

Research Article

The Effect of Edible Coatings in the Preservation of Green OlivesTryfon Kekes ^{†, *}, Constantina Tzia ^{†, *}

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Abstract

The primary objective of the present work was to evaluate the effect of edible coatings in the preservation of green olives. Two different polysaccharides (chitosan and pectin) and a mixture of them were used as edible coatings on table green olives, which were subsequently packaged under modified atmosphere conditions and stored at three temperatures (4, 20, and 40°C). During storage, the weight loss, color change, texture, pH, salinity, acidity, as well as the sensory characteristics of the olives were evaluated. Edible coatings proved to significantly contribute to preserving olive quality by limiting physicochemical and sensory alterations during storage. Pectin showed the strongest preservation performance, limiting weight loss to approximately 1.52% compared with 2.7% for the uncoated samples after 42 days at 4°C, while ΔE remained below 2 throughout storage. Kinetic analysis using the Arrhenius model confirmed that edible coatings decreased the rate of sensory degradation and extended the predicted shelf life of the olives, with pectin coatings showing the greatest increase in shelf life (111 days for pectin-coated olives at 4°C, compared with 64 days for the



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uncoated samples). Overall, the results highlight the potential of pectin-based edible coatings, particularly pectin alone, as a practical natural preservation approach for the food industry. Their application in combination with modified atmosphere packaging may contribute to maintaining the quality, sensory acceptability and commercial shelf stability of green table olives during storage.

Keywords

Olives; edible coatings; chitosan; pectin; food preservation

1. Introduction

Table olives are among the most important traditional products of the Mediterranean diet, with high economic value for the producing countries [1, 2]. They contain significant content of monounsaturated fatty acids (oleic acid), phenolic compounds, and antioxidant components (oleuropein, hydroxytyrosol, and tyrosol), which contribute both to their nutritional value and to their particular sensory characteristics [3-5]. Despite these advantages, table olives are a product sensitive to changes during storage, as physicochemical and microbiological processes lead to alterations such as changes in pH, acidity, color, texture, and sensory characteristics [6, 7]. Additionally, higher storage temperatures accelerate these processes, reducing the product's shelf life and commercial value [8, 9]. Therefore, the development of effective and mild preservation technologies is a key challenge for the food industry. Phenolic compounds like oleuropein, hydroxytyrosol, and tyrosol give table olives their signature bitter, tangy flavor. However, as these compounds oxidize over time, the olives can lose their vibrant color and fresh taste. Using smart preservation techniques to block oxidation keeps the olives physically fresh while protecting the rich flavors consumers actually want to taste.

In recent years, there has been growing interest in using edible coatings as alternative or complementary methods to enhance food preservation [10-13]. Edible coatings form a thin, biodegradable film on the surface of the food, which acts as a semi-permeable barrier against the transport of gases, water vapor and dissolved substances [11, 14, 15]. Thus, oxidation, moisture loss and microbial growth are limited, leading to improved quality maintenance and extended shelf life [14]. Edible coatings for fruits and vegetables have proven particularly effective at preserving texture, color, and sensory characteristics while also supporting the modern trend toward natural, sustainable food packaging solutions [16-18].

Among the biopolymers used for the production of edible coatings, chitosan and pectin are of particular interest due to their functional properties [19, 20]. Chitosan is a natural polysaccharide with antimicrobial activity and film-forming ability, helping reduce microbial growth and maintain the structural integrity of foods [15, 21, 22]. On the other hand, pectin, as a plant-derived hydrocolloid, exhibits excellent barrier properties against oxygen and moisture loss, which is associated with improved color and texture stability [13]. Previous studies have shown that the application of pectin or chitosan coatings to olives contributes to the maintenance of key quality characteristics and an increase in shelf life, while their combination may offer complementary advantages due to a synergistic effect [23-26]. Researchers investigated the combination of chitosan

and pectin because the complementary functional properties of chitosan and pectin might give better barrier and preservation performance than either chitosan or pectin alone. However, a synergistic effect cannot be assumed before the experiment because interactions between the biopolymers chitosan and pectin can also change the film structure and therefore affect the barrier and preservation properties of chitosan and pectin.

Modified atmosphere packaging (MAP) is one of the most important food preservation methods that maintain the natural quality and extend the storage life of fruits and vegetables. The modification of carbon dioxide and oxygen concentrations in the packages could help to maintain freshness and visual appearance of fresh produce by reducing respiration and ethylene production, and/or physiological and pathological deterioration during storage. Furthermore, the combination of edible coatings with modified atmosphere packaging has been proposed as an effective strategy to optimize the preservation of table olives [6, 27]. In a previous study on the preservation of table olives using edible coatings such as chitosan and hydroxypropyl methylcellulose (HPMC) in combination with MAP (N_2 and CO_2/N_2), chitosan was found to be an effective coating material, as well as a modified atmosphere with a mixture of CO_2 and N_2 for packaging [27].

The primary aim of the current study was to evaluate the effect of pectin, chitosan and their mixture as edible coating materials, on the preservation of the quality of green table olives packaged under modified atmosphere (CO_2/N_2) during storage at different temperatures (4, 20, and 40°C). The evaluation determined physicochemical and sensory parameters, including weight loss, color change, texture, pH, acidity, salinity and overall acceptance, while Arrhenius kinetic analysis was applied to predict the shelf life of the product based on their sensory behavior. Although previous studies have demonstrated the potential of chitosan- and pectin-based coatings for food preservation, limited information is available regarding their comparative performance and the effect of their combination on the physicochemical and sensory stability of green table olives under modified atmosphere packaging across a broad temperature range. The study aims to highlight effective natural preservation methods that can contribute to improving the stability and commercial value of table olives.

2. Materials and Methods

2.1 Materials

The green olives and packaging materials were kindly provided by GAEA (Athens, Greece) and VLACHOS BROS. S.A. (Markopoulo, Greece), respectively. High molecular weight Chitosan (Sigma-Aldrich, product no. 419419; degree of deacetylation >75%; viscosity 800-2000 cP at 1 wt.% in 1% acetic acid, 25°C), pectin (Sigma-Aldrich, product no. 93854; degree of esterification 50-75%), and acetic acid were purchased from Sigma-Aldrich Chemical Co. (St. Louis, MO). All the other reagents used in the experiments were of analytical grade.

2.2 Preparation of Edible Coatings

2.2.1 Chitosan 1% w/v

An appropriate quantity of chitosan was weighed to achieve a concentration of 1% w/v and was placed in a beaker. Subsequently, deionized water and an appropriate quantity of acetic acid (60%

w/v) were transferred into the beaker to achieve a final acetic acid concentration of 1% w/v. The mixture was then heated under continuous stirring at 60°C for 20 min, and was then left to mix at 50°C for 24 h. No pH adjustment was performed after preparation of the chitosan solution.

2.2.2 Pectin 1% w/v

An appropriate quantity of pectin was weighed to achieve a concentration of 1% w/v and was placed in a beaker. Subsequently, deionized water was transferred into the beaker, and the mixture was continuously stirred at room temperature until it was completely homogenized.

2.2.3 Pectin-Chitosan (1:1) 1% w/v

The mixtures of the individual edible coatings were prepared following the same methodology as previously described. Subsequently, equal volumes of the two mixtures were mixed, and the resultant mixture was continuously stirred at room temperature for 1 h to be totally homogenized.

2.3 Application of Edible Coatings

Olives were initially stored in plastic bottles fully covered with brine. To decrease the content of initial salinity, brine was removed from the bottles, olives were rinsed three times with water, and then were covered in water for 4 hours. Subsequently, water was drained and olives were placed in filter paper to remove the excess humidity. Each coating solution was left to reach room temperature after its preparation and before its application. Then, the olives were immersed in the edible coating solution and stirred for 2 minutes. Finally, they were removed from it and left to dry under ambient laboratory ($T = 25^{\circ}\text{C}$) conditions until the following day (approximately 18-24 h). Blank samples were maintained in the same conditions and were packaged without any pretreatment.

2.4 Modified Atmosphere Packaging

The BOSS NT42N device was used to fill the package with the modified atmosphere, operated under the following conditions:

- Gas composition: 70% N_2 , 30% CO_2
- Vacuum time: 20 s
- Gas insertion time: 9.9 s
- Sealing time: 3.9 s

The packaging material was placed in the slots of the aforementioned machine, and after the air was removed from its interior, the desired gas composition was inserted. PET/AL/PE doypack bags (12 μm /7 μm /80 μm) were used as packaging material.

The PET/AL/PE multilayer structure was selected because of its high barrier properties, particularly those associated with the aluminum layer. Gas transmission rates for O_2 and CO_2 were not experimentally determined for the specific packaging material used in this study and are therefore not reported.

2.5 Measurements

2.5.1 Weight Loss

The determination of the sample's weight was carried out using a precision analytical balance (± 0.001 g) at the beginning of storage and at each predetermined sampling time. The % weight loss was calculated using equation 1:

$$\% \text{ Weight Loss} = \frac{\text{Initial Weight (g)} - \text{Weight at predetermind samplint time (g)}}{\text{Initial Weight (g)}} \times 100\% \quad (1)$$

2.5.2 Color Difference (ΔE)

Color evaluations were performed with a MINOLTA CR-200 colorimeter (Minolta, Osaka, Japan), which determined the color parameters L, a and b of the Cielab color scale, with illuminant D65 and a 2° standard observer. L corresponds to lightness, a to redness and b to yellowness. Equation 2 was used to calculate the total change in optical response (ΔE) and is a function of L, a and b:

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \quad (2)$$

where L_0 , a_0 , and b_0 are the initial values of the color parameters.

2.5.3 Hardness

For the evaluation of the olives' hardness, the TA-XT2 texture analyzer (Stable Microsystems, Surrey, UK) with a specialized cutting blade (TA-45 craft knife) was used. Olives were cut so that one surface was flat and placed in the center of the analyzer under the following test conditions: speed: 3 mm/s; penetration distance: 15 mm. The peak compression force was reported as hardness (N).

For the subsequent analyses, olive pulp was used, which was prepared using a mixer. Specifically, 4-5 olives, from which the olive stone has been removed, are placed inside the mixer and are mixed until a homogeneous mixture is obtained.

2.5.4 pH

We weighed 2 g of olive pulp and placed it in a beaker, then added 10 mL of deionized water. Subsequently, the value of pH was measured using an electronic pH meter.

2.5.5 Acidity

Initially, 2 g of olive pulp was weighed and placed in a 250 mL beaker, then 100 mL of deionized water. Subsequently, phenolphthalein indicator was added to the solution, and titration was carried out with 0.1 N sodium hydroxide (NaOH) solution. Titration ended at the point where the color of the solution changed from off-white cloudy to pink. The acidity was calculated using Equation 3:

$$\text{Acidity (\%w/w oleic acid)} = \frac{(\text{mL NaOH 0.1 N}) \times 0.1 \times 282}{10 \times \text{Sample Weight (g)}} \quad (3)$$

2.5.6 Salinity

Initially, 0.5 g of olive pulp was weighed and placed in a 250 mL beaker, followed by the addition of 100 mL of deionized water. Subsequently, indicator K_2CrO_4 5% w/v was added to the solution, and titration was carried out with 0.1 N silver nitrate ($AgNO_3$) solution. Titration ended at the point where the color of the solution changed from yellow to slightly reddish brown. The salinity was calculated using Equation 4:

$$\text{Salinity (\%w/w sodium chloride)} = \frac{(\text{mL } AgNO_3 \text{ 0.1 N}) \times 0.05845 \times 10}{10 \times \text{Sample Weight (g)}} \quad (4)$$

2.5.7 Overall Liking

For the determination of the sensory characteristics of the olive samples, a dedicated sensory test form was filled out by each participant. All relevant sensory characteristics (appearance, color, hardness, odor, taste, aroma, and overall liking) were studied.

Ten panelists assessed the sensory attributes of the olive samples. They had been trained in the sensory analysis lexicon and methodology and had prior experience in assessing olive samples. They were asked to evaluate each sample for color, appearance, flavor, texture, taste, and overall acceptability using a nine-point hedonic scale ranging from like extremely (9) to dislike extremely (1) for each sensory characteristic. Although the panel size is fairly small for making conclusions about how the general population might react, the people testing had previous experience with the evaluation of olives. Because of this, the results were mainly used to compare how quality changed between treatments. These results were not meant to show what most people like or dislike in general.

In addition to the overall liking score, the trained panelists evaluated each individual sensory attribute separately, including appearance, color, hardness, odor, taste, aroma, and texture. The use of trained assessors allowed a more reliable and analytical evaluation of the sensory profile of the olive samples and facilitated the interpretation of the relationship between sensory perception and physicochemical measurements.

Particular emphasis was given to the correlation between instrumental and sensory characteristics. Specifically, higher hardness values measured by texture analysis were associated with improved texture acceptability, as firmer olives were perceived as fresher and of higher quality. Similarly, lower color difference values (ΔE), indicating better preservation of the green color of the olives, were positively associated with appearance and color acceptability. Increased discoloration and darkening of the olive surface negatively affected the visual quality and consequently reduced the overall sensory acceptance of the samples.

Furthermore, increased weight loss and pH changes were associated with deterioration of texture and flavor perception, while the preservation of acidity contributed positively to the characteristic sensory profile of green olives. Therefore, the sensory evaluation results were closely linked with the instrumental measurements, confirming that the physicochemical stability provided by edible coatings directly contributed to improved consumer-perceived quality and overall acceptability during storage.

2.5.8 Arrhenius Model

The change in the overall liking of the samples with storage time is satisfactorily described by zero-order kinetics, as described by Equation 5:

$$S = S_0 - k \times t \quad (5)$$

where S is the overall liking value at storage time t , S_0 is the initial overall liking value, and k is the constant rate of overall liking decrease (d^{-1}).

The dependence of the rate of decrease of the overall liking for all samples can be evaluated by applying the Arrhenius equation and assessing the activation energy through Equation 6:

$$\ln(k) = \ln(k_{ref}) - \frac{E_a}{R} \times \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \quad (6)$$

where k is the constant rate of overall liking decrease (d^{-1}), T is the temperature (K), T_{ref} is the reference temperature (298.15 K), k_{ref} is the constant rate of overall liking decrease at the reference temperature (d^{-1}), R is the universal gas constant (J/mol*K), and E_a is the activation energy (J/mol).

The activation energy expresses the sensitivity of a phenomenon to temperature changes, with higher activation energy values indicating a stronger dependence of the degradation rate on temperature, whereas the magnitude of the degradation rate is determined by the corresponding kinetic rate constant. The goodness of fit of the kinetic models was evaluated using the coefficient of determination (R^2), adjusted coefficient of determination (adjusted R^2), and root mean square error (RMSE). R^2 represents the proportion of variability in the experimental data explained by the fitted model, whereas adjusted R^2 accounts for the number of model predictors and observations. RMSE quantifies the average magnitude of the residual error between the experimental and model-predicted values, expressed in the same units as the response variable. Accordingly, higher R^2 and adjusted R^2 values together with lower RMSE values were considered indicative of better model performance.

3. Results and Discussion

3.1 Acidity

Figure 1 depicts the evolution of acidity of all samples across the different storage temperatures.

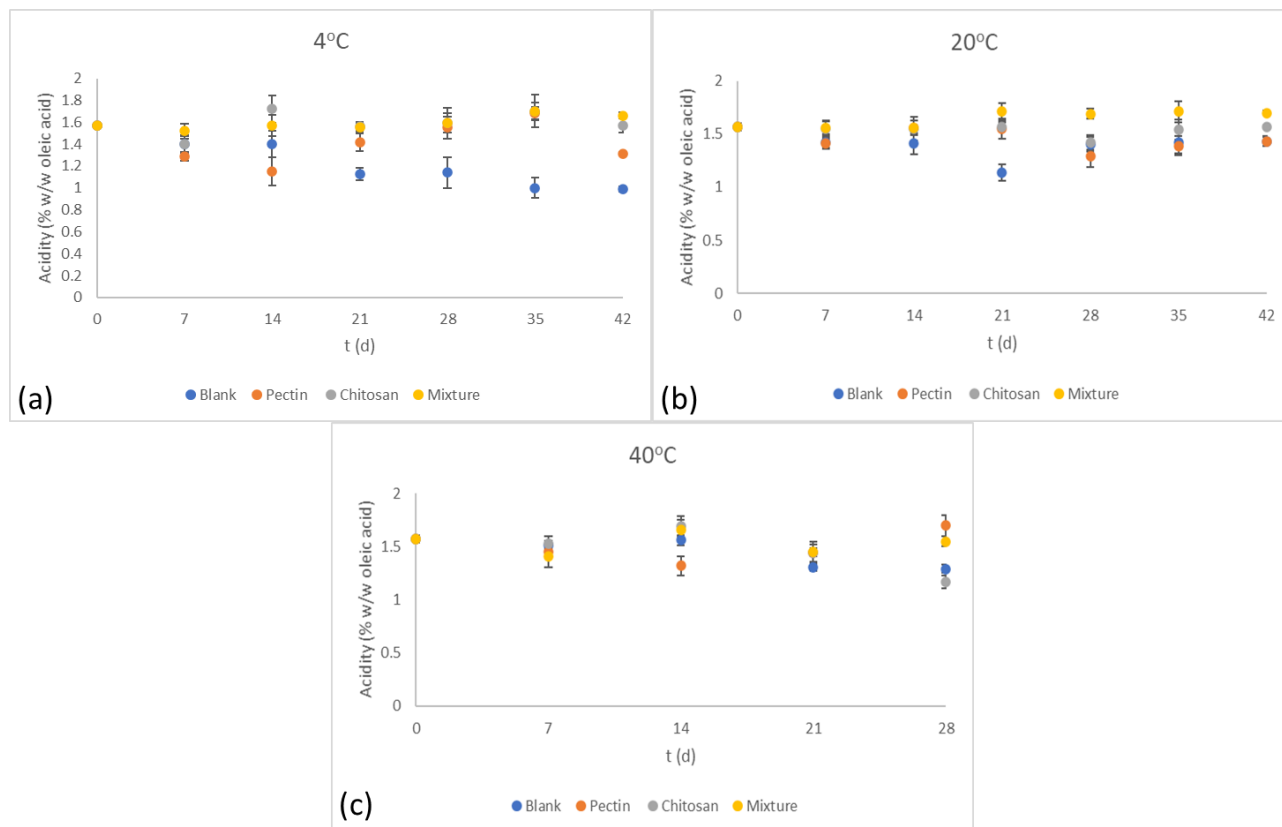


Figure 1 Effect of edible coatings in the acidity of green olives.

The evolution of acidity during storage indicated distinct differences among the applied edible coatings, demonstrating that edible coatings significantly influenced the chemical stability of green olives, with an initial acidity value of 1.57% w/w oleic acid. During storage, the blank samples exhibited a gradual and continuous decrease in acidity, reaching approximately 0.99% w/w oleic acid after 42 days at 4°C. The observed reduction may be attributed to progressive biochemical degradation processes, including possible microbial activity and diffusion of organic acids into the surrounding medium, which are commonly associated with quality deterioration in minimally protected products [28].

In contrast, the coated samples maintained higher acidity values throughout storage, demonstrating the protective role of edible coatings. Pectin-coated olives exhibited an overall increasing trend, reaching a maximum value near 1.68% w/w oleic acid at day 35 at a storage temperature of 4°C before showing a slight decline towards the end of storage. This observation may reflect changes in the distribution and diffusion of organic acids between the olive tissue and the surrounding phase rather than net acid formation. Interactions between the pectin coating and the olive surface may also have temporarily affected mass-transfer behavior. Chitosan-coated olives and those treated with the pectin-chitosan mixture also maintained acidity more effectively than the control, maintaining values above 1.55% for most of the storage period and showing only minor

fluctuations. The retention of acidity may be attributed to the barrier properties of polysaccharide coatings, which likely limited mass transfer phenomena, reduced oxygen permeability, and slowed the metabolic and microbial activity responsible for acid consumption [23, 28].

Storage temperature strongly influenced acidity evolution. At 4°C, acidity remained relatively stable for all treatments, indicating reduced biochemical activity and limited organic acid degradation under refrigerated conditions. At 20°C, acidity changes became more pronounced, particularly in blank samples, reflecting accelerated degradation reactions, while coated olives maintained higher acidity values. At 40°C, acidity decreased much more rapidly, especially in uncoated olives, indicating intensified biochemical deterioration under thermal stress. Nevertheless, coated samples retained significantly higher acidity across all temperatures, with pectin showing the greatest stabilization effect. Overall, increasing temperature accelerated acid loss, while edible coatings mitigated temperature sensitivity and improved chemical preservation.

3.2 Salinity

Figure 2 depicts the evolution of salinity of all samples across the different storage temperatures.

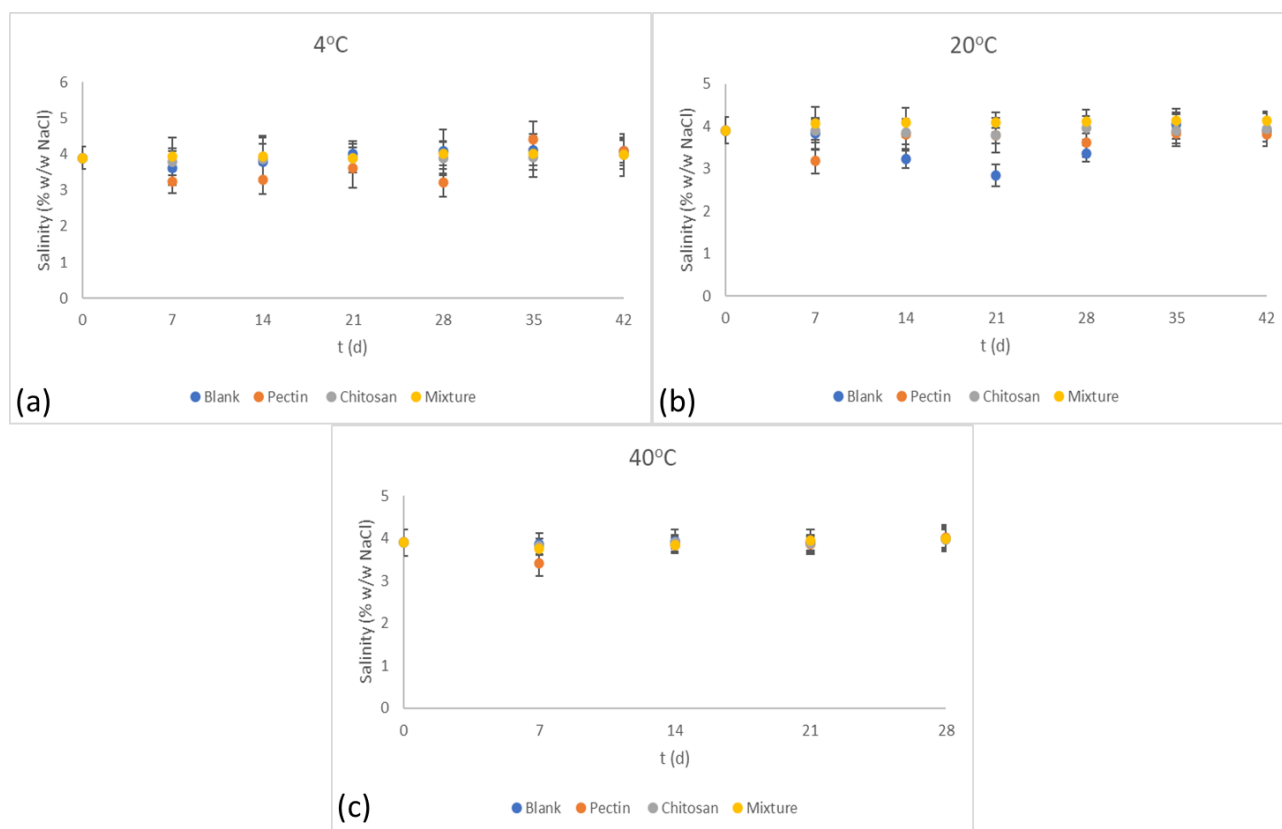


Figure 2 Effect of edible coatings in the salinity of green olives.

Salinity changes are attributed to the solute exchange between olive tissue and the surrounding environment during storage, highlighting the influence of edible coatings on mass-transfer phenomena. The control samples exhibited a gradual increase in salinity from 3.9% to approximately 4.08%, suggesting moisture loss and concentration effects as storage progressed. This increase may also reflect osmotic balance adjustments between the olive pulp and the surrounding medium [29].

Conversely, the coated samples showed moderated fluctuations in salinity throughout storage, indicating improved regulation of ion migration. Pectin-coated olives maintained comparatively lower salinity values during the early storage stages, while chitosan-coated olives and the pectin-chitosan mixture stabilized salinity near the initial levels with only minor variations. These findings confirm that edible coatings function as semi-permeable barriers limiting diffusion processes [28, 29].

Temperature significantly affected the salinity evolution. At 4°C, salinity remained relatively stable due to reduced diffusion rates and limited moisture migration. At 20°C, salinity increased moderately, particularly in the control samples, as the higher temperature enhanced osmotic exchange. At 40°C, changes in salinity became more pronounced due to accelerated moisture evaporation and intensified diffusion phenomena. Despite these effects, coated olives maintained comparatively stable salinity values across all temperatures, confirming the ability of edible coatings to reduce temperature-driven compositional changes.

3.3 ΔE

Figure 3 depicts the evolution of color change of all samples across the different storage temperatures.

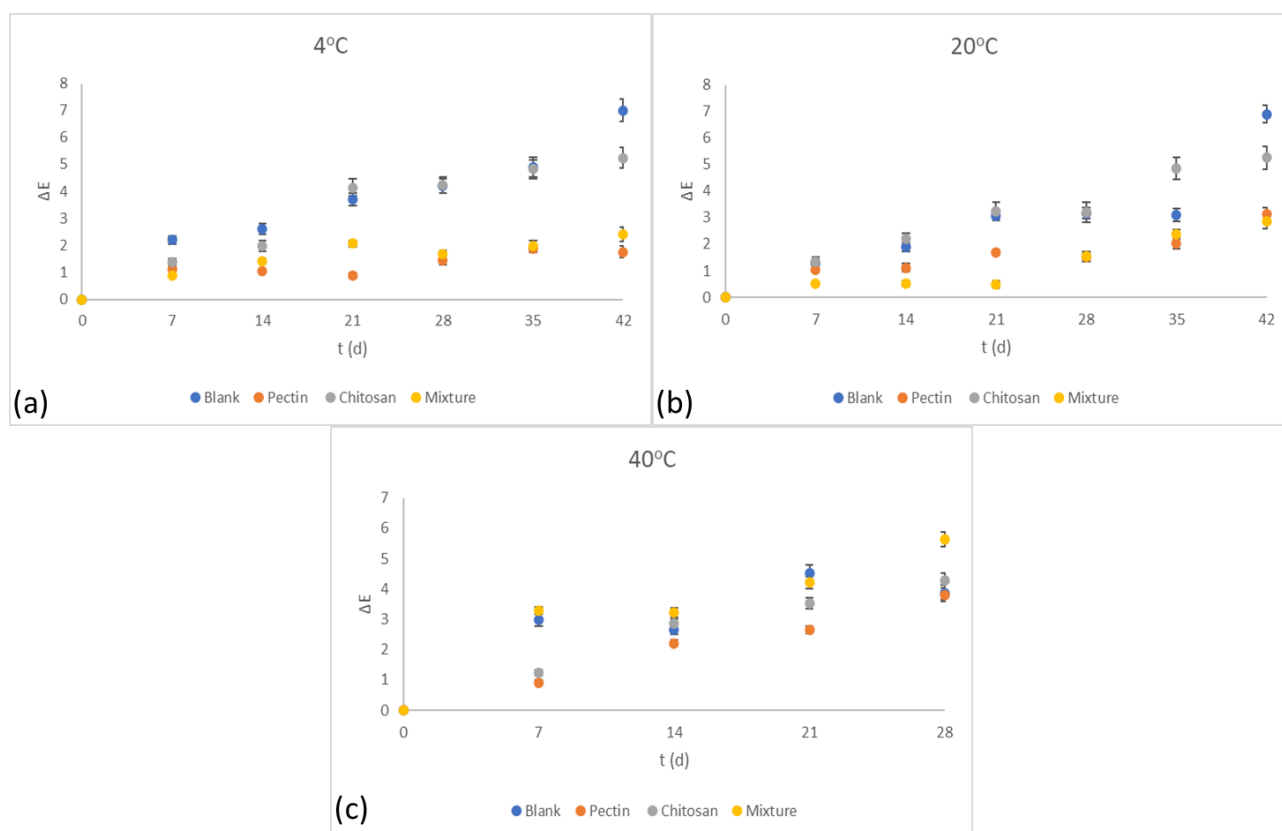


Figure 3 Effect of edible coatings in the color change (ΔE) of green olives.

Color retention is a critical quality parameter influencing consumer acceptance, as visual appearance is often the first attribute evaluated during product selection. All treatments exhibited increasing ΔE values over time, indicating progressive color deterioration during storage; however, the magnitude and rate of change differed significantly among coating treatments. The gradual

increase in color difference suggests ongoing physicochemical reactions, such as pigment oxidation and structural changes within olive tissues, which are typically accelerated without protective barriers.

The blank samples showed the highest color deviation, reaching $\Delta E \approx 7$ after 42 days, reflecting substantial visual degradation and noticeable alterations in surface appearance. In contrast, pectin-coated olives demonstrated remarkable color stability, with ΔE values remaining below 2 throughout storage, indicating lower color change. Chitosan treatment provided moderate protection against discoloration, while the combined pectin-chitosan coating performed better than the control but showed slightly lower stability than pectin alone. These differences suggest that coating composition plays a decisive role in controlling the oxidative and enzymatic processes responsible for color loss [30].

The superior performance of pectin coatings may be associated with their effective oxygen barrier properties, which likely reduced the oxidative reactions responsible for pigment degradation and browning phenomena. Additionally, the coating layer may have limited moisture loss and surface exposure to environmental factors, further contributing to color retention. Overall, these findings highlight the effectiveness of polysaccharide-based edible coatings in maintaining the visual quality of green olives during storage and underline their potential application as natural preservation systems to enhance product marketability [9, 30, 31].

Storage temperature strongly influenced color stability. At 4°C, ΔE values increased slowly for all treatments, indicating that refrigerated storage effectively limited oxidation reactions and enzymatic browning phenomena. The coated samples maintained excellent visual quality under these conditions, with pectin coatings showing minimal color variation throughout storage. At 20°C, color deterioration became more evident, particularly in the blank samples, reflecting accelerated physicochemical reactions compared with refrigerated conditions. The coated olives showed significantly improved stability, confirming the protective barrier effect of the edible coatings under moderate storage temperature. At 40°C, discoloration was markedly accelerated, with the blank samples exhibiting rapid increases in ΔE due to intensified pigment degradation and tissue structural changes. Although coated olives also showed increased color change at elevated temperature, their deterioration rate remained substantially lower than that of the control, demonstrating the ability of edible coatings to mitigate temperature-induced oxidative damage [29].

3.4 Hardness

Figure 4 depicts the evolution of hardness of all samples across the different storage temperatures.

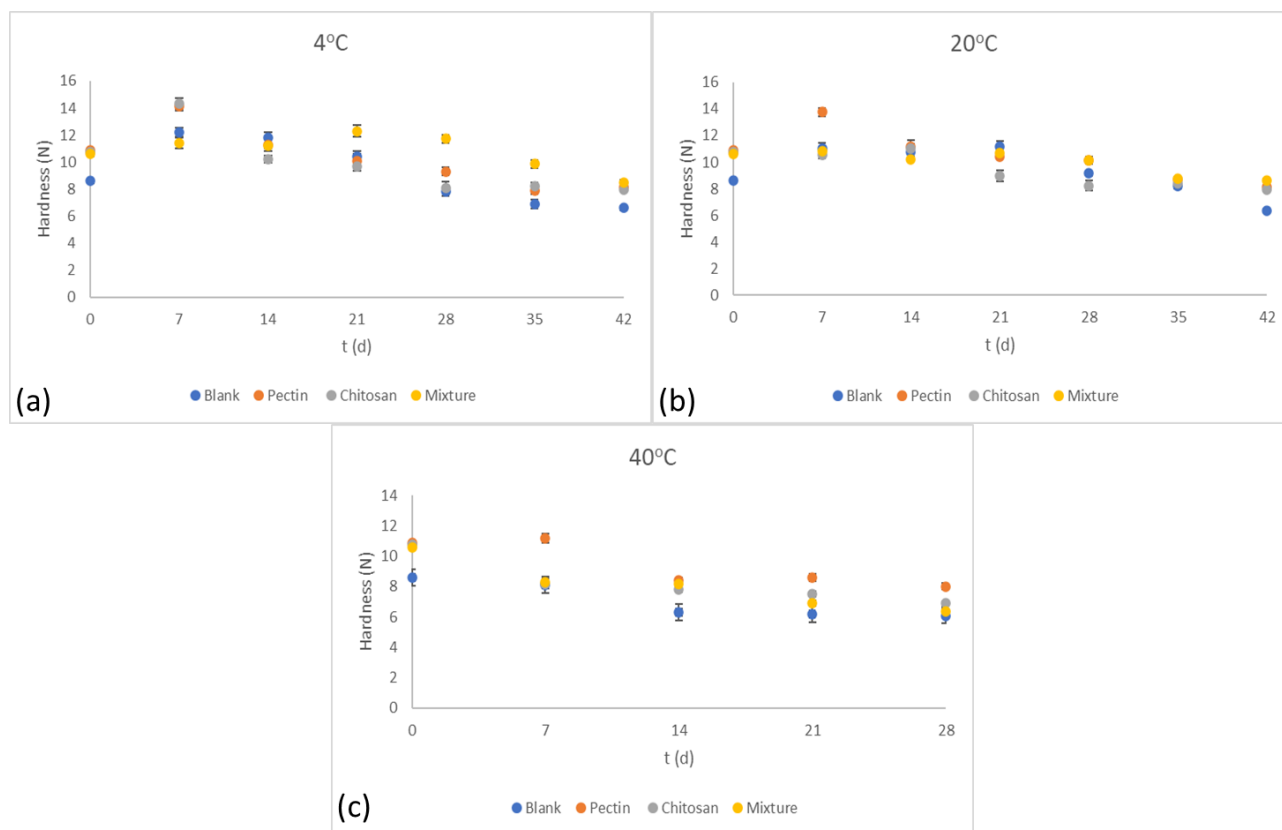


Figure 4 Effect of edible coatings in the hardness of green olives.

Texture analysis revealed a general decline in hardness over storage time, consistent with progressive structural softening of olive tissue. Control samples exhibited the most pronounced reduction in firmness, decreasing from 8.6 N to 6.6 N by day 42 at 4°C, indicating significant loss of structural integrity without protective treatment.

Coated olives initially displayed higher hardness values, suggesting reinforced the tissue structure and protection against mechanical and biochemical deterioration. Pectin-coated olives maintained relatively higher firmness throughout storage, while chitosan-treated samples showed moderate softening. The pectin-chitosan mixture provided improved texture retention during intermediate storage periods, but showed reduced long-term protection compared with pectin alone [32].

Temperature strongly influenced texture degradation. At 4°C, hardness decreased slowly due to reduced enzymatic activity and slower cell wall degradation. At 20°C, softening became more evident, particularly in the control samples, reflecting increased metabolic and enzymatic processes. At 40°C, firmness loss accelerated significantly, indicating rapid structural breakdown under thermal stress [32]. Despite this, coated olives maintained higher hardness values than uncoated samples across all temperatures, with pectin demonstrating the most consistent protective effect.

3.5 pH

Figure 5 depicts the evolution of pH of all samples across the different storage temperatures.

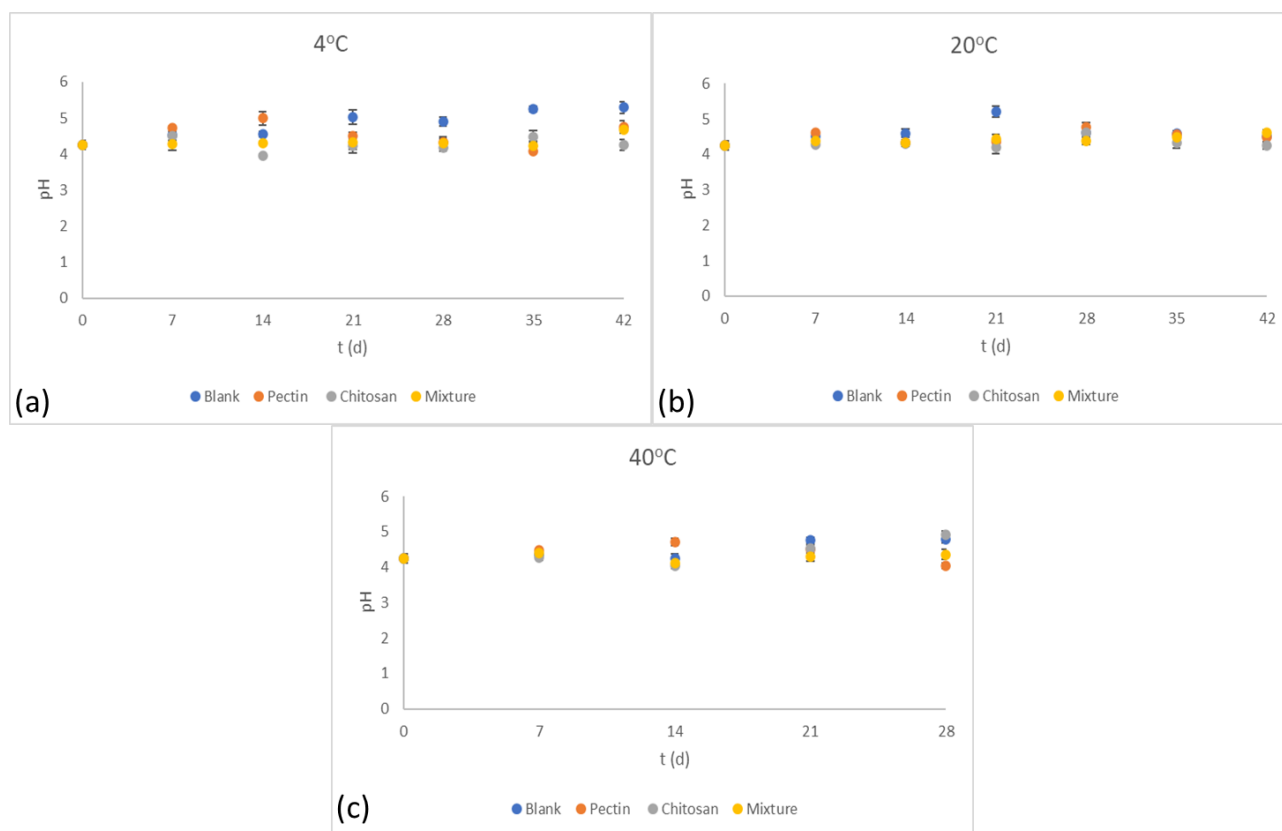


Figure 5 Effect of edible coatings in the pH value of green olives.

The pH values increased in all samples during storage, indicating ongoing biochemical and physicochemical changes accompanied by a gradual reduction in perceived acidity. The blank samples exhibited the largest increase, rising from 4.25 to approximately 5.29, suggesting accelerated quality degradation without protective treatment.

The coated samples showed smaller fluctuations in pH values, demonstrating the stabilizing effect of the edible coatings. The pectin-chitosan mixture maintained the narrowest pH range (4.22 to 4.68), while the pectin and chitosan treatments exhibited intermediate stabilization effects. The coatings likely limited oxygen transfer and moisture loss, reducing physicochemical reactions and microbial activity [23].

Temperature dependence was evident. At 4°C, pH increased only slightly, indicating limited biochemical activity. At 20°C, the increases became more noticeable, especially in the control samples. At 40°C, pH rose rapidly due to intensified spoilage-related reactions. Nevertheless, the coated samples maintained significantly smaller pH variations across all temperatures, confirming their ability to mitigate temperature-induced deterioration.

3.6 Weight Loss

Figure 6 depicts the evolution of weight loss of all samples across the different storage temperatures.

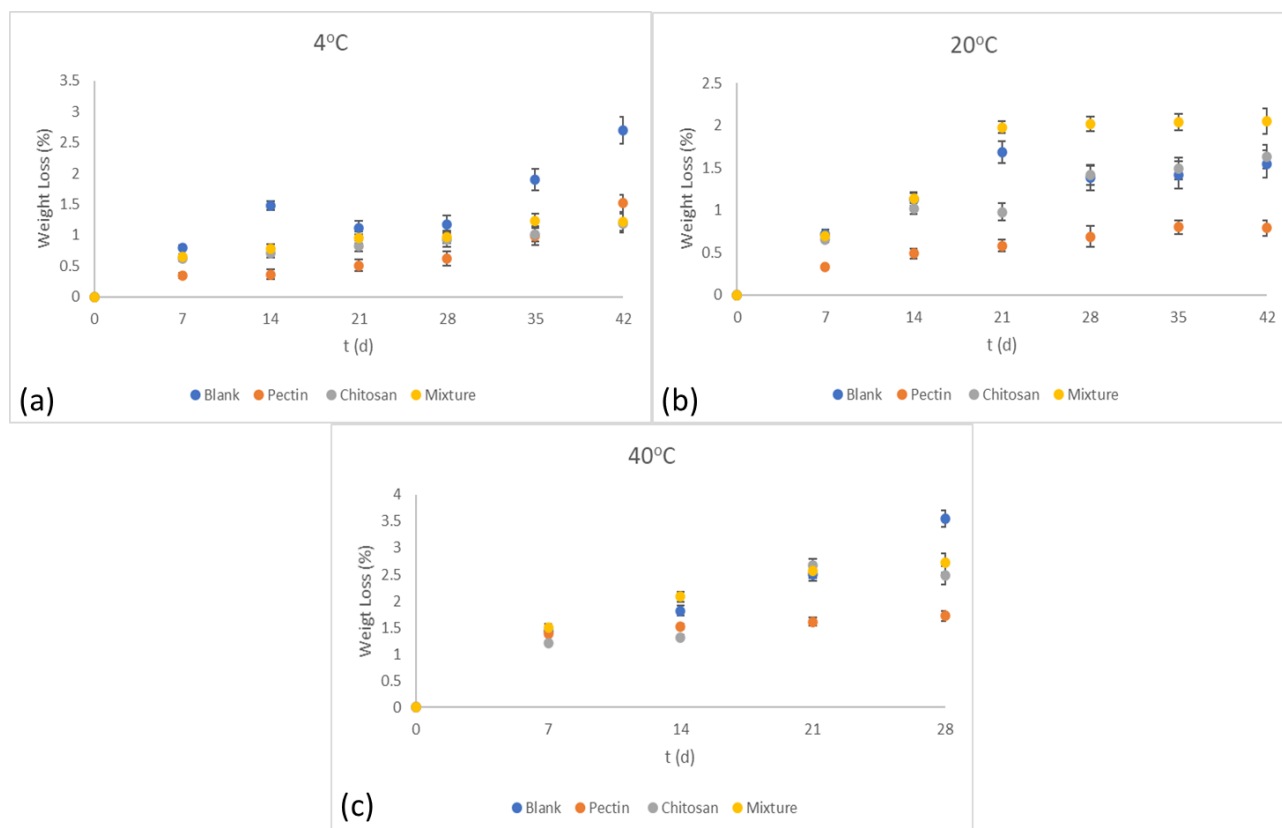


Figure 6 Effect of edible coatings in the weight loss of green olives.

Weight loss increased progressively in all treatments during storage, reflecting continuous moisture migration from the olive tissue to the surrounding environment; however, it was significantly higher in uncoated olives. Control samples reached approximately 2.7% weight loss after 42 days, indicating substantial dehydration and reduced ability to retain internal moisture in the absence of a protective barrier. Such moisture loss is commonly associated with structural weakening, surface shrinkage, and overall quality deterioration during prolonged storage.

In contrast, coated samples exhibited substantially lower weight loss throughout storage, demonstrating the protective role of edible coatings in limiting water evaporation. Pectin coatings provided the greatest reduction in moisture loss, limiting weight loss to approximately 1.52%, followed by chitosan and the pectin-chitosan mixture, which also performed better than the control. The enhanced moisture retention observed in coated olives can be attributed to the formation of a semi-permeable film that reduces water vapor transfer and maintains internal tissue hydration [29]. These results clearly demonstrate the effectiveness of edible coatings as moisture barriers, reducing dehydration and improving preservation of product integrity. Moreover, reduced weight loss is directly associated with better maintenance of texture, visual appearance, and overall shelf stability, reinforcing the role of edible coatings as an effective strategy for extending the storage life of green olives.

Temperature strongly affected dehydration behavior. At 4°C, weight loss remained minimal due to reduced evaporation rates. At 20°C, moisture loss increased gradually, particularly in uncoated olives. At 40°C, dehydration accelerated markedly, producing the highest weight loss values. Despite this, coated olives consistently retained more moisture than controls, demonstrating the effectiveness of edible coatings as water vapor barriers even under elevated temperatures.

3.7 Overall Liking

Figure 7 depicts the evolution of overall liking of all samples across the different storage temperatures.

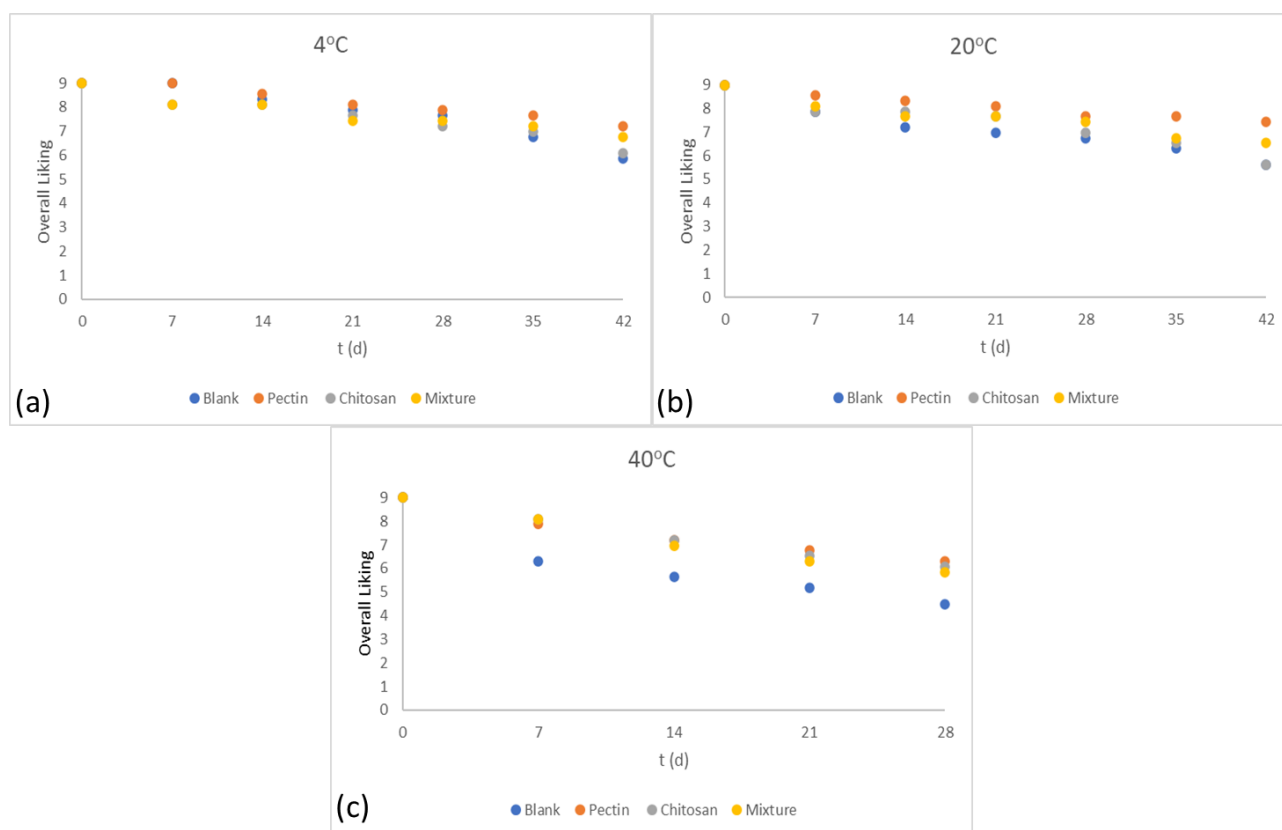


Figure 7 Effect of edible coatings in the overall liking of green olives.

Sensory evaluation revealed a gradual decline in the overall liking scores for all samples during storage, reflecting the progressive deterioration of quality attributes typically associated with extended storage periods. However, the coating treatments significantly delayed the sensory deterioration compared with the control samples, demonstrating the beneficial impact of edible coatings on maintaining consumer-perceived quality. The reduction in sensory scores over time can be attributed to cumulative physicochemical changes affecting appearance, texture, aroma, and flavor.

The blank samples showed the most pronounced decline, decreasing from an initial score of 9 to 6.5 after 42 days, indicating a substantial quality loss and reduced consumer acceptability. In contrast, pectin-coated olives maintained the highest acceptability among all treatments, retaining scores around 8 even at the end of storage, suggesting effective preservation of the desirable sensory attributes. Chitosan-coated olives and those treated with the pectin-chitosan mixture also

improved sensory preservation relative to the control, although they exhibited slightly faster deterioration than pectin alone. The improved sensory performance of the coated samples may be linked to reduced moisture loss, better texture retention, and slower chemical and oxidative changes, all of which contribute positively to overall perception.

Temperature strongly influenced sensory degradation. At 4°C, overall liking declined slowly, indicating effective preservation under refrigerated storage. At 20°C, sensory deterioration accelerated moderately, while coated samples still maintained improved acceptability compared with the control. At 40°C, sensory quality decreased rapidly due to intensified physicochemical degradation; however, coated olives retained higher scores than uncoated samples. Pectin coatings consistently demonstrated the best performance across all temperatures.

These results confirm that edible coatings positively influenced multiple sensory attributes simultaneously, including appearance, texture, aroma, and flavor perception, ultimately extending consumer acceptability and delaying the onset of sensory rejection during storage. The findings further support the application of polysaccharide-based coatings as an effective strategy for enhancing the marketability and shelf life of green olives.

3.8 Arrhenius Model

The estimated values of the degradation rate constants based on the overall liking of the samples are presented in Table 1.

Table 1 Degradation rate constants of the overall liking of the green olives.

Coating	T (K)	k (d ⁻¹)	R ²	Adjusted R ²	RMSE
Blank	277.15	0.0632	0.9448	0.9337	0.2526
	293.15	0.0841	0.9378	0.9253	0.2526
	313.15	0.2330	0.8480	0.7973	0.6062
Pectin	277.15	0.0403	0.9750	0.9700	0.1004
	293.15	0.0410	0.9624	0.9549	0.1016
	313.15	0.1537	0.9557	0.9409	0.1987
Chitosan	277.15	0.0653	0.9516	0.9419	0.1922
	293.15	0.0756	0.9396	0.9276	0.2485
	313.15	0.1601	0.9829	0.9771	0.1387
Mixture	277.15	0.0569	0.9176	0.9011	0.1975
	293.15	0.0629	0.9281	0.9137	0.2058
	313.15	0.1698	0.9759	0.9679	0.1800

The goodness of fit of the zero-order kinetic models was evaluated using R², adjusted R², and RMSE. The R² values ranged from 0.8480 to 0.9829, while the corresponding adjusted R² values ranged from 0.7973 to 0.9771, indicating generally good agreement between the experimental and predicted overall liking values. RMSE values ranged from 0.1004 to 0.6062, with most models exhibiting relatively low prediction errors. The lowest RMSE was observed for pectin-coated olives at 277.15 K (RMSE = 0.1004), whereas the highest was obtained for the blank samples at 313.15 K (RMSE = 0.6062), indicating a comparatively weaker fit under these accelerated storage conditions. Overall, the consistently high R² and adjusted R² values, together with the generally low RMSE values,

support the adequacy of the zero-order kinetic model for describing the sensory degradation of the olive samples during storage. This behavior is consistent with temperature-dependent biochemical and physicochemical reactions, including oxidation, texture softening, and flavor deterioration, which intensify under higher storage temperatures. The markedly higher k values observed at 313.15 K (40°C) are consistent with the strong temperature dependence of sensory deterioration. Increasing temperature accelerates the physicochemical and sensory degradation processes occurring during storage, resulting in substantially higher degradation rate constants. Importantly, although all treatments exhibited increased k values at 313.15 K, the coated samples maintained lower rates than the blank, indicating that the coatings continued to provide a protective effect under accelerated temperature conditions.

Table 2 presents the degradation rate constants and the activation energy of the samples.

Table 2 Degradation reference rate constants of the overall liking and activation energy of the green olives.

Coating	k_{ref} (d ⁻¹)	E_a (kJ/mol)	R^2	Adjusted R^2	RMSE
Blank	0.1260	26.376	0.9211	0.8423	0.1573
Pectin	0.0747	27.248	0.7841	0.5682	0.2914
Chitosan	0.1029	18.169	0.8821	0.7755	0.1316
Mixture	0.0969	22.197	0.8401	0.6801	0.1974

The goodness-of-fit analysis of the Arrhenius models showed R^2 values ranging from 0.7841 to 0.9211, adjusted R^2 values from 0.5682 to 0.8423, and RMSE values from 0.1316 to 0.2914. The blank samples exhibited the highest adjusted R^2 (0.8423), while the pectin treatment showed the lowest adjusted R^2 (0.5682) and the highest RMSE (0.2914), indicating greater deviation between the experimental data and the fitted Arrhenius relationship for this treatment. Thus, although the Arrhenius model adequately described the general temperature dependence of the degradation rates, the goodness of fit varied among treatments, and the pectin-derived kinetic parameters should be interpreted with greater caution. Among the evaluated coatings, pectin exhibited the lowest degradation rate constant at the reference temperature ($k_{\text{ref}} = 0.0747 \text{ d}^{-1}$), indicating slower sensory deterioration than the blank samples (0.126 d^{-1}). This finding highlights the enhanced protective capacity of pectin coatings in preserving sensory quality. The activation energy (E_a) values further clarify the temperature dependence of degradation. Pectin showed the highest E_a (27.248 kJ/mol), followed by the blank (26.376 kJ/mol), indicating that degradation in these samples is more sensitive to temperature changes. In contrast, chitosan exhibited the lowest E_a (18.169 kJ/mol), suggesting that its degradation rate is less influenced by temperature but requires less energy to proceed. The pectin-chitosan mixture presented intermediate values ($k_{\text{ref}} = 0.0969 \text{ d}^{-1}$; $E_a = 22.197 \text{ kJ/mol}$), reflecting moderate degradation behavior and a partial, but not fully synergistic, protective effect.

Overall, while pectin coating most effectively reduced the degradation rate at the reference temperature, its higher activation energy indicates greater sensitivity to temperature variations compared to chitosan.

The activation energy values obtained from the Arrhenius model were closely associated with the physicochemical and sensory stability of the olive samples. In general, samples that exhibited

lower color deterioration (ΔE), reduced weight loss, and improved hardness retention also showed slower sensory degradation rates and longer predicted shelf life.

Pectin-coated olives demonstrated the best preservation of quality characteristics during storage, maintaining lower ΔE values, reduced moisture loss, and higher firmness compared with the control samples. These effects contributed positively to sensory perception, since greener color, firmer texture, and lower dehydration are directly associated with improved appearance and overall acceptability. Consequently, pectin-coated olives exhibited the lowest degradation rate constants and the longest shelf-life values.

The activation energy should be interpreted independently from the absolute degradation rate. While the activation energy reflects the sensitivity of the degradation rate to changes in temperature, the reference degradation rate constant (k_{ref}) describes the absolute degradation rate at the selected reference temperature. Pectin exhibited the lowest k_{ref} (0.0747 d^{-1}), indicating the slowest sensory degradation at the reference temperature, but also the highest E_a (27.248 kJ/mol), indicating a comparatively stronger temperature dependence of its degradation rate. Therefore, the high E_a of pectin does not imply faster deterioration under the investigated conditions; rather, it indicates that the rate of deterioration changes more markedly with temperature. The superior preservation observed for pectin is primarily reflected in its lower degradation rate constants and longer predicted shelf life.

The control samples showed the greatest increase in ΔE , the highest weight loss, and the largest reduction in hardness, which were accompanied by faster decreases in overall liking. Therefore, the Arrhenius kinetic analysis was consistent with both the instrumental measurements and the sensory evaluation results, confirming that edible coatings effectively delayed quality deterioration and improved the storage stability of green olives.

The estimated shelf-life of the green olives based on the overall liking for the different edible coatings and storage conditions is presented in Table 3.

Table 3 Shelf-life of the green olives based on the overall liking.

Coating	T (K)	Shelf-life (d)
Blank	277.15	64.01
	293.15	53.51
	313.15	19.31
Pectin	277.15	111.66
	293.15	109.76
	313.15	29.28
Chitosan	277.15	68.91
	293.15	60.00
	313.15	28.11
Mixture	277.15	79.09
	293.15	71.54
	313.15	26.50

Shelf-life calculations demonstrated substantial improvements due to edible coatings across all storage conditions. At refrigerated conditions (277.15 K), pectin-coated olives achieved the longest

predicted shelf life (approximately 112 days), compared with 64 days for the control samples. Even at elevated temperatures, the coated samples maintained longer predicted shelf lives than uncoated olives, confirming the effectiveness of polysaccharide films in slowing quality loss under accelerated storage conditions. The relatively lower R^2 value for pectin ($R^2 = 0.7841$) indicates a weaker linear fit than the other treatments. Therefore, the predicted shelf-life values for pectin should be interpreted with some caution, particularly when extrapolating beyond the experimental temperature range. Nevertheless, the substantially lower reference degradation rate constant and the consistently longer predicted shelf life of pectin compared with the other treatments support the observed comparative preservation effect. Overall, the Arrhenius analysis verified that edible coatings, particularly pectin, effectively slowed sensory degradation kinetics, reduced temperature sensitivity, and extended product stability across a wide range of storage temperatures, supporting their application as a practical preservation strategy for green olives.

3.9 Limitations of the Present Work

A limitation of the present experimental design is that all samples, including the uncoated control, were packaged under modified atmosphere conditions. Consequently, the results allow the preservation performance of the edible coatings to be compared under MAP conditions but do not permit the independent contribution of MAP to be quantitatively separated from that of the coatings. Future studies should include an uncoated control stored under regular atmospheric conditions, in addition to the MAP control, to enable a more comprehensive assessment of the individual and combined effects of edible coatings and modified atmosphere packaging. A further limitation of the present study is that we did not experimentally determine microbiological indicators. Therefore, although some of the observed changes in pH, acidity and sensory quality may be associated with microbial activity, the present dataset does not allow quantification of the contribution of microbial growth. Future studies should combine physicochemical and sensory analyses with microbiological parameters, including total viable counts and relevant spoilage or pathogenic microorganisms, to provide a more comprehensive assessment of the microbiological safety and shelf-life extension provided by the coatings. A further limitation concerns the statistical characterization of the experimental and kinetic results. The available dataset did not permit the retrospective estimation of 95% confidence intervals for all reported parameters. Therefore, the results are presented using the available experimental values and model estimates, and readers should consider the absence of confidence intervals when interpreting the precision and uncertainty associated with these estimates. Future studies should incorporate sufficient independent replicates to enable the systematic calculation and reporting of 95% confidence intervals for the experimental measurements and estimated kinetic parameters.

4. Conclusions

The present study demonstrated that edible coatings, particularly pectin, are an effective natural and sustainable strategy for preserving the quality of green table olives under modified atmosphere conditions. Coated olives exhibited greater acidity and pH stability, reduced salinity changes and weight loss, and improved color, texture and sensory quality compared with uncoated samples, reflecting the barrier properties of the coatings against gas, water vapor and dissolved substance transfer. Pectin provided the best overall preservation performance, reducing weight loss to

approximately 1.52% compared with 2.7% for the uncoated samples after 42 days at 4°C, while maintaining ΔE values below 2 and an overall liking score of approximately 8 versus 6.5 for the blank. Although increasing storage temperatures accelerated quality deterioration, the coatings mitigated these changes and reduced the sensitivity of the olives to thermal stress. Arrhenius modelling further confirmed the preservation effect of pectin, which exhibited the lowest reference degradation rate constant ($k_{ref} = 0.0747 \text{ d}^{-1}$) and the longest predicted shelf life at 4°C (111.66 days versus 64.01 days for the uncoated samples). Chitosan and the pectin-chitosan mixture also provided significant protection; however, their performance was inferior to pectin, while the mixture showed no synergistic advantage over pectin alone. Overall, these findings highlight pectin coating as a promising mild, natural and sustainable preservation technology capable of extending shelf life while maintaining the physicochemical, sensory and commercial quality of green table olives.

Author Contributions

Conceptualization, T.K. and C.T.; methodology, T.K. and C.T.; software, T.K.; validation, C.T.; formal analysis, T.K.; investigation, T.K. and C.T.; resources, C.T.; data curation, T.K.; writing-original draft preparation, T.K.; writing-review and editing, C.T.; visualization, T.K.; supervision, C.T.; project administration, C.T.; funding acquisition, C.T. All authors have read and agreed to the published version of the manuscript.

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Competing Interests

The authors have declared that no competing interests exist.

Data Availability Statement

The data supporting the findings of this study are included within the article. Additional information is available from the corresponding author upon reasonable request.

AI-Assisted Technologies Statement

The authors used ChatGPT (OpenAI, GPT-5.5) solely to improve the readability and language of the manuscript. The AI-assisted suggestions were reviewed, edited, and verified by the authors, who take full responsibility for the content, accuracy, and integrity of the final manuscript.

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