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Innovative Layer-by-Layer Edible Biopolymer Coatings to Optimize Storage Performance and Maintain Postharvest Quality of 'Barhi' Dates

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Abstract

'Barhi' dates (*Phoenix dactylifera* L.) are highly prized and widely consumed at the khalal stage, but they are only available for a short time, which highlights the importance of extending their storage life. This study examined the effectiveness of edible coatings in delaying ripening and maintaining fruit quality during cold storage (2 °C). The treatments tested were gelatin alone or gelatin combined with chitosan, Aloe vera gel (AVG), or gum arabic, and applied in a layer-by-layer (LbL) approach. A fifth treatment consisting of deionized water was used as a reference untreated control. The fruit parameters measured included weight loss, decay, moisture content, ripening (rutab transformation), firmness, color (lightness and hue angle), total soluble solids (TSS), titratable acidity (TA), TSS/TA ratio, total sugars, total polyphenols, and enzymatic activity. Results indicated that the LbL edible coating was more effective in preserving postharvest quality. Regarding weight loss and decay rate, the results showed that the control treatment consistently had 1.5–5-fold higher deterioration indicators than the coated fruits. Among the tested treatments, the gum arabic and gelatin coating was the most effective compared to the untreated control, reducing weight loss by over 40%, lowering decay by approximately 80%, and maintaining significantly higher moisture content throughout storage. Concerning carotenoid levels, the untreated fruits exhibited approximately 1.2–1.4-fold higher carotenoid content than the coated fruits. Fruits treated with gum arabic and gelatin exhibited the best preservation effect Sby limiting TSS increase and maintaining higher TA compared with the control. This treatment best maintained antioxidant capacity and phenolic content while significantly

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suppressing the activities of polyphenol oxidase and peroxidase. Overall, the LbL coating strategy successfully maintained the quality of 'Barhi' dates by mitigating oxidative and enzymatic degradation throughout storage. Principal component analysis and hierarchical cluster analysis demonstrated that treatments gum arabic and gelatin exhibited superior effectiveness in extending the date storage life in terms of physicochemical properties and antioxidant activity, followed by chitosan and gelatin, and Aloe vera and gelatin, compared to the control fruits over a 60-day storage period.

Keywords: 'Barhi' dates; khalal stage; layer-by-layer coating; chitosan; *Aloe vera*; gum arabic; cold storage; decay

1. Introduction

The date palm (*Phoenix dactylifera*) is an ancient, cultivated tree in Middle Eastern countries, with its fruit considered a major staple food for many people [1,2]. In the Arab culture, dates are important in religious rituals and cherished for their energy and nutrient contents [3]. Dates are also becoming more popular and well-known throughout the world. Their derivatives are especially valued for their high levels of dietary fiber and phenolic compounds [4]. Egypt was the world's top date producer in 2021, accounting for almost 18% of the world's total. Despite that, Egypt exports less than 3% of the world's dates [5,6].

To reach full maturity, the date palm fruit goes through five stages: hababouk, kimri, khalal, rutab, and tamr [7,8]. During the khalal stage, the color of the date fruit changes from green to greenish-yellow, yellow, pink, scarlet, or red, depending on the type of date fruit [9]. Consumers prefer dates during the khalal maturity stage (the first edible color stage), especially for the 'Barhi' variety, hence their storability needs to be extended [10]. Fruits can benefit from edible coatings created from natural biopolymers, which are safer than synthetic materials [11,12]. Studies indicate that edible coatings may decrease the rate of weight loss, oxidative reactions, and physiological problems in fruits, consequently extending their storability [13–15] and improving the quality of climacteric fruits [1]. Chitosan [1,13], Aloe vera extracts [16–18], gum arabic [19], and gelatin [20,21] are some natural edible coating materials.

Chitosan is a natural biopolymer derived from the deacetylation of chitin, which is found in crustaceans, insects, and certain fungi [22]. Chitosan can be used in farming and the food industry thanks to its antimicrobial effects [23]. Its antifungal activities are mostly linked to the impairment of fungal plasma membranes. It may inhibit the development of foodborne pathogens and stimulate host tissue resistance response, positioning chitosan as a possible alternative treatment for fruits [13,24]. Chitosan has been effectively utilized in the covering of fruits, including dates [1,10], guava (*Psidium guajava* L.) [13], plum (*Prunus salicina* L.) [14], and Japanese pear (*Pyrus pyrifolia* (Burm.f.) Nak.) [15]. Aloe vera is a short-stemmed succulent from the Asphodelaceae (Liliaceae) that grows in dry areas [16]. Numerous in vitro and in vivo investigations demonstrate *Aloe vera*'s antifungal efficacy, alongside reduced respiration rates and microbiological degradation [25]. Aloe vera gel (AVG) has been gaining popularity for postharvest treatment of fruits and vegetables. AVG-based coatings reduce moisture loss and maintain quality during storage after harvest [25]. Gum arabic is a biopolymer extracted from the branches and stems of Acacia trees (*Acacia* spp.). It is a safe and cheap food ingredient because it can create films, emulsify, and encapsulate food items [26]. Gelatin is an animal protein that comes from collagen that has been partially broken down in water [27].

Using the layer-by-layer (LbL) technique, edible coating technology, which consists of invisible membranes, can enhance the storage life of fruit by applying it directly to the surface. This has shown positive results compared with formulations or individual coatings [28]. Researchers have effectively combined gelatin with other composite edible coatings, such as chitosan [28,29], gum arabic [20,30,31], and Aloe vera [32,33]. This technique has been assessed for the conservation of fresh fruit. Ahmed et al. [27] showed that combining chitosan with gelatin-based films made for biodegradable packaging makes edible films work better. Moreira Pereira et al. [28] conducted a study demonstrating that the preservation of 'Pedro Sato' guavas at ambient temperature is enhanced with the application of chitosan and gelatin coatings, either separately or via the LbL method. The LbL coating showed the best results for lipid oxidation, weight loss mitigation, color and firmness preservation, and promotion of catalase enzyme activity. Another study by Sui Chin et al. [34] investigated the utilization of fish gelatin and AVG in the fabrication of composite films. They indicated that the moisture content of the films, utilizing gelatin and AVG, was directly correlated to the concentration of AVG, while the films' water solubility and tensile strength decreased with increased AVG concentration. However, the film thickness, color, and capacity to let water vapor through stayed the same. The composite films exhibited smooth surface microstructures similar to those of non-composite gelatin films when examined under a scanning electron microscope. Sánchez et al. [33] found that adding AVG to gelatin could be a good way to improve the quality of packed fruits and vegetables after they are picked by stopping the growth of bacteria, thus extending the storage life of these foods. Adnan Abd et al. [35] found that a mixture of gum arabic and gelatin can keep fruits fresh for a long time because the film protects the food from microbes and the environment. The film has edible ingredients that create a barrier against gas, oxygen, and moisture. Recent work has highlighted the potential of LbL coatings, in which a protein inner layer provides adhesion and structural support, and a polysaccharide outer layer supplies additional barrier and bioactive functions [36,37]. Gelatin can form cohesive inner films, whereas chitosan, gum arabic and AVG contribute antimicrobial, antioxidant, and moisture-control properties when incorporated into outer layers [38,39]. Studies on gelatin–chitosan, chitosan–polysaccharide and AVG–chitosan systems report maintained firmness retention, reduced weight loss, and extended storage life in various fruits, pointing to the promise of gelatin-based double-layer coatings as sustainable packaging solutions [40,41]. Still, few studies compared the effects of natural edible coatings such as chitosan, gum arabic, AVG, and gelatin applied in single or double layers on 'Barhi' dates, despite the diverse formulations reported in the literature. This study seeks to evaluate the impact of edible coating combinations on the storage life, storability, and quality of 'Barhi' dates as postharvest interventions.

2. Materials and Methods

This research was conducted during the 2024 and 2025 seasons, using 'Barhi' dates collected from the experimental orchard at Benha University, Egypt. Fruits were picked by hand at the khalal stage, which is when they were physiologically mature and had a firm, crisp texture and full color [42]. Post-harvest, the dates were meticulously categorized to ensure consistency in size and hue, and all specimens exhibiting physical damage, flaws, or signs of decay were removed. A representative 4.5 kg sample was designated for initial quality assessment on day 0, and divided into three replicates of 1.5 kg each. Before treatment, all fruits were rinsed three times with deionized water to remove surface contaminants and reduce microbial burden. The fruits were subsequently dried using sterile cotton cloths and permitted to air-dry at ambient laboratory temperature (20 ± 2 °C, 65 ± 5%RH) for approximately 30 min. A total of 90 kg of fruit was utilized for the cold storage experiment.

2.1. Coating Preparation

Twenty grams of chitosan (Sigma-Aldrich, St. Louis, MO, USA) were mixed with 100 mL of a water-based solution of glacial acetic acid (1% v/v). The mixture was then gently stirred for an hour at 40 °C using a magnetic agitator. We used a digital pH meter (Model: AD1000, Bucharest, Romania) to change the pH to 5.7–6.0 using 1 M NaOH. The plasticizer was a mix of 0.75 mL/g glycerol, and the emulsifier was 0.2% Tween 80. After being filtered via Whatman No. 1 filter paper (Whatman, Maidstone, UK), the solution was autoclaved at 121 °C for 15 min [43]. Gum arabic powder was used to make a food-grade coating by dissolving 500 g of gum arabic in 5 L of deionized water to get a 10% gum arabic solution. The solution was stirred for an hour at 40 °C and then filtered to remove any contaminants. Glycerol was added to the coating to make it more flexible and stronger. The solution pH was adjusted to 6 using 1 N NaOH measured with a digital pH meter [19]. Aloe vera was extracted from plants grown at a nearby nursery and subsequently submerged in a chlorine solution for one minute. Then, the leaves were cut into bits, chopped in a mixer, and refined to remove the fibrous components. The extract was diluted with deionized water to make a 10% solution, sterilized at 65 °C for 30 min, and then stored at 4 °C until it was needed for the tests [18]. A 4% gelatin solution was prepared in deionized water, then mixed on a hot plate at 60 °C for 30 min, and a 1 N NaOH solution was used to adjust the solution pH to 6 using a digital pH meter. Then, the solution was added to glycerol at a 1% concentration [29].

2.2. Treatments

The fruits were categorized into five treatment groups and assessed across four storage durations. The experiment was conducted using a completely randomized design. Each coating treatment and storage time combination had three replicates, each consisting of a cardboard box containing 1.5 kg of fruit (~75 dates per box, depending on individual date size). The coating procedures involved soaking the dates for three minutes in one of the following solutions:

- T1: 4% gelatin
- T2: 2% chitosan followed by 4% gelatin;
- T3: 10% AVG followed by 4% gelatin;
- T4: 10% gum arabic followed by 4% gelatin; and
- T5: deionized water, which functioned as the untreated control.

The characterization of these materials is shown in Table 1. In the LbL treatments (T2–T4), the fruits were dipped first in the main polymer solution and then in the gelatin solution to form a second layer. The control treatment dates were immersed for three minutes in deionized water. Coating application was performed by individual manual immersion of fruits in the respective coating solutions for three minutes under gentle agitation to ensure complete surface coverage. The coating solutions were continuously stirred during application to maintain homogeneity. After immersion, fruits were removed and allowed to drain for two minutes to eliminate excess coating, then left to air-dry at ambient temperature. Care was taken to avoid fruit-to-fruit contact during drying to ensure uniform coating formation. Each replicate was subsequently divided into two experimental subsets: one used for the assessment of physical attributes, and the other for chemical analyses. fruits were quickly and carefully arranged in perforated cardboard boxes (20 cm × 20 cm × 10 cm) assigned to each replicate to ensure adequate ventilation and maintain consistent handling throughout the postharvest evaluation period. All the treated and control fruits were kept at 2 °C and 90–95% relative humidity. After treatment, the main quality traits of the dates were determined at 15-day intervals: 0, 15, 30, 45, and 60 days. The methodology scheme is presented in Figure 1.

Table 1. Characterization of the different materials used in this study (data adapted from [44–47]).

Parameter	Gelatin (4%)	Chitosan (2%)	Aloe Vera Gel (10%)	Gum Arabic (10%)
Tensile strength (MPa)	20	15	19	8
Viscosity (cP)	500	800	600	900
Specific gravity (g cm^{-3})	1.02	1.01	1.02	1.05
Surface cohesion (MPa)	~20	15	19	8
Coating thickness (μm)	60	50	100	70
Water vapor permeability (g m^{-1} s^{-1} Pa^{-1})	1.0×10^{-10}	8.0×10^{-11}	7.0×10^{-11}	1.2×10^{-10}

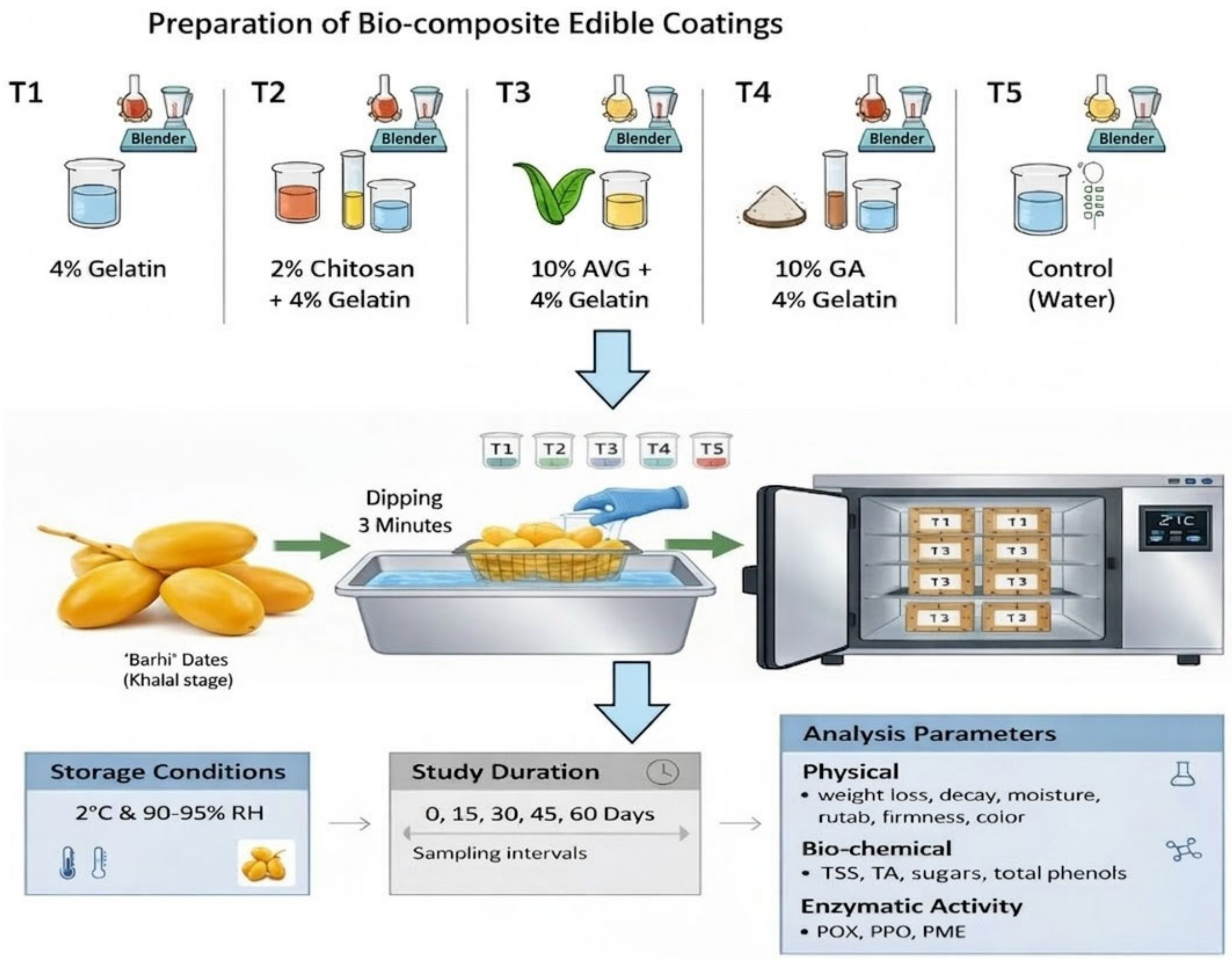


Figure 1. Schematic illustration of the experimental procedures.

2.3. Data Collection and Measurements

2.3.1. Physical Characteristics

After storage, the dates were allowed to equilibrate to ~20 °C before analyses were carried out. Weight loss was calculated for each replicate (box) as follows:

$$\text{Weight Loss (\%)} = \{(\text{Initial fruits weight} - \text{Weight at inspect date})/\text{Initial fruits weight}\} \times 100 \quad (1)$$

Fruit storage stopped when the decay rate reached 25% in the stored fruit. Decay was determined at the replicate (box) level using the following equation:

$$\text{Decay (\%)} = [(\text{Weight of removed fruits/preliminary weight}) \times 100] \quad (2)$$

Fruit moisture content was determined on fifteen dates per replicate of each storage period, by passage in a forced air oven set at 70 °C until constant weight was reached. The following calculation is used to find the moisture content:

$$\text{Moisture content (\%)} = [(\text{Initial weight} - \text{Weight after drying})/\text{Initial weight} \times 100] \quad (3)$$

The fruits were counted every time to determine the rutab percentage. Fruits that showed softening on around 10% of their surface area (visual determination) were called rutab/ripe [48]. The data were displayed as a percentage of the starting storage value.

$$\text{Rutab (\%)} = [(\text{Number of rutab fruits/Initial number of fruits at the start of storage}) \times 100] \quad (4)$$

The firmness of ten dates per replicate of each storage period was determined at two equatorial locations using a hand-held fruit firmness tester (FT-327, Rome, Italy) with an 8 mm cylindrical stainless-steel "plunger" tip [1]. After peeling, two measurements were taken on the flesh of each fruit, and the findings were given in Newton (N). The color of ten dates of each storage period was measured on two opposite sides at the equator using hue angles (°h = $\tan^{-1}$ (b*/a*)) based on the color wheel. The numbers "180," "90," and "0" correspond to green, yellow, and red, respectively. A colorimeter (Model CR-400; Konica Minolta, Tokyo, Japan) was used to measure color lightness (L*) coordinates, which range from 0 for "black" to 100 for "white." Two coordinates define the hue angle: the red/green coordinate (a*), where +a* means red and −a* means green, and the yellow/blue coordinate (b*), where +b* means yellow and −b* means blue [49].

2.3.2. Chemical Characteristics

Chemical characteristics were measured on fifteen dates per replicate at each storage period. The total soluble solids (TSS) percentage of the fruit was measured during storage using a Bellingham & Stanley digital refractometer Model: RFM 340-T. The titratable acidity (TA) percentage was measured by determining the concentration of citric acid with automated titration equipment (TitroLine, TL 5000, SI Analytics, Weinheim, Germany) [50]. Five grams of fruit tissue were homogenized with oxalic acid solution (6%, *w*/*v*) and subjected to centrifugation at 15,000× *g* at 4 °C for 10 min. The supernatant was collected and used to measure the amount of ascorbic acid (V.C.) by oxidizing V.C. with 2,6-dichlorophenol endophenol dye. The results were given as mg/100 g fresh weight (fw) [50]. The Nelson arsenate-molybdate colorimetric approach [51] was used to measure total sugars, and the dinitrosalicylic acid test [52] to measure reducing sugars. The difference between total sugars and reducing sugars represents the amount of non-reducing sugars. The assay by Kähkönen et al. [53] was used to determine the total phenol compounds (g/100 g fw). The assay of Taira and Ono [54] was used to find total tannins (g/100 g fw). Chlorophyll and carotenoid contents in the fruit peel were assessed using the method described by Wellburn [55]. The optical density of the extract was measured using a UV/visible spectrophotometer (Libra SS0PC, Thermo Fisher Scientific, Waltham, MA, USA) at 663 nm for chlorophyll a, 646 nm for chlorophyll b, and 470 nm for carotenoids. The formulae below were used to determine pigment contents in the sample:

$$\text{Total chlorophyll } (\mu\text{g/mL}) = [(12.21\,E663 - 2.81\,E646) + (20.13\,E646 - 2.81\,E663)] \quad (5)$$

$$\text{Total carotenoids } (\mu\text{g/mL}) = [(1000\,E470) - ((3.27 \times (12.21\,E663 - 2.81\,E646) + 104 \times (20.13\,E646 - 2.81\,E663))/198] \quad (6)$$

E is the absorbance at the given spectrum length, and the results were given in mg/100 g of fresh weight (fw) as follows: [Resulting value from each equation × volume extract/(1000 × fw) × 100].

Enzymatic activity was measured on five dates per replicate (box) of each storage period. Frozen pulp was placed in a porcelain mortar, and then liquid nitrogen was added to release the enzymes. After that, the pulp was pounded hard until it was entirely broken down. A gram of the powdered material was placed into a microtube with 2 mL of phosphate buffer (pH 7.6). The mixture was then vortexed and spun at 14,000 rpm for 15 min at 4 °C. After centrifugation, extract samples were taken [56]. The total soluble enzyme activity in the supernatant of each homogenate was measured using a spectrophotometer (UV-160A, Shimadzu, Kyoto, Japan). Peroxidase (POX) activity was measured following the protocol outlined in Hammerschmidt et al. [57]. Pectin methylesterase (PME) activity was assessed according to the methodology established by Hagerman and Austin [58]. Polyphenol oxidase (PPO) activity was evaluated according to the guidelines set forth by Gregory and Bendall [59].

2.4. Cost–Benefit Index and Net Profit Percentage Estimation

Cost–benefit index and net profit percentage were calculated for each coating treatment to provide a concise and practical assessment of its feasibility. The composite index integrates the overall quality performance of the fruits with the associated treatment cost and preparation complexity [60]. The cost–benefit index for treatment was calculated using the following formula:

$$\mathrm{CBIi} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\mathrm{Xij}}{\mathrm{Xj,control}}\right)/\left(\frac{\mathrm{Si}+\mathrm{Ci}}{\mathrm{S,control}+\mathrm{C,control}}\right) \tag{7}$$

where i is treatment, j is attribute, n is number of measured attributes, X is value of attribute, S is storage cost and C = cost of materials. After that, net profit percentage was calculated as follows:

$$\text{Net profit\%} = \left(\frac{\text{control} - \text{CCBi}}{\text{control}}\right) \times 100 \tag{8}$$

2.5. Statistical Analysis

Shapiro–Wilk's and Levene's tests were used to check for numerical normality and homogeneity of variance. CoStat software version 6.303 (Monterey, CA, USA) was used to analyze the data according to a two-way ANOVA test to detect significant factor effects for coating treatments and storage periods [61]. The preliminary analysis indicated no significant differences between the two seasons for any parameters; hence, data from both seasons were combined to comprehensively assess treatment effects. Post hoc comparisons were conducted utilizing Tukey's honestly significant difference (HSD) test at a significance level of $p \leq 0.05$. We used a principal component analysis (PCA) [62] to make the score and loading plot for vegetative growth and biochemical parameters. We used the means of the data matrices [63] to make the two-way hierarchical cluster analysis (HCA) and heat map. JMP Pro 16 (SAS Institute, Cary, NC, USA) was used to perform PCA, HCA, and correlations.

3. Results

3.1. Weight Loss, Decay, and Moisture Content

All of the coating treatments kept the fruit's quality much better than the untreated fruit when it came to weight loss, deterioration, and moisture content (Figure 2). Also, the total weight loss and decay percentages went up slowly over time while they were being stored. The results showed that T4 (10% gum arabic followed by 4% gelatin) had the lowest weight loss and decay at the end of the storage period (on the 60th day). T5 (control) had the highest weight loss and decay (Figure 2A,B). The remaining coating treatments (T1–T3) resulted in intermediate weight loss and decay levels, significantly lower than the control but higher than T4. The amount of moisture in fruit plays an important role in its quality. As time passed, the moisture content dropped considerably (Figure 2C). T4 dates (gum arabic followed by gelatin) lost the least moisture compared to other treated and untreated fruits. The untreated fruits lost significantly more moisture than the treated ones.

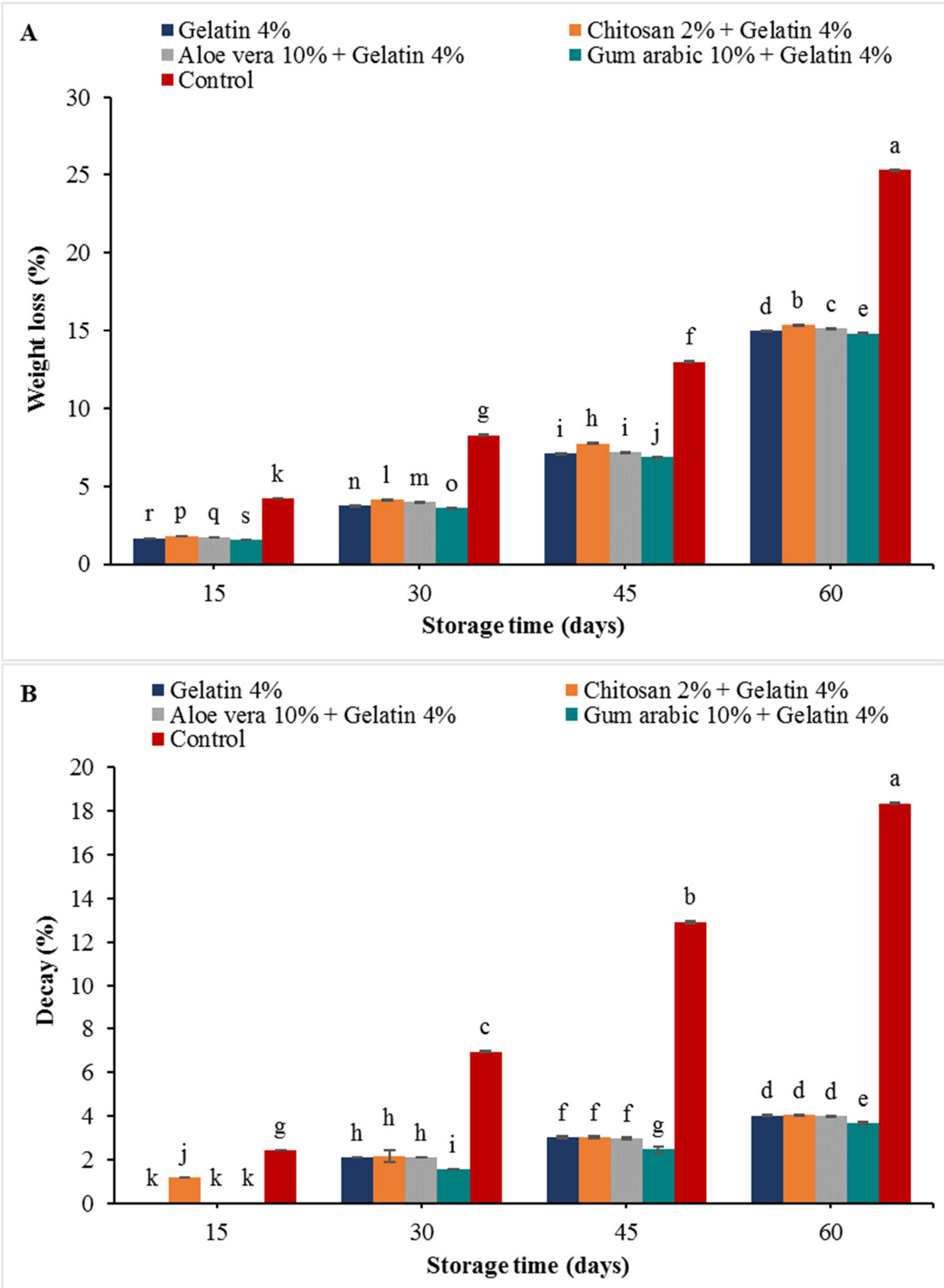


Figure 2. *Cont.*

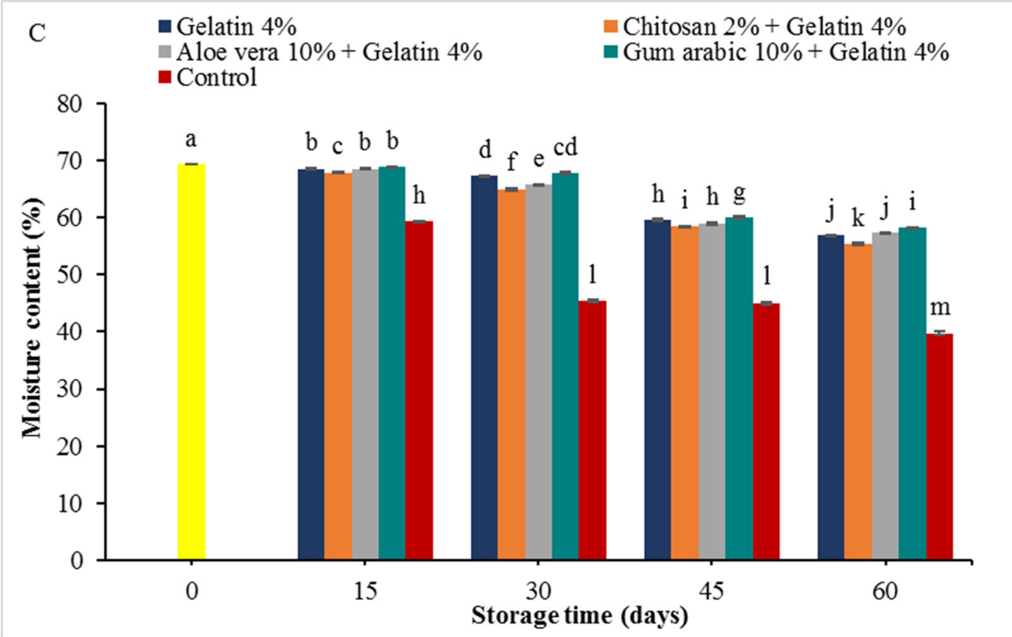


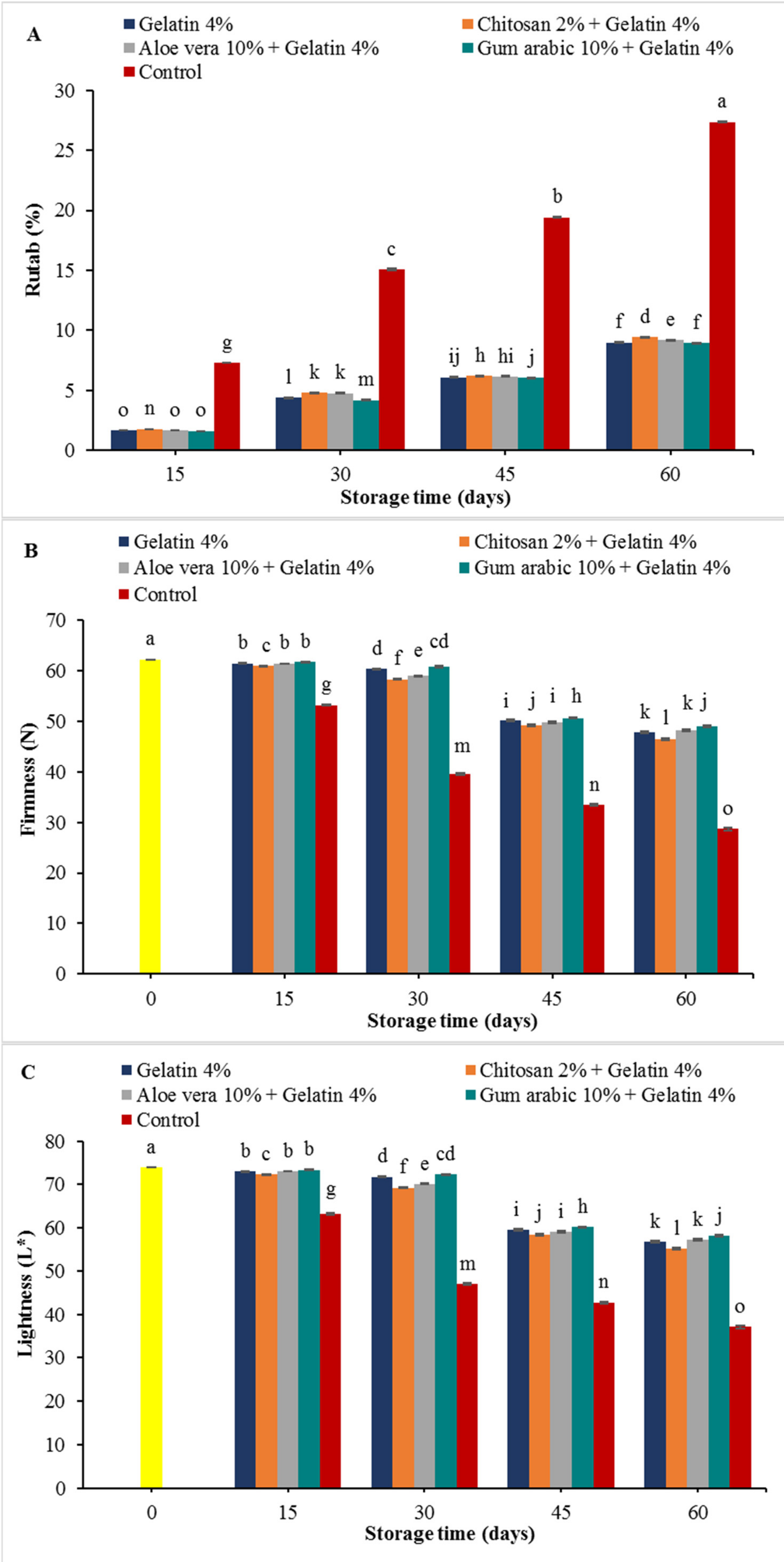
Figure 2. Effects of coating treatments on weight loss (**A**), decay% (**B**), and moisture content% (**C**) of 'Barhi' dates for 60 days cold storage at 2 °C. Yellow bar chart refers to the values of estimated parameters at the experimental beginning(the same as Figures 2–7). Values represent the mean ± SE for three replications. Different letters indicate significant differences among treatments, according to Tukey's HSD test at $p \leq 0.05$.

3.2. Rutab Percentage, Firmness, and Color

In terms of how coating treatments affected the rutab %, the coated fruits showed a slow rate of decay during storage (Figure 3A). After 60 days of cold storage, there were big differences between treatments in how much they raised the rutab %. The T4 had the lowest amount of rutab (Figure 3A). As the storage time got longer, the fruit became softer (Figure 3B). The T4 treatment also showed higher stiffness values during the storage times. The lower value, on the other hand, was linked to the control treatment. Significant differences in color between the treated and control dates were detected, leading to differences in brightness "L*" and hue angle (h°) (Figure 3C,D). As the storage period extended, the color values dropped in all the fruits, but the drop rate was much lower in the coated dates. At day 60, the dates treated with gum arabic + gelatin and Aloe vera + gelatin showed the least change in lightness and color compared to the other treatments and the control.

3.3. Total Soluble Solids, Titratable Acidity, TSS/TA Ratio, and Ascorbic Acid

Increasing the time in cold storage raised the dates' TSS concentration (Figure 4A). There were significant differences between the TSS of coated fruits and the control group for the entire storage period. After 15 and 60 days, the control treatment had higher levels of TSS content (34.9% and 36.9%, respectively), but there were no significant differences between the coating treatments. Titratable acidity dropped with time for all treatments. It was significantly higher in treated dates than in the untreated control (Figure 4B). The TSS/TA ratio increased with storage time, especially for the untreated control followed by Treatment T2 (chitosan 2% + gelatin 4%) (Figure 4C). This parameter was slightly changed by the other treatments. There was a steady drop in ascorbic acid concentration over the 60-day storage period, especially in the control treatment (Figure 4D). There were slight, albeit significant, differences between the coating treatments, with the gum arabic + gelatin treatment generally presenting higher values than all other treatments.



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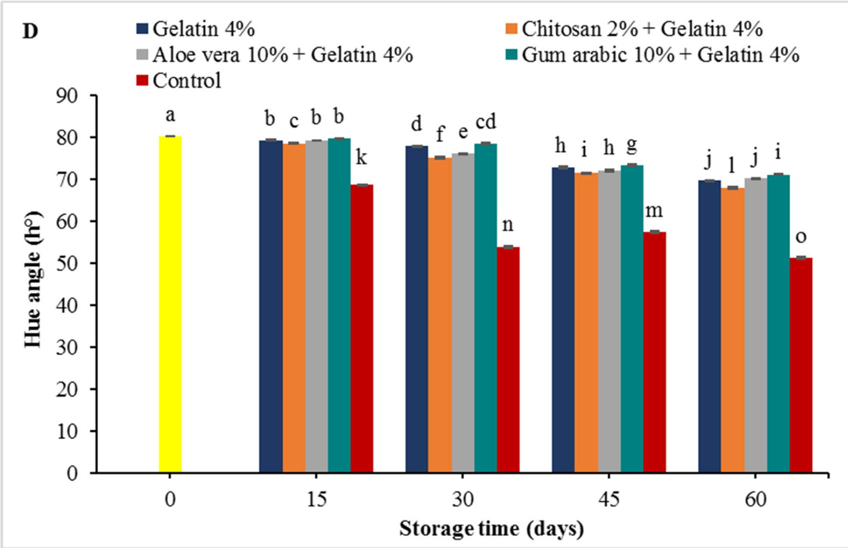
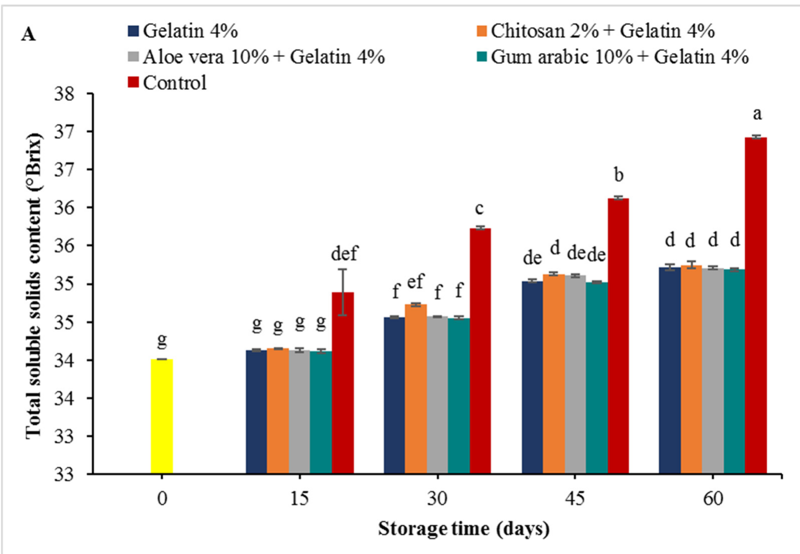


Figure 3. Effects of coating treatments on rutab percentage (**A**), firmness (**B**), lightness (**C**) and hue angle (**D**) of 'Barhi' dates for 60 days cold storage at 2 °C. Values represent the mean ± SD for three replications. Different letters indicate significant differences among treatments, according to Tukey's HSD test at $p \leq 0.05$.

3.4. Total Sugars, Reducing Sugars, and Non-Reducing Sugars

The percentages of total sugars, reducing sugars, and non-reducing sugars all followed the same trend as TSS (Figure 5). The total sugars in the fruits go up till the end of the storage period when they are kept cold. The highest mean total sugars (32.0 and 34.9%) were found in the control group after 15 and 60 days of storage. Other treatments had a big effect on the amount of sugar in fruits. After 60 days of storage, T5 (control) had the most decreasing sugar. The T3 treatment (Aloe vera followed by gelatin) after 60 days of storage had the lowest amount of non-reducing sugar.



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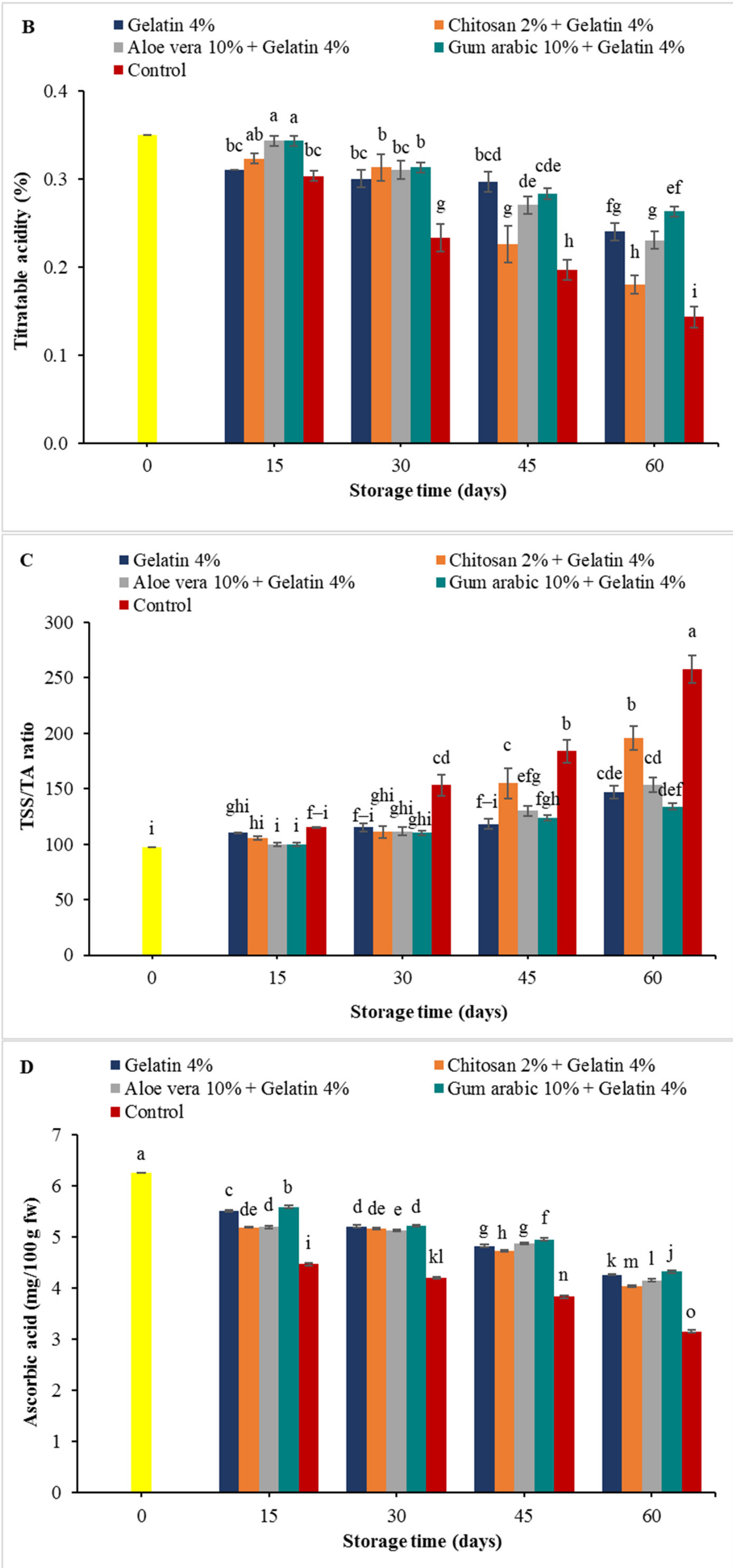

Figure 4. Effects of coating treatments on total soluble solids (**A**), titratable acidity (**B**), TSS/TA ratio (**C**), and ascorbic acid (**D**) of 'Barhi' dates for 60 days cold storage at 2 °C. Values represent the mean ± SD for three replications. Different letters indicate significant differences among treatments, according to Tukey's HSD test at $p \leq 0.05$.

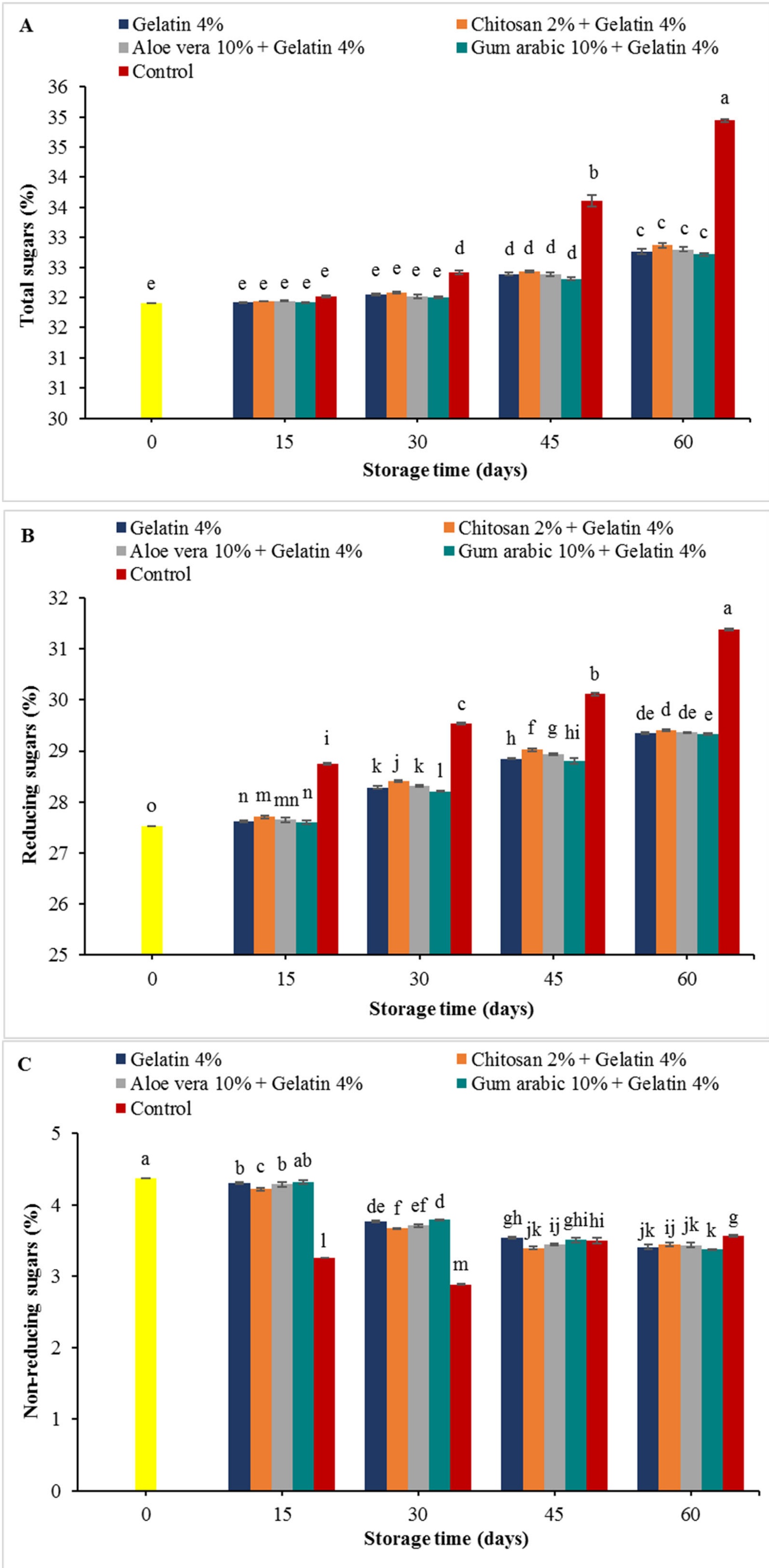

Figure 5. Effects of coating treatments on total sugars% (**A**), reducing sugars% (**B**), and non-reducing sugars% (**C**) of 'Barhi' dates for 60 days cold storage at 2 °C. Values represent the mean ± SD for three replications. Different letters indicate significant differences among treatments, according to Tukey's HSD test at $p \leq 0.05$.

3.5. Total Phenols, Total Tannins, Total Chlorophyll, and Total Carotenoids

Coating significantly affected total phenols and total tannins, which are two important quality criteria (Figure 6A,B). Over the whole storage period, each of these characteristics decreased. The highest amounts of total phenols and tannins were found when the fruit was covered with T4 (gum arabic and gelatin). The untreated control group had the lowest levels of total phenolics and total tannins during storage. After that, treatments had the same effect on these levels in fruits. Total chlorophyll dropped over time and was statistically lower in the control treatment at all storage durations. All other treatments were statistically similar at any storage time (Figure 6C). After 60 days of storage, total carotenoids in untreated fruits went up slowly and then leveled off (Figure 6D). However, there was a small drop in total carotenoids that was linked to the breakdown of total chlorophyll for the entire storage period. This happened in fruit-treated gum arabic and gelatin (T4). The rise in total carotenoids in the control dates indicates that these fruits ripened sooner than the coated fruits (Figure 6C,D).

3.6. Enzyme Activities

Peroxidase activity gradually increased over time in all treatments, especially in the control treatment (Figure 7A). Any fruit coating treatment decreased POX activity compared to the control, with the difference between coated treatments and the control increasing over time. The differences between coating materials were mostly insignificant. When it comes to PPO activity, all of the treatments and the control tend to increase over time (Figure 7B). The control has the fastest PPO, which reaches 1.13 after 60 days, which is higher than all the other samples that were treated. After 60 days, chitosan + gelatin showed the greatest values among the treated fruits, while Aloe vera + gelatin came second. The treatment with gum arabic and gelatin consistently had the lowest numbers among coated treatments, and was still much lower than the control treatment. The LbL edible coating treatment greatly reduced PME activity. The best way to keep it from rising over time was to use chitosan and gelatin together (Figure 7C). Aloe vera + gelatin is better than gum arabic + gelatin, which seems to be the least effective. The quick rise in the control group shows that the treatments help keep the measured parameter stable.

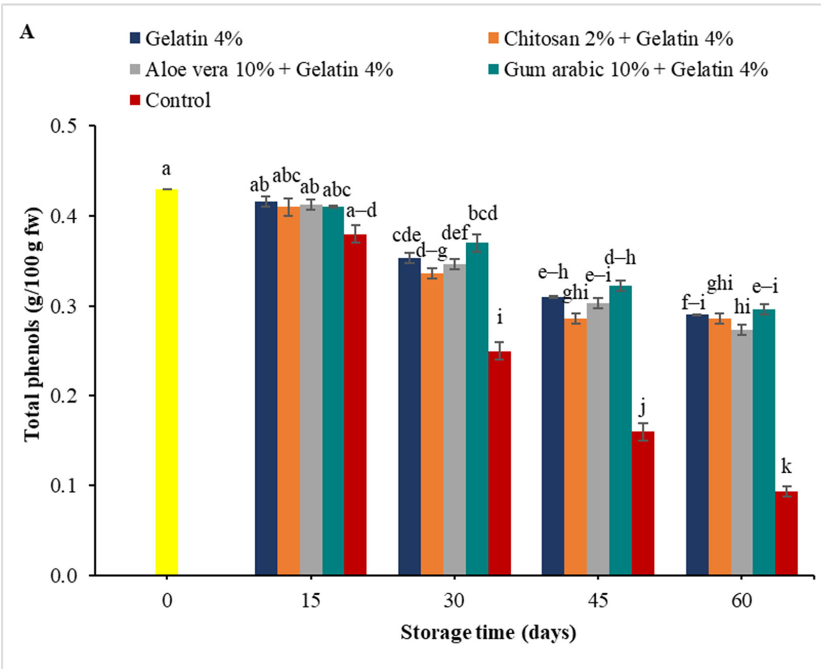

Figure 6. *Cont.*

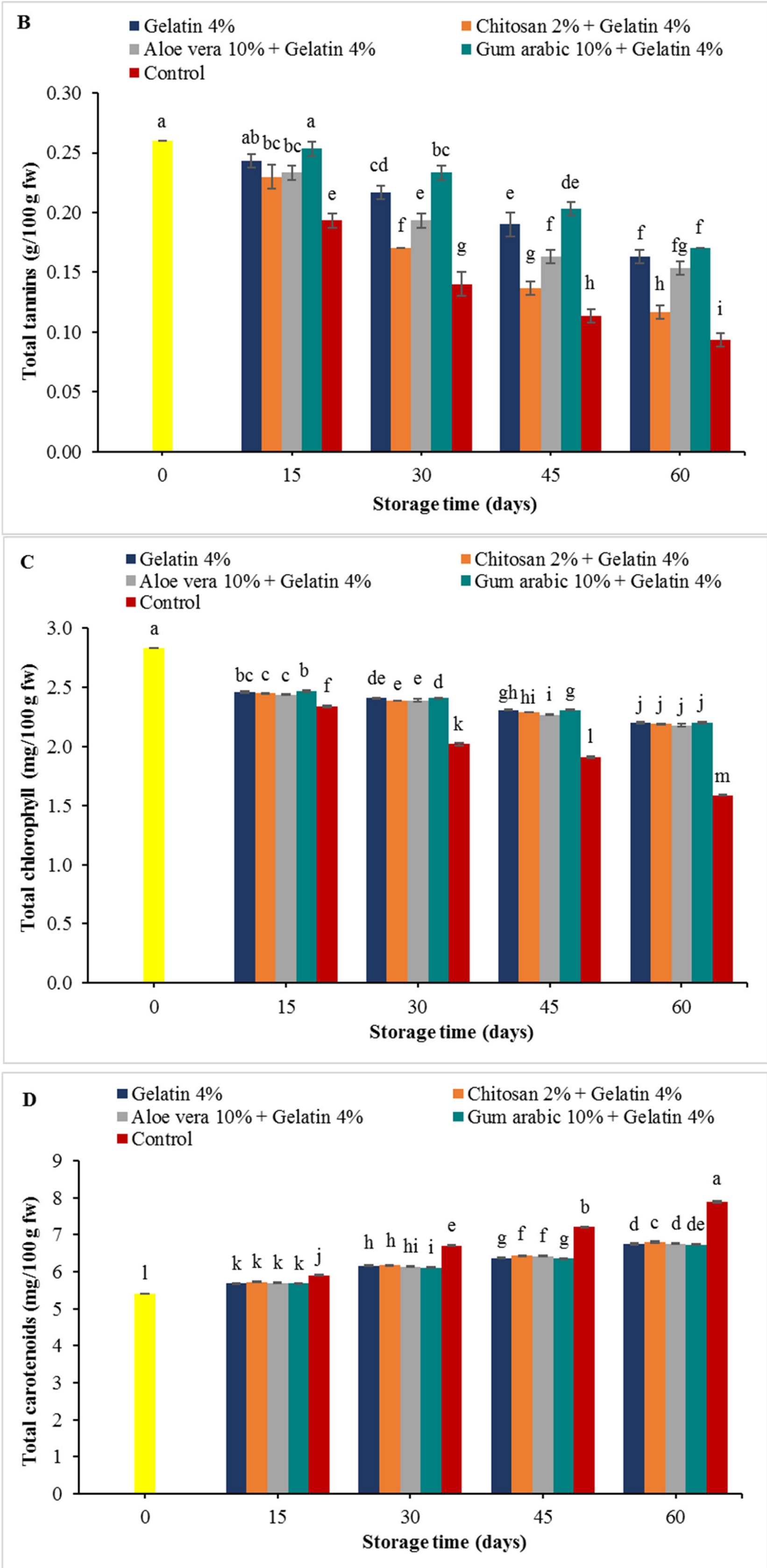

Figure 6. Effects of coating treatments on total phenols (**A**), total tannins (**B**), total chlorophyll (**C**), and total carotenoids (**D**) of 'Barhi' dates for 60 days cold storage at 2 °C. Values represent the mean ± SD for three replications. Different letters indicate significant differences among treatments, according to Tukey's HSD test at $p \leq 0.05$.

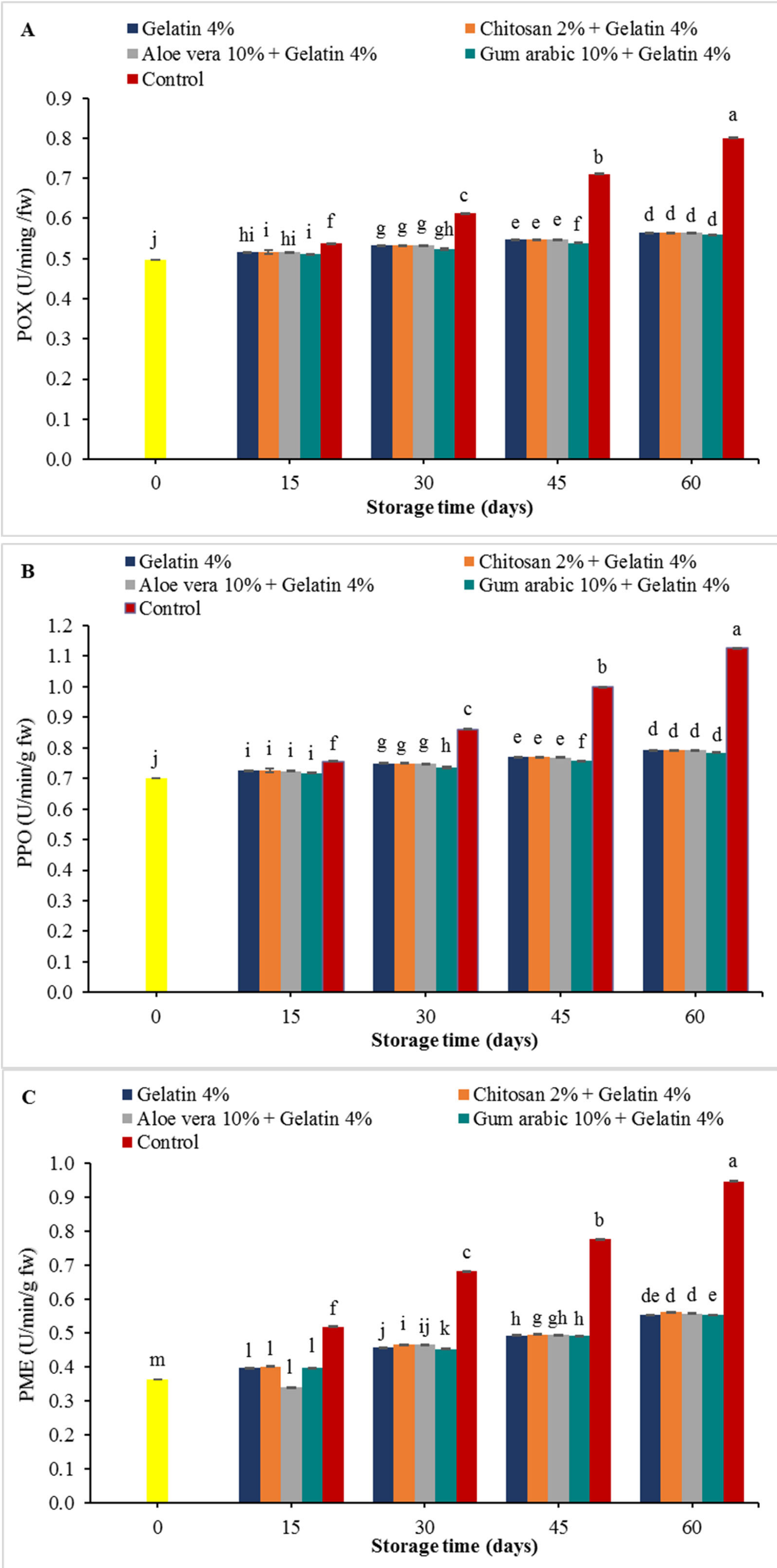

Figure 7. Effects of coating treatments on peroxidase (POX) (**A**), polyphenol oxidase (PPO) (**B**), and pectin methylesterase (PME) activities (**C**) in 'Barhi' dates in cold storage at 2 °C. Values represent the mean ± SD for three replications. Different letters indicate significant differences among treatments, according to Tukey's HSD test at $p \leq 0.05$.

3.7. Principal Component Analysis, Hierarchical Cluster Analysis, and Correlations

The PCA effectively summarized the variability among the measured quality attributes of 'Barhi' dates under different coating treatments and storage periods (Figure 8). The first two principal components (PC1 and PC2) accounted for a significant part of the overall variance, suggesting that most of the data structure was encapsulated within these dimensions. The treatment score plots (Figure 8A) showed that the coated fruits, especially treated with (T4) gum arabic + gelatin followed by (T2) chitosan + gelatin, and (T3) Aloe vera + gelatin, were located on the positive side of the first principal component (PC1). This means that they were linked to higher quality attributes during storage. The control therapy (T5), on the other hand, was grouped on the negative side of PC1, which meant that it did not perform as well overall. The score plots for storage term (Figure 8B) also showed steady shifts along PC1 and PC2, which were in line with gradual changes in quality attributes over time. The score plots of the interaction between treatments and storage period (Figure 8C) verified the same results as before. The qualitative date features showed little change across coating treatments over the first 30 days of storage, as seen by the data points being close together near the plot origin. As time went on, especially after 60 days, the control (T5) exhibited a significant shift toward the negative quadrant correlated with weight loss and quality deterioration the T4 exhibited a unique trajectory. By the end of the 60-day storage period (Figure 8C), T4 showed the most pronounced differentiation along PC1. This "divergence" is not indicative of instability but rather reflects the maximal efficacy of the gum arabic + gelatin coating. T1, T2, T3, and T4 stayed close to the original even after a long time of storage, which shows that they worked to keep the fruit's physicochemical properties. Component 2 (10.5% variance explained) accounted for modest differences, further confirming the finding that coating composition and storage period interact considerably to influence postharvest quality retention. The loading plots (Figure 8D) confirmed this superiority, as T4 at day 60 was the treatment most strongly aligned with the vectors for fruit hardness, antioxidant activity, and TSS retention. This spatial orientation proves that while T2 and T3 offered "stability", T4 provided the most robust protective barrier, effectively decoupling the fruit from the natural senescence path (weight loss and color decay) observed in the control. Therefore, the multivariate analysis reinforces the raw data findings, identifying T4 as the optimum formulation for long-term preservation of 'Barhi' dates. In addition, the loading plots showed that TSS, hardness, and antioxidant activity all had high positive loadings on PC1. At the same time, weight loss and color changes had a negative effect, which made it easier to tell the treatments apart (Figure 8D). PC1 was strongly and positively associated with storage life-related attributes, including firmness retention, total phenolic content, antioxidant activity, and reduced weight loss and decay incidence. In this regard, T4 (10% gum arabic + 4% gelatin) was distinctly separated along the positive side of PC1, particularly at advanced storage periods, reflecting its superior ability to preserve these critical quality parameters. This separation indicates enhanced performance rather than inferior behavior, as T4 showed strong positive loadings with variables directly linked to extended storage life and marketability. The two-way HCA heatmap (Figure 9) corroborated the PCA results by putting treatments with comparable quality profiles together. Coating treatments T4 formed a distinct cluster strongly associated with storage-life–related quality indicators, including superior firmness retention, higher total phenolic and flavonoid contents, enhanced antioxidant activity, greater vitamin C preservation, reduced weight loss, and delayed color changes throughout storage. T2 and T3 consistently grouped together, reflecting their effectiveness in maintaining internal physicochemical balance, particularly TSS and TA, during storage. In contrast, T1 showed moderate performance and clustered separately from the composite coatings, while T5 (control) formed an independent cluster characterized by inferior quality attributes, such as rapid softening, lower phytochemical contents, higher weight loss, and accelerated color deterioration after storage. Pearson's correlation matrix revealed a well-defined and coherent network of associations among the postharvest quality attributes of 'Barhi' dates (Figure 10). Clusters of biochemical and physical traits showed strong positive correlations (deep red cells), indicating synchronous evolution during storage. Total sugars were almost perfectly correlated with reducing sugars (r = 0.99) and non-reducing sugars (r = 0.99), while TSS exhibited similarly high correlations with total sugars (r = 0.98), reducing sugars (r = 0.97), and non-reducing sugars (r = 0.96), confirming the tightly coupled metabolic pathways underlying sweetness accumulation. Bioactive constituents formed a high-correlation cluster, with total phenolics strongly associated with carotenoids (r = 0.88) and total chlorophyll (r = 0.84), while chlorophyll pigments aligned closely with carotenoids (r = 0.91), reflecting coordinated pigment–antioxidant dynamics during storage. Firmness also correlated positively with key quality indicators, including total phenolics (r = 0.89), total chlorophyll (r = 0.84), carotenoids (r = 0.81), and lightness (L*) (r = 0.78), highlighting its role as a structural and physiological marker of fruit quality preservation. In contrast, deterioration-related traits were defined by strong negative correlations (deep blue cells). Weight loss was inversely correlated with total sugars (r = −0.87), reducing sugars (r = −0.86), TSS (r = −0.83), phenolics (r = −0.79), and chlorophyll (r = −0.82). Similarly, decay percentage exhibited pronounced negative correlations with firmness (r = −0.88), total chlorophyll (r = −0.80), and carotenoids (r = −0.77), indicating that tissue degradation and senescence progress opposite to biochemical stability and structural integrity. Colorimetric traits followed predictable physiological patterns, with hue angle strongly associated with total chlorophyll (r = 0.87) and moderately with carotenoids (r = 0.73), while lightness correlated positively with carotenoids (r = 0.79), illustrating how pigment degradation translates into visible color shifts. Notably, coated fruits, particularly (T4) gum arabic + gelatin exhibited more coherent and favorable correlation patterns, reflecting superior maintenance of biochemical, structural, and visual quality throughout the storage period, followed by (T2) chitosan + gelatin and (T3) Aloe vera + gelatin. Altogether, the correlation structure delineates two contrasting physiological clusters: a "quality-preservation cluster" driven by sugars, pigments, phenolics, and firmness, and a "deterioration cluster" characterized by weight loss and decay. This integrated pattern provides a robust framework for identifying key predictors of postharvest performance and guiding strategies to maximize fruit quality retention.

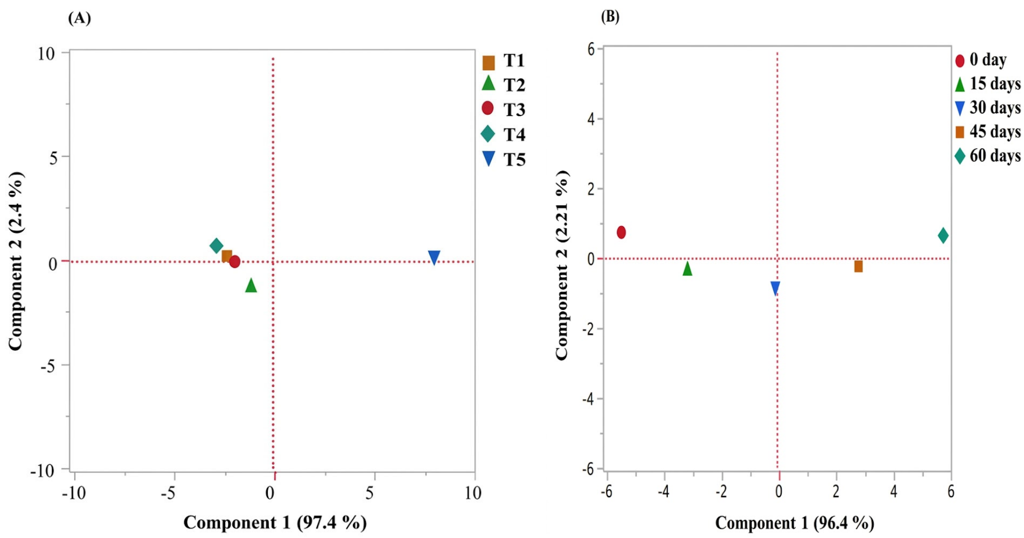

Figure 8. *Cont.*

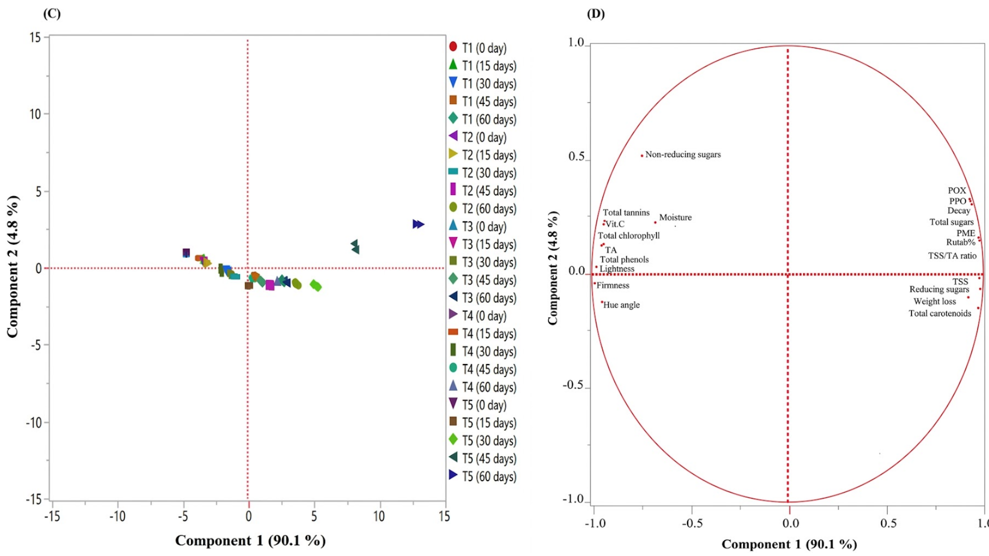

Figure 8. Principal component analysis showing the score plots of treatments (**A**), storage periods (**B**), interaction between treatments and storage periods (**C**), and loading plots (**D**) of the effect of various coating treatments on quality variables of 'Barhi' dates. (T1) gelatin 4%, (T2) chitosan 2% + gelatin 4%, (T3) Aloe vera 10% + gelatin 4%, (T4) gum arabic 10% + gelatin 4%, and (T5) control. Values are the means of three replicates.

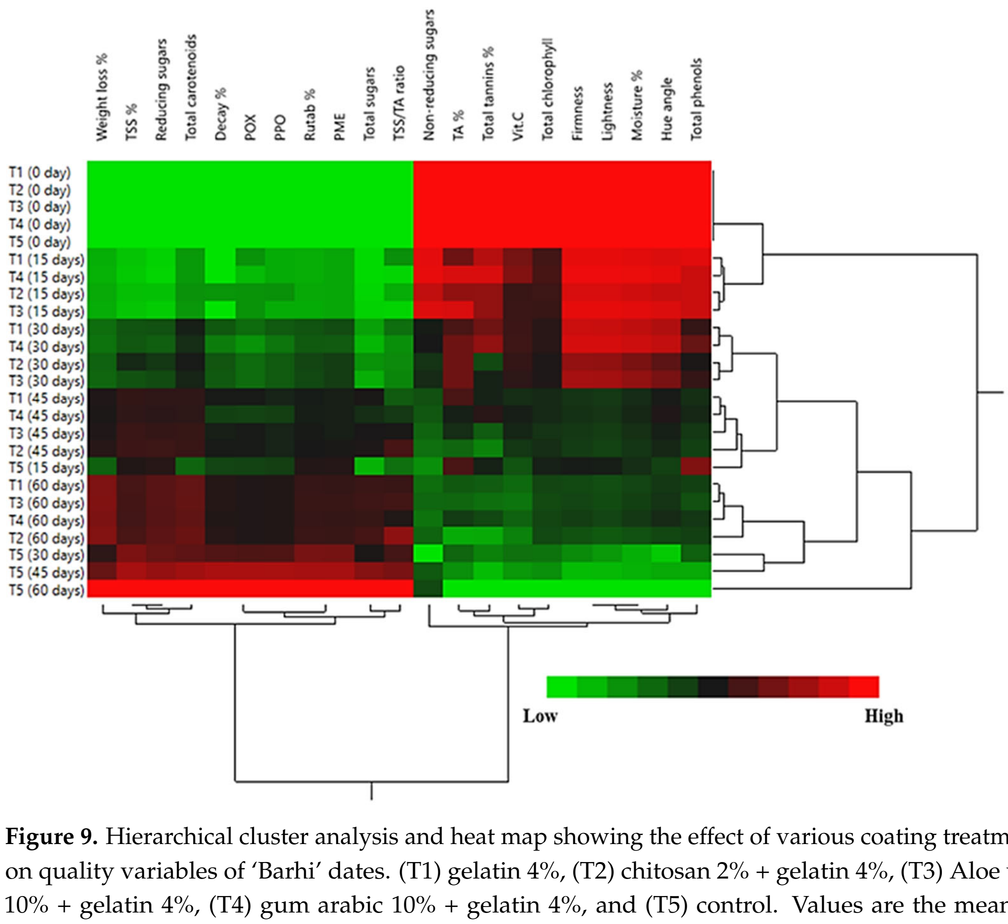

Figure 9. Hierarchical cluster analysis and heat map showing the effect of various coating treatments on quality variables of 'Barhi' dates. (T1) gelatin 4%, (T2) chitosan 2% + gelatin 4%, (T3) Aloe vera 10% + gelatin 4%, (T4) gum arabic 10% + gelatin 4%, and (T5) control. Values are the means of three replicates.

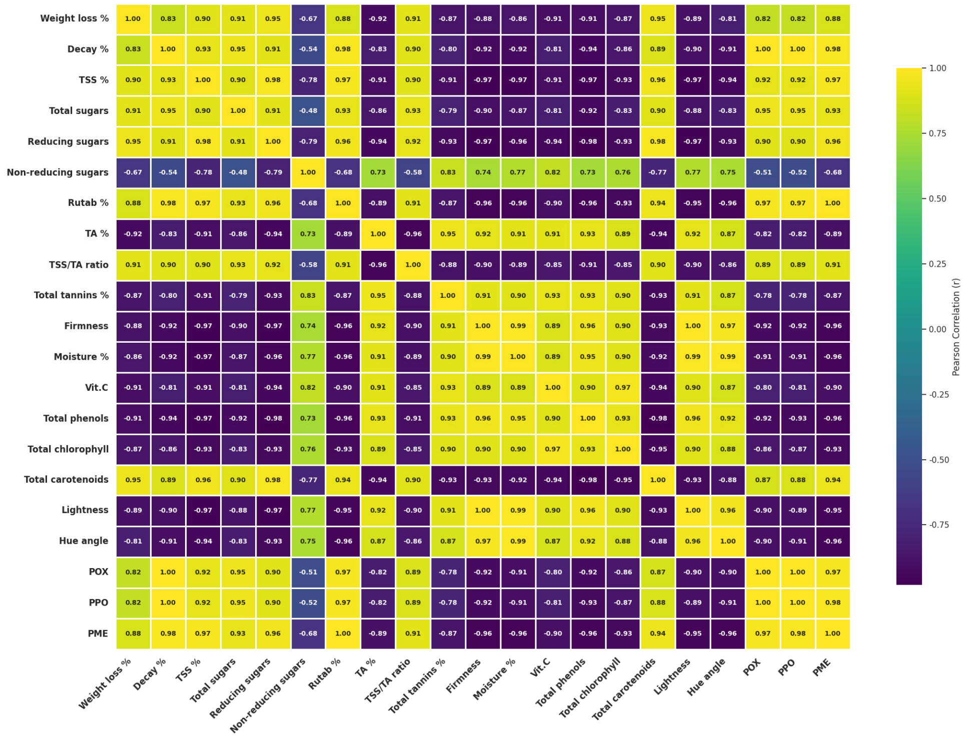

Figure 10. Pearson's correlation heatmap coefficients (r) describing the correlations between quality variables of 'Barhi' dates under various coating treatments.

3.8. External Appearance

Figure 11 illustrates the progressive changes in the external appearance of 'Barhi' dates coated with different edible formulations during cold storage at 2 °C. Overall, uncoated fruits (T5) control deteriorated rapidly, showing early browning, surface shrinkage, and loss of visual freshness. In contrast, all coating treatments (T1–T4) effectively delayed color degradation and preserved the characteristic yellow appearance of the khalal stage. Among them, (T4) gum arabic + gelatin was the most effective, maintaining uniform color, surface brightness, and minimal browning throughout the 60-day storage period. (T3) Aloe vera + gelatin and (T2) chitosan + gelatin also maintained visual quality compared with the control, though slightly less than T4. These coatings acted as semi-permeable barriers, reducing moisture loss and delaying ripening-related physiological changes. Consequently, T3 and T4 maintained fruit firmness and the crisp khalal stage for a longer duration, while control fruits reached the full rutab stage with severe browning and tissue softening by day 45. Collectively, the results demonstrate the potential of edible coatings, particularly gum arabic–based formulations, to extend the postharvest shelf-life and preserve the marketable quality of 'Barhi' dates under cold storage.

3.9. Cost–Benefit Index and Net Profit Percentage

The economic feasibility and efficiency of the applied edible coatings of 'Barhi' dates were evaluated using the CBI and net profit percentage analysis (Figure 12A,B). All investigated coating formulations significantly maintained the cost–benefit index compared to the control group (T5), which exhibited the highest index value of 1.0. Notably, the formulation consisting of gum arabic combined with gelatin (T4) yielded the most favorable results, achieving the lowest cost–benefit index (0.33), followed by T3 (Aloe vera + gelatin) and T2 (chitosan + gelatin). Correspondingly, these treatments demonstrated a substantial increase in net profit percentage, reflecting their capacity to maintain the post-harvest quality of 'Barhi' dates while minimizing economic losses during cold storage at 2 °C. These findings suggest that the integration of gum arabic or chitosan into gelatin-based coatings serves as a highly feasible and cost-effective strategy for enhancing the storage life and marketability of dates.

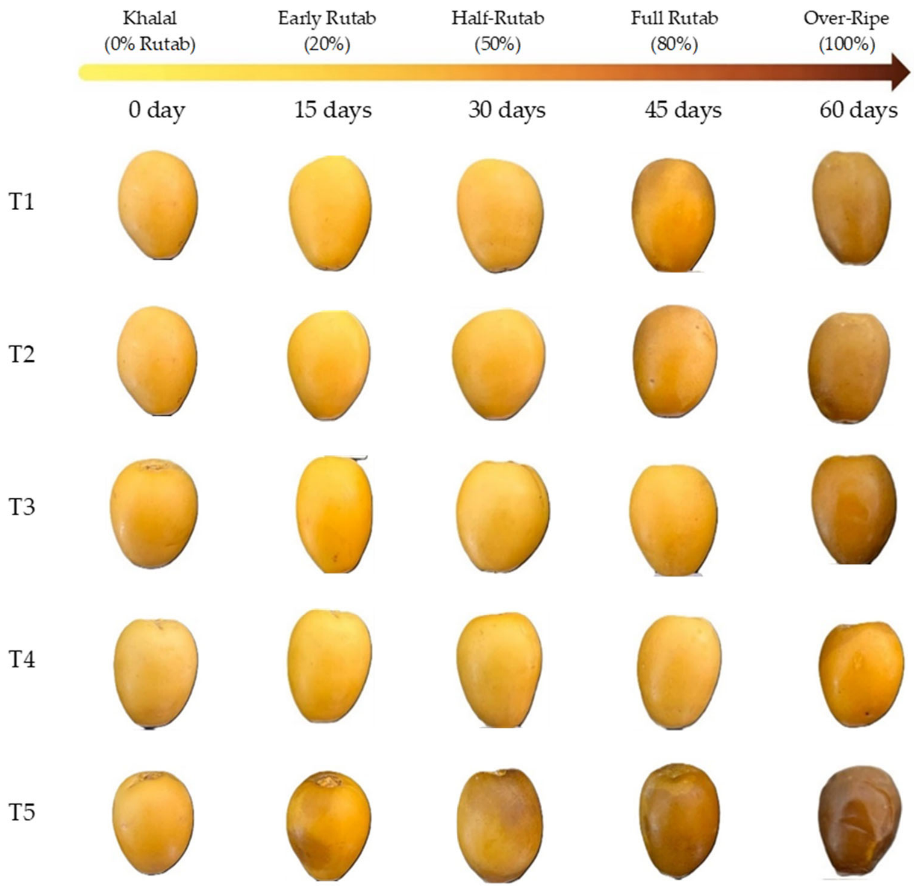

Figure 11. External appearance of 'Barhi' dates coated with different edible formulations during cold storage at 2 °C. (T1) gelatin 4%, (T2) chitosan 2% + gelatin 4%, (T3) Aloe vera 10% + gelatin 4%, (T4) gum arabic 10% + gelatin 4%, and (T5) control.

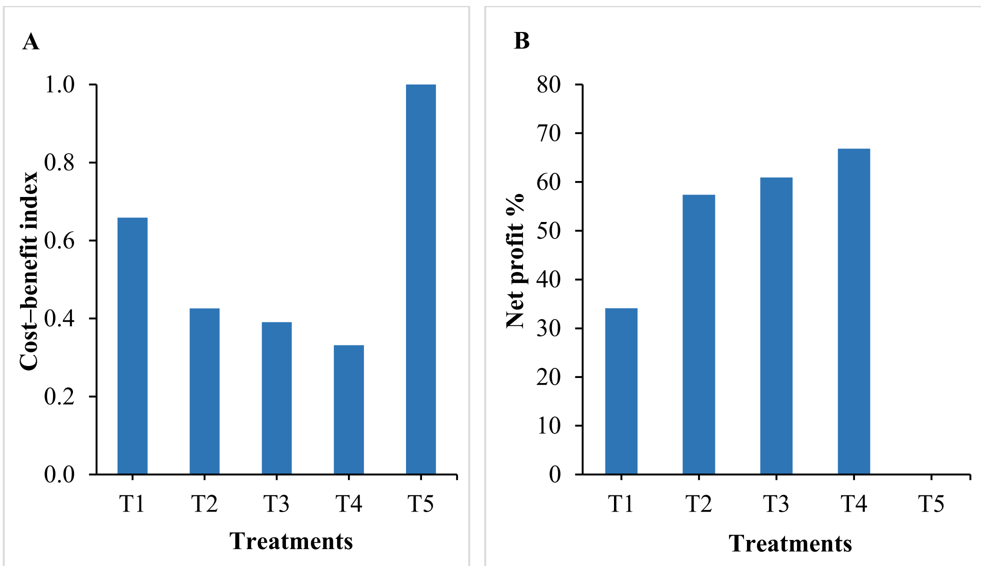

Figure 12. Cost–benefit index (**A**) and net profit% (**B**) of 'Barhi' dates coated with different edible formulations during cold storage at 2 °C. (T1) gelatin 4%, (T2) chitosan 2% + gelatin 4%, (T3) Aloe vera 10% + gelatin 4%, (T4) gum arabic 10% + gelatin 4%, and (T5) control.

4. Discussion

Edible coatings made from natural materials could be a good way to improve the quality and shelf life of food. Composite edible coatings, created using the LbL method, employ alternating biopolymer deposition, facilitating enhanced control over physicochemical attributes and functionality, as a singular material frequently fails to satisfy diverse application needs. The present study investigated whether a gelatin-based LbL coating system composed of chitosan, gum arabic, or Aloe vera could modulate postharvest physiological deterioration of 'Barhi' dates during cold storage. The results indicate that the primary effect of the LbL system was the attenuation of water loss, which subsequently influenced firmness retention, enzymatic browning, sugar accumulation, and antioxidant preservation. Furthermore, the LbL approach relies on electrostatic interactions and interfacial adsorption between biopolymers with opposite charges. Chitosan acts as a positively charged polyelectrolyte, interacting with negatively charged counterparts like gum arabic and Aloe vera polysaccharides. Additionally, gelatin provides hydrogen-bonding interactions and enhances film-forming properties. Together, these interactions facilitate the development of a multilayered, cohesive coating, resulting in improved barrier uniformity and functional performance compared with single or mixed-layer coatings [28,36,37].

4.1. Weight Loss, Decay, and Moisture Content

Our findings demonstrate that the application of chitosan, gum arabic, and AVG using a gelatin-based LbL approach effectively preserved the quality of 'Barhi' dates during cold storage, as evidenced by reduced weight loss and decay percentage, alongside better retention of firmness and moisture content compared with uncoated fruits. These outcomes are consistent with previous reports showing that edible coatings can mitigate postharvest deterioration in climacteric and non-climacteric fruits [15,16,19,28].

Hira et al. [15] reported that multilayer edible coatings extended the storage life of pear fruits and modulated genes associated with ripening and stress responses, resulting in reduced weight loss and delayed softening. Although transcriptomic or physiological parameters such as respiration and ethylene production were not measured in the present study, the similar trends observed in weight loss, decay incidence, and firmness retention suggest that comparable protective effects may be occurring in the coated dates. Likewise, Mendy et al. [16] demonstrated that Aloe vera coatings reduced weight loss in papaya (*Carica papaya* L.), attributing this effect primarily to the hygroscopic nature of the coating, which limits water diffusion from the fruit surface.

In dates specifically, El-Gioushy et al. [19] showed that gum arabic (10–15%) combined with chitosan significantly reduced fruit weight loss during storage, an effect attributed to the formation of a semi-permeable surface layer. This barrier likely moderates gas and moisture exchange between the fruit and its surrounding environment. Our results align with these findings, particularly in the superior performance of the gum arabic–gelatin LbL treatment, which exhibited the lowest weight loss and decay percentage at the end of storage. While coating permeability and respiration rates were not directly quantified in this study, the sustained moisture content and firmness observed provide indirect evidence supporting a protective barrier effect, as previously proposed for polysaccharide-based coatings [12,64].

Furthermore, the reduction in decay percentage observed in coated fruits relative to the control is in agreement with earlier studies on blueberries (*Vaccinium corymbosum* L.) [43], 'Barhi' dates and guava [1,19], and sweet cherries (*Prunus avium* L.) [64,65]. These studies consistently report that edible coatings can limit microbial development, either by restricting moisture availability at the fruit surface or by creating unfavorable conditions for pathogen proliferation. Taken together, the present results extend existing knowledge by confirming that a gelatin-based LbL application of natural polymers can effectively preserve multiple quality attributes of 'Barhi' dates during storage, even in the absence of direct physiological measurements.

4.2. Rutab Percentage, Firmness, and Color

The LbL coating functions as a regulator of the fruit's postharvest physiology. Its primary action as a physical gas barrier suppresses respiration, which in turn slows down the entire ripening program (including softening and senescence). This physiological slowdown, combined with the physical effects on surface moisture, synergistically reduces the fruit's susceptibility to decay, thereby preserving overall quality during cold storage [12,64]. The increase in rutab percentage observed in the control treatment (Figure 3A) corresponds directly with the accelerated softening pattern shown in Figure 3B. As storage progressed to 60 days, untreated fruits exhibited the highest rutab transformation and the lowest firmness values. This inverse relationship indicates a strong negative correlation between rutab percentage and firmness as rutab formation increased, firmness declined. This supports the physiological explanation that enhanced ripening activity in untreated fruits promoted enzymatic degradation of cell wall components, leading to rapid softening and stage transition [65]. Conversely, treatment T4 (gum arabic + gelatin) consistently recorded the lowest rutab percentage and the highest firmness values throughout storage. This demonstrates a positive correlation between firmness retention and delayed rutab transformation. The slower rate of rutab development in coated fruits suggests reduced respiration and suppressed ethylene-mediated ripening processes, which is consistent with the proposed mechanism of semi-permeable coating barriers modifying internal gas exchange and metabolic activity [66]. These results are consistent with other studies, including those by Vieira et al. [43] and Miteluț et al. [66] who indicated that coating maintained fruit firmness, which can be attributed to their antifungal characteristics and epidermal covering, thereby reducing infection and other maturation processes during storage. This aligns with prior research on papaya with chitosan [29], litchi (*Litchi chinensis*) fruit treated with Aloe vera [17], and guava with gum arabic [19]. Lightness (L*) and hue angle (h°) are two essential color measurements that were set up to find color changes in fruit during cold storage [67].

This study examined the impact of coating treatments on the coloration of fresh 'Barhi' dates. When fruits are stored, they often change color, mostly due to enzyme activity (Figure 6C), which usually leads to a decrease in market value [68]. The color shift is mainly caused by the enzyme chlorophyllase breaking down chlorophyll, phenolic chemicals oxidizing, and the dark brown pigments forming in date fruits [69]. The current data suggest that the application of 4% gelatin, either independently or in conjunction with 2% chitosan, 10% AVG, and 10% gum arabic, impeded color change reactions in fresh dates during cold storage (Figure 2C,D). The delayed color change observed in coated 'Barhi' dates appears to result from coordinated physiological modulation of respiration, ethylene activity, and oxidative enzyme systems. While the current findings strongly suggest that gelatin-based composite coatings regulate ripening-associated pigment metabolism, additional physicochemical validation of coating functionality would enhance the scientific rigor of these conclusions [70].

4.3. Total Soluble Solids, Titratable Acidity, TSS/TA Ratio, and Ascorbic Acid

The present results demonstrate that TSS increased progressively in both treated and untreated 'Barhi' date fruits during cold storage, although the magnitude of increase differed among treatments. The rise in TSS during storage is physiologically associated with ripening-related metabolic processes, particularly the enzymatic degradation of cell wall polysaccharides and the hydrolysis of complex carbohydrates into soluble sugars. The activation of hydrolytic enzymes enhances the conversion of pectic substances into water-soluble galacturonic acids, contributing to elevated TSS levels [71]. Additionally, it may be due to a higher evaporation rate and respiration from the date surface [72]. Fruits coated with chitosan + gelatin and gum arabic + gelatin showed the smallest increase in TSS during storage. This moderated rise can be physiologically linked to reduced respiration rate, limited water loss, and attenuated oxidative metabolism under the semi-permeable coating layer. By modifying internal gas exchange and lowering oxygen availability, coatings likely slowed carbohydrate hydrolysis and sugar accumulation [28] These findings are consistent with previous reports [13,73] indicating that edible coatings suppress excessive TSS increases by delaying ripening progression. Moreover, since elevated TSS contributes to increased sweetness and textural softening, the slower rise observed in coated fruits further supports their delayed maturation profile.

Chitosan and gum arabic coatings lower respiration rates, slow down ripening, and slowly raise TSS [35,74]. However, other factors could be at play, like the type of fruit studied, level of ripeness, storage conditions, and coatings thickness [12]. Titratable acidity declined over time in all treatments, reflecting the utilization of organic acids as respiratory substrates during postharvest metabolism. However, coated fruits exhibited a slower rate of TA decline compared with the control. This suggests that coatings reduced metabolic turnover and slowed the consumption of organic acids in the tricarboxylic acid cycle [75]. Our results support earlier studies indicating that gum arabic coating resulted in a small alteration in TA during storage [18]. Similar responses have been documented by Silva et al. [29] in gum arabic–coated fruits and chitosan-treated papaya, where coatings preserved acidity by modulating respiration and metabolic activity [29].

Coating treatments particularly AVG and gum arabic followed by gelatin were the most effective in maintaining higher ascorbic acid levels during cold storage. This protective effect can be physiologically explained by reduced oxygen diffusion, suppressed respiration rate, and lower reactive oxygen species generation within coated fruits. By mitigating oxidative stress, coatings likely slowed ascorbic acid oxidation [76]. Furthermore, the present results showed that ascorbic acid content decreased progressively during storage under all treatments, confirming the natural susceptibility of vitamin C to oxidative degradation. This reduction reflects the rapid conversion of L-ascorbic acid into dehydroascorbic acid, which is further oxidized to diketogulonate by oxidative enzymes during storage. However, the rate of decline was more pronounced in the control fruits compared to the coated treatments, indicating higher oxidative stress and metabolic activity in untreated fruits. The coatings effectively slowed down the loss of ascorbic acid, likely by reducing respiration rate and limiting oxygen diffusion into the fruit tissues, thereby suppressing oxidative enzyme activity. These findings demonstrate that edible coatings preserved antioxidant capacity by delaying oxidative deterioration, whereas untreated fruits depleted vitamin C more rapidly due to enhanced oxidation and ripening [76–78].

4.4. Total Sugars, Reducing Sugars, and Non-Reducing Sugars

The present results confirm that total sugars, including both reducing and non-reducing sugars, increased progressively during storage, reflecting the natural ripening transition of 'Barhi' dates from the khalal to the rutab stage. This trend was particularly pronounced in the control fruits, which presented the highest total sugar values throughout storage, indicating accelerated ripening. In contrast, all coating treatments significantly moderated the increase in sugar concentration, demonstrating their effectiveness in slowing metabolic changes associated with fruit maturation. The rapid sugar accumulation observed in untreated fruits can be attributed to enhanced respiration and intensified enzymatic hydrolysis of polysaccharides and residual starch into soluble sugars [71,79,80].

4.5. Total Phenols, Total Tannins, Total Chlorophyll, and Total Carotenoids

Phenolic chemicals are the most important secondary metabolites in plants. They are powerful antioxidants that protect cells from harm caused by free radicals and change the activity of several enzymes [14]. The present study demonstrated that total phenolics and total tannins declined gradually during storage; however, coated fruits consistently maintained significantly higher values than the untreated control. These findings confirm that edible coatings effectively preserved antioxidant constituents throughout the storage period. The superior performance of T4 (10% gum arabic followed by 4% gelatin) (Figure 5) in retaining the highest total phenolic content directly reflects its ability to reduce oxidative deterioration and metabolic activity. In contrast, the untreated fruits exhibited a sharper reduction in phenolic and tannin contents, likely due to increased respiration rate and enhanced enzymatic oxidation, which accelerate the degradation of phenolic compounds [63]. The observed trend in our results is consistent with previous reports indicating that total phenolics and tannins decrease with prolonged storage in dates [81]. Since phenolic compounds contribute substantially to antioxidant activity, the higher retention of these compounds in coated fruits suggests improved antioxidant capacity and delayed senescence. Therefore, the data clearly demonstrate that the application of edible coatings particularly the gum arabic plus gelatin treatment played a crucial role in preserving bioactive compounds and maintaining fruit quality during storage. The present results demonstrated that total tannin content in 'Barhi' dates decreased progressively as the fruits advanced from the khalal (bisir) stage to the rutab stage, confirming the natural decline of tannins during ripening. However, coated fruits retained higher tannin levels compared with the control throughout storage, indicating that postharvest coating treatments slowed the ripening process and delayed tannin degradation. The reduction in tannins in untreated fruits may be attributed to enhanced metabolic activity and accelerated softening, which are characteristic of the transition to the rutab stage [1]. Similarly, the increase in total carotenoid content observed in the control fruits (Figure 7) further supports the occurrence of faster ripening in untreated samples. Since carotenoid accumulation is closely associated with color development and fruit maturation, the higher carotenoid levels in control fruits indicate earlier progression toward full ripeness. In contrast, coated fruits showed a slower increase in carotenoids, reflecting delayed ripening due to reduced respiration and metabolic activity. These findings are consistent with previous reports showing that coating treatments impede ripening by limiting oxygen availability and reducing respiration rates, thereby preserving bioactive compounds and extending shelf life [10].

4.6. Enzyme Activities

Peroxidase and PPO activities increased progressively during cold storage across all treatments, reflecting natural senescence and cell structure degradation [82]. These enzymes play central roles in phenolic oxidation and enzymatic browning, which negatively affects fruit color and marketability [83]. However, coating treatments especially gum arabic or AVG followed by gelatin significantly suppressed POX and PPO activities compared to the control (Figure 6A,B). Lower enzyme activity indicates delayed tissue deterioration and reduced oxidative stress. The inhibition of these enzymes may be attributed to reduced oxygen diffusion due to coating barrier properties. Higher retention of phenolic compounds, enhanced antioxidant capacity that limits free radical formation, delayed senescence, and reduced substrate oxidation [84]. Thus, the coatings not only slowed ripening but also mitigated enzymatic browning pathways. Polyphenol oxidase is the main enzyme that causes the browning response because it can change monophenols into o-diphenols, which can subsequently be changed into o-quinones, which cause tissue browning [84]. Peroxidase is another essential enzyme in the phenylpropanoid metabolic pathway [85]. Biles and Martyn [86] elucidated the function of POX in injured tissues, detailing its participation in cell wall cross-linking and in tissues affected by pathogens. Higher levels of POX and PPO activities would mean that the tissue is deteriorating over time, whereas lower levels would mean that the tissue is improving. The inhibition of POX and PPO activities by coating treatments may be attributed to the presence of abundant phenolic compounds and to enhanced antioxidant capacity, leading to the elimination of free radicals [68]. Additionally, it may be associated with a postponement of senescence and the delayed oxidation of phenolic substances during cold storage [14,75]. The rise in PME during storage is linked to the ripening process, which mostly results from the breakdown of the middle lamella of the cell wall [87] or due to a fungal infection [88]. In our study, dates covered with gum arabic, AVG, or chitosan, followed by gelatin, may alter the atmosphere surrounding the fruit, thereby reducing the respiration rate and inhibiting ethylene synthesis [62]. The coating had the lowest oxygen consumption rate, which slowed down the ripening process and PME activity [89]. The importance of coating in reducing PME activity and preserving cell wall integrity was evident in its impact on enhancing fruit firmness and diminishing decay incidence [90]. The results demonstrated that the LBL edible coating treatment significantly inhibited the activities of POX, PPO, and PME, thereby validating the findings of the current study, as illustrated in Figure 6, which indicates that the most effective treatment for controlling the increase over time was a combination of 10% gum arabic and 4% gelatin. Finally, the current study demonstrated that the utilization of edible coatings LBL, comprising 2% chitosan, 2% AVG, or 10% gum arabic, followed by 4% gelatin, preserved the quality by retaining antioxidants and texture structure, thereby extending the storage life of 'Barhi' dates for up to 60 days at 2 °C and 90–95% relative humidity. Magri et al. [68] and Silva et al. [29] explain that direct mixing of oppositely charged biopolymers (e.g., chitosan with gum arabic or Aloe vera polysaccharides) can lead to premature complexation, phase separation, or precipitation, which reduces coating homogeneity and functional efficiency. In contrast, LbL self-assembly allows controlled sequential adsorption of polymers, enabling precise regulation of coating thickness, surface charge, and layer composition, as well as functional partitioning of barrier and bioactive properties within the multilayer structure.

In general, according to the current findings, LbL and edible coatings (chitosan, gum arabic, Aloe vera, gelatin–gum systems) modify gas exchange, water loss, enzyme activities, and oxidative status, which together slow physical and biochemical deterioration of dates, consequently extending fruit storage life. Gelatin provides an adherent, flexible protein matrix, while polysaccharide or Aloe vera layers contribute antimicrobial and barrier functions. The effectiveness of the coating treatments in preserving fruit quality, such as phenolics, tannins, and ascorbic acid, and in delaying sugar accumulation can be attributed to their intrinsic physicochemical properties. Gum arabic is a natural polysaccharide with good film-forming ability, moderate oxygen barrier capacity, and low permeability to gases, which helps create a semi-permeable modified atmosphere around the fruit surface. Gelatin, a protein-based biopolymer, enhances film strength, adhesion, and structural integrity, improving the protective barrier against oxygen diffusion and moisture loss. The stacking of gum arabic followed by gelatin likely produced a composite coating with improved mechanical stability and reduced gas exchange compared with single treatments. This semi-permeable barrier reduces respiration rate and ethylene production, thereby slowing enzymatic oxidation and metabolic conversion processes. Consequently, the coated fruits exhibited higher retention of phenolic compounds and tannins, reduced ascorbic acid degradation, slower carotenoid accumulation, and moderated increases in sugar. In contrast, untreated fruits were directly exposed to oxygen, leading to enhanced oxidative reactions, accelerated ripening, and faster biochemical deterioration. Therefore, the preservation of antioxidant capacity and delayed ripening observed in T4 can be directly linked to the barrier properties, film-forming ability, and gas-regulating characteristics of the gum arabic–gelatin coating system.

Our findings align with previous works such as Silva et al. [29] and Moreira Pereira et al. [28], both reporting that LbL gelatin–chitosan coatings on minimally processed papaya and red guava significantly reduced mass loss, maintained firmness and color, stabilized ascorbic acid and carotenoids, and delayed ripening compared with single-polymer coatings, demonstrating clear synergistic effects of the double layer. Similar LbL chitosan–sodium carboxymethyl cellulose or chitosan–alginate systems on mandarins (*Citrus reticulata* Blanco) preserved firmness, TA, and ascorbic acid, and reduced weight loss more effectively than single chitosan layers during cold storage, underscoring the general advantage of polyelectrolyte bilayers over monolayers [91]. Although explicit gelatin–gum arabic and gelatin–Aloe vera LbL systems are less documented, composite gum arabic–chitosan coatings on guava and gum arabic on strawberries (*Fragaria* × *ananassa Duchesne*) markedly decreased weight loss, suppressed fungal decay, and preserved firmness, phenolics and antioxidant activity under refrigerated or ambient storage [92,93]. Semipermeable coatings (chitosan, guar, gum arabic, Aloe vera) act as a barrier to transpiration, lowering weight loss and maintaining higher moisture and firmness in 'Barhi' and 'Zaghloul' dates [10,93]. Coatings delay chlorophyll degradation and carotenoid increase, thus slowing the khalal to rutab color change in 'Barhi' and other dates [1,94]. During khalal to rutab ripening, sucrose is hydrolyzed to glucose and fructose by invertase. Chitosan coatings containing olive cake or orange peel extracts significantly reduced invertase activity and slowed sucrose conversion, thus delaying sweetness increase and softening in 'Barhi' dates [94]. Composite coatings (gelatin + guar + chitosan; chitosan + plant extracts; jojoba oil + gum arabic) resulted in higher total phenols, flavonoids, tannins and antioxidant activity compared with uncoated dates, indicating reduced oxidative degradation of bioactive compounds [10,93,94]. Layer-by-layer edible coatings reduce activities of softening-related enzymes (PME, PG, cellulase and pectinases) and suppressed or delayed (PPO and POX) involved in browning, slowing discoloration, thereby maintaining cell wall structure, and limiting browning, as shown in 'Kinnow' mandarin [91], 'Barhi' dates [94]. Chitosan and Aloe vera have inherent antimicrobial properties; chitosan coatings with olive-cake or orange peel extracts significantly inhibited mold growth on 'Barhi' dates during cold storage [94].

Overall, evidence from gelatin–chitosan LbL systems and chitosan/Aloe vera/gum arabic-based multilayer or composite coatings indicates that protein–polysaccharide double layers can synergistically reduce water loss, slow ripening, suppress pathogens and better preserve bioactive compounds than single coatings, offering a robust, scalable strategy for postharvest preservation of perishable fruits [29].

Collectively, LbL treatment, particularly gum arabic (10%) + gelatin (4%) demonstrated the greatest physicochemical preservation, characterized by the highest tensile strength, surface cohesion, and coating thickness, alongside the lowest oxygen permeability and water vapor permeability. These findings confirm the enhanced structural integrity and barrier efficiency of the multilayer assembly system. In contrast, the control treatment (deionized water) exhibited no measurable film-forming or barrier properties. The obtained data suggest a coordinated physiological response in coated fruits. Attenuated water loss limited concentration-driven increases in TSS, slowed organic acid depletion, and reduced oxidative stress, as reflected by lower PPO and POX activities and better retention of phenolic compounds and ascorbic acid. This integrated response indicates that the LbL system modulated the postharvest metabolic trajectory of 'Barhi' dates rather than affecting isolated quality parameters. Such coordinated modulation extends current knowledge beyond single-layer edible coatings by demonstrating that sequential polymer deposition can influence multiple deterioration pathways simultaneously.

5. Conclusions

Edible coating technologies applied as thin surface layers using the LbL approach represent a promising postharvest strategy for maintaining the quality attributes of fresh fruit during cold storage. In this study, the effects of dual-layer edible coatings consisting of chitosan (2%), Aloe vera gel (2%), or gum arabic (10%), followed by gelatin (4%), were evaluated on the physicochemical and quality characteristics of 'Barhi' dates under cold storage conditions. The results demonstrated that all LbL coating treatments were effective in reducing weight loss and decay percentage and in maintaining firmness, moisture content, and antioxidant-related enzyme activity compared with the uncoated control during storage. Among the tested treatments, the gum arabic–gelatin combination consistently showed superior performance in limiting weight loss and preserving firmness and antioxidant status throughout the storage period. Although physiological parameters such as respiration rate, ethylene production, and coating permeability were not directly measured, the observed preservation of quality attributes is consistent with the protective effects reported in previous studies on edible coatings. Overall, the findings indicate that gelatin-based LbL coatings, particularly those incorporating gum arabic, can effectively maintain key quality parameters of 'Barhi' dates during cold storage. Further research is warranted to characterize coating properties, assess sensory quality and consumer acceptance, and evaluate commercial scale feasibility to support the practical application of this postharvest approach.

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References

1. El-Gioushy, S.F.; El-Masry, A.M.; Fikry, M.; El-Kholy, M.F.; Shaban, A.E.; Sami, R.; Algarni, E.; Alshehry, G.; Aljumayi, H.; Benajiba, N.; et al. Utilization of Active Edible Films (Chitosan, Chitosan Nanoparticle, and $CaCl_2$) for Enhancing the Quality Properties and the Shelf Life of Date Palm Fruits (Barhi Cultivar) during Cold Storage. *Coatings* **2022**, *12*, 255. [CrossRef]
2. Farooq, S.; Maqbool, M.M.; Bashir, M.A.; Ullah, M.I.; Shah, R.U.; Ali, H.M.; Farraj, D.A.A.; Elshikh, M.S.; Hatamleh, A.A.; Bashir, S.; et al. Production Suitability of Date Palm under Changing Climate in a Semi-Arid Region Predicted by CLIMEX Model. *J. King Saud. Univ.-Sci.* **2021**, *33*, 101394. [CrossRef]

3. Ouamnina, A.; Alahyane, A.; Elateri, I.; Abderrazik, M. Pharmacological Insights, Traditional Applications, and Determinants of Phytochemical Composition in Date Palm Fruit (*Phoenix dactylifera* L.): A Comprehensive Review. *J. Food Compos. Anal.* **2024**, *136*, 106784. [CrossRef]
4. Alam, M.Z.; Al-Hamimi, S.; Ayyash, M.; Rosa, C.T.; Yahia, E.M.; Haris, S.; Al-Marzouqi, A.H.; Kamal-Eldin, A. Contributing Factors to Quality of Date (*Phoenix dactylifera* L). *Fruit* **2023**, *321*, 112256. [CrossRef]
5. Medany, M.A.; Mohamed, A.A.A.; Attala, M.A.; Ali, M.H.G. The Future Status of Egyptian Date Palm after the 2.5 Million Palm Trees-National Project. *Sustain. Food Agric.* **2023**, *4*, 20–27. [CrossRef]
6. FAO Statistical Database: Crops and Livestock Products. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 25 June 2023).
7. Hussain, M.I.; Farooq, M.; Syed, Q.A. Nutritional and Biological Characteristics of the Date Palm Fruit (*Phoenix dactylifera* L.)—A Review. *Food Biosci.* **2020**, *34*, 100509. [CrossRef]
8. Alsmairat, N.; Othman, Y.; Ayad, J.; Al-Ajlouni, M.; Sawwan, J.; El-Assi, N. Anatomical Assessment of Skin Separation in Date Palm (*Phoenix dactylifera* L. var. Mejhoul) Fruit during Maturation and Ripening Stages. *Agriculture* **2022**, *13*, 38. [CrossRef]
9. Qadir, A.; Shakeel, F.; Ali, A.; Faiyazuddin, M. Phytotherapeutic Potential and Pharmaceutical Impact of *Phoenix dactylifera* (Date Palm): Current Research and Future Prospects. *J. Food Sci. Technol.* **2020**, *57*, 1191–1204. [CrossRef]
10. Abu-Shama, H.S.; Abou-Zaid, F.O.F.; El-Sayed, E.Z. Effect of Using Edible Coatings on Fruit Quality of Barhi Date Cultivar. *Sci. Hortic. Amst.* **2020**, *265*, 109262. [CrossRef]
11. Mahfoudhi, N.; Hamdi, S. 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. *J. Food Process. Preserv.* **2015**, *39*, 1499–1508. [CrossRef]
12. Nunes, C.; Silva, M.; Farinha, D.; Sales, H.; Pontes, R.; Nunes, J. Edible Coatings and Future Trends in Active Food Life Increasing. *Foods* **2023**, *12*, 3308. [CrossRef] [PubMed]
13. Elmenofy, H. Effect of Natural Antimicrobial Substances with Packaging System on Improving Quality of 'Etmani' Guava (*Psidium guajava* L.) Fruit during Cold Storage. *J. Plant Prod.* **2021**, *12*, 527–540. [CrossRef]
14. Li, H.; Huang, Z.; Addo, K.A.; Yu, Y. Evaluation of Postharvest Quality of Plum (*Prunus salicina* L. Cv. 'French') Treated with Layer-by-Layer Edible Coating during Storage. *Sci. Hortic.* **2022**, *304*, 111310. [CrossRef]
15. Hira, N.; Mitalo, O.W.; Okada, R.; Sangawa, M.; Masuda, K.; Fujita, N.; Ushijima, K.; Akagi, T.; Kubo, Y. The Effect of Layer-by-Layer Edible Coating on the Shelf Life and Transcriptome of 'Kosui' Japanese Pear Fruit. *Postharvest Biol. Technol.* **2022**, *185*, 111787. [CrossRef]
16. Mendy, T.K.; Misran, A.; Mahmud, T.M.M.; Ismail, S.I. Application of Aloe Vera Coating Delays Ripening and Extend the Shelf Life of Papaya Fruit. *Sci. Hortic. Amst.* **2019**, *246*, 769–776. [CrossRef]
17. Ali, S.; Khan, A.S.; Nawaz, A.; Anjum, M.A.; Naz, S.; Ejaz, S.; Hussain, S. Aloe Vera Gel Coating Delays Postharvest Browning and Maintains Quality of Harvested Litchi Fruit. *Postharvest Biol. Technol.* **2019**, *157*, 110960. [CrossRef]
18. Anjum, M.A.; Akram, H.; Zaidi, M.; Ali, S. Effect of Gum Arabic and Aloe Vera Gel Based Edible Coatings in Combination with Plant Extracts on Postharvest Quality and Storability of 'Gola' Guava Fruits. *Sci. Hortic. Amst.* **2020**, *271*, 109506. [CrossRef]
19. El-Gioushy, S.F.; Abdelkader, M.F.M.; Mahmoud, M.H.; Ghit, H.M.A.E.; Fikry, M.; Bahloul, A.M.E.; Morsy, A.R.; Lo'ay, A.A.; Abdelaziz, A.M.R.A.; Alhaithloul, H.A.S.; et al. The Effects of a Gum Arabic-Based Edible Coating on Guava Fruit Characteristics during Storage. *Coatings* **2022**, *12*, 90. [CrossRef]
20. Khorram, F.; Ramezanian, A.; Hosseini, S.M.H. Shellac, gelatin and Persian gum as alternative coating for orange fruit. *Sci. Hortic. Amst.* **2017**, *225*, 22–28. [CrossRef]
21. Soradech, S.; Nunthanid, J.; Limmatvapirat, S.; Luangtana-anan, M. Utilization of Shellac and Gelatin Composite Film for Coating to Extend the Shelf Life of Banana. *Food Control* **2017**, *73*, 1310–1317. [CrossRef]
22. Ali, G.; Sharma, M.; Salama, E.-S.; Ling, Z.; Li, X. Applications of Chitin and Chitosan as Natural Biopolymer: Potential Sources, Pretreatments, and Degradation Pathways. *Biomass Convers. Biorefinery* **2024**, *14*, 4567–4581. [CrossRef]
23. Ke, C.-L.; Deng, F.-S.; Chuang, C.-Y.; Lin, C.-H. Antimicrobial Actions and Applications of Chitosan. *Polymers* **2021**, *13*, 904. [CrossRef]
24. Dhlamini, K.S.; Selepe, C.T.; Ramalapa, B.; Tshweu, L.; Ray, S.S. Reimagining Chitosan-Based Antimicrobial Biomaterials to Mitigate Antibiotic Resistance and Alleviate Antibiotic Overuse: A Review. *Macromol. Mater. Eng.* **2024**, *309*, 2400018. [CrossRef]
25. Shala, A.Y.; Elmenofy, H.M.; Eisa, E.A.E.-H.; Al-Khayri, J.M.P. Antioxidants, Antimicrobial Activities and Edible Coating Application of Aloe Vera. In *In Vitro Propagation and Secondary Metabolite Production (Part 2)*; Anis, M., Khanam, M.N., Eds.; Bentham Science Publishers: Singapore, 2024; pp. 119–160.
26. Arfat, Y.A.; Ejaz, M.; Jacob, H.; Ahmed, J. Deciphering the Potential of Guar Gum/Ag-Cu Nanocomposite Films as an Active Food Packaging Material. *Carbohydr. Polym.* **2017**, *157*, 65–71. [CrossRef] [PubMed]
27. Ahmed, S.; Ikram, S. Chitosan and Gelatin Based Biodegradable Packaging Films with UV-Light Protection. *J. Photochem. Photobiol. B Biol.* **2016**, *163*, 115–124. [CrossRef]

28. Moreira Pereira, E.; Dellinghausen Borges, C.; Santos Formiga, A.; Sidnaldo Pinsetta Junior, J.; Mattiuz, B.-H.; Santos Monteiro, S. Conservation of Red Guava "Pedro Sato" Using Chitosan and Gelatin-Based Coatings Produced by the Layer-by-Layer Technique. *Process Biochem.* **2022**, *121*, 35–44. [CrossRef]
29. Silva, K.G.d.; Cavalcanti, M.T.; Martinsa, L.P.; Alves, R.d.C.; Lucena, F.A.d.; Santos, M.S.A.; Silva, S.X.d.; Costa, F.B.d.; Moreira, I.d.S.; Pereira, E.M. Coatings Based on Gelatin and Chitosan in the Conservation of Papaya (*Carica papaya* L.) Minimally Processed. *Horticulture* **2023**, *9*, 729. [CrossRef]
30. Souza, W.F.C.; Lucena, F.A.; Silva, K.G.; Martins, L.P.; Castro, R.J.S.; Sato, H.H. Influence of Edible Coatings Composed of Alginate, Galactomannans, Cashew Gum, and Gelatin on the Shelf-Life of Grape Cultivar 'Italia': Physicochemical and Bioactive Properties. *LWT* **2021**, *152*, 112315. [CrossRef]
31. Moradi, C.; Hosseini, E.; Rousta, E. Bitter Almond Gum-Fish Gelatin Conjugate Coatings Extend the Storage of Button Mushrooms. *Postharvest Biol. Technol.* **2025**, *222*, 113356. [CrossRef]
32. Radi, M.; Firouzi, E.; Akhavan, H.; Amiri, S. Effect of Gelatin-Based Edible Coatings Incorporated with Aloe Vera and Black and Green Tea Extracts on the Shelf Life of Fresh-Cut Oranges. *J. Food Qual.* **2017**, *2017*, 9764650. [CrossRef]
33. Sánchez, J.T.; García, A.V.; Martínez-Abad, A.; Vilaplana, F.; Jiménez, A.; Garrigós, M.C. Physicochemical and Functional Properties of Active Fish Gelatin-Based Edible Films Added with Aloe Vera Gel. *Foods* **2020**, *9*, 1248. [CrossRef]
34. Chin, S.S.; Han Lyn, F.; Nur Hanani, Z.A. Effect of *Aloe vera* (*Aloe barbadensis* Miller) Gel on the Physical and Functional Properties of Fish Gelatin Films as Active Packaging. *Food Packag. Shelf Life* **2017**, *12*, 128–134. [CrossRef]
35. Adnan Abd, A.; Al-Khafaji, Z. Gelatin and Arabic Gum-Based Food Coating for Food Packaging. *Kufa J. Eng.* **2024**, *15*, 213–230. [CrossRef]
36. Erceg, T.; Rackov, S.; Terek, P.; Šovljanski, O.; Šuput, D.; Travičić, V.; Hadnađev, M. Synergistic effects of bilayer edible coatings: Protein-based and cocoa butter/linseed oil formulation for enhanced food preservation. *Int. J. Biol. Macromol.* **2025**, *306*, 141500. [CrossRef] [PubMed]
37. Niu, C.; Liu, L.; Farouk, A.; Chen, C.; Ban, Z. Coating of Layer-by-Layer Assembly Based on Chitosan and CMC: Emerging Alternative for Quality Maintenance of Citrus Fruit. *Horticulturae* **2023**, *9*, 715. [CrossRef]
38. Lieu, D.; Dang, T.; Nguyen, H. Protein and polysaccharide edible coatings: A promising approach for fruits preservation-recent advances. *Food Chem. X* **2025**, *27*, 102388. [CrossRef]
39. Zhang, K.; Jin, Z.; Wang, M.; Wei, Z. Construction of bilayer emulsion gel with composite essential oils based on A-type gelatin and gum arabic: Potential application in food preservation. *Food Res. Int.* **2025**, *222*, 117807. [CrossRef]
40. Gürler, N. Development of chitosan/gelatin/starch composite edible films incorporated with pineapple peel extract and aloe vera gel: Mechanical, physical, antibacterial, antioxidant, and sensorial analysis. *Polym. Eng. Sci.* **2022**, *63*, 426–440. [CrossRef]
41. Kaur, N.; Somasundram, C.; Razali, Z.; Ahmed, Z. Sustainable Aloe vera/chitosan-based edible coatings reduce postharvest loss of stored fresh figs (*Ficus carica* L.). *Front. Sustain. Food Syst.* **2024**, *8*, 1459600. [CrossRef]
42. Selim, M.A.A.; Nagy, K.S.A.; Mohamed, Z.S. Influence of Packaging and Cold Storage Conditions on the Physio-Chemical Properties of Barhi Date Fruits. *Assiut J. Agric. Sci.* **2020**, *51*, 44. [CrossRef]
43. Vieira, J.M.; Flores-López, M.L.; Rodríguez, D.J.; Sousa, M.C.; Vicente, A.A.; Martins, J.T. Effect of Chitosan–Aloe Vera Coating on Postharvest Quality of Blueberry (*Vaccinium corymbosum*). *Fruit. Postharvest Biol. Technol.* **2016**, *116*, 88–97. [CrossRef]
44. Barik, M.; Bhagyaraj, G.; Dash, K.; Shams, R. A thorough evaluation of chitosan-based packaging film and coating for food product shelf-life extension. *J. Agric. Food Res.* **2024**, *16*, 101164. [CrossRef]
45. Ghasemizad, S.; Pirsa, S.; Amiri, S.; Abdosatari, P. Optimization and Characterization of Bioactive Biocomposite Film Based on Orange Peel Incorporated with Gum Arabic Reinforced by Cr_2O_3 Nanoparticles. *J. Polym. Environ.* **2021**, *30*, 2493–2506. [CrossRef]
46. Said, N.; Sarbon, N. Physical and Mechanical Characteristics of Gelatin-Based Films as a Potential Food Packaging Material: A Review. *Membranes* **2022**, *12*, 442. [CrossRef]
47. Pinzón, M.; Garcia, O.; Villa, C. The influence of Aloe vera gel incorporation on the physicochemical and mechanical properties of banana starch-chitosan edible films. *J. Sci. Food Agric.* **2018**, *98*, 4042–4049. [CrossRef]
48. Al-Qurashi, A.D.; Awad, M.A. Quality Characteristics of Bisir "Barhee" Dates during Cold Storage as Affected by Postharvest Dipping in Gibberellic Acid, Naphthaleneacetic Acid and Benzyladenine. *Fruits* **2011**, *66*, 343–352. [CrossRef]
49. McGuire, R.G. Reporting of Objective Color Measurements. *HortScience* **1992**, *27*, 1254–1255. [CrossRef]
50. AOAC International. *Official Methods of Analysis*, 22nd ed.; AOAC International: Rockville, MD, USA, 2023.
51. Nielsen, S.S. Phenol-Sulfuric Acid Method for Total Carbohydrates. In *Food Analysis Laboratory Manual*; Food Science Texts Series; Springer: Boston, MA, USA, 2010; pp. 47–53.
52. Miller, G.L. Use of Dinitrosalicylic Acid Reagent for Determination of Reducing Sugar. *Anal. Chem.* **1959**, *31*, 426–428. [CrossRef]
53. Kähkönen, M.P.; Hopia, A.I.; Vuorela, H.J.; Rauha, J.-P.; Pihlaja, K.; Kujala, T.S.; Heinonen, M. Antioxidant Activity of Plant Extracts Containing Phenolic Compounds. *J. Agric. Food Chem.* **1999**, *47*, 3954–3962. [CrossRef]

54. Taira, S.; Ono, M. Reduction of Astringency in Persimmon Caused by Adhesion of Tannins to Cell Wall Fragments. *Acta Hortic.* **1996**, *436*, 235–242. [CrossRef]
55. Wellburn, A.R. The Spectral Determination of Chlorophylls a and b, as well as Total Carotenoids, Using Various Solvents with Spectrophotometers of Different Resolution. *J. Plant Physiol.* **1994**, *144*, 307–313. [CrossRef]
56. Sadeghi, B.; Abdossi, V.; Zarrinnia, V.; Hasanzadeh, N. Evaluation of the Effect of Biological Elicitors on the Resistance to Salinity Stress in the Date Palm (*Phoenix dactylifera* L., Cv Stameran). *Acta Sci. Pol. Hortorum Cultus* **2023**, *22*, 103–113. [CrossRef]
57. Hammerschmidt, R.; Nuckles, E.M.; Kuć, J. Association of Enhanced Peroxidase Activity with Induced Systemic Resistance of Cucumber to *Colletotrichum lagenarium*. *Physiol. Plant Pathol.* **1982**, *20*, 73–82. [CrossRef]
58. Hagerman, A.E.; Austin, P.J. Continuous Spectrophotometric Assay for Plant Pectin Methyl Esterase. *J. Agric. Food Chem.* **1986**, *34*, 440–444. [CrossRef]
59. Gregory, R.; Bendall, D. The Purification and Some Properties of the Polyphenol Oxidase from Tea (*Camellia sinensis* L.). *Biochem. J.* **1966**, *101*, 569–581. [CrossRef] [PubMed]
60. Peters, M.S.; Timmerhaus, K.D.; West, R.E. *Plant Design and Economics for Chemical Engineers*, 5th ed.; McGraw-Hill Education: New York, NY, USA, 2003.
61. Snedecor, G.W.; Cochran, W.G. *Statistical Methods*, 7th ed.; Iowa State University Press: Ames, IA, USA, 1990; p. 593.
62. Jolliffe, I.T. Generalizations and Adaptations of Principal Component Analysis. In *Principal Component Analysis*; Jolliffe, I.T., Ed.; Springer Series in Statistics; Springer: New York, NY, USA, 1986; pp. 223–234, ISBN 978-1-4757-1904-8.
63. Michie, M.G. Use of the Bray-Curtis Similarity Measure in Cluster Analysis of Foraminiferal Data. *J. Int. Assoc. Math. Geol.* **1982**, *14*, 661–667. [CrossRef]
64. Afonso, S.; Oliveira, I.; Ribeiro, C.; Vilela, A.; Meyer, A.S.; Gonçalves, B. Innovative edible coatings for postharvest storage of sweet cherries. *Sci. Hortic. Amst.* **2023**, *310*, 111738. [CrossRef]
65. Zhang, Y.L.; Cui, Q.L.; Wang, Y.; Shi, F.; Liu, Y.P.; Liu, J.L.; Nie, G.W. Effect of Carboxymethyl Chitosan-Gelatin-Based Edible Coatings on the Quality and Antioxidant Properties of Sweet Cherry during Postharvest Storage. *Sci. Hortic. Amst.* **2021**, *289*, 110462. [CrossRef]
66. Miteluț, A.C.; Popa, E.E.; Drăghici, M.C.; Popescu, P.A.; Popa, V.I.; Bujor, O.C.; Ion, V.A.; Popa, M.E. Latest Developments in Edible Coatings on Minimally Processed Fruits and Vegetables: A Review. *Foods* **2021**, *10*, 12821. [CrossRef]
67. Abdelkarim, D.O.; Mohamed Ahmed, I.A.; Ahmed, K.A.; Younis, M.; Yehia, H.M.; Zein El-Abedein, A.I.; Alhamdan, A. Extending the shelf life of fresh khalal Barhi dates via an optimized postharvest ultrasonic treatment. *Plants* **2022**, *11*, 2029. [CrossRef]
68. Magri, A.; Landi, N.; Capriolo, G.; Maro, A.; Petriccione, M. Effect of Active Layer-by-Layer Edible Coating on Quality, Biochemicals, and the Antioxidant System in Ready-to-Eat 'Williams' Pear Fruit during Cold Storage. *Postharvest Biol. Technol.* **2024**, *212*, 112873. [CrossRef]
69. Wojdyło, A.; Oszmiański, J. Antioxidant Activity Modulated by Polyphenol Contents in Apple and Leaves during Fruit Development and Ripening. *Antioxidants* **2020**, *9*, 567. [CrossRef]
70. Ahmed, Z.F.R.; Al Shaibani, F.Y.Y.; Kaur, N.; Maqsood, S.; Schmeda-Hirschmann, G. Improving Fruit Quality, Bioactive Compounds, and Storage Life of Date Palm (*Phoenix dactylifera* L., Cv Barhi) Using Natural Elicitors. *Horticulturae* **2021**, *7*, 293. [CrossRef]
71. Golding, J.B.; Ekman, J.H.; McGlasson, W.B. Regulation of Fruit Ripening. *Stewart Postharvest Rev.* **2005**, *1*, 1–12. [CrossRef]
72. Aloui, H.; Khwaldia, K. Natural Antimicrobial Edible Coatings for Microbial Safety and Food Quality Enhancement. *Compr. Rev. Food Sci. Food Saf.* **2016**, *15*, 1080–1103. [CrossRef] [PubMed]
73. Emam, H.E.; Abdel-Hak, R.S.; Ali, E.A.M.; Amin, O.A.; El-Moniem, E.A.A.A. Prolonging Post-Harvest Quality and Storage Life of Pomegranate Wonderful as Affected by Arabic Gum and Different Edible Coatings. *Int. J. Health Sci. Qassim* **2022**, *6*, 3715–3734. [CrossRef]
74. Arnon-Rips, H.; Poverenov, E. Improving Food Products' Quality and Storability by Using Layer by Layer Edible Coatings. *Trends Food Sci. Technol.* **2018**, *75*, 81–92. [CrossRef]
75. Hossain, M.; Karim, M.; Juthee, S. Postharvest Physiological and Biochemical Alterations in Fruits: A Review. *Fundam. Appl. Agric.* **2020**, *5*, 453–469. [CrossRef]
76. Davey, M.W.; Montagu, M.V.; Inzé, D.; Sanmartin, M.; Kanellis, A.; Smirnoff, N.; Benzie, I.J.J.; Strain, J.J.; Favell, D.; Fletcher, J. Plant L-Ascorbic Acid: Chemistry, Function, Metabolism, Bioavailability and Effects of Processing. *J. Sci. Food Agric.* **2000**, *80*, 825–860. [CrossRef]
77. Mditshwa, A.; Magwaza, L.S.; Tesfay, S.Z.; Opara, U.L. Postharvest Factors Affecting Vitamin C Content of Citrus Fruits: A Review. *Sci. Hortic.* **2017**, *218*, 95–104. [CrossRef]
78. Del Caro, A.; Piga, A.; Vacca, V.; Agabbio, M. Changes of Flavonoids, Vitamin C and Antioxidant Capacity in Minimally Processed Citrus Segments and Juices during Storage. *Food Chem.* **2004**, *84*, 99–105. [CrossRef]
79. Chen, H.; Cao, S.; Fang, X.; Mu, H.; Yang, H.; Wang, X.; Xu, Q.; Gao, H. Changes in Fruit Firmness, Cell Wall Composition and Cell Wall Degrading Enzymes in Postharvest Blueberries during Storage. *Sci. Hortic.* **2015**, *188*, 44–48. [CrossRef]

80. Chen, Z.; He, M.; Zhou, Y.; Chen, X.; Zhu, H.; Yang, B.; Jiang, Y.; Qu, H. Degradation of Water-Soluble Polysaccharides in Pulp of Litchi during Storage. *Food Chem.* **2023**, *402*, 134289. [CrossRef] [PubMed]
81. Hassan, A.H.; Omar, A.S.M.; Ibrahim, M.A. Pre and post-harvest studies on Barhi date. *J. Plant Prod.* **2024**, *15*, 541–549. [CrossRef]
82. Chisari, M.; Barbagallo, R.N.; Spagna, G. Characterization of Polyphenol Oxidase and Peroxidase and Influence on Browning of Cold Stored Strawberry Fruit. *J. Agric. Food Chem.* **2007**, *55*, 3469–3476. [CrossRef]
83. Ding, K.; Wang, Y.; Wang, H.; Yuan, L.; Tan, M.; Shi, X.; Lyu, Z.; Liu, Y.; Chen, H. 6-O-Sulfated Chitosan Promoting the Neural Differentiation of Mouse Embryonic Stem Cells. *ACS Appl. Mater. Interfaces* **2014**, *6*, 20043–20050. [CrossRef]
84. Tomás-Barberán, F.A.; Espín, J.C. Phenolic Compounds and Related Enzymes as Determinants of Quality in Fruits and Vegetables. *J. Sci. Food Agric.* **2001**, *81*, 853–876. [CrossRef]
85. Shao, X.; Wang, H.; Xu, F.; Cheng, S. Effects and Possible Mechanisms of Tea Tree Oil Vapor Treatment on the Main Disease in Postharvest Strawberry Fruit. *Postharvest Biol. Technol.* **2013**, *77*, 94–101. [CrossRef]
86. Biles, C.L.; Martyn, R.D. Peroxidase, Polyphenoloxidase, and Shikimate Dehydrogenase Isozymes in Relation to Tissue Type, Maturity and Pathogen Induction of Watermelon Seedlings. *Plant Physiol. Biochem.* **1993**, *31*, 499–506.
87. Deng, Y.; Wu, Y.; Li, Y. Changes in Firmness, Cell Wall Composition and Cell Wall Hydrolases of Grapes Stored in High Oxygen Atmospheres. *Food Res. Int.* **2005**, *38*, 769–776. [CrossRef]
88. Abo-Elyousr, K.A.M.; Al-Qurashi, A.D.; Almasoudi, N.M. Evaluation of the Synergy between Schwanniomyces Vanrijiae and Propolis in the Control of Penicillium Digitatum on Lemons. *Egypt. J. Biol. Pest. Control* **2021**, *31*, 66. [CrossRef]
89. Maftoonazad, N.; Badii, F. Use of Edible Films and Coatings to Extend the Shelf Life of Food Products. *Recent. Pat. Food Nutr. Agric.* **2009**, *1*, 162–170. [CrossRef]
90. Alali, A.A.; Awad, M.A.; Al-Qurashi, A.D.; Mohamed, S.A. Postharvest Gum Arabic and Salicylic Acid Dipping Affect Quality and Biochemical Changes of 'Grand Nain' Bananas during Shelf Life. *Sci. Hortic.* **2018**, *237*, 51–58. [CrossRef]
91. Jurić, S.; Bureš, M.; Vlahoviček-Kahlina, K.; Stracenski, K.; Fruk, G.; Jalšenjak, N.; Bandić, L. Chitosan-based layer-by-layer edible coatings application for the preservation of mandarin fruit bioactive compounds and organic acids. *Food Chem.* **2023**, *17*, 100575. [CrossRef]
92. Tahir, H.; Zou, X.; Shi, J.; Mahunu, G.K.; Zhai, X.; Mariod, A. Quality and postharvest-storage life of cold-stored strawberry fruit as affected by gum arabic (*Acacia senegal*) edible coating. *J. Food Biochem.* **2018**, *42*, 12527. [CrossRef]
93. Aboryia, M.; Omar, A. Effectiveness of Some Edible Coatings on Storage Ability of Zaghloul Date Palm Fruits. *J. Plant Prod. Mansoura Univ.* **2020**, *11*, 1477–1485. [CrossRef]
94. Ghafoor, K.; Al-Juhaimi, F.Y.; Babiker, E.E.; Sarker, M.Z.I.; Ahmed, I.A.M. Effects of Functional Edible Coatings and Storage on Bioactive Compounds, Antioxidant Properties and Sugars in Barhi Dates. *Horticulturae* **2022**, *8*, 1185. [CrossRef]