moisture barrier properties. However, incorporating lipids, polysaccharides, or transglutaminase enhances the physicochemical characteristics and barrier properties of the films. Whey protein coatings can be enhanced with antioxidants and antibacterial substances to inhibit microbiological growth and increase shelf life [6].

Researchers have studied the properties of these materials individually in various food and packaging systems [33, 34]. However, little information is available on the use of these coatings together on fresh figs using goat milk casein. However, the enzymatic protein cross-linking and potential interactions between PPE incorporation and the control of weight loss, decay, and some physicochemical and bioactive properties during fig storage remain poorly understood. Therefore, the current study addresses this gap by comparing casein coating alone and in combination with CA, TG, and PPE.

This study aimed to determine the impact of adding CA, TG, and PPE to goat milk whey protein. The modified goat milk proteins were then used to create new coating materials to increase the storability of figs, a perishable fruit with a short shelf life.

2. Materials and Methods

2.1. Materials

2.1.1. Whey Protein

Goat whey protein powder was obtained from a company (Aplen Power, Austria), and the concentration of whey protein was 81%.

2.1.2. Plant Material or Description of Fig Cultivar

The fig fruits of the local cultivar (Raihane) are medium-sized, featuring a thin greenish-yellow skin, pleasant flavor, and sweet taste, making them suitable for fresh consumption or drying.

2.1.3. Orchard Location and Harvesting Time

Fig fruits were collected by hand from seven-year-old trees at the ripe stage, early on August 6, 2024, from a private orchard in Zamaqy village in the Halabja Governorate of Iraqi Kurdistan region. Fruits with consistent maturity, color, and size were selected, and were free of phenotypic defects such as cuts, bruises, and diseases. The samples were transported to the Halabja Technical College laboratory on the same day of collection.

2.1.4. Treatments and parameters

CO: Control (Dipping in distilled water)

W: Whey protein (50 g)

W+CA: Whey protein (50 g) + Citric acid (1.5%)

W+TG: Whey protein (50 g) + Transglutaminase (50 unit enzyme/g protein)

W+PPE: Whey protein (50 g) + Pomegranate peel extract (1%)

W+CA+PPE: Whey protein (50 g) + Citric acid (1.5%) + Pomegranate peel extract (1%)

W+PPE+TG: Whey protein (50 g) + Pomegranate peel extract (1%) + Transglutaminase (50 unit enzyme/g protein).

For each replication, 2 kilograms of fruits were used.

2.1.5. Sodium Dodecyl Sulfate-Polyacrylamide Gel Electrophoresis

Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) was used to analyze milk proteins using the procedure described by Laemmli [35].

2.1.6. Protein Cross-Linking Caused by Citric Acid

To prepare protein solutions, the powders were dissolved in deionized water (5% w/v) and agitated for two hours at room temperature. To ensure complete disintegration, the solutions were kept at 4°C overnight. The Whey protein solutions were supplemented with citric acid at a final concentration of 5%. Protein solutions devoid of citric acid (1.5%) were used as a control. The pH was then adjusted to 9.0 using a 2 M sodium hydroxide (NaOH) solution. For six hours, all sample solutions were heated to 50°C in water bath. The materials were lyophilized and stored after cross-linking [36].

2.1.7. Preparation of Pomegranate Peel Extraction

In December 2023, pomegranates (Salakhani) were harvested from a private plantation in Halabja Governorate. To remove any residue, the peels were thoroughly cleaned three times under running tap water, disinfected for 30 s in 2% sodium hypochlorite, and then rinsed twice with distilled water. After cleaning, the samples were dried for 72 h at 60 °C in an oven until their weights remained consistent. The ground-up dried skins were stored in sealed glass jars for further use. The obtained PPE was stored in a refrigerator for future use [37].

2.1.8. Coating Solution Preparation

Whey proteins and modified proteins (50 g) were combined with 920 mL of distilled water. The pH was then adjusted to 8 to ensure protein solubility. The pH of the solutions was decreased to 7 once the proteins were fully dissolved, and 30 mL of glycerol was added to increase the flexibility. Subsequently, the volume of the solution was adjusted to 1 L. The solutions were maintained at 90 °C for half an hour in a water bath. Each was degassed for five minutes after the liquids were combined [9, 38].

2.1.9. Fruit Coating

Fig fruit samples were dipped for one minute in the coating solutions according to the treatments and placed on a flat surface for drying at room temperature as shown in figure 1A, while uncoated fruits were dipped in distilled water for one minute. The fig fruits (2 kg of fig) were stored for 12 and 24 days at temperatures of 3 ± 1 and relative humidity of 90–95% in plastic containers as shown in figure

1B [39]. At 0 day of storage the physiochemical characteristics of fig fruits was measured as shown in table 1.

2.1.10. Fig Juice Preparation

The uncoated control and each coating treatment of fig fruits were analyzed prior to storage (day 0) and after each designated storage period. At each sampling time, whole fruits were cut into small pieces and homogenized in a blender (Panasonic MJ-W176P, Japan). Homogenized samples were filtered through cheesecloth [40]. The filtered juice was immediately used for physicochemical and bioactive compound analyses. The same procedure was applied separately to each treatment at each sampling time.

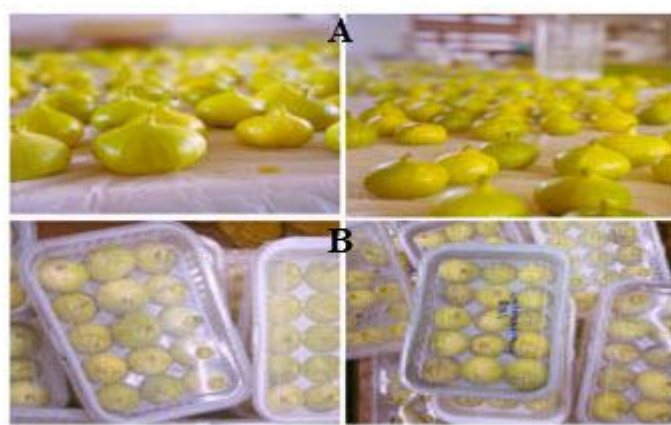


Figure 1: Fig fruit during coating (A) and packaging (B).

Table 1: Phytochemical characteristics of fig fruit prior to preservation (0 day) using a whey protein-based coating.

Tests	TSS (%)	TA (%)	PPO (unit/min/ml)	AO (μg/g)	TFC (μg/g)	AA (mg/100 ml)
0 day	16.00	0.30	0.078	84.72	24.10	1.14

TSS: Total soluble solids, TA: Titratable acidity, PPO: Polyphenol oxidase, AO: Antioxidant, TFC: Total flavonoids, and AA: Ascorbic acid.

2.2. Storage Characteristics of Fig Fruit

2.2.1. Weight Loss (%)

The fruits were weighed at the beginning and end of the storage periods. The weight loss was calculated using the following equation [41].

$$\text{Weight loss (\%)} = \frac{\text{Fruit weight at the beginning of storage} - \text{Weight at the end of storage}}{\text{Fruit weight at the beginning}} \times 100 \quad (1)$$

2.2.2. Decay Percentage (%)

The decay percentage of both coated and untreated fig fruit samples was calculated by dividing the number of decaying samples by the initial number of samples [42, 43].

2.2.3. Total Soluble Solids

The TSS of the juice collected from the coated and control fruits was determined using a refractometer model (Atago/Japan) [44, 45].

2.2.4. Titratable Acidity (%)

The amount of citric acid was measured using the AOAC method (1990) [46].

$$\text{Titrateable Acidity (\%)} = \frac{\text{Normality of NaOH} \times \text{Volume of NaOH} \times \text{Factor equivalent weight}}{\text{Volume of juice used}} \times 100 \quad (2)$$

2.2.5. Antioxidant Activity

Antioxidant capacity (AO) was determined by used 0.1 g of fig juice, the absorbance was measured at 517 nm using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) technique, and the results were reported as µg Trolox equivalents/g fresh [47, 48].

2.2.6. Total Flavonoid Content

Fig juice (0.1 g) used to quantification of total flavonoid content (TFC). The absorbance at 415 nm with aluminum chloride method was used. The findings are reported in µg quercetin equivalents/g [47, 49, 50].

2.2.7. Polyphenol Oxidase Activity

The method outlined by Shi *et al.* [51] was used to measure the enzyme's activity of polyphenol oxidase (PPO). The number of enzyme units/minutes/mL was calculated using the following equation:

$$\text{PPO activity } \left(\frac{\text{units}}{\text{minutes}} \right) = \frac{\text{Change in light absorption within 5 minutes} \times 3}{5 \times 0.001} \quad (3)$$

2.2.8. Ascorbic Acid Content

The ascorbic acid content was estimated by modified spectrophotometric method. One gram of fig juice for the absorbance of the sample solution was determined by UV-Visible spectrophotometer at 295 nm. Standard curve was drawn using pure ascorbic acid at different concentrations. For determination of ascorbic acid content, the absorbance of the sample was compared with the standard curve [52, 53]. The ascorbic acid concentration in the sample extract was calculated from the calibration equation:

$$C = (0.545 \times A) - 0.024 \quad (4)$$

where:

- C = ascorbic acid concentration (µg/mL)
- A = absorbance of the sample at 295 nm.

The final ascorbic acid content was calculated using:

$$\text{Ascorbic Acid } \left(\frac{\text{mg}}{100\text{g}} \right) = \frac{C \times V \times 100}{W \times 1000} \quad (5)$$

where:

- C = concentration obtained from the standard curve (µg/mL)
- V = final extraction volume (mL)
- W = sample weight (g)
- 1000 = conversion factor from µg to mg.

2.3 Statistical Analysis

Before analyzing the data, the normality test was performed. The factorial design (two factors: treatments and storage periods) with three replications was used. SAS version 8.2 was used to analyze the data, and Duncan's multiple range test was used to compare treatment averages at $p \leq 0.05$.

3. Results

3.1. SDS-PAGE of Goat Milk Whey Proteins

Figure 2 shows the electrophoretic patterns of goat whey proteins. The findings showed that the main protein in goat whey is β-lactoglobulin (β-lg). In addition to β-lg, SDS-PAGE revealed that goat whey contains additional proteins, some of which have high molecular weights. The electrophoretic patterns of goat whey proteins were unaffected by citric acid treatment (W+CA). The original protein band intensities on SDS-PAGE, on the other hand, decreased slightly or not at all in treatments involving W+PPE or W+CA+PPE treatment. SDS-PAGE revealed the formation of aggregated whey

proteins in treatment W+TG+PPE, with a higher degree of crosslinking compared to other whey protein treatments, but lower than that observed in casein crosslinking.

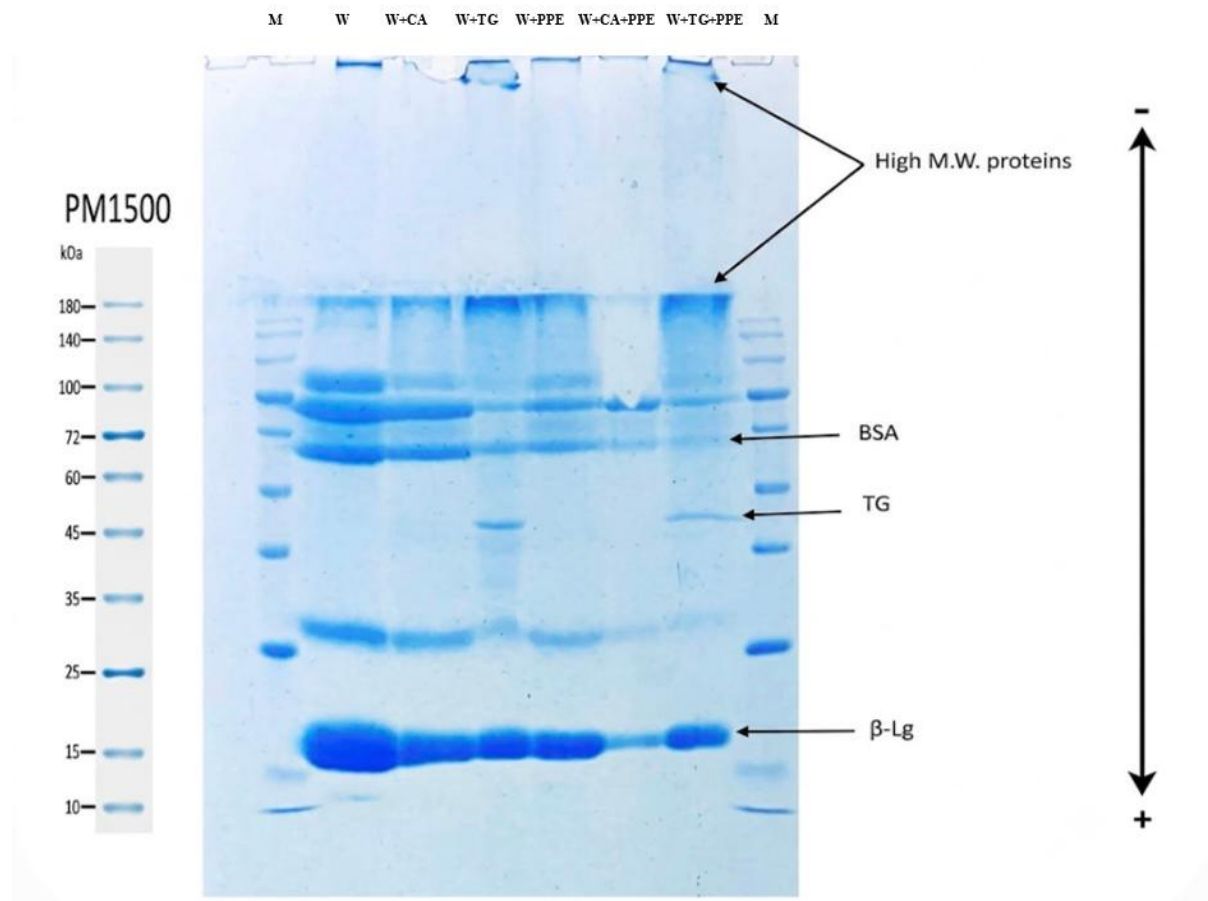


Figure 2: Electrophoretic patterns of goat whey proteins detected by SDS- PAGE.

Lanes: M: represent the molecular weight standard; W: Whey proteins; W+CA: Whey proteins with citric acid; W+TG: Whey proteins with transglutaminase enzyme; W+PPE: Whey proteins with pomegranate peel extract; W+CA+PPE: Whey protein with citric acid and pomegranate peel; W+TG+PPE: Whey protein with transglutaminase and pomegranate peel.

3.2. Assessment of Physicochemical Property

3.2.1. Weight Loss

Fruits coated with W+CA+PPE treatment at 24 days had the lowest weight loss (2.845%). Simultaneously, there was a discernible difference among the different interaction treatments, particularly for the uncoated fruits (Table 2). The substantial variations in the effects of the relationship between storage duration and treatments are evident in table 2, which demonstrates that the weight loss of fig held for 24 d was affected differently by different coverings. For all treatments, the weight loss increased with storage time. However, in each regimen, the proportion of weight reduction in the coated fruits was lower than that in the control group. Depending on the intricate interactions between the coating treatments and storage periods, the efficacy of the coatings changed during the storage period. Compared to uncoated fruits, PPE and CA coatings often reduced weight loss and enhanced the fruit quality.

3.2.2. Decay

Figure 3 and table 2 show the percentage of fig fruit deterioration during storage. During the first 12 days of storage, there was no discernible deterioration, and the decay percentage remained zero for each treatment. However, after 12 days, the incidence of deterioration significantly increased across all treatments. By day 24, all coated fruits had significantly lower decay percentages, whereas uncoated

fruits had the highest percentage (30.293%). The W+CA treatment produced the lowest decay values (6.820%).



Figure 3: Fig fruits after storage periods. CO: Control ,W+CA: Whey protein with citric acid.

3.2.3. Total Soluble Solid

Table 2 demonstrates that total soluble solids (TSS) were significantly affected by the interaction between coating treatments and storage time. Fruits coated with W treatment had the lowest TSS compared to some of the other treatments and untreated fruit, reaching 14.66% throughout the 24-day storage period. The figs coated with W+TG+PPE had the highest significant TSS, reaching 16.33% on day 12 of the storage period. Overall, the TSS decreased in each sample during storage.

3.2.4. Titratable Acidity

Table 2 results show notable differences in titratable acidity (TA) under different treatments and storage durations. However, fruits coated with W+TG+PPE and refrigerated for 24 days had the highest percentage of TA (0.759%). However, fruits coated with W treatment alone at 24 days had the lowest TA value (0.134%).

Table 2: Effects of a casein protein-based covering on the physicochemical composition of fig fruits during storage.

Treatments	Storage periods (Days)	Weight loss (%)	Decay (%)	TSS (%)	TA (%)
CO	12	3.50 ^{bc}	0.00	15.53 ^{ab}	0.40 ^{bcd}
	24	3.96 ^{bc}	30.29 ^a	15.23 ^{abcd}	0.49 ^{cde}
W	12	3.12 ^{def}	0.00	15.33 ^{bc}	0.13 ^h
	24	6.34 ^b	16.59 ^d	14.66 ^c	0.53 ^{bc}
W+CA	12	3.17 ^{def}	0.00	15.46 ^b	0.31 ^{efg}
	24	3.24 ^{def}	6.82 ^e	15.10 ^{bc}	0.58 ^b
W+TG	12	3.41 ^{def}	0.00	15.33 ^{bc}	0.22 ^{fgh}
	24	5.53 ^b	22.46 ^c	15.06 ^{bc}	0.44 ^{bcd}
W+PPE	12	3.25 ^{def}	0.00	15.73 ^{ab}	0.35 ^{def}
	24	2.98 ^{ef}	15.43 ^d	15.06 ^{bc}	0.31 ^{efg}
W+CA+PPE	12	12.99 ^a	0.00	15.33 ^{ab}	0.22 ^{fgh}
	24	2.84 ^f	22.48 ^c	15.66 ^{ab}	0.53 ^{bc}
W+TG+PPE	12	4.08 ^{cd}	0.00	16.33 ^a	0.17 ^{gh}
	24	4.56 ^c	27.72 ^b	15.06 ^{bc}	0.75 ^a

CO: Control treatment; W: Whey proteins; W+CA: Whey proteins with citric acid; W+TG: Whey proteins with transglutaminase enzyme; W+PPE: Whey proteins with pomegranate peel extract; W+CA+PPE: Whey protein with citric acid and pomegranate peel; W+TG+PPE: Whey protein with transglutaminase and pomegranate peel; 12 D: 12 days of storage; 24 D: 24 days of storage. When utilizing Duncan's multiple range test, different letters denote significant differences at the $p \leq 0.05$ level.

3.3. Evaluation of Bioactive Compound Properties

3.3.1. Ascorbic Acid Content

Figure 4 illustrates the impact of treatment combinations and storage duration on the ascorbic acid content of fig. When compared to all other treatments, the fruit coated with W+CA had the highest

significant value (1.368 mg/100 g) on the twelfth day of storage. Following a 24-day storage period, all coated treatments displayed the reduction the ascorbic acid content.

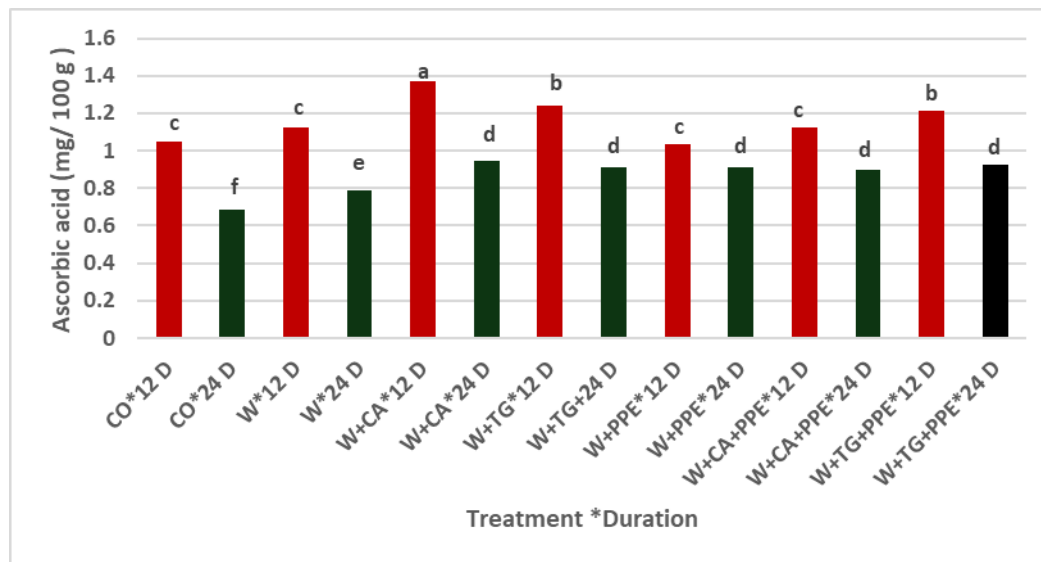


Figure 4: Impact of treatment interactions and storage times on ascorbic acid concentration in fig fruits. CO: Control treatment; W: Whey proteins; W+CA: Whey proteins with citric acid; W+TG: Whey proteins with transglutaminase enzyme; W+PPE: Whey proteins with pomegranate peel extract; W+CA+PPE: Whey protein with citric acid and pomegranate peel; W+TG+PPE: Whey protein with transglutaminase and pomegranate peel; 12 D: 12 days of storage; 24 D: 24 days of storage.

3.3.2. Polyphenol Oxidase Activity

Figure 5 indicates significant differences between the storage period and treatment in polyphenol oxidase activity (PPO). The uncoated fruit showed the lowest PPO (50.20 unit/min/mL) after 12 days of storage. Uncoated fruits showed the highest PPO activity (128.60 unit/min/mL) after 24 d of storage. Fruits coated with W+TG and W+CA+PPE exhibited the lowest PPO activity (44.60 and 46.20 units/min/mL, respectively).

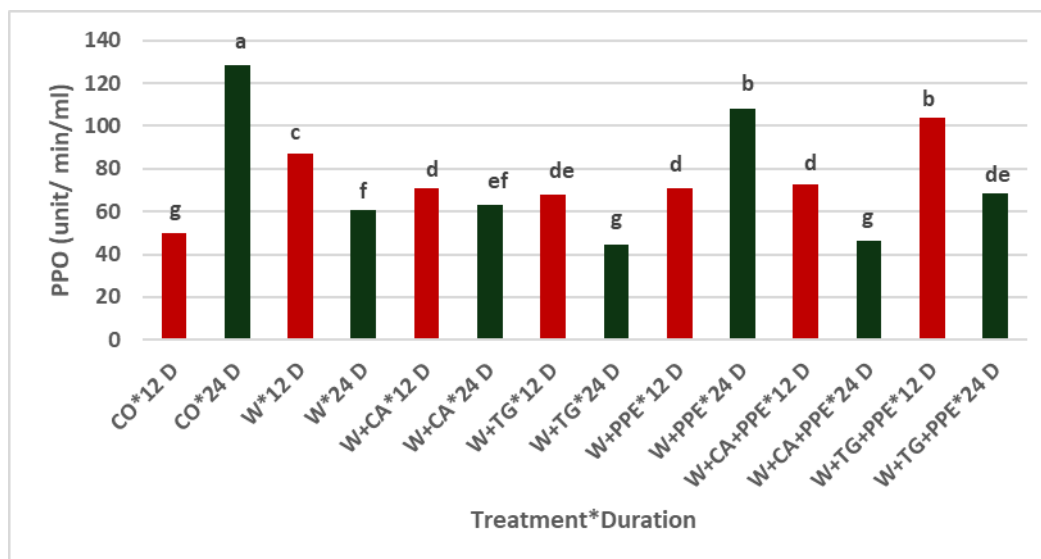


Figure 5: Impact of treatment interactions and storage times on polyphenol oxidase in fig fruits. Using Duncan's Multiple Range Test, distinct letters indicate significant differences at $p \leq 0.05$.

3.3.3. Antioxidant Activity

Figure 6 shows the interaction between treatment and storage duration on the antioxidant activity (AO) during storage periods. In most treatments, the AO progressively declined over time. However, the AO was significantly affected by the coating treatments. The W+CA treatment, maintained for 24

days, had the highest AO level (70.243 $\mu\text{g/g}$), while the W+TG+PPE treatment had the lowest (21.662 $\mu\text{g/g}$).

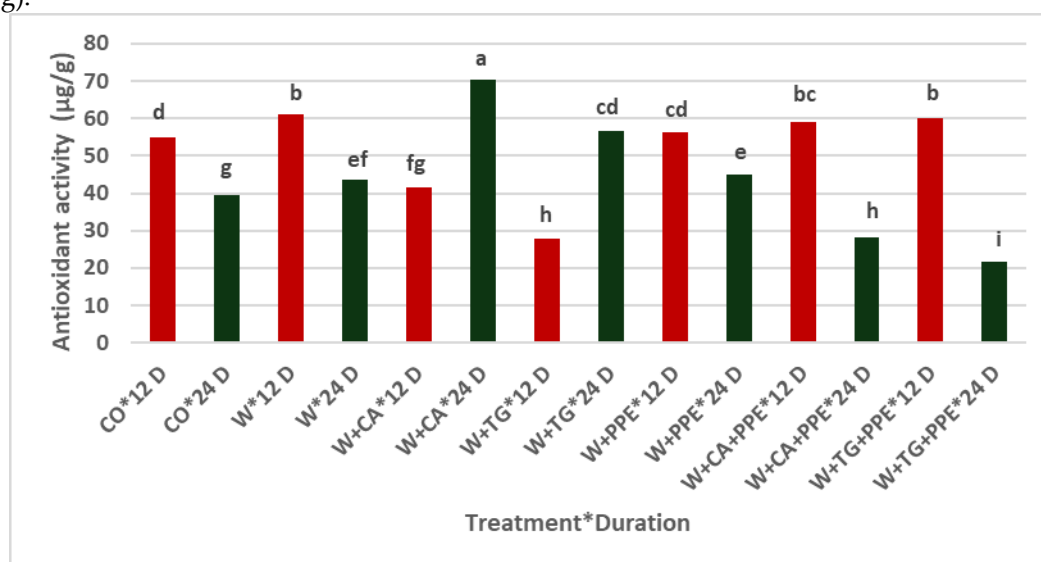


Figure 6: Impact of treatment interactions and storage times on antioxidant content in fig fruit. Using Duncan's Multiple Range Test, distinct letters indicate significant differences at $p \leq 0.05$.

3.3.4. Total Flavonoids Content

Figure 7 shows the substantial differences in TFC between the treatments and storage duration. Fruits coated with W+CA+PPE and kept for 12 days showed the lowest activity, reaching (15.535 $\mu\text{g/g}$), while fruits coated with W material had the highest TFC (30.122 $\mu\text{g/g}$). All covered fruits had significantly higher TFC than the control after 24 d of storage.

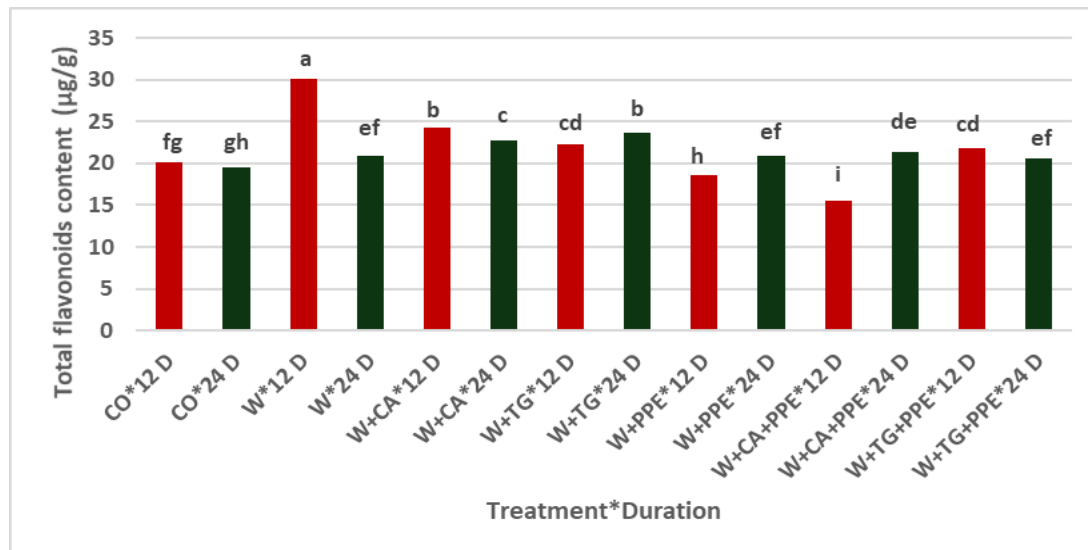


Figure 7: Impact of treatment interactions and storage times on the total flavonoid content in figs. Using Duncan's Multiple Range Test, distinct letters indicate significant differences at $p \leq 0.05$.

4. Discussion

SDS-PAGE of goat milk whey proteins showed different pattern under different treatment conditions. These results are consistent with those reported by Al-Saadi *et al.* [54], who was discovered that the main protein in goat whey is β -lg. The electrophoretic patterns of goat whey proteins were unaffected by citric acid treatment in this study. Although TG produced crosslinked whey proteins, the degree of crosslinking was lower than that of casein crosslinking. This could be because the enzyme cannot access the glutamyl and lysine residues in whey proteins due to their compact structure, which decreases cross-linking [55].

The ability of the edible coating to function as a semi-permeable barrier that restricts gas exchange and moisture evaporation explains the reduced weight loss observed in the coated figs. These include ripening, respiration, transmission, water loss, and ethylene production [56, 57]. The capacity of the edible coating to stop rotting and weight loss, reduce respiration, postpone hardness degradation, and slow down ethylene production and ripening may increase the fruit's shelf life [58, 59].

Protein-based coatings, especially whey protein coatings, offer superior film-forming and moisture-barrier properties because they can form stable cross-linked networks [60]. Additionally, pomegranate peel extract enhances coating quality by decreasing water vapor transmission and boosting the interaction of polyphenols with the coating matrix, resulting in antioxidant activity [61]. Research on pears, strawberries, apples, grapes, pomegranates, and figs has repeatedly demonstrated that during storage, coated fruits retain their quality better and lose less weight than uncoated fruits [10]. These results demonstrate the efficiency of adding whey protein to coatings that contain CA and PPE in preventing moisture loss during storage. Fig fruits are typically highly susceptible to many physiological and pathological conditions during their post-harvest life, such as skin cracking and softening [62]. These structural alterations accelerate degradation and facilitate microbial invasion.

Previous studies have shown that organic acid treatments, particularly citric acid treatment, are beneficial for reducing degradation and preserving the firmness and postharvest quality of peaches [63]. Edible coatings delay deterioration in several ways. In particular, they create a semi-permeable layer that prevents respiration, slows ripening, and regulates gas exchange on the fruit surface. These coatings also limit microbial exposure, further reducing the deterioration. Similar results have been extensively reported for strawberries, where coated fruits frequently show less fungal growth and deterioration than uncoated fruits, which is consistent with these observations [64, 65]. Carboxymethyl cellulose, chitosan, plant extracts, tragacanth gum, CA, and ascorbic acid coatings-maintained fruit quality and reduced microbial growth and degradation [66, 67]. Similar outcomes were observed in tomatoes, where the coated skin decreased oxygen availability and delayed metabolic activity, delaying ripening and minimizing spoilage.

Edible coatings can enhance fruit quality, lower postharvest losses, and increase shelf life [68]. The current findings support the effectiveness of edible coating treatments, particularly those containing CA, in preventing deterioration, preserving fruit quality, and prolonging the shelf life of figs. The most crucial component in determining the nutritional value of a fruit is its TSS content. Fruit sweetness is measured by TSS, which increases throughout ripening when starch is converted to simple sugars by respiration and other catabolic processes [69]. When assessing consumer approval, TSS should be considered as an essential factor [70]. Additionally, adding polysaccharides to support plant-based bioactive chemicals can increase the shelf life of fresh fruits during postharvest storage [71]. Further, fruit TSS maintenance was comparable to other coating types. These have been previously reported, including covering guava fruit with alginate and black cumin extract [72].

Polysaccharides are hydrolyzed during storage, increasing the overall soluble solid concentration [73, 74]. Because aloe vera possesses a semi-permeable gas exchange property that slows the respiration rate, which may be advantageous for TSS, when TSS rose during cold storage, it was recommended to use it. The increase in TSS levels during storage may be due to the concentration of juice caused by degradation, polysaccharide hydrolysis, and moisture loss [75]. However, the fruit's metabolic processes, such as respiration, cause the TSS level to drop during the storage period [76]. Comparable observations have been reported by Abdalla *et al.* [9]. The variations across treatments could be linked to their varying capacities to regulate respiration, water loss, and carbohydrate metabolism during storage, which can be determined by TA [77].

TA is a common method for determining the total concentration of organic acids in fruit. As organic acids are used as substrates in respiration and other metabolic activities, fruit acidity typically peaks at harvest and progressively declines during ripening and storage [78, 79]. Overall, TA increased steadily over the storage period across all treatments. When storage variables, including temperature, relative humidity, light, storage time, and berry physiological parameters, are considered, the acid content of the berries decreases [80]. This decrease is consistent with the physiological behavior of climacteric and non-climacteric fruits, in which organic acids are either transformed into sugars during ripening or broken down as respiratory substrates and senescence [81]. Increased respiration during

storage lowers acidity by accelerating the breakdown of organic acids and carbohydrates [82]. Thus, increased metabolic activity linked to fruit growth may cause the observed decrease in TA levels. However, it has been suggested that the reduced disappearance of organic acids in coated apple fruits after storage may have been caused by the decreased metabolic activity caused by the semi-permeability of edible coatings, which restricts oxygen transfer and delays respiration [83].

The acidity readings of 0.75 to 0.44% indicate that the TA of strawberry samples decreased following storage, balangu gum, and whey protein 1:1 [84]. Furthermore, there is a discernible increase in the fermentative metabolic processes associated with ripening and breakdown of organic acids [85]. The lower acidity readings in the coated samples indicated a decrease in the transpiration rate because fewer organic acids were available to produce the acidity of the fruit [86]. Therefore, the ability of the coatings to lower respiration and postpone the metabolic breakdown of organic acids may be responsible for the greater TA values found in the coated fruits in this study. These results suggest that fruit chemical quality can be successfully maintained by coating treatments, which also help increase the postharvest shelf life.

Ascorbic acid deteriorates rapidly during storage due to oxidation, making it a particularly sensitive component of nutritional quality [80, 87]. Overall, ascorbic acid levels progressively decreased during storage in both covered and untreated fruits. This pattern is consistent with previous research that demonstrated that as storage time increased, ascorbic acid levels dramatically dropped in all treatments. In a similar vein [88] discovered that the vitamin C content dramatically decreased over time. Ascorbic acid is reduced during storage owing to oxidation [89]. Additionally, ascorbic acid levels in both the protected and untreated apples gradually decreased after storage.

The study found that TC3 (Tomato Coating 3) was the best coating combination as it had the least reduction in ascorbic acid concentration (mg/100 g). The TC3 sample had 12.92 mg/100 g at the end of storage, while the control sample had approximately 8.32 mg/100 g. Autoxidation, which occurs when ascorbic acid comes into direct contact with oxygen during fruit respiration, causes the drop in ascorbic acid levels during ripening [90, 91]. During storage, the ascorbic acid levels in the coated and control berries gradually decreased, and comparable results have been document [92]. The ascorbic acid concentrations of the coated and control strawberries decreased by 32.16% and 25.16%, respectively, after five and eight days of storage at 5 ± 1 °C; however, after three and five days at 20 ± 1 °C, it increased by 26.11% and 32.80%, respectively [80]. Ascorbic acid is a water-soluble vitamin; therefore, moisture loss during storage may potentially be a factor in the decrease in ascorbic acid levels, in addition to oxidative damage. When stored for a long time, ascorbic acid may evaporate with moisture [93]. Furthermore, there is a substantial correlation between drop and the berries' physiological state, storage temperature, and relative humidity [94]. Interestingly, some studies have revealed that ascorbic acid levels increase momentarily during ripening before declining [95]. The general declining trend in the current study demonstrates that edible coatings are useful for maintaining the nutritional value of fresh figs and prolonging their postharvest shelf life.

The gradual increase in PPO activity in uncoated fruits during prolonged storage aligns with senescence-induced cellular degradation. As tissue integrity diminishes, the separation between PPO enzymes and phenolic substrates is disrupted, allowing oxygen to interact freely with both components. Consequently, oxidative browning reactions become more pronounced. Comparable trends have been observed in various postharvest studies, where uncoated fruits consistently showed increased PPO activity during extended storage [95]. Moreover, previous research has demonstrated that coating treatments effectively suppress PPO activity. For example, coatings containing chitosan and either citric acid or ascorbic acid significantly decreased PPO activity in plums stored at 5 °C and cherimoya stored at 15 °C [95, 96]. Since the coated fruits showed lower enzymatic activity than the uncoated controls, these outcomes are consistent with recent research. Uncoated fruits stored for 12 days had the lowest PPO activity (50.20 unit/min/ml), suggesting that storage duration alone affects enzyme activity, even without a coating. A reduced storage duration minimizes cell breakdown and oxygen exposure, which decreases the likelihood of enzyme oxidation of phenolic compounds, as noted in several fruits, indicating that PPO activity increases with longer storage times [97].

Fruits treated with combinations of coatings containing bioactive additives like TG, CA, and PPE had significantly lower PPO activity in the range of 44.60 to 46.20 units at 24 d compared to the uncoated

control, according to an important finding from the study. According to other studies that have demonstrated or reported that "edible coatings can slow down enzymatic reactions by creating a physical barrier to limit O₂ availability in the tissues and lowering the enzyme's substrate for activity, this finding indicates that coatings' ability to reduce enzymatic activity may lead to a drop-in activity [98]. Additionally, as stated previously, its extract is also abundant in phenolic compounds that have been shown to directly block PPOs through strong binding affinity and therefore serve as an enzymatic inhibitor to significantly slow down browning during storage [99]. Compared with both coated and uncoated fruit, these mechanisms explain why coatings, including TG, CA, and PPE additives, showed noticeably lower PPO activity after 24 d of storage [100]. Several synergistic processes may be responsible for the reduced PPO activity observed in fruits treated with W+TG and W+CA+PPE formulations. Initially, edible coatings restrict oxygen transport into fruit tissues by creating a semi-permeable barrier, thereby limiting the availability of O₂ needed for enzymatic oxidation [98].

The composition of the coating is essential for preserving the antioxidant levels throughout the extended storage period. Fruit cells are usually shielded against oxidative stress caused by an imbalance in the production of antioxidant enzymes and the removal of reactive oxygen species. During the postharvest phase, elevated intracellular levels of reactive oxygen species can damage biomolecules, particularly cell membranes [101]. This reduction aligns with earlier research indicating a decrease in antioxidant activity over time, edible coatings, and their effects on attributes connected to oxidative activity. The reduction in antioxidant capacity during prolonged storage may result from the oxidation of physiologically active molecules and a sequence of reactions that lead to physiological and biochemical alterations during storage [102]. Similar results were observed when coatings were applied to fruits such as grapes and mangoes. Because of the coating effect, these fruits retained antioxidant-related substances such as flavonoids and phenols for a longer period than uncoated fruits [103].

Coating treatments significantly affected the level of antioxidant preservation. The notably increased antioxidant activity observed in W+CA-treated fruits after 24 days suggests a greater capacity to maintain antioxidant levels when utilizing this material. Citric acid is widely believed to have chelating properties, along with its ability to reduce pH levels. This decrease in the rate of phenolic degradation-causing oxidative events and enzyme activity points to a higher retention of antioxidant chemicals in the final product [104]. By reducing the pH and limiting catalytic oxidation, CA-containing coatings likely slow the degradation of antioxidant molecules, resulting in improved retention. On the other hand, the lower antioxidant activity observed in W+TG+PPE at 24 days may reflect progressive senescence and the eventual depletion of antioxidant compounds despite initial protective effects. In opposition, the lower antioxidant activity observed in W+TG+PPE at 24 days may reflect progressive senescence and the eventual depletion of antioxidant compounds despite initial protective effects.

Additives high in phenols, such as pomegranate peel extract, are recognized for their potent antioxidant capabilities [105]. Their protective efficacy may diminish during prolonged storage because of ongoing oxidative reactions and metabolic consumption. Overall, the results demonstrated that the antioxidant activity declined with storage duration; however, the extent of this decline was strongly dependent on the coating formulation. Coatings incorporating CA showed a superior ability to preserve antioxidant capacity during extended storage, likely due to the combined effects of pH reduction, chelation, and inhibition of oxidative enzymes. These findings support recent research highlighting the benefits of functional edible coatings in enhancing oxidative stability and extending the shelf life of fresh fruit after harvest.

Flavonoids possess potent antioxidant properties and prolong the shelf life of fruits after harvest [106, 107]. This somewhat reduced the respiratory rate and the oxidative degradation of the chemicals, allowing flavonoid compounds to remain for an extended period during the initial phase [108]. However, citric acid and PPE may have altered the stability of flavonoid activity pathways, which could account for the decreased flavonoid activity in the samples, including W, CA + PPE, and W+PPE. This phenomenon might stem from the idea that while phenolic compounds could serve as an external antioxidant source in food, the mixture of whey protein and citric acid may have changed the coating characteristics of the sample, preventing it from effectively preserving the flavonoids in their 'normal' active forms. This suggests that the combination might have accelerated certain chemical changes that

potentially modified the flavonoid activity. Variations in flavonoid activity have been observed in different coating combinations [109].

In general, these studies emphasize that both the type of coating and the storage period are important parameters affecting the maintenance or loss of flavonoids from fruit pieces after harvest. Indeed, coating treatments that control gas exchange and delay oxidative stress tend to show higher flavonoid activity, while other coating approaches that affect fruit physiological processes more dramatically can also cause a greater loss of flavonoids under similar storage regimes [110]. These results reinforce the broader principle observed in postharvest research: coatings that moderate gas exchange, limit oxidative stress, and maintain controlled respiration rates tend to preserve flavonoid content more effectively than others. In contrast, coatings that alter physiological or chemical conditions more dramatically may inadvertently accelerate flavonoid degradation, particularly during the early storage period.

Similar results have been shown for citrus and other horticultural goods, where the protective barrier effect of edible coatings allowed coated fruits to preserve higher amounts of flavonoids than uncoated controls [110]. Similar results were reported in a study: after 25 days of storage, the control fruit samples exhibited the lowest total flavonoid concentration (31.49 mg QE/g DW) of Jara Lebu fruit extract [111].

5. Conclusions

The current study demonstrated the successful application of a modified goat whey protein coating, to preserve the postharvest quality of fresh figs and increase their shelf life. CA, TG, and PPE were added to improve the functional qualities of the coating and reduce quality deterioration during storage. While W+CA improved decay control and preserved antioxidant activity, W+CA+PPE resulted in the greatest reduction in weight loss. The shelf life of fresh figs was extended to 24 days by the enhanced coatings. These findings indicate that modified goat whey protein coatings, particularly those containing CA and PPE, are a viable method for reducing postharvest losses and maintaining fig quality during refrigeration. To achieve a good balance between coating performance, fruit quality, sensory acceptability, and cost-effectiveness, the proportions of W, TG, CA, and PPE should be modified for practical use. To ascertain the scalability, homogeneity, and economic feasibility of the coating process, it should be evaluated under commercial handling, storage, and transportation conditions. Future research should examine the interactions between TG, CA, and PPE in whey protein matrices and their effects on coating structures and barrier qualities. The utilization of additional natural plant-derived extracts or bioactive substances to enhance the protective and antioxidant qualities of coatings should be investigated. Additional examination of the microbiological quality, respiration rate, ethylene generation, texture, color, sensory characteristics, and other biochemical quality variables should be achieved.

Author contributions: **Bnar Mohammed Sadiq:** Conceptualization, Investigation, Methodology, Acquisition, Data curation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jasim Mohammed Salih AL-Saadi:** Supervision, Writing – review & editing. **Ali Muhi Aldeen Omar Aljabary:** Supervision, Writing – review & editing.

Data availability: Data will be available upon reasonable request by authors.

Conflicts of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding: The authors did not receive support from any organization for the conducting of the study.

References:

- [1] Y. Lu, Y. Huang, and R. Lu, "Innovative hyperspectral imaging-based techniques for quality evaluation of fruits and vegetables: A review," *Applied Sciences*, vol. 7, no. 2, p. 189, 2017, doi: [10.3390/app7020189](https://doi.org/10.3390/app7020189).
- [2] E. M. Yahia and A. Carrillo-Lopez, *Postharvest Physiology and Biochemistry of Fruits and Vegetables*. Duxford, U.K.: Woodhead Publishing, 2018, doi: 10.1016/C2016-0-04653-3.

- [3] A. Septembre-Malaterre, F. Remize, and P. Pouchet, "Fruits and vegetables, as a source of nutritional compounds and phytochemicals: Changes in bioactive compounds during lactic fermentation," *Food Research International*, vol. 104, pp. 86–99, 2018, doi:[10.1016/j.foodres.2017.09.031](https://doi.org/10.1016/j.foodres.2017.09.031)
- [4] S. Shankar, A. K. Mohanty, J. R. DeEll, K. Carter, R. Lenz, and M. Misra, "Advances in antimicrobial techniques to reduce postharvest loss of fresh fruit by microbial reduction," *NPJ Sustainable Agriculture*, vol. 2, no. 1, p. 25, 2024, doi:[10.1038/s44264-024-00029-x](https://doi.org/10.1038/s44264-024-00029-x).
- [5] R. R. Sharma, H. Raghavendra, and S. Sethi, "Postharvest Treatments for Horticultural Produce," in *Postharvest Handling and Diseases of Horticultural Produce*. CRC Press, 2021, pp. 43–56, doi: [10.1007/s13197-017-2962-4](https://doi.org/10.1007/s13197-017-2962-4).
- [6] A. Elik, D. K. Yanik, Y. Istanbulu, N. A. Guzelsoy, A. Yavuz, and F. Gogus, "Strategies to reduce post-harvest losses for fruits and vegetables," *Strategies*, vol. 5, no. 3, pp. 29–39, 2019, doi: [10.7176/JSTR/5-3-04](https://doi.org/10.7176/JSTR/5-3-04).
- [7] M. Miranda et al., "Fundamentals of edible coatings and combination with biocontrol agents: A strategy to improve postharvest fruit preservation," *Foods*, vol. 13, no. 18, p. 2960, 2024, doi: [10.3390/foods13182980](https://doi.org/10.3390/foods13182980).
- [8] V. Mihalca et al., "Protein-based films and coatings for food industry applications," *Polymers*, vol. 13, no. 5, p. 769, 2021, doi: [10.3390/polym13050769](https://doi.org/10.3390/polym13050769).
- [9] B. Abdalla, H. Marf, J. M. S. Al-Saadi, A. M. Aldeen, and O. Aljabary, "Storage properties of figs coated using chemically modified whey proteins and caseins," *Euphrates Journal of Agriculture Science*, vol. 14, no. 2, pp. 26–49, 2022.
- [10] M. Paolucci, M. Di Stasio, A. Sorrentino, F. La Cara, and M. G. Volpe, "Active edible polysaccharide-based coating for preservation of fresh figs (*Ficus carica* L.)," *Foods*, vol. 9, no. 12, p. 1793, 2020, doi:[10.3390/foods9121793](https://doi.org/10.3390/foods9121793).
- [11] S. Moccia, F. La Cara, C. Cervellera, G. L. Russo, and M. G. Volpe, "Active edible coating to preserve fresh figs," *Chemical Engineering Transactions*, vol. 87, pp. 181–186, 2021, doi: [10.3303/cet2187031](https://doi.org/10.3303/cet2187031).
- [12] N. Kaur, C. Somasundram, Z. Razali, and Z. F. R. Ahmed, "Sustainable Aloe vera/chitosan-based edible coatings reduce postharvest loss of stored fresh figs (*Ficus carica* L.)," *Frontiers in Sustainable Food Systems*, vol. 8, p. 1459600, 2024, doi: [10.3389/fsufs.2024.1459600](https://doi.org/10.3389/fsufs.2024.1459600).
- [13] H. Rajial and S. Varma, "Edible coatings: A novel approach to extending the shelf life of fruits and vegetables," *Journal of Advances in Biology & Biotechnology*, vol. 27, no. 7, pp. 25–37, 2024, doi: [10.9734/jabb/2024/v27i7963](https://doi.org/10.9734/jabb/2024/v27i7963).
- [14] R. Zhang, R. Liu, J. Han, L. Ren, and L. Jiang, "Protein-based packaging films in food: Developments, applications, and challenges," *Gels*, vol. 10, no. 7, p. 418, 2024, doi: [10.1016/j.carbpol.2018.08.013](https://doi.org/10.1016/j.carbpol.2018.08.013).
- [15] M. N. Khin, S. Ahammed, M. M. Kamal, M. N. Saqib, F. Liu, and F. Zhong, "Investigating next-generation edible packaging: Protein-based films and coatings for delivering active compounds," *Food Hydrocolloids for Health*, vol. 6, p. 100182, 2024, doi: [10.1016/j.fhfh.2024.100182](https://doi.org/10.1016/j.fhfh.2024.100182).
- [16] P. Muthusamy et al., "Air quality prediction in smart environment using lightweight residual network: Sustainable Light-AirNet approach," *Journal of Environmental Nanotechnology, Monitoring & Management*, vol. 13, no. 1, pp. 125–132, 2024, doi: [10.1007/s44187-025-00582-5](https://doi.org/10.1007/s44187-025-00582-5).
- [17] T. Li et al., "Surface hydrophobicity and functional properties of citric acid cross-linked whey protein isolate: The impact of pH and concentration of citric acid," *Molecules*, vol. 23, no. 9, p. 2383, 2018, doi: [10.3390/molecules23092383](https://doi.org/10.3390/molecules23092383).
- [18] H. Nourbakhsh, Z. Emam-Djomeh, A. Madadlou, M. E. Mousavi, A. A. Moosavi-Movahedi, and S. Gunasekaran, "Antioxidant peptidic particles for delivery of gallic acid," *Journal of Food Processing and Preservation*, vol. 41, no. 1, p. e12767, 2017, doi: [10.1111/jfpp.12767](https://doi.org/10.1111/jfpp.12767).
- [19] S. Sakkar, D. Nataraj, K. Venkatesh, Y. Xu, J. H. Patil, and N. Reddy, "Effect of pH on the physicochemical properties of starch films," *Journal of Applied Polymer Science*, vol. 137, no. 15, p. 48563, 2020, doi: [10.1002/app.48563](https://doi.org/10.1002/app.48563).
- [20] S. Liang et al., "Fenugreek gum/casein edible gel film based on polycarboxylic acid cross-linking: Performance characterization, cross-linking mechanism and application," *Food Chemistry*, vol. 519, p. 149751, 2026, doi: [10.1016/j.foodchem.2026.149751](https://doi.org/10.1016/j.foodchem.2026.149751).
- [21] S. Liang et al., "Preparation, characterization and application of gel edible films based on galactomannan and casein," *Food Hydrocolloids*, vol. 163, p. 111143, 2025, doi: [10.1016/j.foodhyd.2025.111143](https://doi.org/10.1016/j.foodhyd.2025.111143).
- [22] W. Zhang, S. Roy, E. Assadpour, X. Cong, and S. M. Jafari, "Cross-linked biopolymeric films by citric acid for food packaging and preservation," *Advances in Colloid and Interface Science*, vol. 314, p. 102886, 2023, doi: [10.1016/j.cis.2023.102886](https://doi.org/10.1016/j.cis.2023.102886).
- [23] M. P. Bönisch, M. Huss, K. Weitzl, and U. Kulozik, "Transglutaminase cross-linking of milk proteins and impact on yoghurt gel properties," *International Dairy Journal*, vol. 17, no. 11, pp. 1360–1371, 2007, doi: [10.1016/j.idairyj.2007.01.019](https://doi.org/10.1016/j.idairyj.2007.01.019).
- [24] J. H. Oh, B. Wang, P. D. Field, and H. A. Aglan, "Characteristics of edible films made from dairy proteins and zein hydrolysate cross-linked with transglutaminase," *International Journal of Food Science & Technology*, vol. 39, no. 3, pp. 287–294, 2004, doi: [10.1111/j.1365-2621.2004.00783.x](https://doi.org/10.1111/j.1365-2621.2004.00783.x).
- [25] J. Yang, T. Gasti, A. Kamkari, A. N. Tabrizi, Y. Ramezan, and W. Zhang, "Casein as a biopolymer for edible packaging: A review on modification strategies and barrier property enhancement," *Food Research International*, vol. 227, art. no. 118246, 2026, doi: [10.1016/j.foodres.2025.118246](https://doi.org/10.1016/j.foodres.2025.118246).
- [26] I. Belgacem et al., "Pomegranate peel extracts as safe natural treatments to control plant diseases and increase the shelf-life and safety of fresh fruits and vegetables," *Plants*, vol. 10, no. 3, pp. 1–13, 2021, doi: [10.3390/plants10030453](https://doi.org/10.3390/plants10030453).
- [27] R. P. Basavaraj, R. K. Tiwari, K. K. Dash, and M. Sharma, "Recent advances in encapsulation of pomegranate peel extract and combination of wall materials: A review of encapsulation technologies, characterization and applications," *Sustainable Food Technology*, vol. 3, no. 1, pp. 123–144, 2025, doi: [10.1039/d4fb00196f](https://doi.org/10.1039/d4fb00196f).
- [28] P. Kandyli and E. Kokkinomagoulos, "Food applications and potential health benefits of pomegranate and its derivatives," *Foods*, vol. 9, no. 2, p. 122, 2020, doi: [10.3390/foods9020122](https://doi.org/10.3390/foods9020122).
- [29] R. Diaz-Herrera et al., "Pomegranate peel polyphenols as an antioxidant additive for the development and characterization of a new active pectin edible film," *eFood*, vol. 4, no. 6, p. e115, 2023, doi: [10.1002/efd2.115](https://doi.org/10.1002/efd2.115).

- [30] S. Hamaideh, A. N. Olaimat, and M. Al-Holy, "Pomegranate peel extract as a natural antimicrobial agent: Extraction methods, biochemical composition, mechanism of action, and application in food packaging," *Sustainable Food Connect*, vol. 2, no. 1, p. 1, 2026, doi: [10.69709/SustainFoodConn.2026.142240](https://doi.org/10.69709/SustainFoodConn.2026.142240).
- [31] Ó. L. Ramos, J. C. Fernandes, S. I. Silva, M. E. Pintado, and F. X. Malcata, "Edible films and coatings from whey proteins: A review on formulation, and on mechanical and bioactive properties," *Critical Reviews in Food Science and Nutrition*, vol. 52, no. 6, pp. 533–552, 2012, doi: [10.1080/10408398.2010.500528](https://doi.org/10.1080/10408398.2010.500528).
- [32] S. Kandasamy et al., "Application of whey protein-based edible films and coatings in food industries: An updated overview," *Coatings*, vol. 11, no. 9, p. 1056, 2021, doi: [10.3390/coatings11091056](https://doi.org/10.3390/coatings11091056).
- [33] H. Chambi and C. Grosso, "Edible films produced with gelatin and casein cross-linked with transglutaminase," *Food Research International*, vol. 39, no. 4, pp. 458–466, 2006, doi: [10.1016/j.foodres.2005.09.009](https://doi.org/10.1016/j.foodres.2005.09.009).
- [34] A. Soleimanzadeh et al., "Recent advances in characterizing the physical and functional properties of active packaging films containing pomegranate peel," *Food Chemistry*, vol. 22, p. 101416, 2024, doi: [10.1016/j.fochx.2024.101416](https://doi.org/10.1016/j.fochx.2024.101416).
- [35] U. K. Laemmli, "Cleavage of structural proteins during the assembly of the head of bacteriophage T4," *Nature*, vol. 227, no. 5259, pp. 680–685, 1970, doi: [10.1038/227680a0](https://doi.org/10.1038/227680a0).
- [36] L. Sharma, H. K. Sharma, and C. S. Saini, "Edible films developed from carboxylic acid cross-linked sesame protein isolate: Barrier, mechanical, thermal, crystalline and morphological properties," *Journal of Food Science and Technology*, vol. 55, no. 2, pp. 532–539, 2018, doi: [10.1007/s13197-017-2962-4](https://doi.org/10.1007/s13197-017-2962-4).
- [37] M. A. Noori and S. A. Sidiq Kasnazany, "Effect of some preharvest treatments on growth, fruit quality and storability of strawberry (*Fragaria × ananassa* Duch.) cv. 'Rubygem' grown under plastic house," *ProEnvironment Promediu*, vol. 16, no. 56, pp. 249–262, 2023.
- [38] C. Han, Y. Zhao, S. W. Leonard, and M. G. Traber, "Edible coatings to improve storability and enhance nutritional value of fresh and frozen strawberries (*Fragaria × ananassa*) and raspberries (*Rubus idaeus*)," *Postharvest Biology and Technology*, vol. 33, no. 1, pp. 67–78, 2004, doi: [10.1016/j.postharvbio.2004.01.008](https://doi.org/10.1016/j.postharvbio.2004.01.008).
- [39] M. Kafkaleto, A. Velliou, M. V. Christopoulos, G. Ouzounidou, and E. Tsantili, "Impact of cold storage temperature and shelf life on ripening physiology, quality attributes, and nutritional value in apricots – Implication of cultivar," *Plants*, vol. 12, no. 15, p. 2875, 2023, doi: [10.3390/plants12152875](https://doi.org/10.3390/plants12152875).
- [40] F. Javed et al., "Stabilization of *Ficus carica* L. Drink by utilizing varying levels of ultrasound-assisted moringa extract as a natural preservative," *Ultrasonics Sonochemistry*, vol. 111, p. 107133, 2024, doi: [10.1016/j.ultsonch.2024.107133](https://doi.org/10.1016/j.ultsonch.2024.107133).
- [41] T. G. Kawhena, U. L. Opara, and O. A. Fawole, "Effects of gum arabic coatings enriched with lemongrass essential oil and pomegranate peel extract on quality maintenance of pomegranate whole fruit and arils," *Foods*, vol. 11, no. 4, p. 593, 2022, doi: [10.3390/foods11040593](https://doi.org/10.3390/foods11040593).
- [42] M. Sharma and C. S. Saini, "Postharvest shelf-life extension of fresh-cut guavas (*Psidium guajava*) using flaxseed protein-based composite coatings," *Food Hydrocolloids for Health*, vol. 1, p. 100015, 2021, doi: [10.1016/j.fhfh.2021.100015](https://doi.org/10.1016/j.fhfh.2021.100015).
- [43] V. Gigante et al., "Designing eco-friendly edible coatings, valorising agro-wastes, to extend the shelf-life of post-harvest strawberries," *Carbohydrate Polymer Technologies and Applications*, vol. 11, p. 100984, 2025, doi: [10.1016/j.carpta.2025.100984](https://doi.org/10.1016/j.carpta.2025.100984).
- [44] N. Kumar, Pratibha, Neeraj, A. T. Petkoska, S. A. Al-Hilifi, and O. A. Fawole, "Effect of chitosan–pullulan composite edible coating functionalized with pomegranate peel extract on the shelf life of mango (*Mangifera indica*)," *Coatings*, vol. 11, no. 7, p. 764, 2021, doi: [10.3390/coatings11070764](https://doi.org/10.3390/coatings11070764).
- [45] S. K. Hamied Taha and A. M. Aldeen Omar Aljabary, "Improving the fig fruits growth and quality by spraying with extracts of moringa leaves and garlic cloves," *Journal of Kirkuk University for Agricultural Sciences*, vol. 13, no. 4, p. 253, 2022, doi: [10.3390/coatings11070764](https://doi.org/10.3390/coatings11070764).
- [46] D. R. Kifle, K. B. Bacha, R. N. Hora, and L. L. Likasa, "Evaluation of microbiome and physico-chemical profiles of fresh fruits of *Musa paradisica*, *Citrus sinensis* and *Carica papaya* at different ripening stages," *PLOS ONE*, vol. 19, no. 1, p. e0297574, 2024, doi: [10.1371/journal.pone.0297574](https://doi.org/10.1371/journal.pone.0297574).
- [47] D. Lateef, K. Mustafa, and N. Tahir, "Screening of Iraqi barley accessions under PEG-induced drought conditions," *All Life*, vol. 14, no. 1, pp. 308–332, 2021, doi: [10.1080/26895293.2021.1917456](https://doi.org/10.1080/26895293.2021.1917456).
- [48] N. A. Tahir, K. S. Rasul, D. D. Lateef, R. R. Aziz, and J. O. Ahmed, "In vitro evaluation of Iraqi Kurdistan tomato accessions under drought stress conditions using polyethylene glycol-6000," *Life*, vol. 14, no. 11, p. 1502, 2024, doi: [10.3390/life14111502](https://doi.org/10.3390/life14111502).
- [49] N. A. Tahir, J. O. Ahmed, H. A. Azeez, W. R. M. Palani, and D. A. Omer, "Phytochemical, antibacterial, antioxidant and phytotoxicity screening of the extracts collected from the fruit and root of wild Mt. Atlas mastic tree (*Pistacia atlantica*)," *Applied Ecology and Environmental Research*, vol. 17, no. 2, pp. 4417–4429, 2019, doi: [10.15666/aeer/1702_44174429](https://doi.org/10.15666/aeer/1702_44174429).
- [50] G. Rigane, H. Ghazghazi, C. Aouadhi, R. Ben Salem, and Z. Nasr, "Phenolic content, antioxidant capacity and antimicrobial activity of leaf extracts from *Pistacia atlantica*," *Natural Product Research*, vol. 31, no. 6, pp. 696–699, 2017, doi: [10.1080/14786419.2016.1212035](https://doi.org/10.1080/14786419.2016.1212035).
- [51] C. Shi, Y. Dai, X. Xu, Y. Xie, and Q. Liu, "The purification of polyphenol oxidase from tobacco," *Protein Expression and Purification*, vol. 24, no. 1, pp. 51–55, 2002, doi: [10.1006/prep.2001.1543](https://doi.org/10.1006/prep.2001.1543).
- [52] R. W. Berg, "Investigation of L(+)-Ascorbic acid with Raman spectroscopy in visible and UV light," *Applied Spectroscopy Reviews*, vol. 50, no. 3, pp. 193–239, 2015, doi: [10.1080/05704928.2014.952431](https://doi.org/10.1080/05704928.2014.952431).
- [53] M. Sohail, M. Ayub, S. A. Khalil, A. Zeb, F. Ullah, S. R. Afridi, and R. Ullah, "Effect of calcium chloride treatment on post-harvest quality of peach fruit during cold storage," *International Food Research Journal*, vol. 22, no. 6, p. 2225, 2015.
- [54] J. Al-Saadi and S. Mohammed, "Study of goat's and cow's milk proteins and their relationship with allergy," *College of Agriculture, University of Baghdad*, 2002, doi: [10.18805/ag.R-2641](https://doi.org/10.18805/ag.R-2641).
- [55] J. S. Al-Saadi, K. A. Shaker, and Z. Ustunol, "Effect of heat and transglutaminase on solubility of goat milk protein-based films," *International Journal of Dairy Technology*, vol. 67, no. 3, pp. 420–426, 2014, doi: [10.1111/1471-0307.12138](https://doi.org/10.1111/1471-0307.12138).

- [56] M. C. Reyes-Avalos et al., "Improvement of the quality and the shelf life of figs (*Ficus carica*) using an alginate–chitosan edible film," *Food and Bioprocess Technology*, vol. 9, no. 12, pp. 2114–2124, 2016, doi: [10.1007/s11947-016-1796-9](https://doi.org/10.1007/s11947-016-1796-9).
- [57] G. Adiletta, L. Zampella, C. Coletta, and M. Petriccione, "Chitosan coating to preserve the qualitative traits and improve antioxidant system in fresh figs (*Ficus carica* L.)," *Agriculture*, vol. 9, no. 4, p. 84, 2019, doi: [10.3390/agriculture9040084](https://doi.org/10.3390/agriculture9040084).
- [58] Z. Li, X. Bi, Y. Dai, and R. Ren, "Enhancing mango anthracnose control and quality maintenance through chitosan and iturin A coating," *LWT*, vol. 198, 2024, doi: [10.1016/j.lwt.2024.115955](https://doi.org/10.1016/j.lwt.2024.115955).
- [59] P. Deng, Z. Wang, J. Bu, Y. Fan, Y. Kuang, and F. Jiang, "Konjac glucomannan-based nanocomposite spray coating with antimicrobial, gas barrier, UV blocking, and antioxidation for bananas preservation," *International Journal of Biological Macromolecules*, vol. 265, 2024, doi: [10.1016/j.ijbiomac.2024.130895](https://doi.org/10.1016/j.ijbiomac.2024.130895).
- [60] J. R. Barone and W. F. Schmidt, "Nonfood applications of proteinaceous renewable materials," *Journal of Chemical Education*, vol. 83, no. 7, pp. 1003–1003, 2006, doi: [10.1021/ed083p1003](https://doi.org/10.1021/ed083p1003).
- [61] U. Siripatrawan and W. Vitchayakitti, "Improving functional properties of chitosan films as active food packaging by incorporating with propolis," *Food Hydrocolloids*, vol. 61, pp. 695–702, 2016, doi: [10.1016/j.foodhyd.2016.06.001](https://doi.org/10.1016/j.foodhyd.2016.06.001).
- [62] A. Allegra, A. Gallotta, F. Carimi, F. Mercati, P. Inglese, and F. Martinelli, "Metabolic profiling and post-harvest behavior of 'Dottato' fig (*Ficus carica* L.) fruit covered with an edible coating from *O. ficus-indica*," *Frontiers in Plant Science*, vol. 9, p. 1321, 2018, doi: [10.3389/fpls.2018.01321](https://doi.org/10.3389/fpls.2018.01321).
- [63] C. Yang, T. Chen, B. Shen, S. Sun, H. Song, D. Chen, and W. Xi, "Citric acid treatment reduces decay and maintains the postharvest quality of peach (*Prunus persica* L.) fruit," *Food Science & Nutrition*, vol. 7, no. 11, pp. 3635–3643, 2019, doi: [10.1002/fsn3.1219](https://doi.org/10.1002/fsn3.1219).
- [64] S. Y. Wang and H. Gao, "Effect of chitosan-based edible coating on antioxidants, antioxidant enzyme system, and postharvest fruit quality of strawberries (*Fragaria x ananassa* Duch.)," *LWT - Food Science and Technology*, vol. 52, no. 2, pp. 71–79, 2013, doi: [10.1016/j.lwt.2012.05.003](https://doi.org/10.1016/j.lwt.2012.05.003).
- [65] D. Khodaei, Z. Hamidi-Esfahani, and E. Rahmati, "Effect of edible coatings on the shelf-life of fresh strawberries: A comparative study using TOPSIS-Shannon entropy method," *NFS Journal*, vol. 23, pp. 17–23, Jun. 2021, doi: [10.1016/j.nfs.2021.02.003](https://doi.org/10.1016/j.nfs.2021.02.003).
- [66] B. Navina, T. Korumilli, and K. J. Rao, "Exploring the potential of tragacanth gum and natural additives to control browning and microbial growth in fresh-cut banana slices," *Discover Food*, vol. 5, no. 1, p. 308, Sep. 2025, doi: [10.1007/s44187-025-00582-5](https://doi.org/10.1007/s44187-025-00582-5).
- [67] D. Singh and R. Kumar, "Edible coatings and plant extract influence decay and biochemical attributes of nectarines," *Indian Journal of Agricultural Sciences*, vol. 91, no. 2, pp. 240–243, 2021, doi: [10.1016/j.foodhyd.2016.06.001](https://doi.org/10.1016/j.foodhyd.2016.06.001).
- [68] A. Kumar and C. S. Saini, "Edible composite bi-layer coating based on whey protein isolate, xanthan gum and clove oil for prolonging shelf life of tomatoes," *Measurement Food*, vol. 2, p. 100005, 2021, doi: [10.1016/j.meafao.2021.100005](https://doi.org/10.1016/j.meafao.2021.100005).
- [69] N. Mahfoudhi and S. Hamdi, "Use of almond gum and gum arabic as novel edible coating to delay postharvest ripening and to maintain sweet cherry (*Prunus avium*) quality during storage," *Journal of Food Processing and Preservation*, vol. 39, no. 6, pp. 1499–1508, 2015, doi: [10.1111/jfpp.12369](https://doi.org/10.1111/jfpp.12369).
- [70] Z. Abebe and Y. T., "Effects of edible coating materials and stages of maturity at harvest on storage life and quality of tomato (*Lycopersicon esculentum* Mill.) fruits," *African Journal of Agricultural Research*, vol. 12, no. 8, pp. 550–565, 2017, doi: [10.5897/AJAR2016.11648](https://doi.org/10.5897/AJAR2016.11648).
- [71] M. Mohebbi, E. Ansarifard, N. Hasanpour, and M. R. Amiryousefi, "Suitability of aloe vera and gum tragacanth as edible coatings for extending the shelf life of button mushroom," *Food and Bioprocess Technology*, vol. 5, no. 8, pp. 3193–3202, 2011, doi: [10.1007/s11947-011-0709-1](https://doi.org/10.1007/s11947-011-0709-1).
- [72] K. Hasan, R. Islam, M. Hasan, S. H. Sarker, and M. H. Biswas, "Effect of alginate edible coatings enriched with black cumin extract for improving postharvest quality characteristics of Guava (*Psidium guajava* L.) Fruit," *Food and Bioprocess Technology*, vol. 15, no. 9, pp. 2050–2064, 2022, doi: [10.1007/s11947-022-02869-2](https://doi.org/10.1007/s11947-022-02869-2).
- [73] A. Islam, R. Acikalin, B. Ozturk, E. Aglar, and C. Kaiser, "Combined effects of Aloe vera gel and modified atmosphere packaging treatments on fruit quality traits and bioactive compounds of jujube (*Ziziphus jujuba* Mill.) fruit during cold storage and shelf life," *Postharvest Biology and Technology*, vol. 187, p. 111855, 2022, doi: [10.1016/j.postharvbio.2022.111855](https://doi.org/10.1016/j.postharvbio.2022.111855).
- [74] M. Rasouli, M. Koushesh Saba, and A. Ramezani, "Inhibitory effect of salicylic acid and Aloe vera gel edible coating on microbial load and chilling injury of orange fruit," *Scientia Horticulturae*, vol. 247, pp. 27–34, 2019, doi: [10.1016/j.scienta.2018.12.004](https://doi.org/10.1016/j.scienta.2018.12.004).
- [75] K. Kaur, W. S. Dhillon, and B. V. C. Mahajan, "Effect of different packaging materials and storage intervals on physical and biochemical characteristics of pear," *Journal of Food Science and Technology*, vol. 50, no. 1, pp. 147–152, 2011, doi: [10.1007/s13197-011-0317-0](https://doi.org/10.1007/s13197-011-0317-0).
- [76] A. Dogan and M. Erkan, "Responses of high carbon dioxide concentration on postharvest quality of fresh fig fruit during storage," *Horticulturae*, vol. 9, no. 3, p. 293, 2023, doi: [10.3390/horticulturae9030293](https://doi.org/10.3390/horticulturae9030293).
- [77] M. D. Ruiz Medina, Y. Quimbata Yupangui, and J. Rualas, "Effect of a protein–polysaccharide coating on the physicochemical properties of banana (*Musa paradisiaca*) during storage," *Coatings*, vol. 15, no. 7, p. 812, 2025, doi: [10.3390/coatings15070812](https://doi.org/10.3390/coatings15070812).
- [78] A. Hussain et al., "Physiological and biochemical variations of naturally ripened mango (*Mangifera indica* L.) with synthetic calcium carbide and ethylene," *Scientific Reports*, vol. 14, no. 1, p. 2121, 2024, doi: [10.1038/s41598-024-52483-9](https://doi.org/10.1038/s41598-024-52483-9).
- [79] R. Thakur et al., "Development and application of rice starch based edible coating to improve the postharvest storage potential and quality of plum fruit (*Prunus salicina*)," *Scientia Horticulturae*, vol. 237, pp. 59–66, 2018, doi: [10.1016/j.scienta.2018.04.005](https://doi.org/10.1016/j.scienta.2018.04.005).
- [80] A. B. Muley and R. S. Singhal, "Extension of postharvest shelf life of strawberries (*Fragaria ananassa*) using a coating of chitosan–whey protein isolate conjugate," *Food Chemistry*, vol. 329, p. 127213, 2020, doi: [10.1016/j.foodchem.2020.127213](https://doi.org/10.1016/j.foodchem.2020.127213).
- [81] S. Bashir et al., "Effect of antimicrobial and antioxidant rich pomegranate peel based edible coatings on quality and functional properties of chicken nuggets," *Molecules*, vol. 27, no. 14, p. 4500, 2022, doi: [10.3390/molecules27144500](https://doi.org/10.3390/molecules27144500).

- [82] İ. Kahramanoğlu, N. P. Bahadır, V. Okatan, and C. Wan, "Impacts of edible coatings enriched with laurel essential oil on the storage life of strawberry 'Camarosa' fruits," *Bragantia*, vol. 81, p. e20210221, 2022, doi: [10.1590/1678-4499.20210221](https://doi.org/10.1590/1678-4499.20210221).
- [83] R. Thakur, P. Pristijono, C. J. Scarlett, M. Bowyer, S. P. Singh, and Q. V. Vuong, "Starch-based edible coating formulation: Optimization and its application to improve the postharvest quality of 'Cripps Pink' apple under different temperature regimes," *Food Packaging and Shelf Life*, vol. 22, p. 100409, 2019, doi: [10.1016/j.foodpsl.2019.100409](https://doi.org/10.1016/j.foodpsl.2019.100409).
- [84] A. Amini, "The influence of composite edible coating of Balangu gum and whey protein on strawberry storability," *Journal of Food Science and Technology*, vol. 22, no. 165, 2025, doi: [10.22034/FSCT.22.165.276](https://doi.org/10.22034/FSCT.22.165.276).
- [85] P. J. Espinoza Montero and L. M. Fernández Martínez, "Recubrimientos comestibles con materiales micro/nanoestructurados para la conservación de frutas y verduras," *infoanalítica*, vol. 8, no. 1, pp. 14–47, 2020, doi: [10.23456789/5370](https://doi.org/10.23456789/5370).
- [86] J. Sherani, "Application of Aloe vera gel and olive oil coatings to enhance fruit quality and shelf-life of ber (*Ziziphus mauritiana* L.)," *Pure and Applied Biology*, vol. 11, no. 1, pp. 159–168, 2022, doi: [10.19045/bspab.2022.110017](https://doi.org/10.19045/bspab.2022.110017).
- [87] A. Mditswa, L. S. Magwaza, S. Z. Tesfay, and U. L. Opara, "Postharvest factors affecting vitamin C content of citrus fruits: A review," *Scientia Horticulturae*, vol. 218, pp. 95–104, 2017, doi: [10.1016/j.scienta.2017.02.024](https://doi.org/10.1016/j.scienta.2017.02.024).
- [88] A. F. Abd El-Khalek, U. K. El-Abbasy, and M. I. Ismail, "Postharvest applications of 1-methylcyclopropene and salicylic acid for maintaining quality and enhancing antioxidant enzyme activity of apricot fruits cv. 'Canino' during cold storage," *Egyptian Journal of Horticulture*, vol. 45, no. 1, pp. 1–23, 2018, doi: [10.21608/ejoh.2017.2405.1037](https://doi.org/10.21608/ejoh.2017.2405.1037).
- [89] M. El-Mogy, H. A. Anean, and B. Alsanius, "Improving strawberry fruit storability by edible coating as a carrier of thymol or calcium chloride," *Journal of Horticultural Science and Ornamental Plants*, vol. 2, no. 3, pp. 88–97, 2010.
- [90] M. Tigist, T. S. Workneh, and K. Woldetsadik, "Effects of variety on the quality of tomato stored under ambient conditions," *Journal of Food Science and Technology*, vol. 50, no. 3, pp. 477–486, 2013, doi: [10.1007/s13197-011-0378-0](https://doi.org/10.1007/s13197-011-0378-0).
- [91] F. Rashid et al., "Effect of fenugreek and flaxseed polysaccharide-based edible coatings on the quality attributes and shelf life of apple fruit during storage," *Food Science & Nutrition*, vol. 12, no. 3, pp. 2093–2103, 2024, doi: [10.1002/fsn3.3909](https://doi.org/10.1002/fsn3.3909).
- [92] S. K. Bose, P. Howlader, X. Jia, W. Wang, and H. Yin, "Alginate oligosaccharide postharvest treatment preserve fruit quality and increase storage life via Absciscic acid signaling in strawberry," *Food Chemistry*, vol. 283, pp. 665–674, 2019, doi: [10.1016/j.foodchem.2019.01.060](https://doi.org/10.1016/j.foodchem.2019.01.060).
- [93] Y. Klopotek, K. Otto, and V. Böhm, "Processing strawberries to different products alters contents of vitamin C, total phenolics, total anthocyanins, and antioxidant capacity," *Journal of Agricultural and Food Chemistry*, vol. 53, no. 14, pp. 5640–5646, 2005, doi: [10.1021/jf047947v](https://doi.org/10.1021/jf047947v).
- [94] W. Jiao, C. Shu, X. Li, J. Cao, X. Fan, and W. Jiang, "Preparation of a chitosan-chlorogenic acid conjugate and its application as edible coating in postharvest preservation of peach fruit," *Postharvest Biology and Technology*, vol. 154, pp. 129–136, 2019, doi: [10.1016/j.postharvbio.2019.05.003](https://doi.org/10.1016/j.postharvbio.2019.05.003).
- [95] E. S. de Brito and N. Narain, "Physical and chemical characteristics of sapota fruit at different stages of maturation," *Pesquisa Agropecuária Brasileira*, vol. 37, no. 4, pp. 567–572, 2002, doi: [10.1590/S0100-204X2002000400020](https://doi.org/10.1590/S0100-204X2002000400020).
- [96] J. Liu, C. Y., H. L., and Y. Chen, "Influence of postharvest citric acid and chitosan coating treatment on ripening attributes and expression of cell wall related genes in cherimoya (*Annona cherimola* Mill.) fruit," *Scientia Horticulturae*, vol. 198, pp. 1–11, 2016, doi: [10.1016/j.scienta.2015.11.008](https://doi.org/10.1016/j.scienta.2015.11.008).
- [97] S. Eshghi, R. Karimi, A. Shiri, M. Karami, and M. Moradi, "Effects of polysaccharide-based coatings on postharvest storage life of grape: Measuring the changes in nutritional, antioxidant and phenolic compounds," *Journal of Food Measurement and Characterization*, vol. 16, no. 2, pp. 1159–1170, 2022, doi: [10.1007/s11694-021-01275-0](https://doi.org/10.1007/s11694-021-01275-0).
- [98] K. Liu, C. Yuan, Y. Chen, H. Li, and J. Liu, "Combined effects of ascorbic acid and chitosan on the quality maintenance and shelf life of plums," *Scientia Horticulturae*, vol. 176, pp. 45–53, 2014, doi: [10.1016/j.scienta.2014.06.027](https://doi.org/10.1016/j.scienta.2014.06.027).
- [99] R. G. Cruz-Monterrosa, A. A. Rayas-Amor, R. M. González-Reza, M. L. Zambrano-Zaragoza, J. E. Aguilar-Toalá, and A. M. Liceaga, "Application of polysaccharide-based edible coatings on fruits and vegetables: Improvement of food quality and bioactivities," *Polysaccharides*, vol. 4, no. 2, pp. 99–115, 2023, doi: [10.3390/polysaccharides4020008](https://doi.org/10.3390/polysaccharides4020008).
- [100] H. Paluzar, S. Mutlu, A. S. Yilmaz, and S. S. Isbilir, "Pomegranate peel extract as a bioactive inhibitor of polyphenol oxidase: a green alternative for extending fresh-cut produce preservation," *Journal of the Science of Food and Agriculture*, vol. 106, no. 2, pp. 870–883, 2026, doi: [10.1002/jsfa.70211Digital](https://doi.org/10.1002/jsfa.70211Digital).
- [101] M. Mohammadi, S. Rastegar, and A. Rohani, "Enhancing Mexican lime (*Citrus aurantifolia* cv.) shelf life with innovative edible coatings: xanthan gum edible coating enriched with *Spirulina platensis*," *BMC Plant Biology*, vol. 24, no. 1, 2024, doi: [10.1186/s12870-024-05606-3](https://doi.org/10.1186/s12870-024-05606-3).
- [102] K. Das and A. Roychoudhury, "Reactive oxygen species (ROS) and response of antioxidants as ROS-scavengers during environmental stress in plants," *Frontiers in Environmental Science*, vol. 2, p. 53, 2014, doi: [10.3389/fenvs.2014.00053](https://doi.org/10.3389/fenvs.2014.00053).
- [103] L. Zhang, S. Zhao, S. Lai, F. Chen, and H. Yang, "Combined effects of ultrasound and calcium on the chelate-soluble pectin and quality of strawberries during storage," *Carbohydrate Polymers*, vol. 200, pp. 427–435, 2018, doi: [10.1016/j.carbpol.2018.08.013](https://doi.org/10.1016/j.carbpol.2018.08.013).
- [104] S. Rastegar, H. Hassanzadeh Khankahdani, and M. Rahimzadeh, "Effectiveness of alginate coating on antioxidant enzymes and biochemical changes during storage of mango fruit," *Journal of Food Biochemistry*, vol. 43, no. 11, p. e12990, 2019, doi: [10.1111/jfbc.12990](https://doi.org/10.1111/jfbc.12990).
- [105] P. Ahlawat and A. Kumari, "Physicochemical alterations in fruits caused by edible coatings during storage: A Review," *Agricultural Reviews*, vol. 46, pp. 693–702, 2025, doi: [10.18805/ag.R-2641](https://doi.org/10.18805/ag.R-2641).
- [106] B. Maringgal, N. Hashim, I. S. Mohamed Amin Tawakkal, and M. T. Muda Mohamed, "Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality," *Trends in Food Science & Technology*, vol. 96, pp. 253–267, 2020, doi: [10.1016/j.tifs.2019.12.024](https://doi.org/10.1016/j.tifs.2019.12.024).
- [107] N. K. Alqahtani, T. M. Alnemr, and S. A. Ali, "Effects of pomegranate peel extract and/or lactic acid as natural preservatives on physicochemical, microbiological properties, antioxidant activity, and storage stability of khalal barhi date fruits," *Foods*, vol. 12, no. 6, p. 1160, 2023, doi: [10.3390/foods12061160](https://doi.org/10.3390/foods12061160).

- [108] M. S. Saleem, S. Ejaz, M. A. Anjum, S. Ali, S. Hussain, S. Ercisli, G. Ilhan, R. A. Marc, and S. Skrovankova, "Improvement of postharvest quality and bioactive compounds content of persimmon fruits after hydrocolloid-based edible coating application," *Horticulturae*, vol. 8, no. 11, p. 1045, 2022, doi: [10.3390/horticulturae8111045](https://doi.org/10.3390/horticulturae8111045).
- [109] S. Panahirad, R. Naghshiband-Hassani, and N. Mahna, "Pectin-based edible coating preserves antioxidative capacity of plum fruit during shelf life," *Food Science and Technology International*, vol. 26, no. 7, pp. 583–592, 2020, doi: [10.1177/1082013220916559](https://doi.org/10.1177/1082013220916559).
- [110] S. Ngubane, S. Z. Tesfay, L. S. Magwaza, and A. Mditshwa, "The effect of composite edible coatings on the postharvest quality of 'Hass' avocado fruit treated at different harvest maturities," *Frontiers in Sustainable Food Systems*, vol. 8, p. 1473731, 2024, doi: [10.3389/fsufs.2024.1473731](https://doi.org/10.3389/fsufs.2024.1473731).
- [111] M. M. Rob, M. M. H. Pappu, M. S. Arifin, T. N. Era, M. Z. Akhi, D. K. Bhattacharjya, and M. S. Kayshar, "Application and evaluation of plant-based edible active coatings to enhance the shelf-life and quality attributes of Jara lebu (*Citrus medica*)," *Discover Food*, vol. 4, no. 1, p. 26, 2024, doi: [10.1007/s44187-024-00094-8](https://doi.org/10.1007/s44187-024-00094-8).