Agrociencia Uruguay 2026 | Volume 30 | Number NE1 | Article e1699
DOI: 10.31285/AGRO.30.1699
ISSN 2730-5066

Investigaciones en pecán en Sudamérica

Effective Management of Pecan Storage Conditions from Post-Harvest Through to Market Sale

Ormando, P. [1,2]; Panozzo, M. [4]; Descalzo, A. [1,3]; Rizzo, S. [1,3]; Moreno, K. [1,3]; Grigioni, G. [1,3]; Frusso, E. [5]; Rossetti, L. [1,3]

[1]*Instituto Nacional de Tecnología Agropecuaria (INTA), Instituto Tecnología de Alimentos (ITA), Buenos Aires, Argentina*

[2]*Universidad Argentina de la Empresa (UADE), Buenos Aires Argentina*

[3]*Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) - Instituto Nacional de Tecnología Agropecuaria (INTA), Instituto de Ciencia y Tecnología de los Sistemas Alimentarios Sustentables (ICyTeSAS, INTA-CONICET), Buenos Aires, Argentina*

[4]*Instituto Nacional de Tecnología Agropecuaria (INTA), EEA Concordia, Entre Ríos, Argentina*

[5]*Instituto Nacional de Tecnología Agropecuaria (INTA), Instituto de Investigación Recursos Biológicos (IRB), Buenos Aires, Argentina*

Editor

Paula Conde
Instituto Nacional de Investigación Agropecuaria (INIA), Canelones, Uruguay

Received *11 Mar 2025*
Accepted *19 Aug 2025*
Published *13 Feb 2026*

Correspondence

Marina Panozzo
panozzo.marina@inta.gob.ar

Abstract

Pecans are a source of protein, fiber, bioactive compounds, and are rich in fatty acids. Their quality depends on postharvest and storage (temperature, light, and relative humidity). Pawnee nuts were dried at 30 °C up to 4% moisture content. In-shell pecans were stored in raffia bags at 20 °C in darkness for two and four months (2M/4M). They were then shelled and vacuum-sealed for 0, 4, 8, and 12 months in darkness, before being exposed to light and ambient light for 0, 20, and 40 days. The attributes evaluated were water activity, moisture (%), peroxidation (meq O_2/kg oil), TBARS (meq MDA/kg nut), luminosity, and instrumental hardness (N). Results were analysed using Dunn's test with a 5% significance level. For 2M, day 0 peroxidation values increased slightly up to eight months of vacuum and darkness, below 2 meq O_2/kg oil. Changes in texture in the fourth and eighth months were related to water activity, and higher peroxide and TBARS values for days 0 and 20, decreasing lightness. At 4M, alterations in water activity, moisture, lightness, and texture, along with higher peroxide and TBARS values, were observed in the fourth and eighth months. Compared to 2M ($p<0.05$), this resulted in a significant decrease in quality. These findings suggest the potential for preserving pecan nuts under 2M conditions, vacuum and darkness for a maximum of eight months, with subsequent immediate sale of shelled nuts.

Keywords: oxidation, postharvest, shelf-life, shelled pecan nut, vacuum-packaging

CC BY

Ormando, P., Panozzo, M., Descalzo, A., Rizzo, S., Moreno, K., Grigioni, G., Frusso, E., & Rossetti, L. (2026). Effective management of pecan storage conditions from post-harvest through to market sale. *Agrociencia Uruguay, 30*(NE1), Article e1699. https://doi.org/10.31285/AGRO.30.1699

Manejo eficiente de las condiciones de almacenamiento de la nuez pecán desde la poscosecha hasta la venta en comercios

Resumen

La nuez pecán es fuente de proteínas, fibra y compuestos bioactivos y es rica en ácidos grasos. Su calidad depende de la poscosecha y el almacenamiento (temperatura, luz y humedad relativa). Nueces Pawnee fueron secadas hasta alcanzar 4% de humedad a 30 °C. Las nueces con cáscara se almacenaron en bolsas de rafia a 20 °C en oscuridad durante dos y cuatro meses (2M/4M). Luego, se pelaron y almacenaron al vacío durante 0, 4, 8 y 12 meses en oscuridad, para luego exponerlas a la luz y ambiente durante 0, 20 y 40 días. Los atributos evaluados fueron: actividad acuosa, humedad (%), peroxidación (meq O_2/kg aceite), TBARS (meq MDA/kg nuez), luminosidad y dureza instrumental (N). Los resultados se analizaron mediante la prueba de Dunn con un 5% de significancia. Para 2M, los valores de peroxidación a día 0 aumentaron levemente hasta ocho meses de vacío y oscuridad por debajo de 2 meq O_2/kg aceite. Los cambios de textura en el cuarto y octavo mes se relacionaron con la actividad acuosa, y valores más altos de peróxidos, TBARS para 0 y 20 días, disminuyendo la luminosidad. En 4M, se observaron alteraciones de actividad acuosa, humedad, luminosidad, textura, junto a mayores valores de peróxido y TBARS en el cuarto y octavo mes. Comparado con 2M ($p<0,05$), esto resultó en una disminución significativa en la calidad. Estos hallazgos sugieren el potencial para conservar nueces bajo condiciones 2M, vacío y oscuridad durante un máximo de ocho meses para luego venderlas peladas en forma inmediata.

Palabras clave: oxidación, poscosecha, vida útil, nuez pecán sin cáscara, envasado al vacío

Gerenciamento eficiente das condições de armazenamento da noz-pecã desde a pós-colheita até a venda em comércios

Resumo

A noz-pecã é fonte de proteína, fibra, compostos bioativos e rica em ácidos graxos. Sua qualidade depende da pós-colheita e do armazenamento (temperatura, luz e umidade relativa). As nozes-pecã foram secas até 4% de umidade a 30°C. As nozes-pecã com casca foram armazenadas em sacos de ráfia a 20°C no escuro por dois e quatro meses (2M/4M). Elas foram então descascadas e seladas a vácuo por 0, 4, 8 e 12 meses no escuro, antes de serem expostas à luz e ao ambiente por 0, 20 e 40 dias. Os atributos avaliados foram: atividade de água, umidade (%), peroxidação (meq O_2/kg de óleo), TBARS (meq MDA/kg de noz), luminosidade e dureza instrumental (N). Os resultados foram analisados usando o teste de Dunn com um nível de significância de 5%. Para 2M, os valores de peroxidação do dia 0 aumentaram ligeiramente até oito meses de vácuo e escuro abaixo de 2 meq O_2/kg de óleo. As alterações de textura no quarto e oitavo mês foram relacionadas à atividade de água, e valores maiores de peróxido e TBARS nos dias 0 e 20, reduzindo a luminosidade. Aos 4M, alterações na atividade de água, umidade, luminosidade e textura, juntamente com valores maiores de peróxido e TBARS, foram observadas no quarto e oitavo mês. Em comparação com 2M ($p<0,05$), isso resultou em uma diminuição significativa da qualidade. Essas descobertas sugerem o potencial de conservar as nozes em condições de 2M, vácuo e escuridão por até oito meses, com subsequente venda imediata das nozes descascadas.

Palavras-chave: oxidação, pós-colheita, vida de prateleira, noz-pecã sem casca, embalagem a vácuo

1. Introduction

Pecan [*Carya illinoinensis* (Wangenh.) K.Koch] orchards in Argentina are spread across three diverse climate regions: central, northeastern, and northwestern. Included in these regions are the provinces of Buenos Aires, Entre Ríos, Corrientes, Misiones, Santa Fe, Córdoba, Catamarca, Salta, Santiago del Estero, Tucumán, and Chaco. Around 10,000 hectares were used for pecan farming in 2021, producing an estimated 2,000 tons per year. However, since many saplings are not yet mature, production should increase dramatically in the next five years, possibly reaching 10,000 tons. The superior genetics of Argentinian pecan trees and the meticulous management of their plantations –including irrigation, fertilization, pruning, and weeding– yield high-quality nuts.

Depending on the variety, harvesting occurs between April and July. The primary pecan cultivars in Argentina originate from the Germplasm Bank of the United States Department of Agriculture (USDA). These cultivars include Sumner, Pawnee, Oconee, Stuart, Cape Fear, Nacono, Shoshoni, Maramec, Choctaw, Forkert, Kernodle, Kiowa, Desirable, Mahan, Harris Super, Starking Hardy Giant, Wichita, and Western Schley. After harvesting, the nuts are transported to conditioning plants, where they undergo cleaning, drying, shelling, size sorting, bagging, and quality control. The finished batches are subjected to quality analysis according to international standards. Shelled and peeled pecans are exported to markets in the United States, Europe, Brazil, Russia, the Middle East, and Southeast Asia (Cámara Argentina de Productores de Pecán, n.d.).

Consuming pecan nuts offers many health benefits. Due to their high nutritional value, they are incredibly healthy, notable for their lipid content (50 to 75%), which makes them susceptible to oxidation (Descalzo et al., 2021; Ribeiro, Klein et al., 2020). Pecan nuts also present other nutrients, including fiber, vitamins, minerals, and flavonoids (antioxidants), as well as being a good source of folic acid. In culinary applications, pecans are used in savory dishes and extensively in bakeries, confectionery, ice cream, and chocolate. Nuts can also be consumed in processed forms such as flour, plant-based milk, oil, and paste. However, the functional, nutritional, and sensory properties of pecan products depend on postharvest processing methods.

The storage conditions of shelled and in-shell nuts, from the field to the local market, are influenced by composition (moisture, lipid content, phytochemicals), postharvest processing, packaging (types of packaging, modified atmosphere, vacuumed), and environmental conditions (temperature, light exposure, and relative humidity (RH)) (Adkison et al., 2021; Prabhakar, Sharma et al., 2022; Yildiz & Karaca, 2024).

Among postharvest processes are heating or drying, which inactivate mold growth and certain hydrolytic and oxidative enzymes, water processing to improve shelling conditions, or freezing for preventing lipid oxidation during storage (Shojaee et al., 2023).

Under improper conditions, pecan quality can deteriorate faster and lead to reduced storage life. Major issues associated with inferior pecan quality include colour darkening and lipid oxidation, resulting in rancid flavour and texture degradation (Prabhakar, Sharma et al., 2022).

Particularly, cultivars impact not only the chemical composition of pecans but also their physical properties, including colour (Ribeiro, Klein et al., 2020). The distinct lipid and antioxidant composition of pecans significantly influences their quality during and after storage. These variables particularly affect lipid oxidation, causing a decrease in the nutritional value, kernel browning and internal browning (IB), reducing colour parameters such as luminosity, b*, and hue°, and increasing oil acidity, peroxide value (PV), and nut respiration (Ribeiro, Ribeiro et al., 2020; Thewes et al., 2021). Beyond lipid and antioxidant content, external conditions are crucial in pecan storage. Factors such as storage temperature, nut moisture, and oxygen partial pressure directly affect unsaturated fatty acid oxidation rates (Ribeiro, Ribeiro et al., 2020). Therefore, maintaining low temperatures is essential for preserving pecan quality during storage, although this requires specialized cold equipment. Pecan moisture content above 4% can promote internal browning during storage and the appearance of fungal activity. However, low pecan moisture content requires prolonged drying periods, exposing the nuts to high temperatures for extended periods, which favours oxidation, leads to colour loss, reduces consumer acceptance, and makes the nuts more fragile during shelling due to low moisture content (Thewes et al., 2021).

The shell is relatively more effective at preventing the entry of air and moisture than most packaging materials. Although retaining the shell is beneficial for preserving pecan quality, handlers prefer shelled nuts to save space during storage and reduce transportation costs. This preference also includes consumers at the local market. Therefore, it is recommended to pack the pecans after shelling to mitigate quality losses. Pecans, when not shelled or packaged, have been found to last between 16 and 70 weeks (approximately 3 to 16 months),

depending on the temperature and relative humidity of the environment (Prabhakar, Sharma et al., 2022). Indeed, oxygen concentration is a critical extrinsic factor for nut quality during storage, as it promotes lipid oxidation, the primary cause of unwanted aroma development in nuts, which occurs when oil, oxygen and a catalyst interact (Choe & Min, 2006).

Meena et al. (2017) found greater fluctuation in the moisture content values of groundnut seeds (*Arachis hypogaea L.*) stored in different packaging materials (gunny bags, high-density polyethylene bags), but it remained constant for vacuum packaging. On the other hand, water activity is the unbound or free water available for chemical, physical, enzymatic, and more specifically microbiological reactions. This parameter is more related to shelf life than moisture content since it is accessible for metabolic and degradative reactions in processed foods (Gama et al., 2018).

The objective of this study was to assess how the quality of shelled 'Pawnee' pecan nuts responds to storage conditions that simulate local marketing environments. The experimental design included two initial storage durations (two and four months) (2M-4M), after which the nuts were shelled and vacuum-packed for 0, 4, 8 and 12 months (mv). Following vacuum storage, the nuts were subjected to simulated retail conditions at room temperature with artificial light exposure (8 hours/day at 179 Lux) for 0, 20, and 40 days.

To evaluate the impact of these conditions on nut quality, the following parameters were measured: water activity, moisture content (%), peroxide value (meq O_2/kg oil), TBARS (meq MDA/kg nut), lightness (L*), and instrumental hardness (N).

2. Materials and Methods

2.1 Sample Preparation

Pawnee pecans were collected manually from the orchard trees of the Agricultural Experimental Station Concordia (INTA) in Entre Ríos Province, Argentina, in 2020. Nuts were dried at 30 °C in a dehumidified dryer to a kernel moisture content of 4%.

The dried in-shell samples were placed individually into raffia bags (clean mesh bags) and randomly split into two postharvest lots for evaluation. These groups were identified based on postharvest conditions of two and four months (2M/4M) and stored in the dark under ambient conditions (19.8 ± 2.80 °C, 72.5 ±1.42 % relative humidity, RH). After two or four months (2M/4M), all the samples were manually hand cracked and shelled. After that, shelled kernel pecans were vacuum-packed bags (Cryovac, Model BK50LA) of 58 microns thickness. Each package consisted of 100 g pecan kernels stored at room temperature (20 ± 0.5 °C) for 4, 8 and 12 months under vacuum (mv).

Subsequently, at each time point, samples were retrieved from the polypropylene bags and transferred, in triplicate, to transparent polycarbonate display boxes for 20 and 40 days to simulate retail display conditions under controlled light exposure (8 hours per day at 179 lux) (Figure 1).

At the determined time intervals, pecan kernel samples were withdrawn for physical and biochemical analysis attributes: Water activity (aw), Moisture content (Mc, %), Peroxide values (meq O_2/kg pecan oil), TBARS (meq MDA/kg pecan nut), Lightness (L*), and Hardness (H, N) obtained by Textural Profile Analysis.

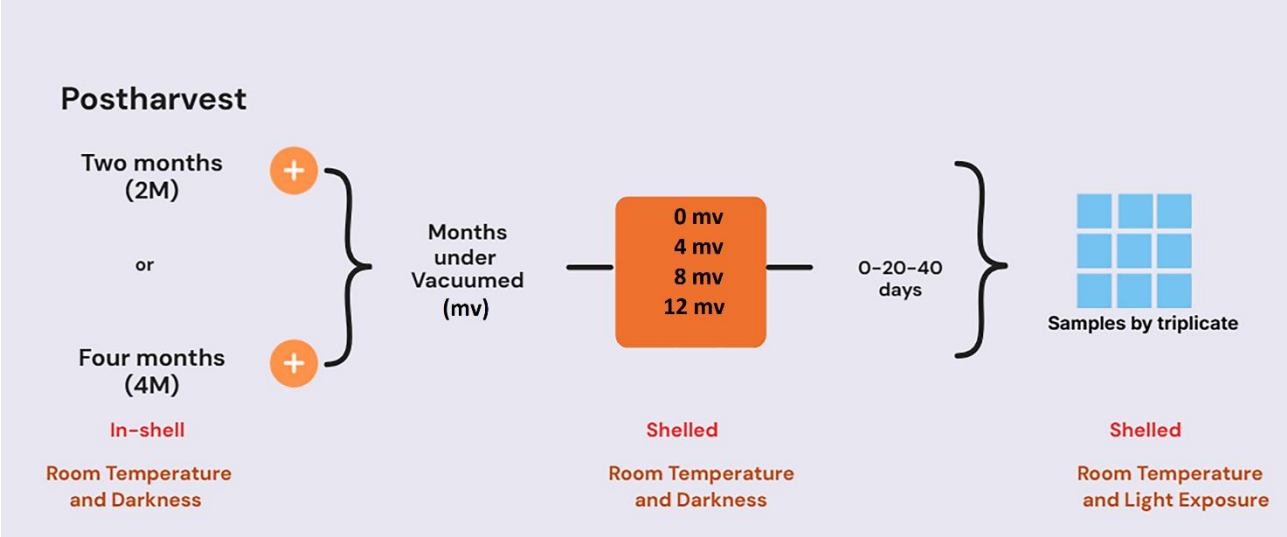

Figure 1. Pecan samples preparation

2.2 Water Activity [aw]

Water activity (aw) was measured in sextuplicate using an AquaLab Series instrument (Decagon Devices, Inc., Pullman, WA, USA) at 25 °C. Measurements were performed on kernels stored in transparent display boxes throughout the light exposure storage period.

2.3 Moisture Content [Mc]

Moisture content was performed using an oven drying at 105 °C, following AOAC 925.10 (Association of Official Analytical Chemists [AOAC] 2023a).

2.4 Lipid Oxidation Analysis

2.4.1 Oil Content

The oil content was determined using the Soxhlet method (AOAC, 1999), with continuous distillation in hexane (Soxtec System HT 1043, Extraction Unit, Foss, Sweden).

2.4.2 Peroxide Values

The peroxide value (PV) determination was carried out on oil obtained from the kernel by cold pressing, according to the AOAC method 965.33.2005 (AOAC, 2023b). Approximately 5 g of oil, accurate to 0.05 g, were weighed directly into a pre-set 250 ml Erlenmeyer flask, and the exact weight was recorded. 30 ml of acetic acid: chloroform solution (3:2, v/v) were added and stirred vigorously until dissolved. Then, 0.5 ml of a saturated potassium iodide solution was added, stirred, and left to rest in the dark for 1 min.

Subsequently, 30 ml of distilled water were added, and the mixture was titrated, with continuous stirring, using a 0.01 N sodium thiosulfate solution until the yellow colour disappeared. Afterward, 0.5 ml of a 1% (w/v) starch solution was added, and titration continued until the blue colour disappeared. The volume of sodium thiosulfate used was recorded.

$$PV = (S \times N \times 1000) / (g\ oil) \qquad \text{(Equation 1)}$$

Where:

S = mL of sodium thiosulfate solution consumed.

N = normality of the sodium thiosulfate solution.

2.4.3 Thiobarbituric Acid Reactive Substances (TBARS)

Pecan kernels samples (4 g) were chopped and homogenized with propyl gallate 0.5% in EDTA 0.5%. Trichloroacetic acid solution 20% was added, the samples were centrifuged at 10,000 *g* and filtered. Three aliquots were separated, an equal volume of 2-thiobarbituric acid 0.02 M was added to two of them and distilled water to the third. The samples were incubated 1 h at 80 °C for the development of colour. TBARS were determined at maximum absorption (530 nm) and concentrations were calculated using 1,1,3,3-tetraethoxypropane as a standard within the range from 0 to 0.5 × 10^6 mol/l. Results were expressed as mg of malondialdehyde (MDA) equivalents/kg.

TBARS were calculated as follows:

Mg eq MDA/kg sample) = (OD 532 nm)/ Slope g/mol) × (72.06 g MDA)/(mol) × (85/100) ×10^6 mg/kg x dilution factor /weight (g) (Equation 2)

Where:

OD is the optical density at 532 nm.

MDA (malondialdehyde): where TEP (1,1,3,3-tetraethoxypropane) is used as standard for MDA equivalents.

1 mol TEP = 1 mol MDA reacting with TBA; 72.06 g/mol is the molecular weight of malondialdehyde, with a recovery of 85% for the system and conversion from mg to kg (Descalzo et al., 2021).

2.5 Physical Attributes: Lightness and Hardness

2.5.1 Colour

The pecans were carefully shelled using a hand cracker to obtain unbroken kernels to measure colour, a uniform layer of pecan kernels was positioned with their dorsal side facing the colorimeter lens. The measurements were conducted using 40 g of kernels, which were divided into three groups (n = 3, pseudo-replicates), each consisting of approximately 4-7 pecans (Prabhakar, Bock et al., 2022). Colour parameters were measured using a Chroma Meter CR-400 colorimeter (Minolta Co., Ramsey, Nueva Jersey, USA) and Commission Internationale de l'éclairage L*a*b* parameters were determined. The instrumental conditions used were artificial illuminant D65, 8 mm port size and a 2° standard angle observer. Colorimeter was calibrated according to the manufacturer's instructions using a white plate (Y = 93.8, x = 0.3155, y = 0.3319). The averages of three samples were considered for colour data analysis.

2.5.2 Hardness

The instrumental Texture Profile Analysis was performed using a commercial Texture Analyzer (Model TA-XT2i) by Stable Micro Systems, New York. It has a 50 kg load capacity, and the settings were 20% compression, pretest and post-test speeds of 3 ms^{-1}, and a crosshead speed of 0.25 ms^{-1}.

To get uniformly shaped samples, 8 cylindrical cores (3 mm diameter) were removed from the kernel by using a cork borer and cut to 5 mm in length with a sharp razor blade to obtain square ends. Each sample was placed vertically on the flat plate of the texture analyser and was compressed twice by a 25 mm diameter acrylic, flattened, cylindrical probe (Surjadinata et al., 2021).

2.6 Statistical Analysis

Results were subjected to non-parametric analysis (Kruskal-Wallis and Dunn test) at a 5% significance level using R version 4.4.2 (R Core Team, 2024) to compare samples to evaluate the shelf life and vacuumed store

for two and four months on shelled pecan nuts and unshelled under ambient conditions. Effect size was evaluated with the Wilcoxon test using the FSA package panel.

2.7 Experimental Design

For each storage treatment, storage type, and variables measurements were completed in triplicate. All results were expressed as mean ± standard deviation. All factors were crossed.

3. Results

Nut quality was evaluated through measurements of water activity (aw), moisture content (%), peroxide value (meq O_2/kg oil), TBARS (meq MDA/kg nut), lightness (L), and instrumental hardness (N). Postharvest conditions 2M and 4M were analysed independently. In the figures, groups subjected to different daylight exposures that share a letter do not differ significantly within each postharvest condition (2M or 4M). Additionally, we examined the behaviour of quality parameters as they approached critical thresholds –for example, similar water activities with higher moisture content, and the peroxide value of 2 meq O_2/kg oil, which marks the onset of primary oxidation.

3.1 Water Activity

Free water, or water activity, is key for chemical, physical, enzymatic, and microbial reactions. Aw is a better indicator of shelf life than moisture content because it shows how much water is usable in food. The changes in water activity of vacuum-packaged pecans after light exposure are shown in Figure 2.

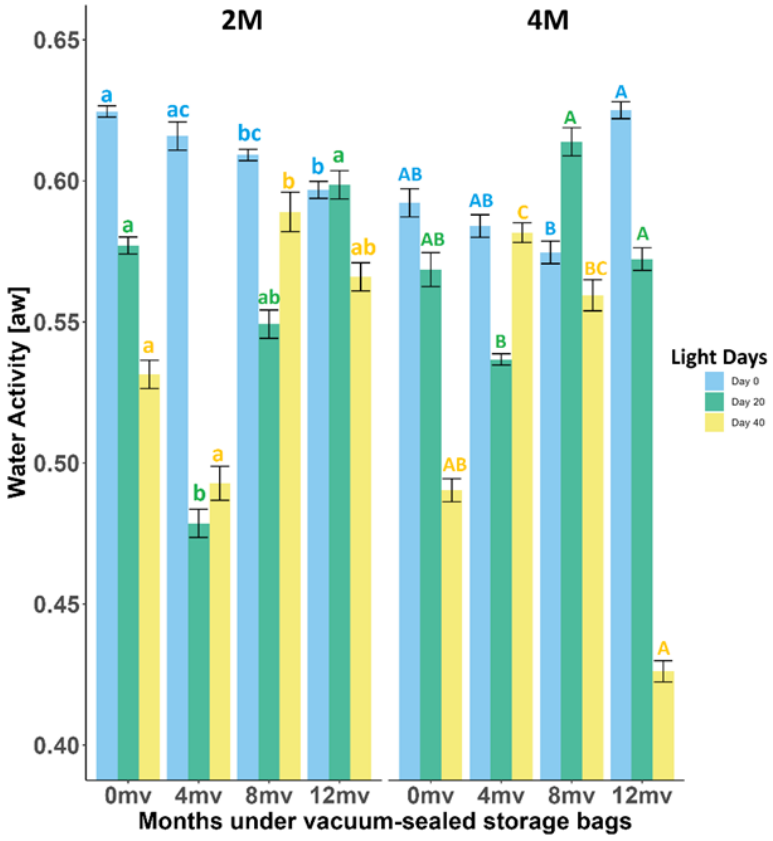

Figure 2. Evolution of water activity (aw) values of shelled pecan kernels during light exposure days

Shared letters between groups indicate similar results with no statistically significant differences within each postharvest condition (2M/4M).

Initially, at day 0, the 2M pecan kernels had higher aw values, and they also decreased linearly during twelve months. According to Dunn test results, significance was found between 0 vs 8 months, 0 vs 12 months, and 4 vs 12 months ($p<0.05$) with a large effect size.

A decline was observed in this variable's value, which decreased from 0.624 ± 0.002 to an endpoint of 0.596 ± 0.003. This range is included in the intermediate moisture food (IMF) zone, in which an aw of 0.6 is typical for pecan nuts, as defined by Taoukis and Richardson (2020).

It was observed that during 20 and 40 days of light exposure conditions, the aw values decreased sharply in 4 mv followed by a rapid increment. Particularly, for day 20, from 0 to 4 months vacuum packaged, the aw value diminished from 0.577 ± 0.003 to 0.478 ± 0.005 and then reached its highest point (0.598 ± 0.005) from 4 to 12 months vacuum packaged, with statistical significance ($p<0.05$). Similar behaviour was observed for day 40, including statistical differences for 0-8 mv and between 4-8 mv vacuum packaged conditions ($p<0.05$).

With 4M postharvest assays, for day 0, aw values were lower than 0.6 for the initial eight months. Because of this, the significance was presented between 8 and 12 months ($p<0.05$). Also, the aw profile slightly decreased until month eight of vacuum condition. For days 20 and 40, month four seems to present an important time reference because both conditions exhibited remarkable changes in their behaviour. While day 20 increased values, with significant differences between 4-8 months, and 4-12 mv. In the case of day 40, differences were found for 0-4 mv, 4-12 mv and 8-12 mv ($p<0.05$).

3.2 Moisture Content

The moisture content is a measure of the total water in a product, expressed as % (percent) or g/100 g (g water in 100 g pecan nuts). Figure 3 shows the variations in moisture content of pecan kernels vacuum-packed and during light exposure for 0, 20, and 40 days.

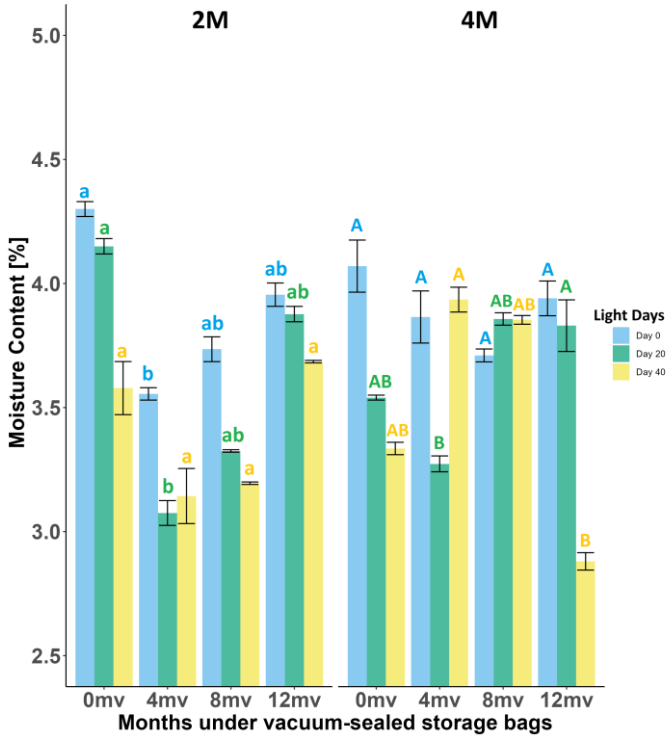

Figure 3. Evolution of moisture content of shelled pecan kernels during light exposure days

Shared letters between groups indicate similar results with no statistically significant differences within each postharvest condition (2M/4M).

The moisture content at the 2M case exhibited a similar behaviour for days 0 and 20, with initial values slightly greater than 4%. Month four also presented a relevant month for changing moisture values between 0-4 mv storage with significant differences for days 0 and 20 ($p<0.05$). For day 40, no differences were found ($p<0.05$).

The 4M postharvest condition, day 0, showed slowly diminishing values through 12 months, with an initial value of 4.07 ± 0.11% and an endpoint slightly below it, without significant differences during evaluated storage time and preserved due to vacuum ($p>0.05$). A significant difference was found between 4 vs. 12 months for both light exposure for cases day 20 and 40 ($p<0.05$).

Exposure to light and oxygen resulted in a decrease in moisture content, except for 4M postharvest conditions on day 20-8 Mv with 3.857 ± 0.025% with a corresponding 0.614 ± 0.005 aw value. In this study, we observed that moisture content remained high even at similar water activity (aw) levels during the postharvest condition (2M and 4M). This phenomenon is attributed to reduced viscosity, increased solute dissolution, and tissue swelling that activates catalytic sites. As a result, desorption systems with higher moisture content tend to exhibit accelerated oxidation (Taoukis & Richardson, 2020).

3.3 Lipid Oxidation Analysis

To monitor lipid oxidation, PV and TBARS parameters were measured. Total lipids for postharvest periods of two months (2M) and four months (4M) showed values of 67.6 ± 0.3% and 69.0 ± 0.2%, respectively. The PV, expressed in meq/ O_2 kg oil, indicates the level of primary oxidation products. Figures 4 and 5 display changes in PV and TBARS parameters for samples stored under different conditions.

In this study, we consider a peroxide value (PV) of up to 2 meq O_2/kg oil during vacuum storage as an acceptable limit, as suggested by Gama et al. (2018). This indicates good product quality in terms of lipid oxidation, comparable to that of almonds.

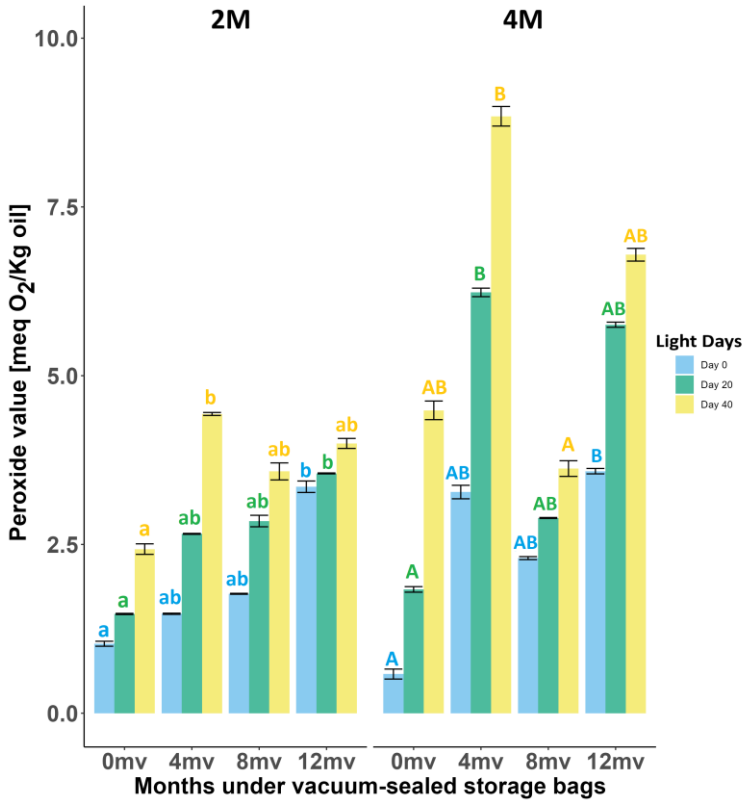

Figure 4. Evolution of peroxide values of shelled pecan kernels during light exposure days

Shared letters between groups indicate similar results with no statistically significant differences within each postharvest condition (2M/4M).

Under the 2M condition, PV values showed a slight increase from day 0 until 8 months, remaining below 2 meq O_2/kg oil during vacuum storage. Throughout the storage period, PV consistently rose, increasing from 1.029 ± 0.037 to 3.355 ± 0.085 meq O_2/kg oil for day 0, and from 1.470 ± 0.009 to 3.552 ± 0.007 meq O_2/kg oil for day 20, with statistical differences observed at 0-12 mv ($p<0.05$). On day 40, PV values ranged from an oxidized level of 2.431 ± 0.074 to 3.990 ± 0.074 meq O_2/kg oil, with only 0-4 mv being statistically significant ($p<0.05$), thus showing onset of oxidation earlier than for the other groups.

In contrast, for the 4M postharvest condition, even though pecans were stored in their shells for four months, this did not prevent lipid oxidation. PV values showed continuous fluctuations. From day 0, statistically significant differences were noted between the initial and final 12 vacuumed months ($p<0.05$). For days 20 and 40 in month four (4mv), PV values peaked sharply (6.234 ± 0.063 and 8.843 ± 0.145), then decreased rapidly before slightly rising again. Conditions 0-4 mv and 4-8 mv were statistically different ($p<0.05$) for days 20 and 40, respectively.

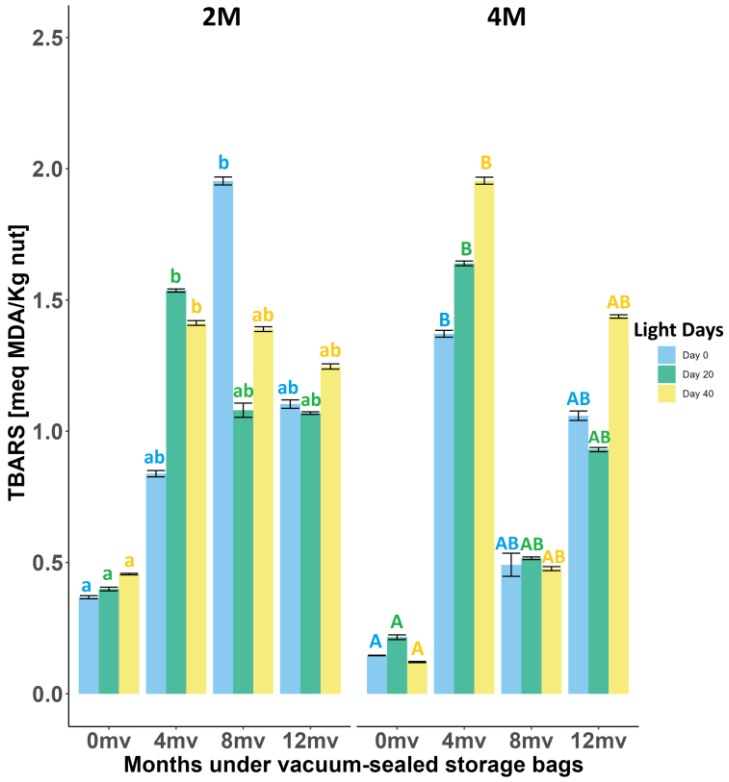

Figure 5. Evolution of TBARS of shelled pecan kernels during light exposure days

Shared letters between groups indicate similar results with no statistically significant differences within each postharvest condition (2M/4M).

The final oxidation products were performed measuring TBARS values. At the beginning of the experiment, the kernels exhibited very low TBARS values. The TBARS levels rose differently depending on storage time for each sample. Observable variations were identified at 2M for day 0 (1.968 ± 0.015) for 0-8 mv, day 20 (1.533 ± 0.006) for 0-4 mv, and day 40 (1.408 ± 0.009) for 0-4 mv.

Throughout the 4M postharvest period, TBARS showed a clear, oscillating pattern. All daily assays revealed statistically significant differences ($p<0.05$) in storage conditions (0-4 mv). Notably, the TBARS values for the 4M were higher than 2M, showing values as 1.385 ± 0.013, 1.630 ± 0.009, 1.968 ± 0.013, for day 0, 20, and 40, respectively. As in the case of PV, the onset of oxidation is presented earlier for the 4M than for 2M post-harvest.

3.4 Physical Attributes: Lightness and Hardness

This study focused solely on Lightness and Hardness to better understand their storage behaviour.

3.4.1 Colour

The L* values determined by the colorimeter represent the degree of lightness; lower values indicate reduced lightness or more dark kernels.

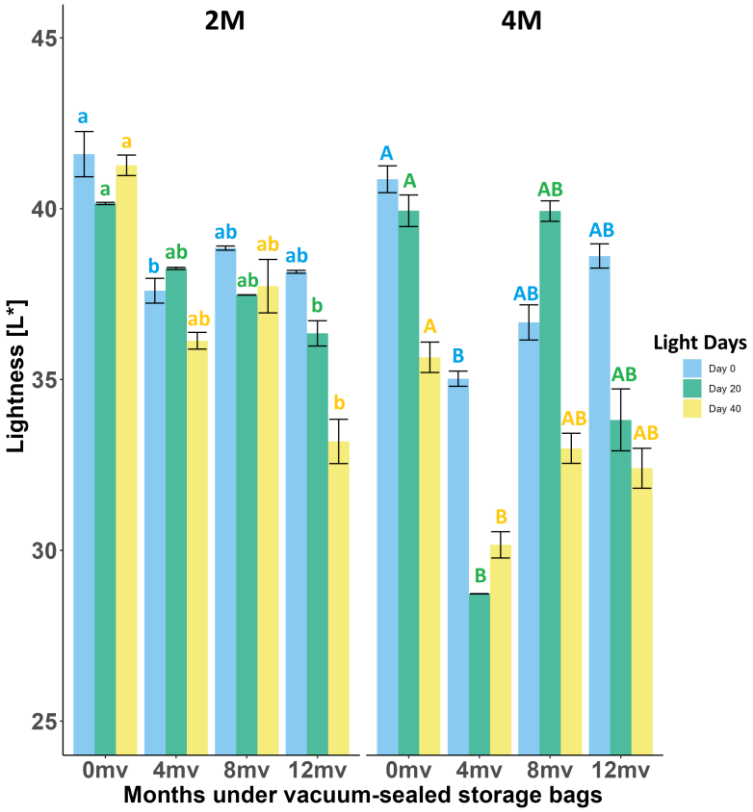

Figure 6. Evolution of lightness (parameter L*) values of shelled pecan kernels during light exposure days

Shared letters between groups indicate similar results with no statistically significant differences within each postharvest condition (2M/4M).

The Lightness profile in Figure 6 also showed on 2M a similar pattern under light exposure, preserving the lightness for a longer storage period, with significant differences only observed at 0-4 mv for day 0, and 0-12 mv for the extended light condition: day 20 and 40 ($p<0.05$).

In 4M postharvest condition, lightness values initially decreased sharply by 0 to 4 mv. We observed fallen points at 35.023 ± 0.222, 28.725 ± 0.005, 30.159 ± 0.384 for day 0, 20, and day 40, respectively. Then, it increased rapidly before slightly rising again, except on day 20, where a diminished value was observed at the end of the storage period. The 0-4 mv conditions were only statistically different ($p<0.05$) for day 0 and days 20 and 40, respectively.

3.4.2 Hardness

Hardness is measured by the peak force (N) required during the compression of any material and it has been used as an indicator of textural quality. The Hardness parameter values are presented in Figure 7 for both postharvest treatments (2M/4M).

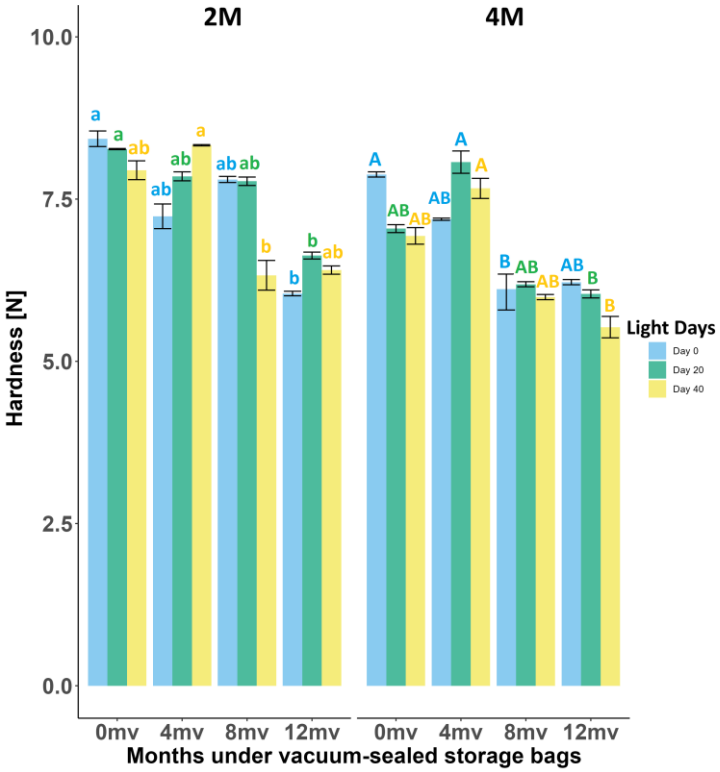

Figure 7. Evolution of hardness values of shelled pecan kernels during light exposure days

Shared letters between groups indicate similar results with no statistically significant differences within each postharvest condition (2M/4M).

Not only is moisture content expected to affect texture characteristics, but changes in lipid levels are also influential. In Figure 7, for the initial postharvest conditions, statistically significant differences ($p<0.05$) were observed only at 0-12 mv for day 0 and day 20, with moisture content slightly above 4% and lower peroxide values. For the last exposure condition (day 40), statistically significant relevance ($p<0.05$) was only observed at 4-8 mv.

The 4M case showed the diminishing hardness parameter for day 0 at 0-8 mv with statistically significant differences ($p<0.05$). For day 20 and 40, the differences were observed at 4-12 mv ($p<0.05$). Even though this postharvest condition was stored two months long compared to 2M, with reduced moisture content, the PV values showed continuous fluctuations.

4. Discussion

Moisture content and water activity are important parameters that affect the shelf-life of nuts (Kharel et al., 2019). Water activity is a parameter more closely related to shelf-life than moisture content, as it determines the availability of free water for metabolic and degradative reactions in processed foods (Gama et al., 2018). During all experiments, the 4M postharvest condition presented lower values than 2M. However, this variable presented diminishing values during this storage study at the intermediate moisture food values zone. In this sense, preserved pecans with their shells may reduce aw value, and these results should also be evaluated, including moisture content and lipid oxidation behaviours, due to crossing intermediate moisture food values, as defined by Taoukis and Richardson (2020).

The authors Kazantzis et al. (2003) studied the conservation of shelled and unshelled almonds after six months. They observed that almond shells form a barrier against moisture and oxygen, with the shell being able to absorb water from the inside of the nut and/or prevent the interior from absorbing moisture/water from the surrounding

environment. Revised literature suggested that the optimum water activity for storage of almonds, Brazil nuts, cashew nuts, hazelnuts, macadamia nuts, pecan nuts, pine nuts, pistachios, and walnuts is lower than 0.53, and a temperature of 25 °C (Gama et al., 2018). One of the most important factors for maintaining the quality and shelf life in nuts is the moisture content. The importance of the presence of water is clear if the shelf life of a dehydrated food is to be extended.

Moisture content above 4% in pecans can cause internal browning and fungal activity during storage. Conversely, low moisture content requires prolonged drying at high temperatures. It should be noted that the dehydration process itself can cause a production of free radicals which could enter lipid oxidation reactions, colour loss, reduced consumer acceptance, and increased fragility during shelling (Siebeneichler et al., 2023; Taoukis & Richardson, 2020; Thewes et al., 2021). Because of their high content of unsaturated fatty acids, pecans are susceptible to these types of rancidity when free moisture is abundant (Ribeiro, Klein et al., 2020; Ribeiro, Ribeiro et al., 2020; Shojaee et al., 2023; Thewes et al., 2021; Yildiz & Karaca, 2024). In another study, authors Phatanayindee et al. (2012) explained that the moisture content of macadamia nuts in their shells is a key factor affecting their hydrolytic and oxidative rancidity.

If we observed the aw and moisture content in this shelf-life study, at the initial time, both postharvest 2M and 4M showed a moisture content of over 4% and aw values major of 0.6. For days 20 and 40, as in the case of aw, month four presents an important time reference for remarkable changes in their behaviour. Considering similar water activity (aw), higher moisture content is predicted to improve mobility due to increased water activity, lower viscosity, and more catalysts because of swelling and greater solute dissolution. Desorption systems are expected to oxidize more rapidly. Besides this, Taoukis and Richardson (2020) also suggested that the rate of lipid oxidation decreased when the water activity was between 0.2-0.4.

Padehban et al. (2018) studied and monitored the effect of different temperatures (4, 25 and 35 °C) and atmospheres (vacuum, CO_2, and normal air) on the physicochemical and sensory properties of the wild almond kernel during 15 weeks of storage. In this study, the moisture content of all samples decreased with the extended storage time. On the other hand, Meena et al. (2017) found a greater fluctuation in the moisture content values of groundnut seeds (*Arachis hypogaea L.),* stored in different packaging materials (gunny bags, high-density polythene bags), but it was constant for vacuum packaging, contrary to Padehban et al. (2018) monitoring studies, and the same as our results using vacuum packaging.

Pecan nuts are rich in fatty acids, notably, the unsaturated to saturated fatty acid ratio is about 13.54, with 93% of the oil being unsaturated fatty acids (Descalzo et al., 2021). Indeed, peroxide values are influenced by the cultivar, harvest timing, storage delay after harvest, ecological conditions, cultural management practices during the growing season, and post-harvest handling procedures (Gama et al., 2018). Based on experimental values of Taoukis and Richardson (2020), the peroxide value (meq/kg oil) varies when comparing similar water activity (aw) but with different moisture contents. Despite the vacuumed packaging, not only did the PV and TBARS values fluctuate throughout the storage period, but the moisture contents varied as well.

PV values showed a slight increase from day 0 until 8 months, remaining below 2 meq O_2/kg oil during vacuum storage for 2M conditions. This indicates good product quality in terms of lipid oxidation, comparable to almonds (Gama et al., 2018). These results suggest that shelled pecans can be effectively preserved under vacuum and darkness, making them suitable for immediate sale. If market exposure is limited to 20 days, PV values remain lower than those reported by Gama et al. (2018). Particularly, we observed a rising point (3.253 ± 0.08 meq O_2/kg oil) at 4M, this value is higher than we observed at 2M, which indicates lower product quality in terms of lipid oxidation. These values also showed that waiting longer periods of time from harvest has a detrimental effect on the quality of the nuts.

In this study only lightness and hardness variables were selected for better behaviour understanding during storage assays. Light accelerates lipid oxidation. Pecans, walnut and almond kernels stored under light conditions exhibit higher peroxide values, compared to those stored in darkness, regardless of the temperature. Therefore, managing light exposure during the storage of kernels is crucial to minimize light-induced reactions that degrade quality (Gama et al., 2018; Jensen et al., 2001; Mexis et al., 2009; Ribeiro et al., 2022). In addition to this, pecan moisture content above 4% can promote internal browning during storage (Thewes et al., 2021).

Lightness is also regarded as one of the primary indicators of freshness and quality in pecan kernels. Our findings for the 2M scenario showed a) moisture content with initial values slightly above 4% on days 0 and 20, b) lower peroxide values, and c) a comparable trend when exposed to light, maintaining the lightness for a longer storage period compared to the 4M condition. For 4M postharvest conditions, month four presented an important time reference for remarkable changes in variables aw and moisture behaviors, and the lightness parameter showed an oscillating profile.

The Texture Profile Analysis (TPA), developed by Bourne (1977), has been found by Ocon et al. (1995) to be a suitable method for measuring texture in pecans. This attribute is an important indicator of pecan quality (Prabhakar et al., 2023). The absence of crispiness can discourage buyers from consuming pecans and might discourage them from purchasing future products (Prabhakar, Sharma et al., 2022). To ensure the best texture, pecans should have a moisture content between 3.5 and 4%. Below this range, the kernels become too brittle and prone to damage, while above it, they quickly become stale due to increased enzymatic activity and loss of crispness (Yang et al., 2025).

During the 2M storage condition, the hardness profile showed less oscillation than in the 4M condition. Despite being stored for two months longer and moisture content being reduced, the PV values showed continuous fluctuations that might affect the hardness of 4M profile.

5. Conclusions

This study highlights the critical role of postharvest storage conditions in maintaining the functional, nutritional, and sensory quality of shelled ‘Pawnee’ pecan nuts. Our findings demonstrate that:

Under the 2M condition, peroxide levels exhibited a slight initial increase but remained below 2 meq O_2/kg of oil throughout eight months of dark vacuum storage. Water activity (aw), peroxide levels, and TBARS values increased both at the outset and after 20 days of light exposure. Texture changes became noticeable at four and eight months, coinciding with a reduction in lightness. Hardness declined gradually over time, with a significant drop observed at 12 months due to prolonged exposure to light. Luminosity also showed a consistent downward trend, culminating in a marked reduction at 12 months, particularly when light exposure exceeded 20 days. In contrast, the 4M condition presented more substantial changes in aw, moisture content, lightness, and texture. Peroxide and TBARS levels rose significantly at four and eight months, indicating a notable decline in product quality. Additionally, a sharp decrease in luminosity was observed at four months, coinciding with elevated oxidation markers.

To ensure optimal quality, pecans should be stored in their shells for up to 2M postharvest, and vacuum-sealed for up to eight months (8 mv) prior to sale. During retail display, light exposure should be limited to no more than 20 days, and elevated temperatures should be avoided.

These results underscore the importance of controlled storage conditions in preserving pecan quality. Vacuum storage under dark conditions (2M) offers superior protection against lipid oxidation compared to ambient light

exposure (4M). The findings provide actionable insights for optimizing postharvest handling and retail display strategies to maintain product integrity.

Acknowledgements

The work is part of the INTA National Program of Agroindustry, Added Value, and Bioenergy, supported by the projects PEI119.

Transparency of Data

Data not available: The data set that supports the results of this study is not publicly available.

Author Contribution Statement

	PO	MP	AD	SR	KM	GG	EF	LR
Conceptualization	■	■	■			■		■
Data curation	■	■						
Formal analysis	■							■
Funding acquisition						■		
Investigation								■
Methodology		■		■	■	■	■	■
Project administration						■		
Supervision								■
Writing – original draft	■							
Writing – review and editing		■				■		■

References

Adkison, C., Richmond, K., Lingga, N., Bikoba, V., & Mitcham, E. (2021). Optimizing walnut storage conditions: Effects of relative humidity, temperature, and shelling on quality after storage. *HortScience*, *56*(10), 1244-1250. https://doi.org/10.21273/HORTSCI15881-21

Association of Official Analytical Chemists. (1999). *Official methods of analysis* (15th ed.).

Association of Official Analytical Chemists. (2023a). AOAC Official Method 925.10: Solids (Total) and loss on drying (Moisture) in flour — Air oven method. In G. W. Latimer (Ed.), *Official Methods of Analysis of AOAC International* (22nd ed.). Oxford University Press.

Association of Official Analytical Chemists. (2023b). AOAC Official Method 965.33: Peroxide value of oils and fats — Titration method. In G. W. Latimer (Ed.), *Official Methods of Analysis of AOAC International* (22nd ed.).

Bourne, M. C. (1977). Texture profile analysis. *Food Technology, 32*, 62-66.

Cámara Argentina de Productores de Pecán. (n.d.). *CAPPECÁN*. https://cappecan.com.ar/

Choe, E., & Min, D. B. (2006). Mechanisms and factors for edible oil oxidation. *Comprehensive Reviews in Food Science and Food Safety*, *5*(4), 169-186. https://doi.org/10.1111/j.1541-4337.2006.00009.x

Descalzo, A. M., Biolatto, A., Rizzo, S. A., Pérez, C. D., Frusso, E. A., Carduza, F., & Rossetti, L. (2021). Oxidative stability parameters and sensory properties of in-shell "Stuart" pecans *[Carya illinoinensis (Wangenh.) K. Koch]* stored at different temperatures under non-accelerated conditions. *Postharvest Biology and Technology, 179*, Article 111591. https://doi.org/10.1016/j.postharvbio.2021.111591

Gama, T., Wallace, H. M., Trueman. S. J., & Hosseini-Bai, S. (2018). Quality and shelf life of tree nuts: A review. *Scientia Horticulturae*, *242*, 116-126. https://doi.org/10.1016/j.scienta.2018.07.036

Jensen, P. N., Sørensen, G., Engelsen, S. B., & Bertelsen, G. (2001). Evaluation of quality changes in walnut kernels (Juglans regia L.) by Vis/NIR spectroscopy. *Journal of Agricultural and Food Chemistry*, *49*(12), 5790-5796. https://doi.org/10.1021/jf010509t

Kazantzis, I., Nanos, G. D., & Stavroulakis, G. G. (2003). Effect of harvest time and storage conditions on almond kernel oil and sugar composition. *Journal of the Science of Food and Agriculture, 83*(4), 354-359. https://doi.org/10.1002/jsfa.1312

Kharel, K., Prinyawiwatkul, W., Yemmireddy, V. K., Graham, C. J., & Adhikari, A. (2019). Effect of hot water treatment of in-shell pecans on physicochemical properties and consumer acceptability of roasted pecan kernels. *International Journal of Food Science & Technology, 54*(5), 1884-1891. https://doi.org/10.1111/ijfs.14096

Meena, M. K., Chetti, M. B., & Nawalagatti, C. M. (2017). Influence of different packaging materials and storage conditions on the seed quality parameters of groundnut (Arachis hypogaea L.). *International Journal of Pure & Applied Bioscience, 5*, 933-941. https://doi.org/10.18782/2320-7051.2707

Mexis, S. F., Badeka, A. V., & Kontominas, M. G. (2009). Quality evaluation of raw ground almond kernels (Prunus dulcis): Effect of active and modified atmosphere packaging, container oxygen barrier and storage conditions. *Innovative Food Science & Emerging Technologies, 10*(4), 580-589. https://doi.org/10.1016/j.ifset.2009.05.002

Ocon, A., Anzaldua-Morales, A., Quintero, A., & Gastelum, G. (1995). Texture of pecans measured by sensory and instrumental means. *Journal of Food Science, 60*(6), 1333-1336. https://doi.org/10.1111/j.1365-2621.1995.tb04585.x

Padehban, L., Ansari, S., & Koshani, R. (2018). Effect of packaging method, temperature and storage period on physicochemical and sensory properties of wild almond kernel. *Journal of Food Science and Technology*, *55*(9), 3408-3416. https://doi.org/10.1007/s13197-018-3239-2

Phatanayindee, S., Borompichaichartkul, C., Srzednicki, G., Craske, J., & Wootton, M. (2012). Changes of chemical and physical quality attributes of macadamia nuts during hybrid drying and processing. *Drying Technology*, *30*(16), 1870-1880. https://doi.org/10.1080/07373937.2012.703275

Prabhakar, H., Bock, C. H., Kerr, W. L., & Kong, F. (2022). Pecan color change during storage: Kinetics and Modeling of the Processes. *Current research in food science*, *5*, 261-271. https://doi.org/10.1016/j.crfs.2022.01.015

Prabhakar, H., Kerr, W. L., Bock, C. H., & Kong, F. (2023). Effect of relative humidity, storage days, and packaging on pecan kernel texture: Analyses and modeling. *Journal of texture studies*, *54*(1), 115-126. https://doi.org/10.1111/jtxs.12723

Prabhakar, H., Sharma, S., & Kong, F. (2022). Effects of postharvest handling and storage on pecan quality. *Food Reviews International*, *38*(7), 1485-1512. https://doi.org/10.1080/87559129.2020.1817066

R Core Team. (2024). *R: A language and environment for statistical computing* (version 4.4.2) [Software]. https://www.R-project.org/

Ribeiro, S. R., Klein, B., Ribeiro, Q. M., Dos Santos, I. D., Genro, A. L. G., Ferreira, D. F., Hamann, J. J., Barin, J. S., Cichoski, A. J., Fronza, D., Both, V., & Wagner, R. (2020). Chemical composition and oxidative stability of eleven pecan cultivars produced in southern Brazil. *Food Research International*, *136*, Article 109596. https://doi.org/10.1016/j.foodres.2020.109596

Ribeiro, S. R., Klein, B., Santos, I. D. D., Thewes, F. R., Brackmann, A., Both, V., & Wagner, R. (2022). Effects of controlled atmosphere and storage temperature on the quality of shelled 'Barton' pecan nuts during long-term storage. *Food Research International*, *158*, Article 111498. https://doi.org/10.1016/j.foodres.2022.111498

Ribeiro, S. R., Ribeiro, Q. M., Klein, B., dos Santos, I. D., Forgiarini, S., Hamann, J. J., Cichoski, A. J., Fronza, D., Brackmann, A., Both, V., & Wagner, R. (2020). Effect of low oxygen on quality attributes of 'Barton' pecan nuts after long-term storage at different temperatures. *Scientia Horticulturae, 263*, Article 109098. https://doi.org/10.1016/j.scienta.2019.109098

Shojaee, A., Rastegar, S., Tajeddin, B., & Sayyad-Amin, P. (2023). Quality preservation of walnut kernels: Effect of storage temperature and vacuum packaging. *Erwerbs-Obstbau*, *65*(6), 2407-2418. https://doi.org/10.1007/s10341-023-00944-2

Siebeneichler, T. J., Hoffmann, J. F., Galli, V., & Zambiazi, R. C. (2023). Composition and impact of pre- and post-harvest treatments/factors in pecan nuts quality. *Trends in Food Science & Technology, 131*, 46-60. https://doi.org/10.1016/j.tifs.2022.11.010

Surjadinata, B. B., Brusewitz, G. H., & Bellmer, D. D. (2021). Pecan texture is affected by moisture content before freezing and thawing rate. *Journal of Food Process Engineering, 24*(4), 253-272. https://doi.org/10.1111/j.1745-4530.2001.tb00543.x

Taoukis, P. S., & Richardson, M. (2020). Principles of intermediate-moisture foods and related technology. In G. V. Barbosa-Cánovas, A. J. Fontana, Jr., S. J. Schmidt & T. P. Labuza (Eds), *Water activity in foods: Fundamentals and applications* (pp. 385-424). John Wiley & Sons. https://doi.org/10.1002/9781118765982.ch16

Thewes, F. R., Both, V., Brackmann, A., Schultz, E. E., Berghetti, M. R. P., Soldateli, F. J., Wendt, L. M., Führ, A., Wagner, R., & Ribeiro, S. R. (2021). Interaction of oxygen and moisture content on 'Barton' and 'Jackson' pecan storage. *Postharvest Biology and Technology, 179*, Article 111584. https://doi.org/10.1016/j.postharvbio.2021.111584

Yang, V. E., Kerr, W. L., Pegg, R. B., & Kerrihard, A. L. (2025). Effects of packaging and storage temperature on shelled pecan quality. *Postharvest Biology and Technology, 222*, Article 113366. https://doi.org/10.1016/j.postharvbio.2024.113366

Yildiz, A. Y., & Karaca H. (2024). The protective role of shell, packaging technique and storage temperature in lipid oxidation in walnuts of different varieties. *Postharvest Biology and Technology*, *210,* Article 112747. https://doi.org/10.1016/j.postharvbio.2023.112747