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ORIGINAL ARTICLE

Food Chemistry, Engineering, Processing and Packaging

Development of an Edible Film - Lined Tetra Pak: Accelerated Shelf Life of Extra Virgin Olive Oil

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ABSTRACT

Background: Extra virgin olive oil (EVOO) is a lipid foodstuff renowned for its health-promoting properties. Nevertheless, its quality is highly susceptible to degradation influenced by packaging and storage conditions.

Aim: This study aimed to develop Tetra Pak packages lined with edible films to preserve the stability of EVOO, predict its shelf life under accelerated storage conditions, and evaluate the efficacy of these films in preserving key quality parameters.

Materials and Methods: EVOO from the Coratina cultivar was packaged in Tetra Pak containers lined with edible films based on gelatin, gum Arabic, and a gelatin-gum Arabic composite. The packages were stored under accelerated aging conditions at 20, 40, and 60°C. The oxidative stability and quality of the oil were assessed by monitoring peroxide value (PV), free fatty acids (FFA) content, and the concentration of bioactive compounds (chlorophylls, carotenoids, and total polyphenols). The mechanical and physical properties of the edible films were also characterized.

Results: The results demonstrated that the application of edible films significantly ($p < 0.05$) extended the predicted shelf life of EVOO compared to the uncoated control. Packaging lined with gum Arabic proved most effective, conferring a shelf life of 920 days, which is attributed to its superior barrier proprieties against oxygen permeation and its intrinsic antioxidant activity. The composite film and gelatin film provided shelf lives of 870 days and 744 days respectively, while the unlined control exhibited the shortest shelf life of 569 days.

Conclusion: The findings indicate that edible films, particularly those based on gum Arabic, can markedly preserve the oxidative stability and extend the shelf life of EVOO. This research highlights the potential of biodegradable edible coatings as a sustainable and effective alternative to conventional packaging, offering significant implications for the development of eco-friendly food packaging solutions for high-value lipid products.

Keywords: Extra virgin olive oil; EVOO; Edible packaging; Shelf life; Oxidative stability; Peroxide value; Free fatty acids.

Article Information

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1 INTRODUCTION

Virgin olive oil (VOO), a cornerstone of the Mediterranean diet, is widely recognized for its considerable health benefits. According to established standards, VOO is produced by exclusively mechanical means from fresh fruits (*Olea europaea* L.) without the use of thermal treatments, chemical additives, or refining processes. The production process typically involves a sequence of steps, including grinding, malaxation, decantation, centrifugation, and filtration (Lolis *et al.*, 2020).

The quality of VOO is multifaceted, influenced by a combination of factors, including olive variety, agricultural practices, climate, fruit ripeness, harvesting techniques, post-harvest handling, and extraction methods (Halla *et al.*, 2019; El Yamani *et al.*, 2022; Lozano-Castellón *et al.*, 2024). Critically, packaging and storage conditions are paramount to preserving its sensory and nutritional properties over time (Sona *et al.*, 2020).

Packaging serves a critical in protecting food products from external aggressors such as light, oxygen, moisture, and contaminants, thereby extending shelf life (Han, 2014). In recent years, there has been a notable surge in interest regarding biodegradable films derived from polysaccharides, proteins, or lipids. These films are valued for their

environmental sustainability and their potential to incorporate antimicrobial and antioxidant agents (Sona *et al.*, 2020).

The shelf life of VOO is highly susceptible to storage conditions. Exposure to oxygen, temperature, light, and the type of packaging material used can lead to its deterioration. Common packaging options include dark or light glass, tinplate, plastic, and multilayer pouches (Kontominas, 2017). During storage, hydrolytic and oxidative processes degrade the oil's quality, altering its acidity and peroxide value and causing a loss of minor constituents that contribute to its distinctive sensory and nutritional attributes (El Yamani *et al.*, 2022).

Despite its natural antioxidant content, including tocopherols, phenolic compounds, and pigments such as chlorophylls and carotenoids, VOO is not immune to oxidation. Chlorophyll responsible for the oil's color, can act as antioxidants in darkness but as pro-oxidants when exposed to light, further compromising the oil's stability (Halla *et al.*, 2019 and Li *et al.*, 2020).

To address these challenges, shelf-life studies, whether conducted through real-time storage under normal conditions or accelerated shelf-life testing (ASLT), are essential for evaluating packaging performance. ASLT, which involves subjecting products to elevated environmental conditions, offers a cost-effective and time-efficient approach to predicting deterioration when paired with reliable kinetic models (Addisu *et al.*, 2019).

Therefore, this study aimed to develop and evaluate biodegradable edible films as internal linings for Tetra Pak packaging. The research specifically aims to preserve the oxidative stability and extend the shelf life of virgin olive oil. The research specifically investigates the effects of gelatin, Arabic gum, and their combination on the oil's quality parameters under accelerated storage conditions.

2 Materials and Methods

2.1 Olive Oil Sample

This study utilized virgin olive oil from the 'Coratina' cultivar, which was provided by the Olive Research Department, Horticulture Institute, Agricultural Research Center, Giza, Egypt. The fatty acid composition of the oil, determined via gas chromatography, was as follows: palmitic acid ($C_{16:0}$) 15.20%, palmitoleic acid ($C_{16:1}$) 0.73%, maragic acid ($C_{17:0}$) 0.05%, margoleic acid ($C_{17:1}$) 0.07%, stearic acid ($C_{18:0}$) 2.13%, oleic acid ($C_{18:1}$) 69.20%, linoleic acid ($C_{18:2}$) 10.71%, linolenic acid ($C_{18:3}$) 0.95%, arachidic acid ($C_{20:0}$) 0.45%, gadoleic acid ($C_{20:1}$) 0.40%, and behenic acid ($C_{22:0}$) 0.11%.

2.2 Analytical Reagents and Equipment

All chemicals and solvents were of analytical grade, and were obtained from El-Gomhoria Company, Cairo, Egypt. Gelatin was purchased from PIOCHM, and Arabic gum was procured from Naturia Food Industry.

2.3 Preparation of Packaging Materials

Preparation of Edible Films

Edible films were prepared using gelatin, Arabic gum, and their combination. For the individual film formulations, 3 g of either gelatin or Arabic gum powder was dissolved separately in 100 mL of distilled water, heated to 75°C, and stirred for 30 minutes. For the composite film, a 1:1 mixture of gelatin (3 g) and Arabic gum (3 g) was dissolved in 100 mL of hot water (75°C) under continuous stirring for 30 minutes. To enhance flexibility, glycerol was incorporated to all formulations at a concentration of 30% (w/w) per 100 mL of solution. The resulting solutions were continuously stirred and then poured onto Tetra Pak surfaces to a thickness of approximately 2 mm (Figure 1), then dried at 40°C for 12 hours (Ganesan *et al.*, 2019).

Figure 1. Preparation of Tetra Pak Lined with Edible Solution

Three types of packaging materials were utilized in this study:

- **Packaging A:** Transparent plastic (PET)
- **Packaging B:** Brown-amber glass bottle with a butyl/Teflon screw cap
- **Packaging T (Control):** Unlined Tetra Pak, including Tetra Pak with different edible films made from:
  - T-Gelatin: Tetra Pak lined with gelatin film
  - T-Gum: Tetra Pak lined with Arabic gum film
  - T-G-G: Tetra Pak lined with a gelatin and Arabic gum mixture film.

Pouches measuring 6.5 × 15.5 cm were sealed using a thermal heat sealer (Shuman, 0.6KW, Sealing speed 1–12 m/min, range of temp 0-300°C) at 250°C for 30 seconds.

2.4 Physical Characteristics of Films

Determination of Water Vapor Permeability (WVP)

WVP tests were conducted in accordance with the procedure by Berthet *et al.* (2015). A circular film sample, larger than the inner diameter of the test cup, was sealed over the top of the cup using paraffin oil. The cup was filled with 50% distilled water and then placed in a desiccator containing calcium chloride to maintain 0% relative humidity (RH), while the interior of the cup maintained a 100% RH. The weights of the cups were recorded hourly for 10 hours, with specimens of each film being tested. The water vapor transmission rate (WVTR) was calculated using Equations (1) according to Kester & Fennema (1986) updated by Tanada-Palmu & Grosso (2003), Berthet *et al.* (2015). While, water vapor permeability (WVP) was calculated using Equation (2) in accordance with ASTM E95-E95 (1995):

$$WVTR = \frac{\Delta m}{\Delta t A} \quad (1)$$

$$WVP = WVTR \frac{L}{\Delta P} \quad (2)$$

Where $\Delta m/\Delta tA$ is the moisture gain weight per unit time (g/s), A is the area of exposed film (m^2). L is the thickness of the film (mm), and ΔP is the difference in partial pressure.

Light Transmission and Film Transparency

The transparency of the film was estimated using spectrum transmission meter (LS108), visible light at 550nm. Film samples, cut into 2 × 8 mm rectangles, were analyzed for light barrier properties Light transmission was measured at wavelengths between 395 and 550 nm for ultraviolet (UV) and visible light, with a specific measurement at 550 nm.

Mechanical properties

The mechanical properties of the edible film samples (gelatin, Arabic gum, and the mixture) were assessed using a Brookfield Texture Analyzer CT3. The films were cut into 2 × 10 cm strips and clamped with pneumatic grips using a force of 10 g, as per ASTM D 882-02 (ASTM D 882-02., 2002; Berthet *et al.*, 2015).

Fourier Transform Infrared (FTIR) Spectrophotometry

FTIR analysis was performed on film samples using an INVENIOS-Bruker FTIR spectrophotometer with a diamond ATR crystal. The scanning range was 4000–500 cm^{-1} to identify the functional groups present in both film and 3D-shaped samples.

2.5 Storage Conditions

Coratina olive oil was stored in three different types of lined Tetra Pak packaging, which were compared against unlined Tetra Pak, plastic, and glass containers. A total of nine packs (three for each selected temperature) were stored in the dark in incubators at three different temperatures: 20, 40, and 60°C for a duration of up to two months. At predefined intervals during storage, a pack from each condition was removed for analytical determinations.

2.6 Quality Properties

The free fatty acids (FFAs) and peroxide value (PV) were measured following the methods outlined by AOAC in 2019. The UV absorption at 232 nm (K_{232}) and 270 nm (K_{270}) was determined according to IOC (2022) using a spectrophotometer photoLap 7600 UV-VIS -WTW. Fatty acid composition was analyzed via gas chromatography following the preparation of methyl esters, using an Agilent 6890 series gas chromatograph equipped with a DB23 column (60 m × 0.32 mm) as per ISO (2017). Total polyphenol content, expressed as mg gallic acid per kg of oil, was evaluated using the method described by Gutfinger (1981). Pigment content, including chlorophylls and carotenoids, was determined spectrophotometrically according to the method of Mínguez Mosquera *et al.* (1991).

2.7 Shelf-Life Prediction

Accelerated self-life testing (ASLT) was employed to evaluate oil stability. To predict the shelf-life of the Coratina olive oil, a slope, an intercept, and a correlation coefficient were calculated based on the Arrhenius equation through linear regression analysis by accelerating temperature (20, 40, and 60°C) to measure the temperature dependence of quality deterioration in the samples. The Arrhenius equation is expressed as:

$$k = k_0 \exp\left(\frac{-Ea}{RT}\right)$$

Where k represents the reaction constant at temperature T (absolute temperature in Kelvin), k_0 is the pre-exponential factor, E_a is the activation energy (J/mol), and R is the universal gas constant ($8.314 J \cdot mol^{-1} \cdot K^{-1}$).

Oil samples were subjected to constant elevated temperatures of 20, 40, and 60°C within a controlled environmental chamber for eight weeks. Oxidative deterioration was monitored weekly by measuring the peroxide value (PV), fatty acid composition, and the reaction constant (k) (Vanessa *et al.*, 2022).

2.8 Statistical analyses

All measurements were conducted in triplicate unless otherwise specified. Statistical analysis was performed using

CoStat statistical software (CoHort Software, Monterey, CA, USA). A one-way analysis of variance (ANOVA) was employed to evaluate the effect of different film-forming materials (T-Gelatin, T-Gum, and T-G-G) on the characteristics of the edible films. A two-way ANOVA was conducted to assess the interaction between storage temperature and packaging type on the quality properties of the oil. All statistical analyses were conducted at a 95% confidence level ($p < 0.05$).

3 Results and Discussion

3.1 Edible Film Characterization

Water Vapor Permeability (WVP)

The water vapor permeability (WVP) of the edible films was quantitatively analyzed, revealing that the (Gelatin +Gum) sample exhibited the lowest WVP value (0.03827 g•mm/m²•h•Pa), indicating the best water vapor barrier properties (Table 1). In comparison, the Arabic gum sample had the highest WVP (0.15753 g•mm/m²•h•Pa), reflecting the poorest barrier performance. The Gelatin sample showed an intermediate WVP value (0.04418 g•mm/m²•h•Pa), representing moderate barrier properties. These results highlight that blending gelatin and Arabic gum (Gelatin+Gum) significantly improves water vapor barrier performance compared to films made solely from gelatin or Arabic gum.

Table 1. Water Vapor Permeability (WVP) Values for Edible Films

Sample	Slop	Thickness	Area	WVTR	WVP (g·mm/m²·day·Pa)
Gelatin	0.0388	0.143	0.0013	30.892	0.044175± 0.001[b]
Gum	0.1522	0.13	0.0013	121.178	0.157531± 0.010[a]
Gelatin + Gum	0.0189	0.254333	0.0013	15.048	0.038271± 0.001[c]

Note: Mean values with different letters in each column are significantly different ($p < 0.05$).

Light transmission and film transparency

The optical properties of the edible films were evaluated at three distinct wavelengths: 395 nm (near-UV), 430 nm (blue light), and 550 nm (visible light). As displayed in, Table 2, data revealed that the gelatin film possessed relatively high transmittance values across all wavelengths, with 74.366% at 395 nm, 84.033% at 430 nm, and 84.533% at 550 nm. The Arabic gum sample demonstrated similar performance, with slightly higher transmittance at 395 nm (75.966%) but marginally lower values at 430 nm (82.9%) and 550 nm (84.333%). In contrast, the (Gelatin + Gum) sample exhibited the lowest transmittance, particularly at 395 nm (55.533%) and 430 nm (73.2%), while maintaining a comparable value at 550 nm (82.933%).

Table 2. Light Transmission for Different Edible Films

	550 nm/VL	430/BL	395/PL
Gelatin	74.36 ± 1.40[a]	84.03 ± 6.98[a]	84.53 ± 0.75[a]
Gum	76.90 ± 1.49[a]	82.90 ± 6.93[a]	84.33 ± 0.57[a]
Gelatin + Gum	55.53 ± 2.28[b]	73.20 ± 0.00[b]	82.93 ± 8.64[a]

Note: Mean values with different letters in each column are significantly different ($p < 0.05$).

These results indicate that combining gelatin and Arabic gum (Gelatin + Gum) effectively reduces light transmittance, especially in the UV and blue light spectrum, which could enhance the film's light-blocking properties, making it more suitable for applications requiring reduced light permeability.

3.2 Mechanical Properties of Edible Film

Tensile Strength

The tensile strength and elongation at break values for the edible films are presented in Figure 2. Gelatin-based films exhibited the highest tensile strength among the three formulations (37.363MPa), indicative of a strong and rigid film structure attributed to the cohesive protein network of

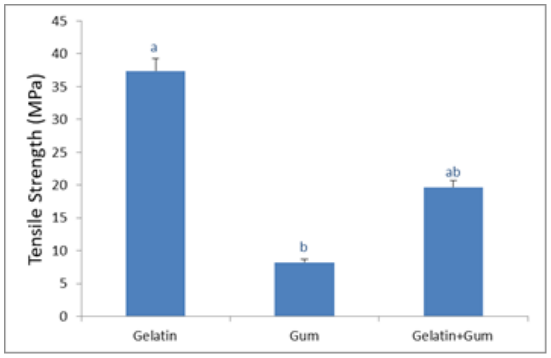

Figure 2. Tensile Strength of Different Edible Films
Mean values with different letters in each column are significantly different ($p < 0.05$)

gelatin. Conversely, Arabic gum films demonstrated the lowest tensile strength (8.247 MPa), highlighting their inherently less rigid and more flexible molecular structure due to weaker polymer interactions compared to gelatin. The gelatin and Arabic gum combination displayed an intermediate tensile strength value of 19.6525 MPa, suggesting that blending gelatin with Arabic gum reduces the rigidity of gelatin films while increasing the tensile strength compared to Arabic gum alone. The blend achieves balanced structural integrity.

Elongation at Break

As illustrated in Figure 3, the gelatin-based films demonstrated significant elongation (57.75%), indicating good flexibility alongside high tensile strength. Arabic gum films exhibit the highest elongation (81.94%), indicating their superior flexibility due to their softer and more elastic nature. In contrast, the elongation of the gelatin and Arabic gum blend (39.97%) is much lower than that of either gelatin or Arabic gum alone. This suggests that blending reduces the film's ability to stretch, likely a result of specific interactions between the two polymers, which create a less elastic structure.

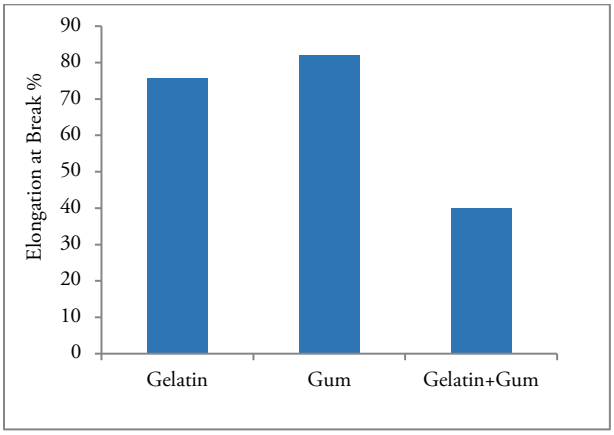

Figure 3. Elongation at Break of Different Edible Films

3.3 Fourier Transform Infrared (FTIR) Spectrophotometry

The FTIR spectra of the films provided insights into their molecular composition and interactions. As displayed in Figure 4 and Table 3 the gelatin film spectrum showed characteristic protein signatures, specifically the Amide I band near 1645 cm^{-1} and the Amide II band near 1543 cm^{-1}, which confirm the presence of gelatin. Additional peaks around 2925 cm^{-1} and 2850 cm^{-1} correspond to organic C-H stretching. The peaks in the 1000–500 cm^{-1} region are also consistent with the gelatin matrix.

Figure 5 and Table 4 present the major peaks for the Arabic gum. The strong O-H stretching band near 3386 cm^{-1}, the C-H stretching band at 2926 cm^{-1}, and the C-O stretching bands in the 1078–1020 cm^{-1} range align with the polysaccharide-rich chemical composition of Arabic gum, (Quazeem *et al.*, 2023).

Finally, the FTIR spectrum of the gelatin and Arabic gum composite film, displayed in Table 5 and Figure 6, clearly indicates the presence of both polymers. Overlapping functional group signals, such as O-H and N-H stretching bands at 3323 cm^{-1}, the Amide I band at 1648 cm^{-1}, and the C-O stretching near 1070 cm^{-1}, demonstrate the combined contributions of the protein (gelatin) and the polysaccharide (Arabic gum) within the blended film.

3.4 Quality Parameters of Olive Oil

The oxidative quality of olive oil was assessed by determining the peroxide value (PV), specific extinction coefficients at 232 nm (K_{232}) and 270 nm (K_{270}), and free fatty acid (FFA) content. The PV is associated with the formation of peroxides and hydroperoxides, which are unstable and readily decompose into secondary oxidation products, such as aldehydes and ketones. The K_{232} and K_{270} values serve as

Table 3. The Major Peaks Observed and Their Corresponding Assignments for Gelatin

Wavenumber (cm^{-1})	Functional Group / Bond	Interpretation
Broad peak around 3322 cm^{-1}	O-H and N-H stretching vibrations,	Indicating the presence of hydroxyl (-OH) and amino (-NH) groups.
Peaks around 2925 and 2850 cm^{-1}	C-H stretching (alkyl groups)	These peaks arise from C-H stretching vibrations in aliphatic chains, typical for organic polymers like gelatin
Amide I band at ~1645 cm^{-1}	C=O stretching vibration	Which is characteristic of protein structures like gelatin.
Amide II band around 1543 cm^{-1}	This region corresponds to N-H bending and C-N stretching vibrations (amide II band),	Further confirming the presence of gelatin
Between 1200–1000 cm^{-1}:	C-O stretching vibrations	Stretching in polysaccharides, carbohydrates
Sharp peaks between 1000–500 cm^{-1}:	These could correspond to C-H bending	Providing unique spectral features of the materials present.

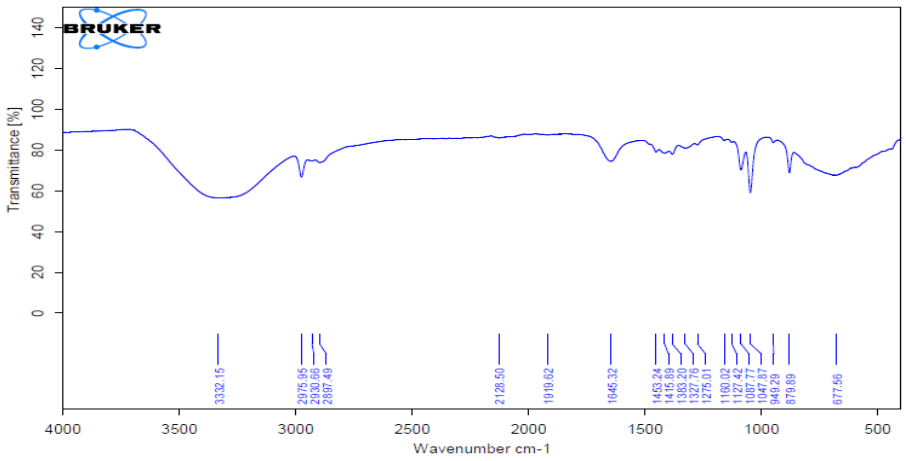

Figure 4. FTIR for Gelatin Edible Film

Table 4. The Major Peaks Observed and Their Corresponding Assignments for Arabic Gum

Wavenumber (cm^{-1})	Functional Group / Bond	Interpretation
Broad peak at ~3386 cm^{-1}	O-H stretching vibration,	Indicative of the presence of hydroxyl groups. Arabic gum contains polysaccharides with abundant hydroxyl (-OH) groups.
Vibrations around 2926 and 2850 cm^{-1}	C-H stretching	Characteristic of aliphatic C-H stretching in organic compounds, which could originate from the Arabic gum lining.
Peak at ~1648 cm^{-1}	C=O stretching vibrations	Often seen in polysaccharides or proteins. Arabic gum, a natural polymer, contains carboxyl functionalities
Prominent peaks between 1400–1000 cm^{-1}	C-O stretching vibrations and C-H bending in polysaccharides	This confirms the polysaccharide nature of Arabic gum
Around 1078–1020 cm^{-1}	Represents C-O-C or C-O	Stretching in the sugar backbone of Arabic gum.
(1000–500 cm^{-1})		corresponding to the characteristic vibrational modes of Arabic gum

Table 5. The Major Peaks Observed and Their Corresponding Assignments for Gelatin and Arabic Gum

Wavenumber (cm^{-1})	Functional Group / Bond	Interpretation
Broad peak at ~3323 cm^{-1}	This corresponds to O-H stretching vibrations from hydroxyl groups (Arabic gum) and N-H stretching vibrations from amino groups (gelatin).	The broadness reflects the combined contributions of both materials.
At ~2920 and ~2850 cm^{-1}	C-H stretching vibrations	These peaks arise from C-H bonds in aliphatic chains, indicating organic components from biopolymers.
Amide I band at ~1648 cm^{-1}	This band is a signature of gelatin and corresponds to the C=O	Stretching vibration of the protein backbone (Amide I).
Amide II band near ~1543 cm^{-1}	The peak reflects the N-H bending and C-N	Stretching vibrations of gelatin's protein structure.
C-O stretching vibrations (1200–1000 cm^{-1})	this region shows prominent peaks due to C-O-C and C-O stretching vibrations	Characteristic of polysaccharides in Arabic gum.

indicators of early-stage and secondary oxidation, respectively, while the FFA content measures the extent of hydrolytic activity (Allouche *et al.*, 2007).

As shown in Figures: 7, 8, 9, and 10), the initial values for the PV, K_{232}, K_{270} and FFAs content of the extra-virgin olive oil (EVOO) were below the maximum levels established by the International Olive Council (IOC, 2022): PV ≤ 20 meq O2/kg oil, K_{232} ≤ 2.5, K_{270} ≤ 0.22, and FFAs ≤ 0.8% (expressed as oleic acid).

Storage temperature had a significant effect on the peroxide value (PV) of all olive oil samples. PV increased progressively in all samples, with a notably more rapid rate of increase observed in oils stored at 60°C. The oxygen impermeability of Tetra Pak (with and without edible film) and glass packaging limited oxygen available, thereby inhibiting further peroxide production. In contrast, the oxygen-permeable nature of the plastic packaging facilitated more rapid oxidative reactions. Consequently, oil samples stored in plastic packaging exhibited a more rapid deterioration in PV. These results suggest that limiting oxygen availability can suppress many oxidative interactions, as oxygen strongly affects antioxidant compounds (Psomiadou and Tsimidou, 2002), who also investigated the feasibility of using edible films in olive oil packaging.

The results depicted in Figure 7 indicate that the rate of PV increase in oil packaged in T(G-G) was comparable to that of oil stored in glass packaging (B) and was slower than that of the control package (T). By the end of the storage period, PV had increased from 4.65 to 61.46, 59.43, and 69.78 meq O2/kg oil for the T(G-G), glass packaging (B), and control (T), samples, respectively. These findings are consistent with previous studies (Carpine *et al.*, 2015; Stoll *et al.*, 2017), which suggest that edible films applied to Tetra Pak packaging effectively protect oil from oxidation. As noted, both K_{232} and K_{270} values increased during storage, with higher rates of increase observed at 60°C. By the conclusion of the storage period, all oil samples stored at 60∘C had exceeded the IOC limits for PV, K_{232}, and K_{270} (Figure 8 and 9).

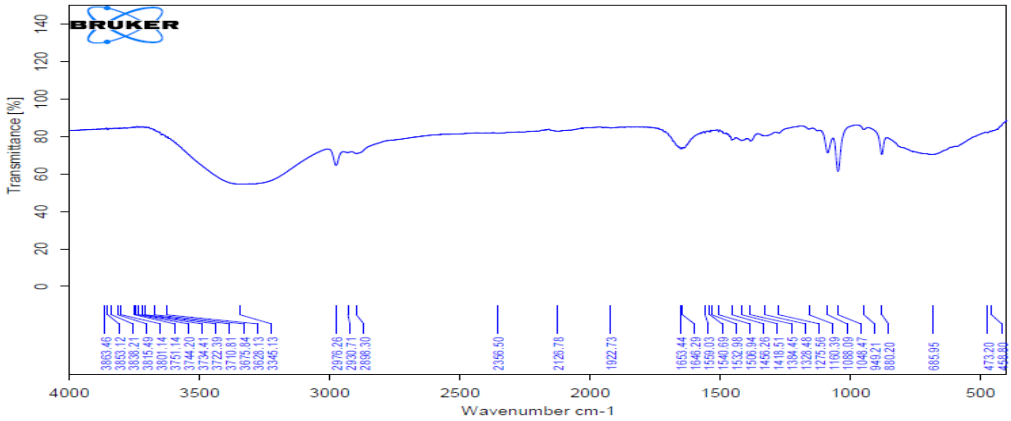

Figure 5. FTIR for Arabic Gum Edible Film

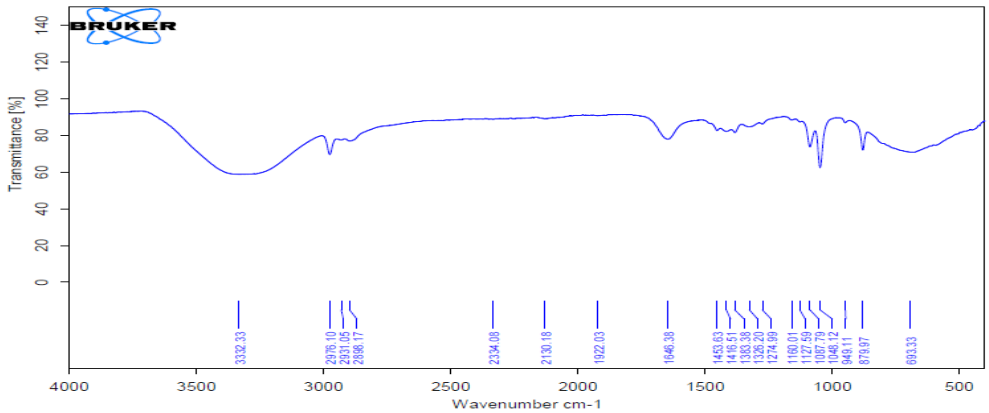

Figure 6. FTIR for the Mix of Gelatin and Arabic Gum Edible Film

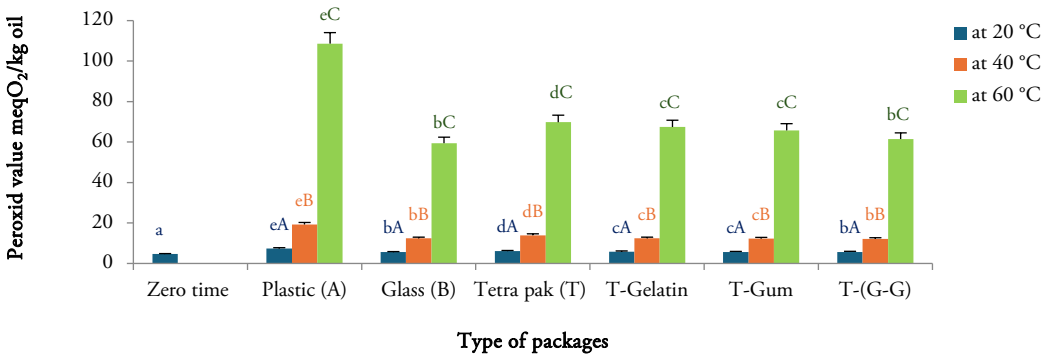

Figure 7. Influence of Storage Temperature on Peroxide Value of Olive Oil in Different Packages After Eight Weeks

a, b, c, d, e, f, and g, are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

The free fatty acids (FFA) content of the olive oil samples increased with storage temperature. Oils stored at 20°C and 40°C exhibited only slight increases in FFA over eight weeks, while those stored at 60°C experienced a significant rise. After 8 weeks, the FFA content of samples stored at 20°C had increased slightly across all packaging types. At 40°C, FFA values ranged from 0.6% to 0.7%, remaining within the IOC limit of 0.8%. However, at 60°C, the FFA content of all samples exceeded the IOC limit, with oil stored in plastic packaging (A) reaching over 3.3%, thereby classifying it as "lampante" olive oil, which is unsuitable for consumption.

Bioactive components, such as carotenoids and chlorophylls, play a vital role in olive oil by extending its shelf life during storage and contributing to its color. While chlorophylls can reduce autoxidation in the dark, they act as pro-oxidants in the presence of light, making light exposure a key factor in olive oil deterioration (Choe & Min, 2006). Phenolic compounds, which act as natural antioxidants by donating hydrogen atoms to oxidation radicals (Morelló *et al.*, 2004), also contribute to the positive sensory attributes of virgin olive oil (Khalil *et al.*, 2024).

Figures 11, 12, and 13 clearly demonstrate that bioactive components including chlorophylls, carotenoids, and total polyphenols decreased in all samples over the eight-week storage period at 20, 40, and 60°C in the various packaging types (T-Gelatin, T-Gum, T(G-G), control (T), glass (B), and plastic (A). The reduction in these components was more pronounced at higher temperatures, with plastic packaging demonstrating the least effective preservation. At 60°C, oils in plastic packaging (A) recorded the lowest levels of chlorophylls (0.29 mg/kg), carotenoids (0.05 mg/kg), and total polyphenols (91.40 mg/kg). In contrast, T(G-G) and glass packaging (B) performed better, with T(G-G) retaining 1.77 mg/kg chlorophylls, 0.73 mg/kg carotenoids, and

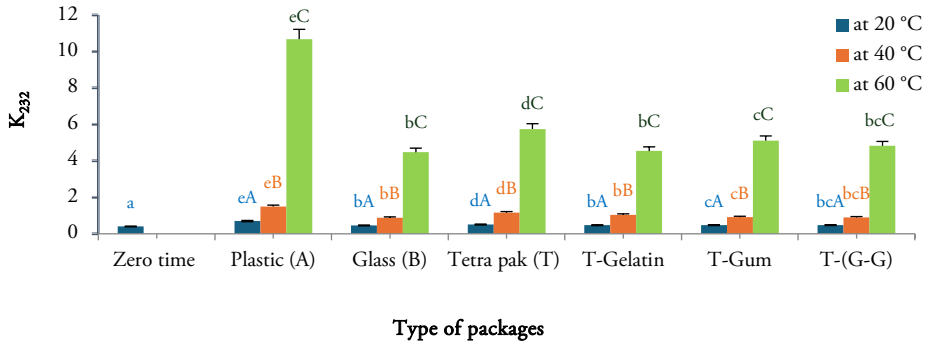

Figure 8. Influence of Storage Temperature on K_{232} of Olive Oil in Different Packages After Eight Weeks

a, b, c, d, e, f, and g are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

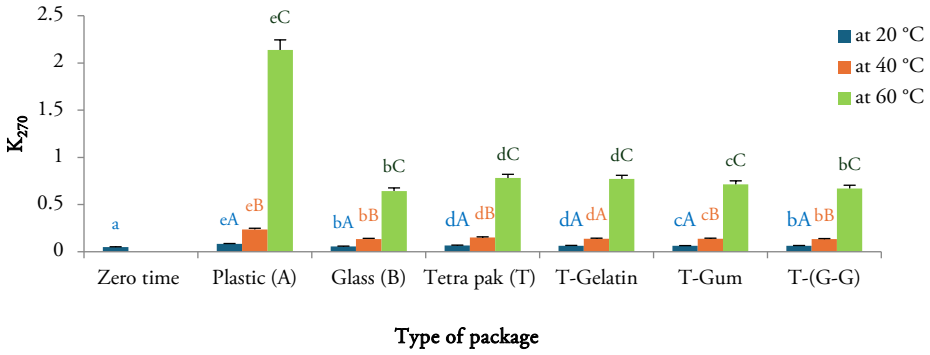

Figure 9. Influence of Storage Temperature on K_{270} of Olive Oil in Different Packages after Eight Weeks

a, b, c, d, e, f, and g are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

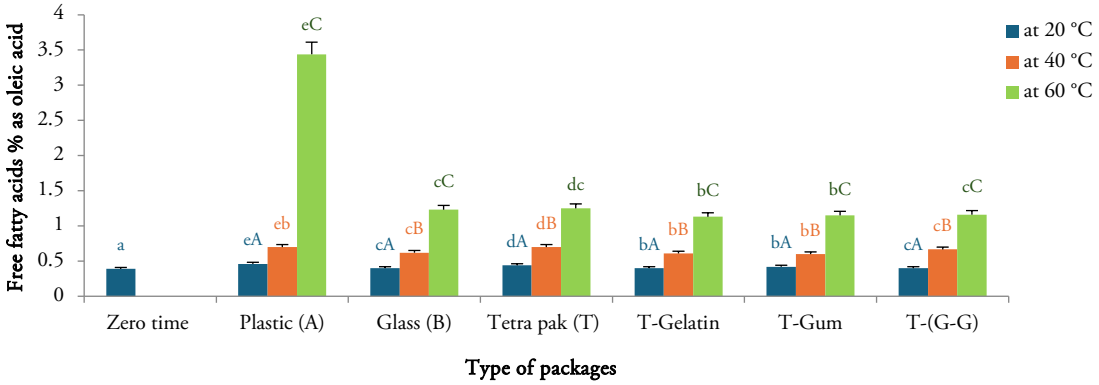

Figure 10. Influence of Storage Temperature on Free Fatty Acids of Olive Oil in Different Packages after Eight Weeks

a, b, c, d, e, f, and g are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

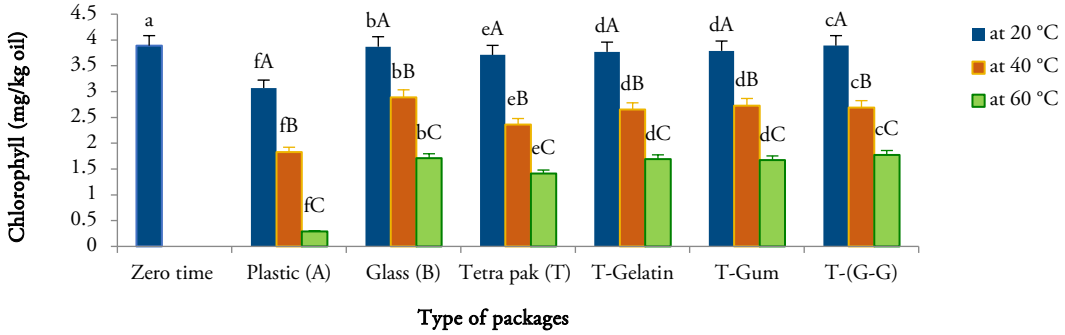

Figure 11. Influence of Storage Temperature on Chlorophyll Content of Olive Oil in Different Packages after Eight Weeks

a, b, c, d, e, f, and g are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

387.11 mg/kg total polyphenols, and glass packaging retaining 1.71 mg/kg chlorophylls, 0.71 mg/kg carotenoids, and 394.90 mg/kg total polyphenols under the same conditions.

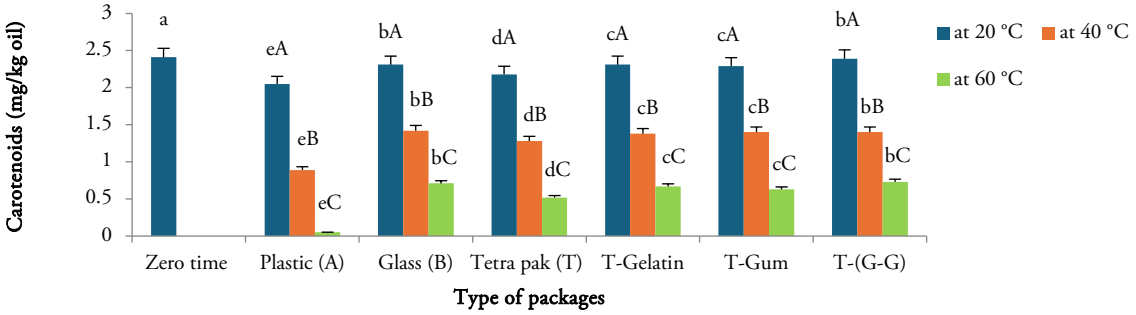

Figure 12. Influence of Storage Temperature on Carotenoid Content of Olive Oil in Different Packages after Eight Weeks

a, b, c, d, e, f, and g are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

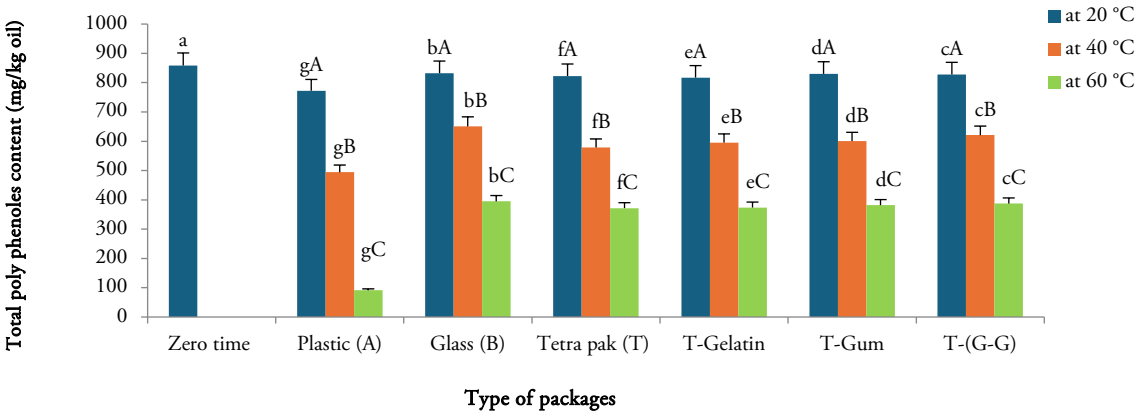

Figure 13. Influence of Storage Temperature on Total Poly Phenols Content (as mg gallic acid/kg oil) of Olive Oil in Different Packages after Eight Weeks

a, b, c, d, e, f, and g are used to compare means of results for types of packaging after storage time. A, B, C are used to compare means of results at each temperature after storage time. Mean values with different letters are significantly different ($p < 0.05$)

This decrease in bioactive components is primarily attributed to oil oxidation, which is influenced by oxygen permeability and packaging materials. Plastic packaging (A) showed higher rates of antioxidant loss due to its greater oxygen permeability and potential migration of active compounds between the oil and the packaging material. These results confirm the importance of packaging in preserving the quality of olive oil during storage.

3.5 Prediction of Accelerated Shelf Life of Olive Oil

The accelerated shelf life of olive oil stored in Tetra Pak with various lining materials was evaluated using both zero-order and first-order reaction kinetics. These kinetic models are frequently applied in food stability studies to predict the time required for quality parameters to reach established critical limits. In this investigation, the peroxide value (PV) served as the primary indicator of oxidative stability, as it is a reliable measure of oil quality that reflects the initial stages of lipid oxidation (Velasco & Dobarganes, 2002). To determine the shelf life, the rate of peroxide formation was quantified under accelerated storage conditions (20, 40, and 60°C), and the reaction kinetics were then applied to extrapolate the shelf life under normal storage conditions. The first-order kinetic model proved particularly effective in capturing the degradation dynamics of the olive oil, (Martín-Torres *et al.*, 2022), as it assumes that the rate of oxidation is directly proportional to the concentration of reactants.

The results of the accelerated shelf-life analysis for olive oil stored in different packaging materials are summarized in Table 6. The findings reveal significant differences in the oxidative stability and shelf life of the olive oil depending on the type of lining applied to the Tetra Pak material.

Table 6. Accelerated Shelf-Life for Olive Oil Packed in Tetra Pak Lined and Unlined

Packaging Material	Shelf Life of olive oil/ days
Unlined Tetra Pak (T)	569
T- Gelatin	744
T- Gum	920
T- (G- G)	870

Tetra Pak lined with Arabic gum (T- Gum) exhibited the longest projected shelf life, lasting 920 days. This superior oxidative stability is attributed to the excellent barrier properties of Arabic gum, which restricts oxygen and moisture penetration. Furthermore, Arabic gum possesses inherent antioxidant properties that enhance its protective effect against oxidative degradation and contribute to its ability to extend shelf life (Mirghani *et al.*, 2018; Patel & Goyal 2015).

Tetra Pak lined with a combination of gelatin and Arabic gum T(G-G) yielded a shelf life of 870 days. This outcome highlights the synergistic effect of combining the two materials, as the gelatin provides structural integrity while Arabic gum enhances the barrier properties and antioxidant action.

In contrast, the Tetra Pak lined with gelatin alone (T-Gelatin) exhibited a shelf life of 744 days. Although gelatin offered moderate protection, its barrier properties were inferior to those of the linings containing Arabic gum, indicating that gelatin alone is less effective in preventing oxidative degradation.

The unlined control package, Tetra Pak (T), demonstrated the shortest shelf life, lasting only 569 days. This result underscores the critical role of the lining materials in extending the shelf life of olive oil by minimizing its exposure to oxygen and light.

The results of this study clearly demonstrate that the type of lining material significantly influences the oxidative stability and shelf life of olive oil. Linings containing Arabic gum, either alone or in combination with gelatin, provide superior protection against oxidative degradation compared to unlined or gelatin-only linings.

4 Conclusion

This study successfully demonstrates the significant impact of edible films on the oxidative stability and shelf life of olive oil stored under accelerated conditions. The application of edible films as a lining for Tetra Pak packaging considerably enhanced the oil's stability. Specifically, packaging lined with Arabic gum, both alone or in combination with gelatin, exhibited superior performance compared to unlined or gelatin-only linings. These results underscore the critical role of barrier and antioxidant properties in mitigating oxidative degradation.

The utilization of the first-order reaction model proved effective in predicting shelf life, confirming its relevance in food stability studies. These findings emphasize the potential of edible films as a viable solution for packaging sensitive products such as olive oil, thereby extending their shelf life, reducing food waste, and supporting broader industrial and sustainability goals.

Future research should focus on exploring the scalability and economic feasibility of these materials for broader commercial adoption.

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