Chapter

Oxidative Stability and Sensory Properties of Pecan Nuts

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Abstract

Pecans are the nut with the higher oil content. In addition, they present a large number of polyunsaturated fatty acids, which are susceptible to oxidation. Oxidative damage in pecans is traduced in lower quality aspects, appearance of rancidity and acidity, loss of sweetness and firmness, darker kernels, and darker shells. The use of different strategies for the conservation of entire and shelled nuts is discussed in terms of oxidation and the consequences on nuts quality.

Keywords: pecan, *Carya illinoinensis*, oxidation, volatiles, sensory, postharvest, tocopherols, antioxidants

1. Introduction

Pecans nuts are the seeds of *Carya illinoinensis* (Wangenh.) K. Koch. They are an important source of vitamins and minerals, such as vitamin E, folic acid, calcium, magnesium, phosphorus, potassium, several B vitamins, and zinc. They are also rich in fatty acids, having around 58.1 to 68.18 g oil/100 g of nut. Particularly, the unsaturated/saturated fatty acids ratio is around 13.54, with 93% of unsaturated fatty acids in the oil [1].

They also contain β-sitosterol and squalene ranging from 88.74 to 220.42 mg 100 g^{-1} and 30.98 to 115.59 mg 100 g^{-1}, respectively [2]. This is a disadvantage for the conservation of the nuts and oils because unsaturated fatty acids are prone to oxidative damage. But on the other side, they contain a high level of γ-tocopherol (the main form of vitamin E in pecans) and polyphenols, especially epigallocatechin-3-gallate (EGCG), recognized as a health promoter compound [3] and ellagic acid associated with hepatoprotective activity [4]. Recently, the determination of the proximal composition in 11 cultivars of Brazilian pecans [2] showed total phenolic content variations ranging from 19.88 mg GAE g−1 (“Desirable” pecans) to 45.25 mg GAE g−1 (“Imperial”).

Pecans are also a source of protein between 6.88 and 9.26 g .100 g^{-1} nut with low carbohydrate content (between 4.92 and 17.33 g 100 g^{-1} nut), and dietary fiber (5.55 to 15.94 g 100 g^{-1} nut).

In terms of dietary issues, pecans have the lowest net carbohydrates content of any nuts. In fact, one ounce of pecans contains just 1.1 grams of net carbohydrates. This means its consumption is possible, while following a low-carb diet.

2. Lipid composition in terms of oxidative stability

Pecan nuts are rich in fats, with a net yield of around 58.1–66.18 g oil/100 g of nut mass. Six classes of lipids were separated and identified as complex lipids, monoglycerides, α-β-diglycerides, α-α'-diglycerides, sterols, and triglycerides. Triglycerides were predominant with a mean concentration for the six cultivars equal to 71.25 g/l00g of nutmeat [5]. The total content of unsaturated fatty acids in the oil is as high as 93%. The unsaturated fatty acids are a group of lipids containing one or more double bonds in the structure. Monounsaturated fatty acids (MUFAs) contain one double bond in the fatty acid chain. If two or more double bonds are present, they are referred to as polyunsaturated fatty acids (PUFAs).

The number of double bonds has an impact in terms of cell membrane mobility. The higher PUFAs, the higher lipid mobility within membranes. Saturated fatty acids (SFAs) do not contain double bonds in their structure and contribute to a more rigid cellular structure. The low ratio of saturated to unsaturated fatty acids in the cell membranes increases membrane fluidity and permeability [6].

Omega-6 linoleic acid and omega-3 alpha-linolenic are essential fatty acids that cannot be synthesized endogenously by most of the animals; therefore, their constant dietary intake is crucial [7].

The chromatographic profile of Stuart pecans [6] fatty acids is shown in **Figure 1**.

The largest peak corresponds to oleic acid (C18: 1 n-9), followed by linoleic acid (C18: 2 n-6). This picture is typical of the fatty acids profile of pecan products (Picture from the Food Science laboratory INTA). Indeed, pecan varieties show a

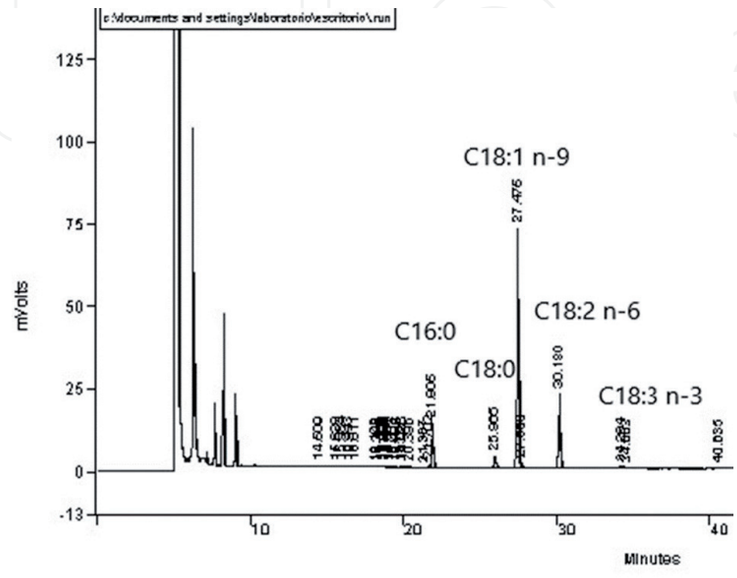

Figure 1.
Gas chromatography (GC-FID) typical profile of pecan nuts.

		Main fatty acids								
Country	**Variety**	**C16:0**	**C18:0**	**C18:1n9**	**C18:2n6**	**C18:3n3**	**ΣSFA**	**ΣUFA**	**ΣPUFA**	**PI**
BR	Barton	6.53 ± 0.37 a	2.46 ± 0.31 abcd	66.92 ± 0.27 ab	22.50 ± 0.22 abc	0.93 ± 0.01 a	9.0	90.4	23.4	41.1
BR	Chickasaw	5.64 ± 0.18 a	3.07 ± 0.25 abcd	72.86 ± 0.10 a	16.91 ± 0.14 c	0.86 ± 0.01 a	8.7	90.6	17.8	36.8
BR	Desirable	5.68 ± 0.21 a	3.64 ± 0.27 abc	69.79 ± 0.25 ab	19.38 ± 0.13 c	0.87 ± 0.01 a	9.3	90.0	20.3	38.6
BR	Imperial	6.10 ± 0.06 a	3.20 ± 0.15 abcd	68.69 ± 0.11 ab	20.58 ± 0.04 abc	0.82 ± 0.01 a	9.3	90.1	21.4	39.4
BR	Importada	6.46 ± 0.15 a	2.66 ± 0.15 abcd	68.57 ± 0.97 ab	19.81 ± 0.26 bc	1.06 ± 0.02 a	9.1	89.4	20.9	39.1
BR	Jackson	6.48 ± 0.07 a	4.01 ± 0.07 a	68.12 ± 0.14 abc	19.99 ± 0.20 bc	0.76 ± 0.01 a	10.5	88.9	20.8	38.5
BR	Mahan	5.66 ± 0.13 a	3.49 ± 0.29 abcd	72.99 ± 0.05 a	16.27 ± 0.12 c	1.02 ± 0.01 a	9.2	90.3	17.3	36.6
BR	Melhorada	6.40 ± 0.21 a	3.82 ± 0.20 ab	68.40 ± 0.29 abc	19.77 ± 0.07 bc	0.98 ± 0.03 a	10.2	89.2	20.8	38.8
BR	Moneymaker	5.80 ± 0.12 a	3.34 ± 0.23 abcd	69.50 ± 0.13 ab	19.86 ± 0.05 bc	0.86 ± 0.01 a	9.1	90.2	20.7	39.0
BR	Stuart	5.68 ± 0.08 b	2.414 abcd	69.42 ± 0.38 bc	18.54 ± 0.40 e	1.02 ± 0.05 ab	10.4	89.0	19.6	37.9
BR	Success	6.40 ± 0.36 a	4.44 ± 0.23 abcd	65.53 ± 0.43 abc	22.06 ± 0.12 abc	0.90 ± 0.01 de	10.8	88.5	23.0	40.2
US	Western	8.18 ± 1.66 a	2.0 ± 0.66 bcd	54.33 ± 5.65 c	34.08 ± 5.94 a	1.4 ± 0.77 a	10.2	89.8	35.5	50.5
US	Barton	7.53 ± 2.63 a	2.1 ± 0.49 bcd	66.3 ± 11.83 abc	22.45 ± 9.62 abc	1.43 ± 0.36 a	9.6	90.2	23.9	41.9
US	Success	6.85 ± 0.69 a	1.93 ± 0.42 abcd	63.15 ± 7.06 abc	29.18 ± 7.82 abc	1.45 ± 0.41 a	8.8	93.8	30.6	47.9
US	Stuart	7.23 ± 1.26 a	1.85 ± 0.38 abcd	61.28 ± 5.9 abc	25.5 ± 5.51 abc	1.53 ± 0.53 a	9.1	88.3	27.0	43.9
US	Schley	7.9 ± 1.01 a	1.8 ± 0.42 cd	59.4 ± 3.00 abc	29.63 ± 1.80 abc	1.38 ± 0.57 a	9.7	90.4	31.0	47.2
US	Texas Prolific	7.1 ± 1.24 a	1.95 ± 0.79 cd	57.1 ± 5.12 bc	33.35 ± 5.18 ab	1.325 ± 0.62 a	9.1	91.8	34.7	50.3
US	Hayes	7.67 ± 1.74 a	1.65 ± 0.52 d	59.75 ± 5.74 abc	29.5 ± 6.69 abc	1.3 ± 0.7 a	9.3	90.5	30.8	47.0
AR	Stuart	6.84 ± 0.54 a	2.52 ± 0.12 abcd	60.55 ± 1.06 abc	26.63 ± 0.78 abc	1.09 ± 0.08 a	9.4	88.3	27.7	43.9

SFA (saturated fatty acids); UFA (total Unsaturated fatty acids); PUFA (Polyunsaturated fatty acids); Peroxidizability Index (PI) = [(%Monoenoic × 0.025) + (%Dienoic × 1) + (%Trienoic × 2)], as stated previousl [9]. Numbers in yellow indicate the highest levels and in gray the lowest values.
Different letters within column indicate significant differences ($p < 0.05$).

Table 1.
Main fatty acids in pecan kernels from Brazil, US and Argentine varieties (g/100 g fat).

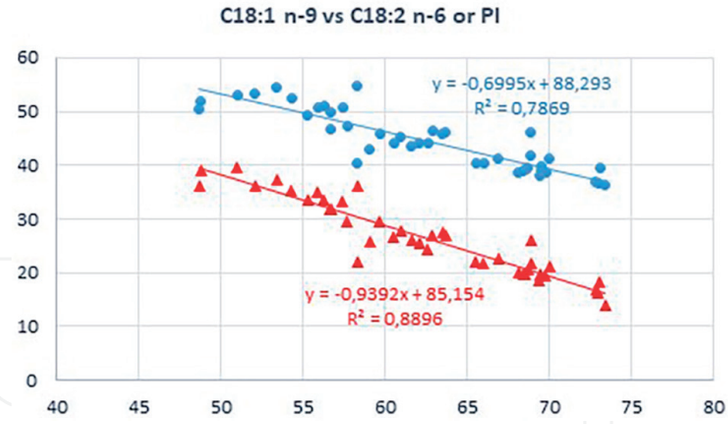

Figure 2.
Relationship between oleic acid, linoleic acid and Peroxidizability Index. Dots in blue indicate C18: 1 n-9 vs. PI; triangles in red indicate C18: 1 n-9 vs. C18: 2 n-6.

conservative fatty acids profile with slightly different shapes attributable mainly to the genetic, environmental, and plant phenological status [8]. In **Table 1**, the means of major fatty acids are shown in different cultivars from different regions (US, Brazil, and Argentina).

As lipid composition is critical for oxidative stability, different fatty acids and their indexes are presented in **Table 1**. Oleic acid (C18: 3, n-9) is the main constituent of pecan fatty acids. It has one double bond at the carbon in position nine. Therefore, this FA is relatively stable in terms of oxidation. Its concentration in pecan kernels is inversely proportional to the linoleic acid (C18: 2, n-6) concentration (**Figure 2**) and consequently to the peroxidizability index (PI).

The peroxidizability index may indicate the susceptibility of pecans to oxidation. At higher levels of oleic acid, the lower PI in the samples. Mahan showed the lowest total PUFA level and consequently the lowest PI. The variation in the lipid content affected the pecan stability, as oxidative damage induces quality loss and correlates positively with rancidity [8].

Taking together all the data in **Table 1**, it is noticeable that the samples with higher oleic acid (C18: 1 n-9) presented lower levels of linolenic acid (C18: 2 n-6), that is, Mahan vs. Western with a negative and significant linear correlation (R2 = 0.89), as illustrated in **Figure 2**.

By virtue of the number of peroxidizable double bonds, samples with higher oleic acid are more stable and show less PI. Apparently, during the development, oleic acid is transformed into linoleic acid by the action of desaturates. As the proportion of oleic acid increased or decreased, it was in tandem with an opposite change in linoleic acid. The ratio oleic/linoleic coincided with the ratio oleic/PI, indicating the susceptibility of the cultivars [8]. Therefore, it can be considered for breeding programs or further postharvest handling in terms of oxidative stability.

Desirable pecans grown at two different locations (BW and CW) showed differences in their oleic-linoleic composition. The fatty acid profile may depend on environmental conditions, cultivar, maturity, and horticultural practices. Thus, the selection of appropriate cultivation conditions is an important factor to consider when selecting pecan cultivars [10].

For example, increasing the nitrogen fertilization rate increases the protein content and oleic acid levels in kernels. At the same time, it showed a tendency to lower tocopherol contents [11].

	Pecan oil Variety								
Fatty acid	**Shoshoni**	**Desirable**	**Kernodle**	**Success**	**Mahan**	**Starking**	**Stuart**	**Cheyenne**	**INTA Delta I**
Palmitic acid (C16:0)	5.79 ± 0.07 d	5.40 ± 0.02 f	5.65 ± 0.10 de	5.52 ± 0.12 ef	6.11 ± 0.10 c	6.68 ± 0.01 a	6.33 ± 0.04 bc	6.42 ± 0.03 b	6.69 ± 0.13 a
Palmitoleic acid (C16:1)	0.07 ± 0.01 cd	0.08 ± 0.01 bc	0.07 ± 0.00 d	0.10 ± 0.01 a	0.07 ± 0.00 cd	0.08 ± 0.00 bc	0.08 ± 0.00 bcd	0.08 ± 0.00 bc	0.09 ± 0.00 b
Margaric acid (C17:0)	0.05 ± 0.00 a	0.06 ± 0.00 a	0.06 ± 0.01 a	0.06 ± 0.00 a	0.06 ± 0.00 a	0.06 ± 0.01 a	0.06 ± 0.00 a	0.06 ± 0.00 a	0.07 ± 0.01 a
Heptadecanoic acid (C17:1)	0.05 ± 0.00 abc	0.06 ± 0.00 ab	0.06 ± 0.01 ab	0.06 ± 0.00 a	0.05 ± 0.01 bc	0.04 ± 0.00 c	0.05 ± 0.00 abc	0.05 ± 0.00 bc	0.06 ± 0.01 abc
Esteáric acid (C18:0)	2.47 ± 0.02 e	2.72 ± 0.02 cd	1.96 ± 0.03 h	2.82 ± 0.04 b	3.02 ± 0.02 a	2.65 ± 0.01 d	2.22 ± 0.04 g	2.34 ± 0.02 f	2.78 ± 0.01 bc
Oleic acid (C18:1 trans)	0.03 ± 0.00 a	0.01 ± 0.01 a	0.02 ± 0.01 a	0.02 ± 0.00 a	0.03 ± 0.01 a	0.02 ± 0.01 a	0.02 ± 0.01 a	0.02 ± 0.01 a	0.02 ± 0.01 a
Oleic acid (C18:1 cis n-9)	62.64 ± 0.10 c	67.71 ± 0.04 a	62.26 ± 0.41 c	65.01 ± 0.11 b	59.63 ± 0.02 e	49.44 ± 0.01 h	60.99 ± 0.06 d	52.52 ± 0.04 g	54.54 ± 0.09 f
Linoleic acid (C18:2 n-6)	27.27 ± 0.07 f	22.56 ± 0.02 h	28.40 ± 0.32 e	25.07 ± 0.06 g	29.37 ± 0.05 d	38.94 ± 0.02 a	28.61 ± 0.03 e	36.77 ± 0.01 b	33.90 ± 0.08 c
Linolenic acid (C18:3 n-3)	1.20 ± 0.00 e	0.99 ± 0.01 g	1.12 ± 0.01 f	0.91 ± 0.00 h	1.29 ± 0.02 d	1.73 ± 0.01 a	1.22 ± 0.01 e	1.33 ± 0.00 c	1.47 ± 0.00 b
Araquidonic acid (C20:0)	0.13 ± 0.01 c	0.14 ± 0.01 abc	0.10 ± 0.00 d	0.15 ± 0.00 a	0.14 ± 0.00 a	0.14 ± 0.00 abc	0.12 ± 0.01 c	0.13 ± 0.00 bc	0.14 ± 0.00 ab
Erudic acid (C20:1)	0.27 ± 0.01 a	0.26 ± 0.01 a	0.27 ± 0.01 a	0.26 ± 0.00 a	0.20 ± 0.00 bc	0.18 ± 0.01 c	0.27 ± 0.01 a	0.28 ± 0.01 a	0.21 ± 0.00 b
Behenic acid (C22:0)	0.03 ± 0.00 ab	0.02 ± 0.00 b	0.03 ± 0.00 ab	0.02 ± 0.00 b	0.03 ± 0.01 ab	0.03 ± 0.00 a	0.03 ± 0.00 ab	0.03 ± 0.00 ab	0.03 ± 0.00 ab

Different letters within column indicate significant differences ($p < 0.05$).

Table 2.
Fatty acids profile in pecan oil from Argentine cultivars (g/100 g pressed oil).

As expected, the fatty acids profile in pecan oil resembles those from kernels, as fat is the major constituent of pecan nuts (**Table 2**).

As shown in **Table 2**, results in extracted pecan oil, the desirable variety had the higher oleic/linoleic relationship, whereas starking showed the lowest, as demonstrated for the pecan oil extracts [12].

Oil is highly susceptible to oxidation, because it does not have the protective structure of the nut proteins and polyphenols, with a shell containing antioxidants. The presence of a large number of phenolic compounds in pecan nut shells may explain the protective activity.

3. Antioxidants in pecan shell, oil, and nuts

3.1 Shells

Recently, the presence of 29 and 27 phenolic compounds in nut shells in aqueous and hydro-alcoholic phases has been reported, respectively, from samples submitted to ultrasonic-assisted extraction. The major compounds resulted in catechin (>260 mg/g dry sample); gallic acid (>120 mg/g dry sample); epicatechin (>24 mg/g dry sample); myricetin (>12 mg/g dry sample); ellagic acid (>11 mg/g dry sample); and vanillin (> 6 mg/g dry sample). Other minor compounds are chlorogenic acid, vanillic acid, siryngic acid, epicatechingallate, fustin, P-coumaric acid, taxifolin, ferulic acid, rosmarinic acid, quercetin, salicylic acid, myricetin, eriodictyol, naringenin, and galangin [13].

3.2 Nuts and oil

The main antioxidant in pecan oil is γ-tocopherol 24.97 ± 0.90 (mg/100 g), followed by α-tocopherol 1.65 ± 0.02 (mg/100 g). The presence of γ-tocopherol and a high concentration of oleic acid are associated with the high oxidative stability of pecan nut oil [14]. In previous work, we described that in Stuart pecans, tocopherols ranged from 5.8 to 142 mg kg^{-1} nut of α- and γ- tocopherol, respectively. Minor quantities of β- + δ- tocopherols were also detected (less than 0.5 $mg.kg^{-1)}$ [6].

Phytosterols are bioactive compounds that act on oxidative stability in plant cell membranes. They have in their chemical structure, a steroid nucleus with hydroxyl groups (3-β-hydroxyl group), which could be related to a mild antioxidant activity exerted in the lipid phase of biological membranes [15]. β-sitosterol is the main component of pecan sterols (approximately 75%), and its concentration is variable and depends on their ripening state. In Tunisian pecans, the changes in 4-desmethylsterol, 4-monomethylsterol, 4, 4-dimethylsterol, and phytostanol composition were quantitatively and qualitatively investigated during the ripening of three varieties (Mahan, Moore, and Burkett). Fifteen phytosterols and one phytostanol were quantified. The greatest amount of phytosterols (2852.5 mg/100 g of oil) was detected in the Mahan variety, 20 weeks after the flowering date (WAFD). Moore had the highest level of phytostanols (7.3 mg/100 g of oil) at 20 WAFD. Phytosterol and phytostanol contents showed a steep decrease during pecan nut development. Results from the quantitative characterization of pecan nut oils revealed that β-sitosterol, Δ5-avenasterol, and campesterol were the most abundant phytosterol compounds at all ripening stages [16]. Also, they protected oil and fruits from oxidative processing. It has been shown that in fried pecans, tocopherols and phytosterols were the main functional components in the oil-soluble part, to avoid oxidation [17].

The values for total carotenoids in cultivars varied from 0.897 to 1.403 μg/g of oil without any significant difference among cultivars for total carotenoid content [18].

Some antioxidants reported in the literature are extracted in **Table 3**.

C. illinoensis (variety)	Total Phenolic Activity (mg CAE/g)	γ-tocopherol (μg/g)	Phytosterols (PE) (μg/g)	Reference
Kanza	106 ± 2.3	105 ± 1		Oil [10]
Nacono	76 ± 2.2	135 ± 4		
Kiowa	76 ± 2.5	72 ± 6		
Pawnee	72 ± 0.9	100 ± 1		
Shawnee	71 ± 1.9	102 ± 2		
Desirable CW	70 ± 2.0	84 ± 1		
Desirable BW	62 ± 2.3	126 ± 5		
Stuart		139 ± 3		kernel
Sioux		311 ± 3		[19]
Pawnee		86.8 ± 3		
Cheyenne	21.6			Kernel
Choctaw	23			[20]
Desirable	19.5			
Pawnee	20			
Stuart	22.7			
Summer	19.3			
Western	21.9			
Wichita	24.4			
MV (mixed varieties 2009)	130.30 ± 3.45 (shell extract)	381 ± 4	2200	Oil and shell extract [21]
MV (mixed varieties 2010)	145.41 ± 8.16 (shell extract)	238 ± 5	2100	
Barton (2009)	94.04 ± 2.66 (shell extract)	334 ± 41	1900	
Barton (2010)	181.49 ± 6.97 (shell extract)	260 ± 10	1900	
Stuart		393		Oil [8]
Sioux		291		
Choctaw		221		
Barton		410		
Shawnee		369		
Desirable		313		
C. cathayensis	19.4	72.1	β-sitosterol: 728 stigmasterol:144 fucosterol:101 campsterol: 21.3	Kernel [17]

Table 3.
Main antioxidants in pecans: γ-tocopherol, phytosterols and total phenols.

4. Oxidative stability

The conservation of pecan nuts is important in terms of their quality because the sensory defects are undesired for commercial purposes and further consumption.

Many authors described the oxidative stability of nuts with accelerated assays. Indeed, the results may be useful to understand the relationship between biochemical and sensory properties, but they do not predict properly the mechanisms under real storage conditions, because higher temperatures may accelerate lipid oxidation/degradation and Maillard reactions with the concomitant formation of Strecker products that are not expected or are less produced under low-temperature storage [22].

Sensory defects can be predicted in pecans by multiple biochemical indicators. Rancid flavor, moisture, and conjugated dienes were representative of quality deterioration, whereas secondary oxidation products related to higher thiobarbituric acid reactive substances (TBARS) [23]. Other authors indirectly associated the odor of treated pecans with oxidative deterioration and rancid flavor using an e-nose with a sensor array [24]. Recently, a report indicated that storage temperatures below 10°C were more effective to preserve Barton pecans than low oxygen atmospheres with 20, 3 and 1.5 Kpa O2 [25]. In addition, the breakdown of flavonoids and reaction products from Maillard browning could be responsible for the formation of the reddish-brown

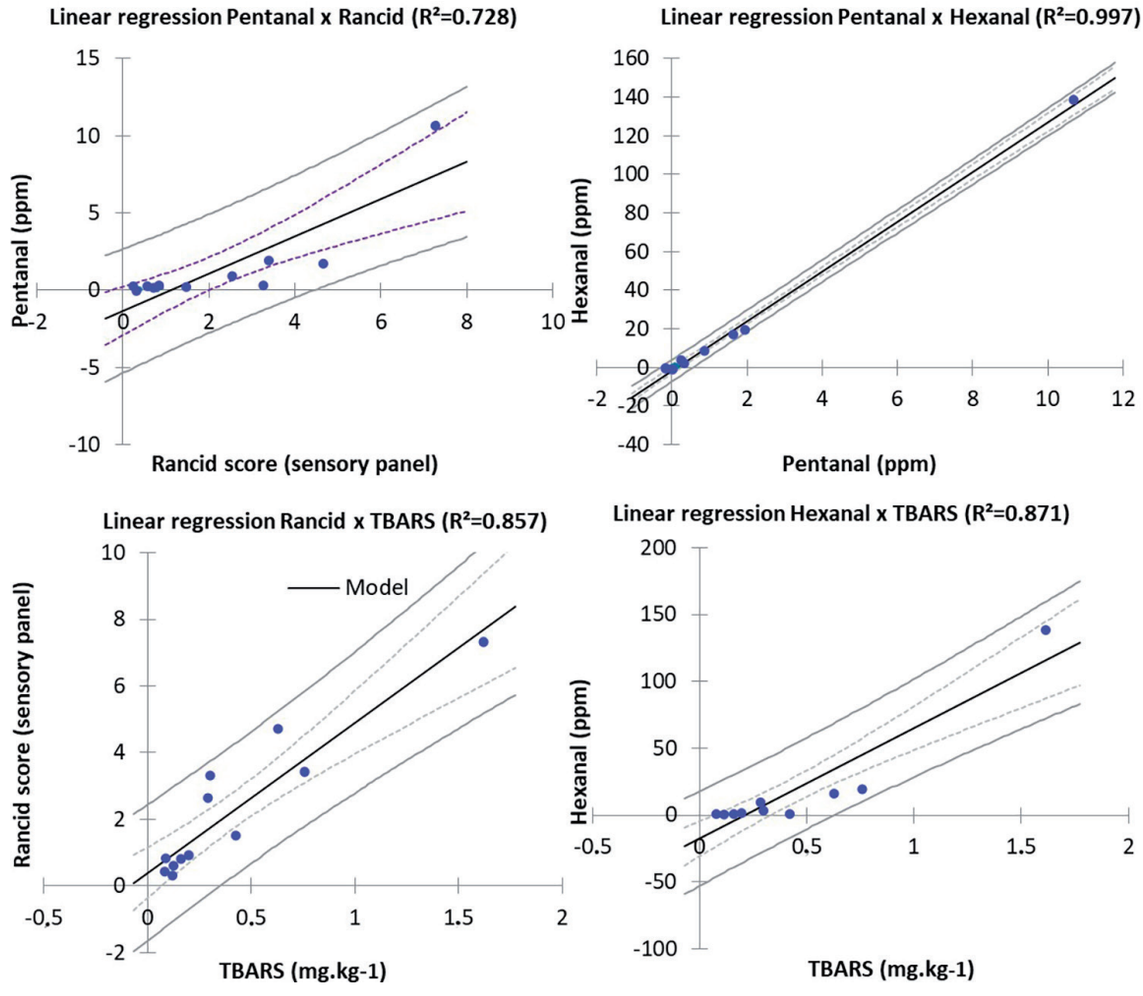

Figure 3.
Linear regression between hexanal, pentanal and TBARS as predictors for rancid flavor in Stuart pecans.

color observed in degraded nutmeats. Browning can be predicted using a mathematical model with a first-order decay equation [26].

Moreover, the conservation of pecan nuts for 10 months postharvest is interesting because it allows producers to commercialize their product until the next harvest period. They may be stored in clean burlap bags, at a maximal atmosphere humidity of 70%, and in a dark, clean, and ventilated chamber.

In previous work, we have described that the TBARS value (thiobarbituric acid reactive substances), hexanal, and pentanal were the main predictors of pecan oxidative stability [6]. The degradation of linolenic acid produced hexanal and pentanal as major volatile aldehydes [23], [27] as a result of the cleavage and oxidation of the double bonds. Hexanal and pentanal correlated positively between them, indicating a similar occurrence. Both volatiles were produced in the samples but at different concentrations.

Interestingly, both volatiles showed a positive and significant correlation with TBARS and rancid score, as determined by a sensory panel [6]. Some correlations are shown in **Figure 3**.

This feature may indicate that a TBARS value of 1 corresponds to a rancid score of 5, using a 10-cm nonstructured scale where the lower extreme meant "extremely weak" and the upper extreme meant "extremely strong." Therefore, a TBARS value equal to 1 (mg.kg-1) can be signaled as the threshold value to perceive pecan kernels as rancid.

Oxidation progress within the storage of pecans is independent of the concentration of tocopherols content in the samples. Both α- and γ-tocopherols are preserved during unshelled pecans storage at either refrigerated or room temperature, whereas oxidation triggering measured by TBARS started at seven months postharvest, regardless of the storage temperature [6].

5. Conservation of pecans and sensory attributes

Many authors describe different strategies for the conservation of nuts. These strategies comprise shelled nuts with different packaging and atmosphere environments, as well as in shell conservation, mainly for in-bulk storage in pecan facilities under different temperatures and oxygen conditions. The compromise between energy cost and pecan quality maintenance will depend on producers' and retailers' possibilities.

5.1 Shelled nuts under vacuum storage at room temperature

In a previous work, shelled nuts were submitted to room temperature storage, either within nylon-polyethylene bags, or in polypropylene containers. They were conserved for 150 days. Peroxides were raised in both treatments as well along with the time of storage. They described a significant linear reduction ($p < 0.0001$) in all the sensory characteristics (visual color, typical flavor, odor, and texture) during the storage period. The acceptability scores were similar for both types of packaging, indicating that vacuum treatment did not contribute to prolonging the pecan's shelf-life [28]. The shelf life for both treatments was determined in 120 days of storage. After that time, sensory scores dropped below six (scale 1 to 10).

5.2 Raw and roasted shelled pecans stored at room temperature

Roasting promoted the oxidation of the lipids, with higher TBARS and peroxides levels compared with raw nuts. However, the nonsignificant differences in rancid

aroma and rancid flavor between raw and roasted pecans implied that the sensory response was not sensitive enough to differentiate any increase in oxidative products at an early stage of storage. In this study, panelists did not differentiate the lightness of the raw and roasted products, whereas darkening was indicated in roasted pecans using instrumental measurements.

Storage affected the crunchiness of raw and roasted pecans, with those stored at 65% relative humidity (RH), having lower scores than those stored at 55% RH. During storage, rancid aroma and flavor developed in both raw and roasted pecans with higher records for roasted ($p < 0.05$). Varying the relative humidity, 55% and 65% RH, during storage, did not affect flavor or aroma scores significantly for either raw or roasted pecans [23].

5.3 Shelled coated pecans

Shelled "Desirable" pecans were coated with different mixtures of (MC = methylcellulose, CMC = carboxymethyl cellulose, HPC = hydroxypropyl cellulose, PG = propylene glycol, BHA = butylated hydroxyanisole, BHT = butylated hydroxytoluenecaboxy methyl cellulose). All types of coating preserved pecan kernels from oxidative damage compared with uncoated pecans. Coated kernels initially had slightly higher off-flavor, perhaps due to the coating itself, but had less off-flavor and better overall flavor after nine months of storage. Also, the hexanal levels after five months of storage were twofold less in coated than in uncoated kernels. For that reason, the coating could reduce lipid oxidation (i.e., rancidity) and preserve the color during marketing at ambient temperature by limiting oxygen contact with the kernel lipids. This strategy would reduce costs to the pecan industry and improve quality for the consumers [29].

5.4 Shelled pecans stored at different temperatures and different packaging conditions

"Stuart" shelled pecans were stored for 12 months at 20°C, 2°C, and − 15°C packaged in cellophane bags or bi-laminated polythene-aluminum bags flushed with nitrogen. The rise in oxidation (TBARS) between the fourth and tenth month was 10-fold, 4-fold; 4.6-fold, and 4.6-fold for 20°C; 2°C, and − 15°C, respectively. Under nitrogen, oxidation showed no differences between temperatures. TBARS increase was 5.0-fold, 4.6-fold, and 3.7-fold for 20°C; 2°C, and − 15°C, respectively (**Figure 4**). Differences in lipid oxidation were also noticeable in color (**Figure 5**). Nuts stored in cellophane bags were less conserved than under nitrogen. This assay demonstrated that the use of bilaminated bags and nitrogen atmosphere conserved the quality of the nuts, without the necessity of using low-temperature storage. Without nitrogen, refrigeration or freezing were the suitable options. Unshelled pecans showed higher oxidation and darker color after 10 months of storage (Experimental data from INTA).

5.5 Shelled and unshelled pecans stored at 20°C and −15°C temperatures under modified atmosphere conditions

Dried shelled and unshelled "Barton" pecans were separated into two parts, one submitted to 1-MCP (SmartFresh®, 0.14% of active ingredient as maturation inhibitor) at a concentration of 1.0 μL L^{-1}. Four groups (shelled and unshelled, with

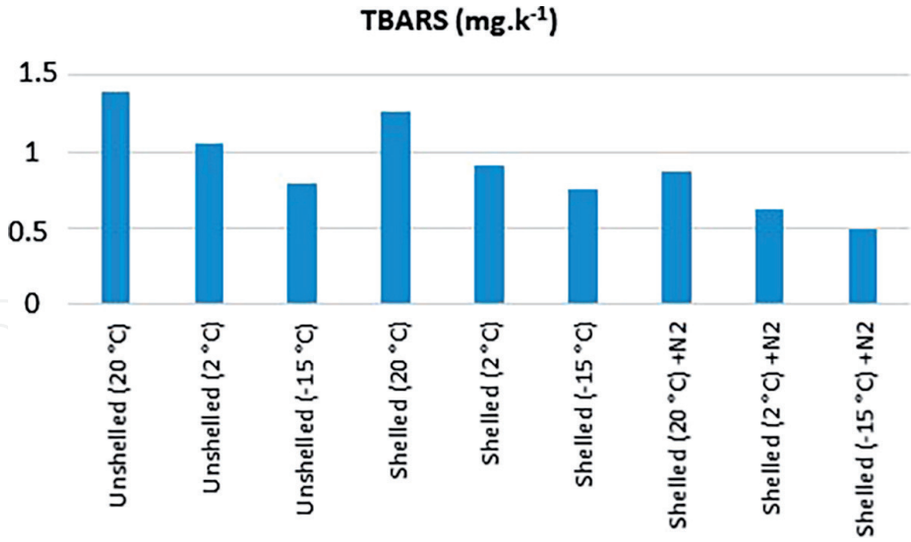

Figure 4.
TBARS levels of shelled pecans stored under different packaging and temperature conditions. TBARS assay at the laboratory of Food Science and Technology, INTA.

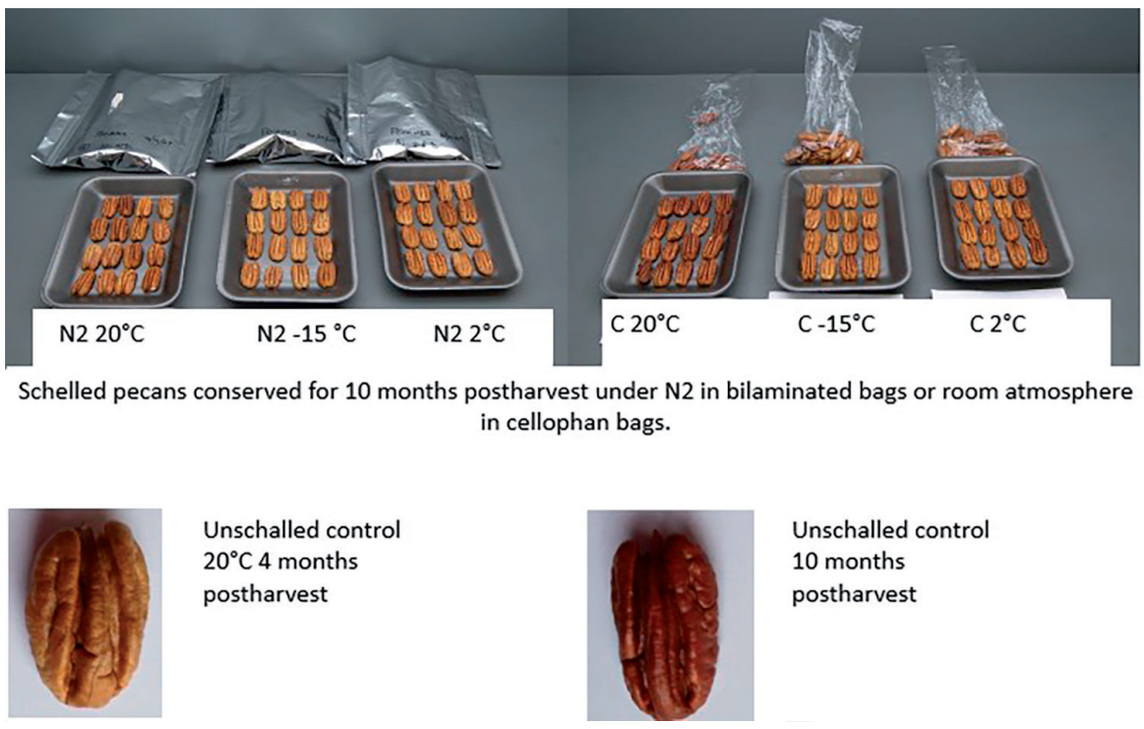

Figure 5.
Aspect of pecans stored in different bags, with or without nitrogen and different temperatures. Color assay at the laboratory of Food Science and Technology, INTA.

or without MCP-1 treatment) were stored under ambient temperature (17 ± 5.1°C) and relative air humidity (78.3 ± 11.2%). Each treatment was identified and placed separately into raffia bags until evaluation.

Since pecans respire and continue to have enzymatic activity throughout storage unless deactivated using heat or irradiation, it is essential to maintain the packaging environment that can slow down the rate of deterioration.

Results showed that 1-MCP application inhibited excessive acidity and lipid peroxidation in both shelled and unshelled nuts. Luminosity was better conserved

in unshelled pecans. Also, some unwanted aldehydes were produced at lower levels, indicating some protective action of the shell. Nonetheless, 1-MCP treatment in this condition reduced the abundance of these volatile compounds.

The conservation of the shells prevented oxidative damage in the nuts. In summary, unshelled pecans stored under ambient conditions and with a 1-MCP application showed the best quality [30].

5.6 Unshelled pecans stored at room temperature and 2°C

Unshelled "Stuart" pecans were dried to a moisture content of 3–4% and placed in individual clean mesh bags, conserved either at 2 ± 1°C or at 20 ± 1°C at 65% of relative humidity in the dark for 10 months. These conditions resemble postharvest practices in pecan facilities.

Refrigeration did not avoid the trigger of oxidation, measured by TBARS, hexanal, and pentanal. But it restricted the final levels of oxidation compounds. Refrigerated storage of in-shell pecans resulted in differences detected at both biochemical and sensory scores, with significantly higher signs of oxidative deterioration at 20°C compared with storage temperature at 2°C.

Oxidative damage showed an exponential evolution that triggered from day 210 at 20°C and 30 days later at 2°C. A similar behavior was observed for the presence of rancid taste and typical flavor loss during postharvest storage.

The conservation of unshelled nuts at 2°C prevented the excessive formation of these compounds, compared with the conservation at 20°C, but it did not prevent the initiation of the oxidative process. Moreover, the results of sensory trials showed that pecans lost their typical flavor and sweetness, whereas augmented the bitter and rancid taste along with the storage with enhanced deterioration at 20°C compared with 2°C [6].

5.7 In shell pecans are stored at room temperature, refrigerated storage, and different oxygen partial pressure (pO2)

"Barton" unshelled pecans were stored in containers and placed in three rooms at 20, 10, and 1.5°C and under three different pO2, 20 kPa (ambient condition), 3 kPa, and 1 kPa. The ambient temperature (20°C) allows for avoiding refrigeration. Refrigerated storage (8–10°C) is currently adopted by companies. The lowest temperature used as a control was 1.5°C. After 12-month storage, pecans kept at room temperature (20°C) showed increased acidity and color change.

Luminosity decreased at 20°C with respect to other refrigeration conditions. However, samples kept at 20°C and with lower pO2 (3 and 1 kPa) maintained higher luminosity and less oxidation indicators throughout storage.

Therefore, adopting lower temperatures (1.5 and 10°C) resulted more effective at maintaining quality regardless of the atmosphere condition, without any significant differences in the luminosity and the presence of volatile aldehydes and acids production.

The use of low pO2 in storage facilities has shown positive results, especially at higher temperatures (20°C). There was little difference in quality between 1 and 3 kPa; thus, pO2 near to 3 kPa can be recommended, especially when there are required lower energy costs with refrigeration [24].

6. Conclusions

Pecans are nuts rich in oil and, especially in unsaturated fatty acids making them prone to oxidation. Oxidative damage leads to a decrease in overall quality, appearance of rancidity, loss of sweetness, typical flavor, darkening, and texture defects. Unshelled pecans stored at room temperature begin oxidizing between 6 and 8 months postharvest. This can be avoided or diminished using low-temperature of storage until reaching the next harvest period. Other strategy for retail is the storage of shelled pecans, but they are more susceptible to oxidation than shelled nuts because the shell contains many phenolic antioxidants that can form a protective barrier against oxidation. For that reason, shelled nuts may be submitted to coating, packaging, and temperature or the use of a modified atmosphere to preserve the quality of kernels.

The use of nitrogen or atmosphere modifiers allowed to store of unshelled pecans at room temperature. Research on packaging and atmosphere may be also a key factor in the storage and distribution of bulk nuts in 25 kg bags.

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Conflict of interest

The authors declare no conflict of interest.

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