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ORIGINAL ARTICLE

Effect of conductive hydro-dried active packaging on the oxidative stability of peanuts

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Abstract

Lipid oxidation is a key factor contributing to quality deterioration in high-fat foods like peanuts, limiting shelf life and consumer appeal. While conventional aluminum-laminated plastic packaging provides effective protection, its environmental impact prompts interest in more sustainable alternatives. This study examines two-layer composite films composed of a plastic film and an antioxidant-incorporated edible film, designed to preserve roasted peanuts during 8-month storage. To achieve this, sodium alginate- and sodium caseinate-based films containing sodium ascorbate were produced using the innovative conductive hydro-drying method, forming a multilayer structure as the edible layer dried directly onto the conventional plastic film. Water activity, color, lipid oxidation parameters (free fatty acidity, peroxide value, p-anisidine value, conjugated dienes, and aldehydes), and sensory attributes were evaluated. Conductive hydro-dried active films effectively slowed oxidation and demonstrated performance comparable to commercial packaging in physicochemical properties, lipid oxidation, and sensory responses. Free fatty acidity remained around 0.7 mg KOH/g oil in active (PAA and PCA) and commercial (T) packages. Despite a rapid increase from an initial 8.5 meq/kg, peroxide values in PCA- and T-packaged samples remained below 27 meq/kg over 8 months, unlike the control and P groups, which exceeded 30 meq/kg. Similarly, ρ-anisidine values remained within legally permitted limits for both active and commercial packaging. Sensory panelists did not detect off-odors at the end of storage and rated active-packed samples similarly to peanuts stored in commercial films. These results support the potential of this technology as a sustainable packaging approach for oxidation-sensitive foods.

Keywords Conductive hydro-drying · Lipid oxidation · Roasted peanuts · Antioxidant activity · Edible films · Sodium alginate

Introduction

Roasted peanuts are a popular snack food in the world valued for their low price, nutritional quality, and rich flavor (Tonetto et al. 2025). However, due to their high proportion of fat content (particularly unsaturated fatty acids), they are highly prone to lipid oxidation during storage (de Freitas Floriano et al. 2023; Wang et al. 2023). This oxidative degradation can lead to off-flavor rancidity, discoloration, loss of beneficial nutrients, and ultimately affect the shelf life and consumer acceptability negatively. In order to offset such issues, packaging solutions ought to effectively limit oxygen exposure and control moisture while also maintaining product quality over time.

Aluminum-laminated polypropylene (PP) and low-density polyethylene (LDPE) are conventional packaging materials extensively utilized in the packaging of nuts because of their superior barrier properties (Modaresi and Niazmand 2021; Kaur et al. 2023). Nevertheless, these materials are not biodegradable, and their widespread use raises environmental concerns related to plastic waste and recyclability, especially in the case of multilayer structures that combine different polymers. Recently, research efforts have increasingly focused on developing sustainable alternatives, including edible and biodegradable films that can serve as functional packaging layers (Wu et al. 2021; Kumar et al. 2022; Yanat et al. 2025; Yanat and Schroën 2025). These films can provide physical barriers to oxygen and moisture,

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as well as carriers for active compounds such as natural antioxidants. This is particularly relevant in nut packaging, where, due to the limitations of the filling technology, vacuum cannot be applied before nitrogen flushing. Therefore, it results in approximately 0.3% to 5% residual oxygen in the package (Rozo et al. 2024; López-Carballo et al. 2025). When used in multilayer formats—whether entirely biodegradable or combined with small amounts of conventional materials—these films may offer a realistic pathway toward more sustainable packaging. Such hybrid structures can help reduce plastic or aluminum content while still meeting performance requirements for food protection and safety (Matthews et al. 2021; Lacourt et al. 2024). Incorporating antioxidant-rich edible layers with thin conventional polymer films offers a practical balance of food protection, functionality, and environmental sustainability.

A favorable approach in this regard is the use of edible films embedded with antioxidants, which can help slow down lipid oxidation and contribute to shelf life extension (Zhu 2021; Muñoz-Tebar et al. 2023). However, the majority of the conventional film-forming methods based on thermal processes such as oven drying or heat-assisted casting that can promote degradation of the heat-sensitive active substances during processing (Nerín 2010; Yanat et al. 2022). This is likely to restrict the actual antioxidant performance of the food packaging. In contrast, conductive hydro-drying has recently been introduced as an alternative film-forming technique for active edible films (Küçüközet et al. 2026). Unlike conventional drying, this method enables faster water removal at lower surface temperatures, helping to retain the functionality of heat-sensitive active substances. Although conductive hydro-drying has been successfully applied to heat-sensitive foods such as spices (Juri-Morales et al. 2024; Negi et al. 2025), its application as a fabrication method for antioxidant-active packaging materials has not yet been comprehensively investigated.

In this study, we evaluate the performance of a novel conductive hydro-dried edible film embedded with antioxidants, used as part of a multilayer packaging structure for roasted peanuts. To prepare the films, we employed the conductive hydro-drying method to form sodium caseinate and sodium alginate films, which were combined with a conventional plastic film as part of the multilayer system. To achieve antioxidant activity, sodium ascorbate was incorporated during the edible film preparation. The performance of the packaging system is assessed through the analyses of oxygen levels inside the package, water activity, color stability, lipid oxidation, and sensory evaluations. By demonstrating the use of conductive hydro-drying specifically for active packaging applications, this work aims to contribute to the development of innovative antioxidant-active systems that preserve food quality while supporting more sustainable packaging solutions.

Materials and methods

Materials

Salted roasted peanuts were purchased from Çelik Kuruyemiş (Antalya, Türkiye). Upon arrival, their composition was immediately determined, and the peanuts were quickly packaged for use in the required analyses. A 65 µm thick multilayer film that composed of 45 µm polypropylene (PP), 12 µm polyethylene terephthalate (PET), and 8 µm polyethylene (PE), were sourced from Polinas (Manisa, Türkiye). The PP/PET/PE film was used in the production of multilayer films with active conductive hydro-dried films. To make a comparison with current active packaging practise, sodium ascorbate-treated, roasted peanuts packaged in aluminum-laminated plastic package (sample coded as T) was obtained from Çelik Kuruyemiş (Antalya, Türkiye). The materials used to fabricate the edible films, including sodium alginate, sodium caseinate, and glycerin, were obtained from Alfasol (Istanbul, Türkiye). An acrylic emulsion adhesive, Kemiline CE 911, was purchased from Kemiteks (Istanbul, Türkiye) to laminate the edible film with the plastic film. Sodium ascorbate was purchased from Erlab (Istanbul, Türkiye). All other solvents and chemicals of analytical grade were supplied by Merck (Rahway, NJ, USA).

Film preparation

As detailed in a recent study (Küçüközet et al. 2026), the packaging materials were produced following a specific process. First, edible film mixtures of sodium caseinate and sodium alginate were prepared through modified methods from previous studies (Küçüközet and Uslu 2018; Karimi Khorrami et al. 2021). All film mixtures contained 30% (w/w) glycerin as a plasticizer. For those designated for antioxidant functionality, sodium ascorbate was also incorporated at a 30% (w/w) loading level. This concentration was justified by preliminary experimental results and previous studies indicating optimal antioxidant activity at this weight ratio (Sangatash et al. 2016; Modaresi and Niazmand 2021). Both mixtures were then passed through a 125 µm sieve and treated in an ultrasonic water bath to remove air bubbles.

Conductive hydro-drying was employed for drying process. A glass plate was placed on a water bath, ensuring full contact with the bottom surface. The water temperature was maintained at 70 °C during drying. The PP/PET/PE plastic film was placed on the glass, and acrylic adhesive was

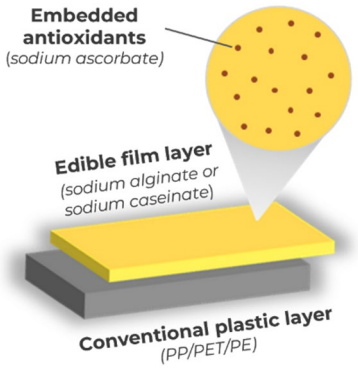


Fig. 1 Illustration of conductive hydro-dried multilayer packaging structure

Table 1 The composition and codes of peanut packages

Code	Composition
C	Control, peanuts stored in a glass jar contains atmospheric air
P	PP/PET/PE plastic film
T	Aluminum-laminated plastic film (commercial package) + sodium ascorbate-treated peanuts
PAA	Plastic film + sodium alginate edible film + sodium ascorbate
PCA	Plastic film + sodium caseinate edible film + sodium ascorbate

spread on its surface. After the adhesive dried, the edible film solution was applied and dried for one hour to complete the multilayer film production. Figure 1 illustrates the structure of the multilater film.

Packaging of peanuts

Initially, the films were thermally sealed on three sides at approximately 140 °C for 7 s using an impulse sealer (Impulse Sealer, Metronic, Eastvale, CA, USA). Each package was filled with 100 g of roasted salted peanuts. Subsequently, the remaining open side was sealed using a modified atmosphere packaging (MAP) machine (KV-600, Lipovak, Sakarya, Türkiye) after the internal gas composition was adjusted to 5% oxygen and 95% nitrogen. Low-oxygen MAP is widely used for lipid-rich foods because reducing the O_2 level (typically to ~ 1–10%) effectively suppresses oxidative reactions responsible for quality deterioration, while nitrogen serves as an inert balance gas to displace oxygen and prevent package collapse or anaerobic off-flavors (Wu et al. 2022).

Table 1 presents the content and codes of peanut packages used in this study. Five sample groups were examined to evaluate the effect of conductive hydro-dried active films on roasted peanut quality during storage: C, unpackaged peanuts stored in ambient air, served as the baseline reference; P, peanuts packaged only with the conventional plastic film, represented the packaging material without active functionality; T, sodium ascorbate-treated peanuts packaged in a commercial aluminum-laminated film, served as the industrial benchmark; PAA, peanuts packaged with the conductive hydro-dried multilayer film containing a sodium alginate-based active layer with sodium ascorbate; and PCA, peanuts packaged with the multilayer film containing a sodium caseinate-based active layer with sodium ascorbate.

Sample characterization

Color

Peanut samples were ground individually for 1 min using a coffee grinder (Clipper, Arzum, Istanbul, Türkiye). The color parameters L*, a*, and b* were measured using a colorimeter (Minolta CR-400, Osaka, Japan) based on the CIE Lab color space. The CIE Lab system provides a three-dimensional representation of color, where the L* value indicates lightness ranging from 0 (black) to 100 (white), the a* value represents the green to red axis, and the b* value represents the blue to yellow axis. Prior to each measurement, the device was calibrated using a standard white calibration plate.

Water activity

The water activity (a_w) of ground peanut samples was measured at 0, 2, 4, 6, and 8 months using a water activity meter (Labswift-a_w, Novasina AG, Lachen, Switzerland).

Monitoring lipid oxidation during storage

Lipid oxidation in roasted salted peanut kernels was evaluated by measuring free fatty acidity, peroxide value, p-anisidine value, conjugated diene value, and the amounts of selected volatile compounds (hexanal, pentanal, and octanal). Volatile compounds were analysed using ground peanut samples, while the other analyses were performed using extracted peanut oil.

For oil extraction, 80 g of roasted peanuts were ground using a coffee grinder (Arzum Clipper, Istanbul, Türkiye), and 400 ml of n-hexane was added. The mixture was vigorously stirred at room temperature for 6 h using a magnetic stirrer. It was then filtered through coarse filter paper and washed several times with fresh n-hexane to remove any remaining solids. The solvent was removed using a rotary evaporator at 35 °C under vacuum (HEI-VAP, Heidolph Instruments, Schwabach, Germany), and the resulting peanut oil was used for analyses.

Determination of free fatty acids (FFA)

Free fatty acidity (FFA) was determined according to AACC Method 58–15.01 (American Association of Cereal Chemists 2000). For the analysis, 5 g of peanut oil was mixed with 75 ml of a 1:1 (v/v) ethanol/diethyl ether solution to ensure complete dissolution. The mixture was titrated with 0.1 N ethanolic potassium hydroxide using phenolphthalein (1% phenolphthalein in ethanol, v/v) as an indicator. Free fatty acidity (% oleic acid), and the acid value (mg KOH/g oil) was calculated using Eq. 1 and Eq. 2, respectively:

$$FFA\,(\%oleicacid) = \frac{V \times N \times F \times 100}{m \times 1000} \tag{1}$$

$$Acidvalue\,(mgKOH/goil) = \frac{V \times 56.11 \times N}{m} \tag{2}$$

where V is the volume of 0.1 N ethanolic KOH used (ml), N is the normality of the ethanolic KOH solution (0.1 N), F is the equivalent weight of the expressed fatty acid (for oleic acid: 282 mg KOH/g), m is the weight of the oil sample (g), and *56.11* is the molecular weight of KOH (mg/mmol).

Measurement of peroxide value (PV)

The peroxide value was determined titrimetrically according to the AOCS Official Method Cd 8–53 (AOCS 2009). For the analysis, 5±0.05 g of peanut oil was weighed into a flask, followed by the addition of 30 ml of an acetic acid:chloroform mixture (3:2, v/v) to ensure complete dissolution of the oil. Then, 0.5 ml of potassium iodide solution was added, and the mixture was shaken for 1 min. After this period, 30 ml of distilled water and a few drops of 1% starch solution were added. The resulting mixture was titrated with 0.1 N sodium thiosulfate solution until the purple colour disappeared. The same procedure was applied to a blank sample, and the peroxide value was calculated using Eq. 3:

$$Peroxidevalue\,(meqO_2/kgoil) = \frac{((V_s - V_b) \times N \times 1000}{m} \tag{3}$$

where V_s is the volume of sodium thiosulfate used for a sample, V_b is the volume of sodium thiosulfate used for blank, N is the normality of sodium thiosulfate, and m is the weight of peanuts. The peroxide value is expressed as the amount of peroxide in milliequivalents (meq) present in 1000 g of the sample.

Determination of ρ-anisidine value

The ρ-anisidine value was determined spectrophotometrically according to the method of Paquot, (2013). A gram of peanut oil was mixed with 25 ml of iso-octane (2,2,4-trimethylpentane), and the absorbance of the solution was measured at 350 nm using a UV–VIS spectrophotometer (Carry60, Agilent Technologies, Santa Clara, CA, USA), against a blank solution of iso-octane. Subsequently, 5 ml of the iso-octane/oil solution was taken, and 1 ml of a ρ-anisidine solution (2.5 g ρ-anisidine/1000 ml acetic acid) was added. The blank sample was prepared by adding 1 ml of the ρ-anisidine solution to 5 ml of iso-octane. After allowing the solutions to stand for 10 min, the spectrophotometer was calibrated with the blank solution, and the absorbance of the sample was measured at 350 nm. The obtained absorbance values were then used in Eq. 4 to calculate the ρ-anisidine value:

$$\rho - anisidinevalue\,(dimensionlessindex) = \frac{(25 \times (1.2 \times A_2 - A_1)}{m} \tag{4}$$

where, A_2 represents the absorbance of the oil solution after reaction with p-anisidine, A_1 refers to the absorbance of the solution before the reaction, and m indicates the sample amount in grams.

Determination of conjugated dienes value

A 0.25 g of peanut oil was weighed into a 25 ml volumetric flask, and the volume was made up to the calibration mark with cyclohexane. The absorbance of the resulting solution was measured at 232 nm using a UV–Vis spectrophotometer (Carry 60, Agilent Technologies, Santa Clara, CA, USA) against pure solvent as the blank. The necessary dilutions to ensure the absorbance values fell within the 0.2–0.8 range were performed with cyclohexane. Conjugated diene values were calculated using Eqs. 5 and 6 as follows:

$$K_{232} = \frac{A_{232}}{c \times l} \tag{5}$$

$$C_2\,(\%absorbance) = (K_{232} - 0.007) \times 0.84 \tag{6}$$

where, K_{232} is the specific extinction coefficient at 232 nm, A_{232} is the absorbance at 232 nm, c is the concentration of the oil in the solution (g/ml), l is the path length of the cuvette (cm), typically 1 cm. Moreover, C_2 is the calculated conjugated dienes value, number of 0.007 and 0.84 values represent the corrections made based on baseline shifts or impurities, following the method-specific guidelines.

Analysis of volatile compounds

Depending on the storage conditions of peanuts, the formation of aldehyde compounds hexanal, pentanal and octanal is observed as a result of advanced lipid oxidation. The analysis of volatile compounds (hexanal, pentanal, octanal) formed from lipid oxidation in peanuts was performed using gas chromatography–mass spectrometry (GC-MS) (QP2010-Plus, Shimadzu, Kyoto, Japan). The volatile compounds were extracted by static headspace solid-phase microextraction. A gram of ground peanut sample was transferred into a 20 ml vial, which was immediately sealed with silicone rubber–teflon caps and placed into the injection unit of the instrument. After extraction at 70 °C, the vials were stirred at 250 rpm and incubated for 5 min, followed by absorption of volatile compounds onto a 50/30 µm divinylbenzene-carboxen-polydimethylsiloxane fiber (Supelco, Bellefonte, PA, USA) for 20 min. For desorption of the volatile compounds, the fiber was inserted into the injection block for 5 min, initiating the analysis.

GC-MS analysis conditions were as follows: carrier gas helium (He) at 70 kPa and 1.29 ml/min flow rate; injection mode split 100; injection block temperature 250 °C; column TRB-5MS; oven temperature program starting at 40 °C with 1-min hold, ramping at 20 °C /min to 120 °C with an 8-min hold, then ramping at 20 °C /min to 240 °C with a 2-min hold; interface temperature 250 °C; ion source temperature 200 °C; mass range 35–300 amu; scan rate 0.45 s.

Peak areas of volatile compounds detected in the samples were calculated using the instrument software (GCMS-TQ, Shimadzu, Kyoto, Japan), with values normalized to sample mass (per g of peanuts) and quantified relative to an internal standard. Identification of compounds and retention times were confirmed by matching mass spectra with Wiley Registry/NIST Mass Spectral Library (Wiley, Hoboken, NJ, USA).

Sensory evaluation

Sensory evaluation was conducted at the 6th and 8th months of the storage period. The paired comparison ranking test method was used for the evaluation. This method is based on comparing all possible pairs of a given set of samples using Friedman analysis.

The test was carried out with 20 panelists selected from among graduate students in the Department of Food Engineering at Akdeniz University. Ten paired combinations were created from all possible pairs of five different samples (e.g., AB, AC, AD, AE, BC, BD, BE, CD, CE, DE), and these were presented to the panelists. Panelists were asked to evaluate each pair separately. During the evaluation, they were instructed to indicate which sample they preferred in each pair based on criteria such as appearance, odor, bitter taste, and oxidised taste, and to complete the sensory evaluation form (Drake et al. 2023).

For each evaluation, the selected sample in a pair was given a ranking point, from 1 to 5. The total score for each sample was calculated using Eq. 7. The results were analysed using Friedman's T test, and the T value was determined using Eq. 8.

$$Total score of a sample = Total of rows + (2 \times Total of columns) \tag{7}$$

$$T = \left(\frac{4}{p \times t}\right) \sum_{i=1}^{t} R^2 - \left(9 \times p \times [t-1]^2\right) \tag{8}$$

where, T refers to Friedman's T value, p is the number of panelists, t denotes the number of samples (treatments), and R^2 represents the square of the sum of the sample totals.

Then, the T value was then compared with the critical T value (T_k) obtained from the "table of chi-square distribution critical values for different degrees of freedom and probabilities." Finally, significant differences among the samples were identified using Eq. 9;

$$HSD = q_{\alpha,t,\infty}\sqrt{\frac{p \times t}{4}} \tag{9}$$

where, HSD is Tukey's honest significant difference value, and $q_{(\alpha,t,\infty)}$ represents the upper critical value for the Tukey HSD multiple comparison procedure at significance level α. In the paired-comparison test design, lower total preference scores indicate higher panellist liking, as they reflect more frequent selection of a sample; accordingly, within each storage period, the sample with the lowest total score was considered the most preferred by the panelists.

Statistical analysis

All statistical analyses were performed using The SAS System for Windows (Version 9.0; SAS Institute Inc., Cary, NC, USA). Prior to hypothesis testing, ANOVA assumptions were verified within the software environment: normality of residuals was evaluated using the Shapiro–Wilk test and homogeneity of variance was assessed using Levene's test. As all datasets met these assumptions ($P > 0.05$), Analysis of Variance (ANOVA) was subsequently applied to determine significant differences among treatments. When significant effects were detected, mean separation was conducted using Duncan's multiple range test at a 95% confidence level.

Table 2 Changes in L*, a* and b* color values depending on packaging type and storage time

Film type	2nd month	4th month	6th month	8th month
L values*				
C	64.15±1.75[a]	61.12±4.73[a]	66.10±5.21[a]	65.57±3.17[a]
P	63.23±2.88[a]	63.50±2.04[a]	64.63±4.24[a]	66.79±3.49[a]
T	66.30±3.63[a]	63.09±2.09[a]	64.84±3.27[a]	64.48±0.43[a]
PAA	65.51±0.89[a]	61.30±1.13[a]	65.70±2.19[a]	63.91±0.97[a]
PCA	64.02±1.01[a]	61.38±2.09[a]	63.65±2.15[a]	64.45±2.51[a]
a values*				
C	9.49±1.21[a]	8.39±2.51[a]	8.16±2.71[a]	7.58±0.45[b]
P	8.81±2.33[a]	8.28±0.57[a]	8.00±2.66[a]	7.66±1.60[b]
T	8.01±0.90[a]	8.27±2.54[a]	9.04±2.39[a]	9.78±1.11[a]
PAA	10.02±0.32[a]	10.22±1.15[a]	9.13±1.24[a]	9.92±1.25[a]
PCA	8.88±0.25[a]	10.63±0.75[a]	9.73±0.87[a]	9.74±1.49[a]
b values*				
C	31.21±1.41[a]	32.24±2.95[a]	29.53±2.36[a]	28.60±1.49[b]
P	32.00±3.19[a]	30.69±3.61[a]	31.39±3.19[a]	28.15±1.52[b]
T	31.60±0.93[a]	29.85±1.88[a]	29.90±3.19[a]	32.58±0.95[a]
PAA	32.66±2.83[a]	31.00±1.16[a]	31.37±2.92[a]	33.19±1.12[a]
PCA	31.61±2.62[a]	31.31±1.84[a]	31.75±1.40[a]	32.83±0.81[a]

*C: Control (glass jar with atmospheric air), P: Plastic film (PP/PET/PE), T: Aluminum-laminated commercial film + sodium ascorbate-treated peanuts, PAA: Plastic film + alginate edible film with sodium ascorbate, PCA: Plastic film + caseinate edible film with sodium ascorbate. Different letters indicate significant differences ($P<0.05$)

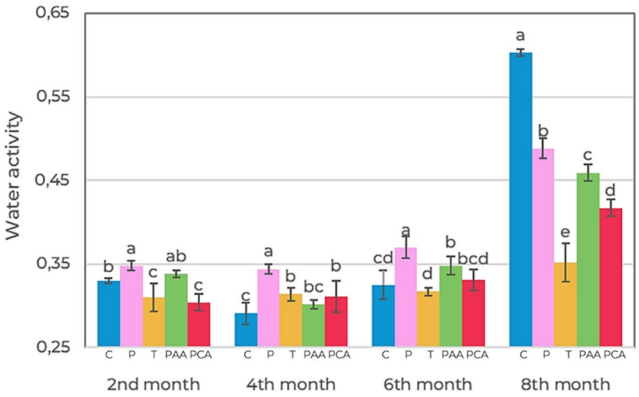


Fig. 2 Changes in water activity values depending on packaging type and storage time. C: Control (glass jar with atmospheric air), P: Plastic film (PP/PET/PE), T: Aluminum-laminated commercial film + sodium ascorbate-treated peanuts, PAA: Plastic film + alginate edible film with sodium ascorbate, PCA: Plastic film + caseinate edible film with sodium ascorbate. Different letters indicate significant differences ($P<0.05$). Error bars represent standard deviations ($n=3$)

Results and discussion

Color of peanuts

Table 2 demonstrates L*, a*, and b* color scores of stored peanuts. No significant differences were observed in the L* values of peanuts depending on the film type or storage duration. However, by the 8th month, the a* and b* values of the C and P samples had decreased significantly compared to both their initial values and those of the other packaging groups ($P<0.05$). This decrease is thought to be due to the degradation of pigments such as β-carotene and lutein, which are known to contribute to the characteristic yellow hue of peanuts during storage (Lavelli and Sereikaitė 2022; de Freitas Floriano et al. 2023). In contrast, the color parameters (L*, a*, b*) of peanuts stored in antioxidant-enriched packaging films remained stable throughout the 8 months, indicating a protective effect of the active compounds against oxidation and therefore, pigment degradation.

Water activity

The water activity values of stored peanuts were presented in Fig. 2. Before storage, the water activity of the peanuts ranged between 0.30 and 0.31. During the first four months of storage, no significant changes in water activity were detected in the packaged samples, except for sample C. Notably, an increase in water activity was observed in all peanut samples after the sixth month of storage. This increase was most pronounced in sample C, whereas the sample packaged with the T, which is the commercial package, exhibited minimal increases in water activity. This phenomenon is attributed to the considerably lower water vapor permeability of aluminum compared to other materials. At 8th month, the water activity of peanuts packaged with the T material was about 0.35, while those packaged with P, PAA, and PCA films showed values ranging from 0.41 to 0.48. In contrast, control samples reached a water activity value of 0.61.

Overall, it was observed that the packaging material had a significant effect on the water activity. Although by the end of the storage all samples except for T exhibited water activity values above 0.40, indicating a higher susceptibility of peanuts to lipid oxidation (Ghorbani and Hosseini 2017; Sartori et al. 2018), the performance of the conductive hydro-dried active films was satisfactory during the first six months of storage. This apparent contradiction can be explained by the interplay between barrier and active functions: despite a_w values exceeding 0.40 at later stages, the presence of sodium ascorbate and reduced oxygen ingress in conductive hydro-dried films helped delay oxidative reactions. In other words, the antioxidant activity and improved gas barrier behavior of the active films partially compensated for the critical a_w conditions, mitigating oxidative damage even in a range typically associated with higher oxidation risk.

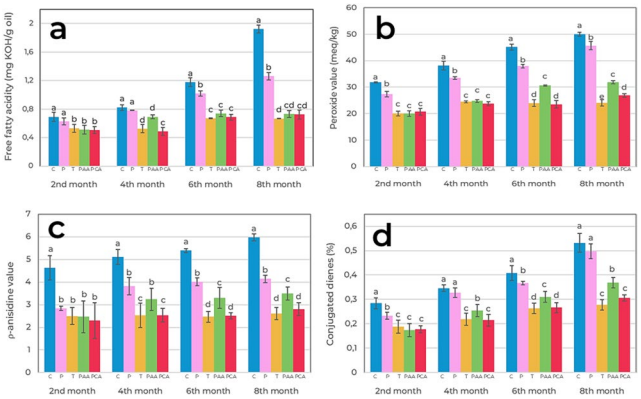


Fig. 3 Changes in free fatty acidity (**a**), peroxide value (**b**), ρ-anisidine value (**c**), and conjugated dienes (**d**) of 8-months stored peanut samples. C: Control (glass jar with atmospheric air), P: Plastic film (PP/PET/PE), T: Aluminum-laminated commercial film + sodium ascorbate-treated peanuts, PAA: Plastic film + alginate edible film with sodium ascorbate, PCA: Plastic film + caseinate edible film with sodium ascorbate. Different letters indicate significant differences ($P < 0.05$). Error bars represent standard deviations ($n = 3$)

Lipid oxidation during storage

Figure 3 illustrates changes in lipid oxidation indicators, including free fatty acidity (a), peroxide value (b), *ρ*-anisidine value (c), and conjugated dienes (d). The initial free fatty acidity of the peanuts was 0.45 mg KOH/g oil and increased significantly in all samples during storage. Notably, the acidification rate in the C and P groups was significantly higher ($P < 0.05$) compared to other packaging types, with the C group reaching an exceptionally high value of 1.92 mg KOH/g oil at month 8. Samples packaged with PAA, PKA, and T films showed similar, more moderate increases, with free fatty acidity values around 0.7 mg KOH/g oil at the end of storage. According to Codex Alimentarius Commission (1995), the free fatty acidity in raw peanuts should not exceed 1 in peanuts, indicating that all groups except C maintained acceptable acidity levels throughout storage.

Peroxide value, an indicator of primary lipid oxidation, was initially 8.5 meq/kg in the samples. During the first two months, all peanut samples exhibited a rapid increase in peroxide value (Fig. 3b). By month 2, samples packaged with T, PAA, and PCA films showed significantly lower values (20.0–21.4 meq/kg) compared to the C (31.8 meq/kg) and P (27.4 meq/kg) groups. Although the rate of increase slowed down after this point, peroxide values in the C and P samples continued to rise, surpassing 30 meq/kg by months 2 and 4, respectively. In contrast, peroxide values in samples packaged with PCA and T films remained below 27 meq/kg throughout the 8-month storage period. Another indicator of early-stage oxidation, the conjugated dienes (%) value, exhibited a trend similar to that of peroxide values (Fig. 3d). Conjugated diene levels steadily increased in all groups over time, with the highest concentrations observed in the control samples. In contrast, the T and PCA packaging groups showed the most favorable results, maintaining conjugated diene levels around 0.3% at the end of the storage period.

Secondary oxidation products, assessed by *ρ*-anisidine values (Fig. 3c), exhibited a similar pattern to primary oxidation markers. The initial *ρ*-anisidine value of 1.57 increased rapidly during the first two months, reaching approximately 2.5 in samples packaged with T, PCA, and PAA films. After this period, *ρ*-anisidine levels stabilised in the T and PCA groups, whereas they continued to rise in the C and P groups, reaching elevated levels of 5.98 and 4.14, respectively, by month 8. The lowest *ρ*-anisidine values at the end of storage were recorded in the T and PCA groups, with final values of 2.62 and 2.80, respectively.

Figure 4 shows the peak areas of pentanal (a), hexanal (b), and octanal (c), which are advanced lipid oxidation products causing off-flavor and odor in foods. For this analysis, peanut samples from the C, T, and PCA groups were examined. Similar to early oxidation trends shown in Fig. 3, aldehyde formation was highest in the C group during storage. There was generally no statistically significant difference in the levels of aldehyde compounds formed between peanuts packaged using commercial packaging and those packaged with active conductive hydro-dried composite films.

Overall, lipid oxidation remained at minimal levels in peanuts packaged with both T and PCA films; it should be noted that T samples contained sodium ascorbate–treated peanuts, further contributing to oxidative stability. These findings indicate that active composite films produced via conductive hydro-drying provide superior protection against lipid oxidation. As demonstrated in our previous

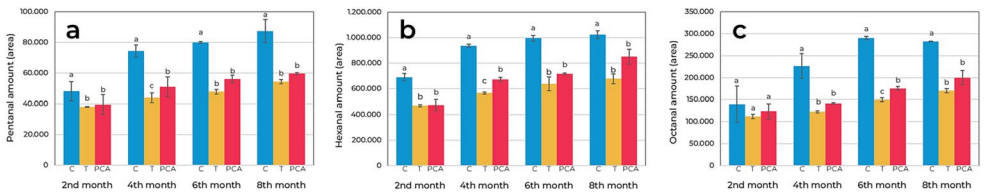


Fig. 4 The changes in pentanal (**a**), hexanal (**b**), and octanal (**c**) volatile compounds of stored peanuts. C: Control (glass jar with atmospheric air), T: Aluminum-laminated commercial film + sodium ascorbate-treated peanuts, PCA: Plastic film + caseinate edible film with sodium ascorbate. Different letters indicate significant differences ($P < 0.05$). Error bars represent standard deviations ($n = 3$)

Table 3 Total liking scores of stored peanuts at months 6 and 8, with Tukey HSD multiple comparison test results

6th month		8th month	
C	144[a]	P	151[a]
T	109[b]	T	109[b]
PCA	113[b]	PCA	107[b]
PAA	114[b]	PAA	116[b]

*C: Control (glass jar with atmospheric air), P: Plastic film (PP/PET/PE), T: Aluminum-laminated commercial film + sodium ascorbate-treated peanuts, PAA: Plastic film + alginate edible film with sodium ascorbate, PCA: Plastic film + caseinate edible film with sodium ascorbate. Different letters indicate significant differences ($P < 0.05$)

**Lower total scores correspond to higher preference by panellists

study (Küçüközet et al. 2026), the conductive hydro-drying process minimizes thermal degradation of antioxidant compounds during film formation, thereby preserving their oxygen-scavenging activity. Compared to conventional drying techniques commonly reported for antioxidant-active packaging systems, the preservation of antioxidant integrity in conductive hydro-dried films likely enhances their ability to delay free radical propagation and reduce oxygen availability at the food–film interface. This mechanism aligns with the reduced peroxide values observed in the present study.

Sensory analysis

Total scores and Tukey HSD multiple comparison test results are shown in Table 3. In this test structure, lower total scores indicate higher liking, as they represent samples that were preferred more frequently during the paired comparisons. Therefore, the sample with the lowest total score in a given storage month is interpreted as the most liked by the panelists. The Friedman test was applied to determine whether differences between ranking sums were statistically significant, and Tukey's HSD test was subsequently used to identify which samples differed from each other in terms of liking. At month 6, panelists detected rancid and bitter flavors in the control group, which also received the lowest liking scores based on Tukey HSD results. By month 8, control samples were found to have an unpleasant odor and were considered spoiled. No significant difference ($P < 0.05$) was observed between T, PCA, and PAA groups at either month 6 or 8, indicating that conductive hydro-dried films performed similarly to the commercial aluminum-laminated reference (T) in terms of liking scores. Importantly, no off-odor was detected even at month 8 in samples packaged with T and active films. These sensory evaluation findings support the lipid oxidation data, confirming that novel packaging effectively maintained product quality throughout storage and suggesting that conductive hydro-dried films could feasibly replace the commercial structure without compromising consumer acceptance.

Conclusion

In this work, we demonstrated the novelty of using conductive hydro-drying to produce sodium alginate– and sodium caseinate–based multilayer films containing sodium ascorbate as an active edible layer for roasted peanuts. During 8 months of storage, these active multilayer films maintained oxidative stability at levels comparable to commercial aluminum-laminated packaging, with free fatty acidity remaining consistently low and both peroxide and p-anisidine values staying well below commonly accepted rancidity thresholds and within legally permitted limits. Peanuts stored in the active films also retained acceptable color and water activity, and sensory panelists rated them similarly to the commercial reference, with no detectable off-odors at the end of storage. Collectively, these results indicate that conductive hydro-dried edible multilayers can protect lipid-rich products like peanuts without compromising oxidative stability, physicochemical quality, or consumer acceptance.

These findings suggest that active conductive hydro-dried packaging offers a promising alternative for peanut storage with potentially reduced environmental impact. While these sustainability benefits remain indicative rather than conclusive without a dedicated life cycle assessment (LCA) or quantitative data, replacing aluminum layers with an edible, water-removable coating may ease layer separation and reduce reliance on hard-to-recycle laminates. Thus, our approach should be seen as a preliminary step toward more sustainable multilayer systems rather than a definitive solution. It is also recommended that these films be further investigated for use with other oxidation-sensitive and/or other sensitive food products. Given its compatibility with scalable production, this method has broader potential for industrial applications in food packaging.

Author contributions Ahmet Oktay Küçüközet: Conceptualization, Investigation, Methodology, Formal analysis. Murat Yanat: Conceptualization, Investigation, Visualization, Writing—original draft. Mustafa Kemal Uslu: Conceptualization, Formal analysis, Methodology, Funding acquisition, Writing—review and editing.

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Data availability The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

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

Ethical approval All research involving human participants was conducted ethically and responsibly, in full compliance with all relevant codes of experimentation and legislation. The human sensory evaluation component of this study was performed in accordance with the principles outlined in the Declaration of Helsinki. All participants were volunteers who provided informed consent before their participation. They were informed of their right to withdraw from the study at any time without penalty.

Consent to participate Not applicable. All authors consented to the publication.

Consent for publication Not applicable. No data/image has been reproduced.

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