


Article

Chemical Composition, Fatty Acid Profile, and Optimization of the Sacha Inchi (*Plukenetia volubilis* L.) Seed-Roasting Process Using Response Surface Methodology: Assessment of Oxidative Stability and Antioxidant Activity

Nelsy Bocanegra Morales and Paula Galeano Garcia * 

Grupo de Investigación en Productos Naturales Amazónicos—GIPRONAZ, Facultad de Ciencias Básicas, Universidad de la Amazonia, Florencia 180001, Colombia; n.bocanegra@udla.edu.co

* Correspondence: p.galeano@udla.edu.co

Abstract: This study aimed to optimize the roasting conditions for sachá inchi (*Plukenetia volubilis* L.) seeds using the central composite design (CCD) of the response surface methodology (RSM). The antioxidant activity and oxidation indicators (peroxide and TBA values) were assessed, along with the impact of roasting on the fatty acid profile and chemical characterization of the seeds using gas chromatography. The results demonstrated that roasting partially increased the indicators of lipid oxidation in the oil extracted from roasted seeds, as well as the antioxidant activity of the seeds. The optimal roasting conditions were determined using CCD and RSM, resulting in an optimized temperature of 134.28 °C and 18.84 min. The fatty acid contents were not significantly affected by the roasting intensity, whereas a higher presence of amino acids was found in the seeds roasted at 140 °C for 15 min. In conclusion, it is suggested that the optimal roasting conditions for enhancing amino acid presence, improving antioxidant activity, and maintaining oxidative stability in sachá inchi seeds fall within the temperature range of 134–140 °C and a roasting duration of 15–20 min.

Keywords: sachá inchi; roasting; oxidative stability; antioxidant activity; fatty acids



Citation: Bocanegra Morales, N.; Galeano Garcia, P. Chemical Composition, Fatty Acid Profile, and Optimization of the Sachá Inchi (*Plukenetia volubilis* L.) Seed-Roasting Process Using Response Surface Methodology: Assessment of Oxidative Stability and Antioxidant Activity. *Foods* **2023**, *12*, 3405. <https://doi.org/10.3390/foods12183405>

Received: 22 June 2023

Revised: 19 July 2023

Accepted: 25 July 2023

Published: 12 September 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The Amazon region is home to a vast array of plant species, which are of great significance to global agriculture [1]. However, there are still numerous lesser-known fruit species that have potential economic value owing to their chemical properties. Sachá inchi (*Plukenetia volubilis* L.) is an oleaginous Amazonian fruit tree from the Euphorbiaceae family, commonly referred to as “wild peanut”, “Inca peanut”, “Inca inchi”, or “mountain peanut” [2,3]. Sachá inchi is widely distributed in South America, particularly in the Amazon River basin. Peru currently leads sachá inchi production and industry, with an annual seed production of approximately 1200 tons [4]. Nevertheless, other countries, such as Colombia, Ecuador, and Bolivia, have also begun to engage in agricultural and economic ventures [5]. In Colombia, sachá inchi cultivation has expanded to the southern regions of the country, notably the departments of Putumayo, Caquetá, Meta, Guaviare, and Cauca [6], showing promising economic potential and offering possibilities for replacing illicit crops in conflict-affected areas in Colombia [7].

P. volubilis cultivation has recently been implemented in various Asian countries, particularly in China, Cambodia, Thailand, and Laos [8]. Historical records pertaining to the use of sachá inchi primarily emanate from Peru, where ethnic groups have cultivated it for centuries as a source of sustenance and medicine [9]. Traditionally, roasted and salted seeds, or those coated with chocolate, are consumed. Furthermore, the seeds are pressed to obtain oil and ground to produce flour [10]. However, sachá inchi has predominantly served medicinal purposes, as evidenced by an ethnobotanical study conducted in San

Martín, Peru [8,11]. Indigenous communities blend oil and ground seeds to create a cream for skin rejuvenation, alleviate muscular pain, and mitigate rheumatism. Additionally, oil and roasted seeds are utilized to manage cholesterol levels, promote cardiovascular health, and address gastrointestinal conditions [11]. Multiple studies have also demonstrated the bioactive properties of sacha inchi, endowing it with significant potential in the food, pharmaceutical, and cosmetic industries [12]. Presently, sacha inchi is commercially available in the form of oil, encapsulated oil, seeds, and protein powder, serving as a dietary supplement [8].

The chemical composition of sacha inchi varies depending on the plant part, with the seeds being of particular interest due to their high oil content (35–60%) and protein content (27%). The oil stands out because of its elevated levels of linolenic (ω -3) and linoleic (ω -6) acids, which account for approximately 45% and 35% of the total unsaturated fatty acids (UFAs), respectively. These fatty acids are renowned for their health benefits in preventing cardiovascular diseases, cancer, and hypertension [9,13,14]. Additionally, the presence of essential amino acids such as cysteine, tyrosine, threonine, and tryptophan [15] makes roasted sacha inchi seeds and sacha inchi oil highly valuable as functional foods, earning the title of “superfood” due to their exceptional nutritional value [16].

The roasting process of sacha inchi seeds plays a crucial role in snack production. This process involves subjecting the seeds to temperatures ranging between 80 and 120 °C, which enhances their flavor and aroma while eliminating undesirable tastes resulting from the presence of compounds such as tannins, saponins, and phytic acid [17,18]. This is also safer because sacha inchi contains appreciable amounts of alkaloids, saponins, and lectins, which may be toxic if consumed before cooking [18]. Nevertheless, it is important to note that thermal treatment affects both the chemical composition and nutritional properties. Cisneros et al. [19] conducted a study on sacha inchi oil and observed that roasting enhanced its oxidative stability and antioxidant capacity through the formation of phenolic compounds. Similar studies on cashews and hazelnuts have reported decreases in tocopherol and carotenoid content, as well as certain phenolic compounds, such as protocatechuic acid, phloretin-2-O-glucoside, catechin, and epicatechin, following roasting or drying [20,21]. Nonetheless, it is worth mentioning that the total phenolic content and antioxidant capacity tend to increase [22], indicating that roasting induces structural changes within the cellular matrix of food, potentially leading to the formation of novel phenolic compounds.

Furthermore, Bueno-Borges et al. [23] found that toasting the seeds at 160 °C for 15 min reduced the antinutrient content and increased the antioxidant activity of methanolic extracts of the seeds, while the oil oxidation indicators remained within acceptable quality limits. In another study, three types of cooking processes were analyzed: uncooked, roasted at 160 °C for 6 min, and boiled at 100 °C for 13 min. The results indicate that roasted sacha inchi is distinguishable by its high antioxidant content (polyphenol, flavonoid, and free radical scavenging activity) [18]. Based on these findings, the objective was to optimize the toasting conditions of the seeds using a central composite design (CCD) within a temperature range of 80–200 °C and a time range of 10–20 min. The present study aimed to evaluate the oxidative stability of oil and the antioxidant activity of methanolic seed extracts. Additionally, the profile of fatty acids in oil and the chemical composition of seeds at low (80 °C, 20 min), medium (140 °C, 15 min), and high (200 °C, 20 min) toasting were analyzed.

2. Materials and Methods

2.1. Collection and Toasting of Sacha Inchi Seeds

The encapsulated fruits of sacha inchi were donated by the Sacha Caquetá association in the municipality of Doncello (Caquetá, Colombia) when they were ripe and dry. Seeds were manually dehusked and toasted in a conventional oven. Response surface methodology (RSM) was used in the present study to optimize the toasting conditions. In the central composite design (CCD), the factors, levels, temperatures (80–200 °C) and times

(10–20 min) were evaluated, with antioxidant activity and oxidation indicators (peroxide value and TBARS value) used as response variables. The selection of design levels was based on a literature review. Thirteen roasting conditions were applied with five repetitions at the central point (Table 1). After roasting, the seeds were cooled to room temperature and stored to prepare hydroalcoholic extracts.

Table 1. The central composite design and responses of the dependent variables to the sachu inchi roasting seeds and oils.

Temperature (°C)	Time (min)	Roasted Seed Extracts	Roasted Seed Oils	
		ABTS ^a	Peroxide Value ^b	TBA Value
200	10	2828.37	3.18	0.032
80	20	2616.59	1.94	0.018
80	10	2606.69	1.91	0.016
140	15	2736.72	2.02	0.024
140	12.5	2727.10	1.98	0.025
140	15	2728.39	2.03	0.022
140	17.5	2764.69	1.93	0.022
170	15	2788.67	2.05	0.03
200	20	2905.99	3.25	0.035
140	15	2724.51	1.97	0.026
110	15	2637.58	1.44	0.019
140	15	2729.56	1.96	0.028
140	15	2728.15	1.72	0.025

^a Values are expressed as $\mu\text{mol EAA/g grain}$. ^b Values are expressed as mEqO_2/kg (milliequivalents of oxygen per kilogram of seed).

2.2. Sachu Inchi Oil Extraction

The oil extraction process was conducted by cold pressing using a Mega KPD-30A hydraulic press, exerting a force of 30 tons. A total of 100 g of sachu inchi seeds was packed into fine mesh cloth bags to prevent any solid particles from contaminating the oil. An applied force of 450 kg/cm^2 was used for oil extraction at room temperature. The extracted oil was meticulously collected using a Pasteur pipette, decanted, and stored in an amber glass container at $-40 \text{ }^\circ\text{C}$ until subsequent analysis [19].

2.3. Assessment of Antioxidant Capacity

2.3.1. Preparation of Hydroalcoholic Extracts

A total of 1 g of the sample was dissolved in 15 mL of a 70:30 (*v/v*) methanol (Merck, Rahway, NJ, USA)/water solution and stirred for 1 h at room temperature. The extract was then centrifuged at 4500 rpm for 15 min at room temperature. The supernatant was filtered and adjusted to a volume of 25 mL by using the same solvent. The extracts were stored in amber vials at $4 \text{ }^\circ\text{C}$.

2.3.2. ABTS Free Radical Scavenging Method

To prepare the ABTS (Merck) cationic radical, a solution of 7 mM ABTS and 2.45 mM potassium persulfate was mixed. After 24 h, the $\text{ABTS}^{+\cdot}$ solution was diluted with phosphate-buffered saline (PBS) at pH 7.4, until an absorbance of 0.700 ± 0.020 at 734 nm was reached. For the analysis, 3 μL of the extract was mixed with 295 μL of the diluted $\text{ABTS}^{+\cdot}$ solution, and the absorbance was measured at 734 nm after 30 min of reaction in the dark [24]. Antioxidant activity was determined using a calibration curve with ascorbic acid standards, and the results were expressed as $\mu\text{mol equivalents of ascorbic acid (Merck)}$ per gram of sample ($\mu\text{mol EAA/g sample}$).

2.4. Thiobarbituric Acid (TBA) Value and Peroxide Value

The peroxide value was determined using the standard IDF 74A:1991 method [25,26]. This method quantifies the hydroperoxides formed by the primary oxidation of lipids, and the results are expressed in milliequivalents of oxygen per Kg of oil. The TBA value was determined using the methodology described previously by Zeb and Ullah [27] with some modifications. A weight of 0.05–0.5 g of oil was added to a volume of 3 mL with glacial acetic acid in a Falcon tube. Then, 3 mL of a thiobarbituric acid (TBA) (Sigma-Aldrich, St. Louis, MO, USA) solution (200 mg in 100 mL of glacial acetic acid (Sigma-Aldrich)) was added, and the mixture was placed in a water bath at 95 °C for 1 h. After cooling to room temperature, the intensity of coloration was measured at 532 nm using a spectrophotometer [28].

2.5. GC-FID Fatty Acid Profile

The fatty acid profiles of raw sachu inchi oil and oils from lightly roasted (80 °C, 20 min), moderately roasted (140 °C, 15 min), and highly roasted (200 °C, 20 min) samples were determined using gas chromatography following the Colombian standard method NTC 4967 [29]. Methyl esters of fatty acids were analyzed on an Agilent Technologies (Santa Clara, CA, USA) gas chromatograph (6890N) equipped with a split/splitless injector, a flame ionization detector (FID), and a DB-225 capillary column (30 m × 0.25 mm, 0.25 µm, Agilent Technologies). The injector and detector temperatures were set at 250 °C and 220 °C, respectively [29]. The oven was initially maintained at 75 °C and programmed using a time-based heating ramp to 220 °C at a rate of 5 °C/min. Helium was used as the carrier gas with an injection volume of 0.2 µL. The results are expressed as grams of fatty acids per 100 g of oil.

2.6. Characterization by Gas Chromatography–Mass Spectrometry (GC-MS)

Chloroform (Merck)/methanol (Merck)/water extracts (1:3:1 *v/v*) of raw sachu inchi seeds that were lightly roasted (80 °C, 20 min), moderately roasted (140 °C, 15 min), and highly roasted (200 °C, 20 min) were lyophilized. To the lyophilized samples, 20 µL of *O*-methoxylamine in pyridine (15 mg/mL) (Sigma-Aldrich) was added, followed by vortexing at 3200 rpm for 5 min and incubating in the dark at room temperature for 16 h. Silylation was performed by adding 20 µL of BSTFA with 1% TMS (Sigma-Aldrich), followed by vortexing for 5 min and incubating at 70 °C for 1 h. Finally, the samples were cooled to room temperature for 30 min, and 180 µL of heptane (Merck) was added. The mixture was vortexed for 10 min at 3200 rpm.

GC-MS analysis was performed using an Agilent Technologies 7890B gas chromatograph coupled with an Agilent Technologies GC/Q-TOF 7250 time-of-flight mass spectrometer. The system was equipped with a split/splitless injection port (250 °C, split ratio of 50) and an Agilent Technologies 7693A automatic injector. Electron ionization (EI) was operated at 70 eV. An Agilent Technologies J&W HP-5MS column (30 m, 0.25 mm, 0.25 µm) was used with helium as the carrier gas at a constant flow of 0.7 mL/min. The oven temperature was programmed to increase from 60 °C (1 min) to 325 °C at a rate of 10 °C/min. The transfer line, filament, and quadrupole temperatures were maintained at 280 °C, 230 °C, and 150 °C, respectively. Mass spectrometry detection was performed in the range of 50–600 *m/z* at a speed of 5 spectra/min.

3. Results and Discussion

3.1. The Effect of Roasting on the Organoleptic Properties of Sachu Inchi Seeds

The roasting process of sachu inchi seeds induces notable modifications in their physical attributes, leading to discernible changes in color, flavor, and aroma [15,19]. Initially, the untreated seeds exhibit a creamy hue, which undergoes a subtle transition to a light brown shade as the roasting temperature gradually increases within the range of 80–140 °C. Upon reaching higher roasting temperatures (170–200 °C), the seeds acquired a more pronounced dark brown coloration (Figure 1). Concurrently, elevated roasting temperature intensifies

the aroma reminiscent of peanuts, while the typical astringent taste of beans diminishes. However, it is worth noting that beyond the threshold of 200 °C, the seeds tended to undergo carbonization, imparting an undesirable bitter taste. Similarly, changes in color and odor have been observed in oil [16,19].

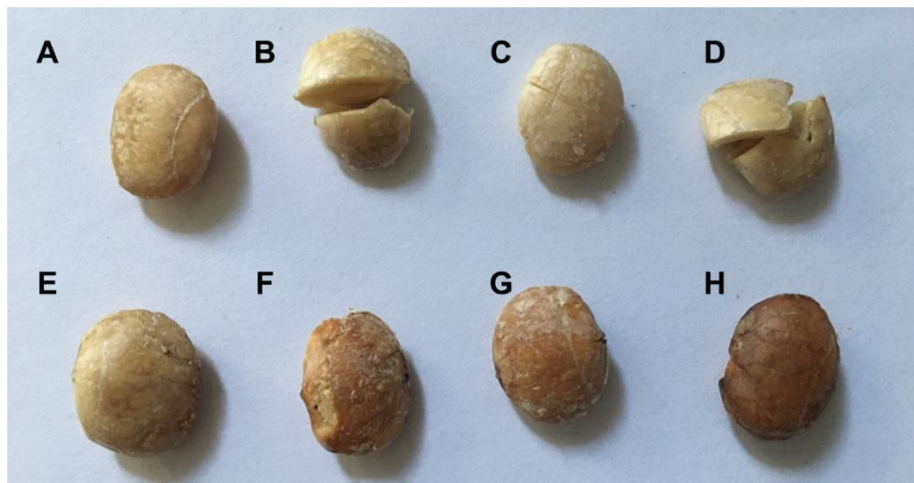


Figure 1. The effect of roasting on the physical appearance of the sachu inchi seeds in different heat treatments: unroasted (A); 80 °C, 10 min (B); 80 °C, 20 min (C); 110 °C, 15 min (D); 140 °C, 15 min (E); 170 °C, 15 min (F); 200 °C, 10 min (G); 200 °C, 20 min (H).

3.2. The Effect of Roasting on the Antioxidant Activity in Sacha Inchi Seeds

To optimize the temperature and roasting time parameters for sachu inchi seeds, an experimental design using response surface methodology was employed. The objective of this study was to investigate the impact of these variables on both the antioxidant activity of the seeds and the indicators of oxidation in sachu inchi oil.

Figure 2A presents a response surface plot depicting the intricate relationship between the independent variables (temperature and time) and the response variable represented by antioxidant activity ($\mu\text{mol EAA/g seed}$). The antioxidative activity response attained its highest value at a temperature of 200 °C and a toasting duration of 20 min. The experimental results were fitted to a well-fitting quadratic model with an insignificant lack of fit ($p > 0.05$). The ANOVA yielded a high coefficient of determination (R^2) of 0.9947, with a coefficient of variability (%CV) of 0.28. Both temperature and time variables were found to be statistically significant ($p < 0.05$), with temperature exhibiting a particularly high level of significance ($p < 0.0001$). The temperature range of 80–200 °C and the time range of 10–20 min exert a statistically significant (95%) influence on antioxidative activity. Furthermore, they exhibit positive effects, wherein an enhancement in their values leads to increased antioxidant activity (Figure 2B). Furthermore, the graph demonstrates that lower temperatures and shorter roasting times correspond to decreased antioxidant activity (blue color), whereas higher temperatures and longer roasting times result in increased antioxidant activity (red color) (Figure 2A).

The antioxidant activity of sachu inchi seeds roasted at different temperatures and exposure times was assessed using the ABTS method. The results demonstrate an increase in antioxidant activity following roasting, ranging from 2606.69 $\mu\text{mol EAA/g seed}$ (at 80 °C for 10 min) to 2905.99 $\mu\text{mol EAA/g seeds}$ (at 200 °C for 20 min) (Table 1). Consistent with these findings, Bueno-Borges (2018) reported that the highest roasting temperature (160 °C for 15 min) resulted in greater antioxidant activity in sachu inchi seeds.

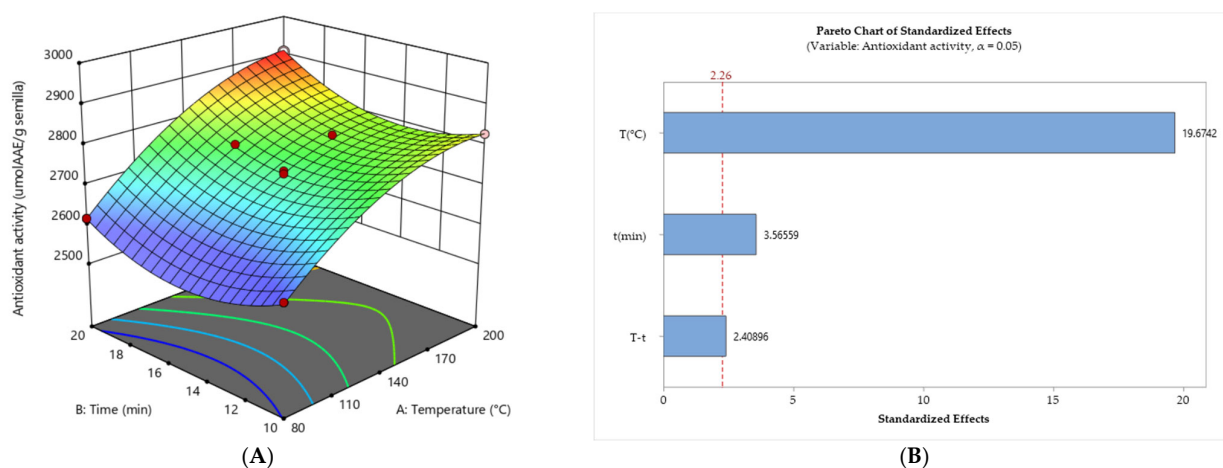


Figure 2. (A) The 3D response surface plot illustrates the impact of roasting temperature and time on the antioxidant activity of sacha inchi seeds. (B) Pareto chart showing the standardized effect of independent variables and their interaction on the antioxidant activity.

In nature, the presence of phenolic compounds, either free or covalently bound to other groups or molecules, has been documented [30]. Roasting disrupts these bonds, leading to an increase in antioxidant activity. Additionally, the Maillard reaction during roasting generates compounds with antioxidant properties, which likely contribute to the observed increase in antioxidant activity at specific roasting temperatures [23,31]. This heat-induced enhancement of antioxidant activity has also been reported for other food products [32,33].

Similar observations have been made in studies involving peanut oil (*Arachis hypogaea* L.) [34] and sesame seeds (*Sesamum indicum* L.), wherein the formation of dicarbonyl compounds, acrylamide, and 5-hydroxymethylfurfural was detected [35]. Furthermore, roasted sunflower seeds have been found to contain volatile compounds, including aldehydes, alcohols, ketones, pyrazines, and furans, resulting from Maillard and lipid oxidation reactions [36]. These compounds exhibit secondary oxidation with potential reducing properties [31]. Notably, certain Maillard products have shown promising anticancer and antimicrobial properties [37], thereby broadening their potential benefits beyond enhancing the antioxidant capacity of food.

3.3. The Effect of Roasting on Sacha Inchi Oil Oxidation

Sacha inchi oils were obtained by cold pressing roasted seeds at various temperatures and exposure times (Table 1). Figure 3 presents the response surface plot, demonstrating the interplay between the independent variables (temperature and time) and the response variables, namely the peroxide value (mEqO₂/kg) and TBA value. The peroxide value showed a satisfactory fit with a quadratic model ($R^2 = 0.9574$, %CV = 6.65) (Figure 3A), while the TBA value exhibited a linear relationship with an acceptable fit ($R^2 = 0.9017$, %CV = 7.68) (Figure 3B). Both fitted models present a non-significant lack of fit ($p > 0.05$). The ANOVA results revealed a high significance for temperature ($p < 0.0001$), whereas time had no significant influence on the response variables of oxidative stability. The Pareto charts (Figure 3C,D) illustrate that temperature (80–200 °C) had a significant effect (95%), whereas time (10–20 min) did not exhibit a significant effect (95%) on the variables of oxidative stability. However, both temperature and time have positive effects, meaning that an increase in their values leads to an increase in the peroxide and thiobarbituric acid (TBA) values. Figure 3A,B indicates that lower roasting temperatures corresponded to decreased peroxide and TBA values (depicted in blue), whereas higher temperatures and longer exposure times led to increased values (depicted in red).

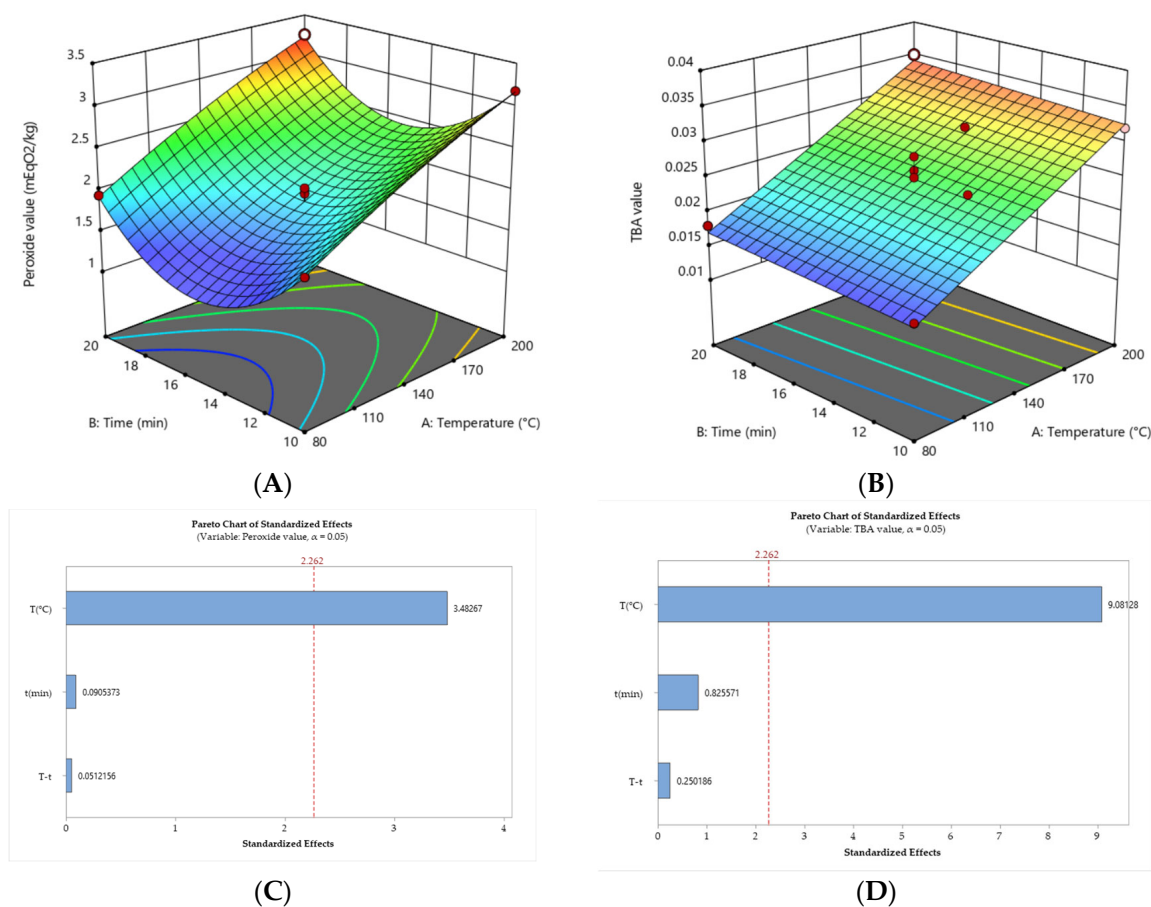


Figure 3. The 3D response surface plot depicts the relationship between time and temperature and their effect on two parameters: (A) peroxide and (B) TBA value. Pareto chart showing the standardized effect of independent variables and their interaction on the oxidation indicators, (C) peroxide, and (D) TBA value.

Similar to antioxidant activity (Table 1), the oxidation indicators demonstrated an increasing trend with increasing temperature. TBA values ranged from 0.016 (80 °C, 10 min) to 0.035 (200 °C, 20 min), suggesting that roasting affects lipid oxidation in sachu inchi oils, leading to the formation of secondary oxidation products, primarily aldehydes [27]. The reaction between 2-thiobarbituric acid (TBA) and malondialdehyde (MDA), the primary marker of lipid peroxidation, yields a colored complex that can be measured spectrophotometrically [27].

The peroxide value increased from 1.91 mEqO₂/kg of oil (80 °C, 10 min) to 3.25 mEqO₂/kg of oil (200 °C, 20 min) (Table 1), indicating an increase in primary oxidation products, which is attributed to the accumulation of hydroperoxides resulting from the attack of free radicals on unsaturated fatty acids, such as linolenic acid [32,34], which is present in high concentrations in sachu inchi oils [19]. The increase in oxidation indicators with the intensity of roasting, linked to high linolenic acid content, has also been reported for flaxseed oil [38] and other seeds [34,39].

The increase in antioxidant capacity and oxidative stability can be attributed to the newly formed Maillard products and the formation of phenolic compounds [32,39]. Furthermore, melanoidins produced as a result of the Maillard reaction improve oxidative stability and impart distinct color and flavor characteristics to the oil [39]. Despite the increase in peroxide values observed at higher roasting temperatures, they remained below the permissible limits for high-quality oil (below 10 meqO₂/kg) [40]. Thus, the temperatures and exposure times assessed for sachu inchi seed roasting in DCC did not have a negative impact on oxidative stability. Oil is likely capable of resisting oxidative deteriora-

tion, lipid hydrolysis, and microbial degradation by eliminating moisture content through thermal treatment. Roasting, along with encapsulation and the addition of natural antioxidants, is considered one of the methods to reduce the peroxidation of polyunsaturated fatty acids [3,15,41,42].

3.4. Fatty Acid Profiles of Sacha Inchi Oil

The fatty acid composition of sachu inchi oil subjected to different thermal treatments is presented in Table 2. The most abundant fatty acids are linolenic acid (43.3–44.3 g/100 g), linoleic acid (33.7–35.0 g/100 g), oleic acid (11.3–12.4 g/100 g), palmitic acid (4.59–4.91 g/100 g), stearic acid (3.36–3.68 g/100 g), docosanoic acid (0.02–0.07 g/100 g), and eicosanoic acid (0.114–0.134 g/100 g). Saturated fatty acids (palmitic acid, stearic acid, eicosanoic acid, and docosanoic acid) are present in low amounts, accounting for 9% of the total, while unsaturated fatty acids (linolenic acid, linoleic acid, and oleic acid) are highly abundant, accounting for 91% of the total. These findings indicate that sachu inchi oil could be a favorable dietary option owing to its low saturated fatty acid content, which is consistent with previous studies by Cisneros et al. [19], Kim and Joo [14], and Hamaker et al. [43]. Notably, even at the high toasting temperature of 200 °C for 20 min, the fatty acid profile of sachu inchi oil remained largely unaffected, which is consistent with the findings reported by Cisneros et al. [19] at lower toasting temperatures (102 °C for 10 min), as well as similar observations in the fatty acid profiles of oils derived from other oilseeds [44,45].

Table 2. Changes in the fatty acid composition of unroasted and roasted sachu inchi seeds during thermal treatments.

Fatty Acid	Oil Sample			
	Unroasted Seeds	Lightly Roasted Seeds (80 °C, 20 min)	Medium Roasted Seeds (140 °C, 15 min)	Highly Roasted Seeds (200 °C, 20 min)
Palmitic acid (C16:0)	4.74 ± 0.05 *	4.59 ± 0.05	4.60 ± 0.05	4.91 ± 0.05
Stearic acid (C18:0)	3.36 ± 0.04	3.37 ± 0.04	3.47 ± 0.04	3.68 ± 0.04
Eicosanoic acid (C20:0)	0.117 ± 0.001	0.120 ± 0.001	0.114 ± 0.001	0.134 ± 0.001
Docosanoic acid (C22:0)	0.04 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.07 ± 0.01
Oleic acid (C18:1)	11.8 ± 0.1	11.3 ± 0.1	11.5 ± 0.1	12.4 ± 0.1
Linoleic acid (C18:2)	33.7 ± 0.4	33.8 ± 0.4	35 ± 0.4	34.5 ± 0.4
α-Linolenic acid (C18:3)	43.3 ± 0.5	43.8 ± 0.5	44.3 ± 0.5	43.2 ± 0.5

* The values are expressed in (g/100 g) of oil.

Keawkim and Na Jom [46] discovered that thermal treatment significantly increases the levels of free fatty acids in both germinated and non-germinated sachu inchi seeds. This effect is likely attributed to the heat-induced degradation of lipase activity, which tends to decrease at higher temperatures and prolonged exposure times. Consequently, damaged cells containing hydrolytic enzymes may contribute to elevated levels of free fatty acids following toasting [46].

According to Fanali et al. [13], sachu inchi oil offers more beneficial nutraceuticals because of its considerably higher ω6 content than common oilseeds such as canola, flaxseed, sunflower, and soybean oil. Moreover, the well-balanced ratio of ω3 to ω6 fatty acids in sachu inchi oil, which approaches the ideal range of 1:4 to 1:10, exerts a significant hypocholesterolemic effect. Additionally, it contributes to the prevention of cardiovascular and inflammatory diseases while reducing the risk of cancer [14,15].

3.5. GC-MS Profile of Sachu Inchi Seeds

Dynamic changes in unroasted and roasted sachu inchi seeds at different temperatures and times are presented in Table 3. Thirty-one identified metabolites were classified into five groups. Group I contained eight amino acids, group II contained three fatty acids, group III contained eight organic acids, group IV contained two alcohols, and group V contained ten sugars. In the GC-MS analysis, 24 compounds were identified in unroasted

sacha inchi seeds, 25 in lightly toasted seeds (80 °C, 20 min), 24 in moderately toasted seeds (140 °C, 15 min), and 21 in highly roasted seeds (200 °C, 20 min), including amino acids, organic acids, fatty acids, alcohols, and sugars (Table 3). Of the thirty-one identified compounds, sixteen were found to be common in all four samples, indicating that the degree of toasting did not affect the presence of these components in the seeds.

Table 3. Chemical composition of sacha inchi seeds with different heat treatments.

Groups	Compounds	Roasted Seed			
		From Unroasted Seeds	Lightly Roasted Seeds (80 °C, 20 min)	Medium Roasted Seeds (140 °C, 15 min)	Highly Roasted Seeds (200 °C, 20 min)
Amino acids	L-Valine	+	+	+	+
	L-Alanine	+	ND*	+	+
	L-Aspartic acid	ND	+	+	ND
	L-Leucine	ND	+	ND	ND
	L-Serine	+	+	+	ND
	L- Glutamic acid	ND	+	+	ND
	4-Aminobutanoic acid	ND	ND	+	ND
	L-5-Oxoproline	+	+	+	+
Fatty acids	Linoleic acid	+	+	+	+
	α-Linolenic acid	+	+	+	+
	Palmitic acid	+	+	+	+
Organic acids	2-Hydroxyglutaric acid	ND	+	ND	ND
	Glyceric acid	+	+	ND	+
	Butanoic acid	+	ND	ND	ND
	Malic acid	+	+	+	+
	2-Butenedioic acid	+	ND	ND	ND
	Butanedioic acid	+	ND	ND	ND
	Lactic acid	+	+	+	+
Glycolic Acid	+	+	+	+	
Alcohols	2,3-Butanediol	+	+	+	+
	Glycerol	+	+	+	+
Sugars	D-Fructose	+	+	+	+
	Meso-erythritol	+	+	+	+
	D-Arabinose	+	+	+	+
	L-(-)-Arabitol	+	+	+	+
	D-Glucose	+	+	+	+
	D-Mannitol	+	+	+	+
	Scyllo-inositol	+	+	+	+
	Myo-Inositol	+	+	+	+
	D-Chiro-Inositol	ND	+	ND	ND
Sacarose	ND	+	+	+	

* ND: not detected. The highlighted compounds were not previously reported in sacha inchi.

Of 24 identified compounds, 20 have been previously reported in both sacha inchi seeds and oil. An essential amino acid (L-valine) and two essential fatty acids (linolenic acid and linoleic acid) were found in both roasted and unroasted seeds. The presence of essential compounds, which cannot be synthesized by the body and, therefore, must be obtained through diet, makes sacha inchi a “superfood” with significant benefits for human health [47,48]. L-valine was detected in all heat treatments, whereas L-leucine was only present in low-temperature roasting. Wang et al. [15] have also identified other essential amino acids in sacha inchi seeds, including lysine, isoleucine, tyrosine, and threonine. Generally, there was a higher concentration of amino acids during medium roasting, but their levels decreased at 200 °C, which aligns with Keawkim and Na Jom’s [46] finding of a slight reduction in amino acid content at 180 °C during prolonged roasting. The non-essential amino acids identified included L-alanine, L-serine, L-glutamic acid, and L-5-oxoproline. L-5-oxoproline, present in all heat treatments, is a cyclic amino acid formed through the dehydration of glutamate [49] or heating of L-glutamic acid between 160 and 180 °C [50]. This may explain the disappearance of L-glutamic acid at 180 °C and the presence of L-5-oxoproline at higher temperatures. Furthermore, the non-protein amino acid 4-aminobutanoic acid and gamma-aminobutyric acid (GABA) were detected

at 140 °C. GABA is a powerful bioactive compound that is crucial for brain function, acting as an inhibitory neurotransmitter in the central nervous system and exhibiting hypotensive effects [51].

It has been demonstrated that the increase in free amino acids during roasting is attributed to the denaturation of certain proteins [21,47]. The findings from this study revealed a higher presence of amino acids in medium-roasted samples, followed by lightly roasted samples, and a decrease in high-roasted samples. The decrease in certain amino acids at high roasting temperatures can be attributed to their oxidation and the formation of advanced glycation end-products, such as carboxymethyllysine (CML) and carboxyethyllysine (CEL), resulting from the reaction of amino acids with reducing sugars. Consequently, high temperatures can cause structural damage and modification of amino acid residues [52]. Therefore, the cooking and roasting processes generate Maillard reactions (glycation), leading to various pathways and interactions, including caramelization, Strecker degradation, and decomposition of sulfur-containing amino acids, depending on the roasting intensity [53]. Thus, a roasting temperature of 140 °C with a 15 min exposure improved the amino acid content compared to the other treatments.

Similarly, eight sugars were found in all the heat treatments. The reducing sugars D-glucose and D-fructose, sucrose, and myoinositol have been reported in other studies on sacha inchi seeds [46,54,55]. These sugars may be responsible for the formation of Maillard reaction products during toasting, contributing to the characteristic color and flavor of the toasted seeds. Sugars and amino acids found in toasted seeds are essential substrates for the formation of color, flavor, and aroma during the Maillard process [46]. Furthermore, these compounds also contribute to the formation of Maillard reaction products that are associated with improved antioxidant properties and oxidative stability [37]. Previous studies have identified some Maillard reaction products in sacha inchi seeds, such as pyrazines, which can be formed through the sugar–amino acid system [46]. Similar effects of roasting have been observed in other fruits, further supporting the presence of Maillard products contributing to antioxidant properties [32].

In addition to amino acids and sugars, organic acids have also been detected in sacha inchi seeds. Lactic acid and glycolic acid were present in all treatments and could be formed through the conversion of sucrose and fructose into their intermediates, 1,2-endiol and 2,3-endiol, respectively (Figure S1) [56,57]. These organic acids are involved in Maillard reactions and may contribute to the characteristic flavor and aroma of toasted seeds. Malic acid was detected in all treatments, whereas 2-hydroxyglutaric acid was found only in seeds toasted at 80 °C, and 2-butenedioic acid and butanedioic acid were identified in untoasted seeds. For fatty acids, thermal treatment did not affect the content of sacha inchi oil, and the results indicated that the degree of toasting did not influence their presence in the seeds.

4. Conclusions

The roasting process of sacha inchi seeds led to a slight increase in the oxidation indicators in the oil and the antioxidant capacity of the seeds. The optimal roasting conditions were determined using a central composite design and response surface methodology, resulting in a recommended temperature of 134.28 °C and a duration of 18.84 min. These conditions were based on peroxide value, TBA value, and antioxidant activity. Interestingly, roasting intensity did not significantly affect the content of polyunsaturated fatty acids, such as linolenic acid and linoleic acid. Among the amino acids, the highest level was observed in seeds roasted at 140 °C, followed by those roasted at 80 °C, and unroasted seeds. However, at a roasting temperature of 200 °C, both amino acids and organic acids decreased. Notably, the sugar content showed minimal changes with varying roasting intensity. Therefore, it can be concluded that the optimal roasting conditions to enhance the presence of amino acids, improve antioxidant activity, and maintain oxidative stability in sacha inchi seeds fall within the range of 134–140 °C and 15–20 min.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/foods12183405/s1>, Figure S1: Reaction scheme for acid formation from primary thermal degradation products of glucose.

Author Contributions: N.B.M. and P.G.G., conceptualization. N.B.M., investigation, writing—original draft, and visualization. P.G.G. writing—review and editing, supervision, resources, and methodology. N.B.M. methodology, image processing, investigation, and formal analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Sistema General de Regalías and Minciencias, grant number BPIN 2020000100031, and Universidad de la Amazonia.

Data Availability Statement: The datasets generated for this study are available on request to the corresponding author.

Acknowledgments: The authors would like to thank Francis Sanchez for his advice on experimental design. They also extend their thanks to the Taller de Mecánica Fina at the Universidad de la Amazonia for providing the hydraulic press used for cold-pressing the sacha inchi seed oil. Additionally, they would like to acknowledge the Sacha Caquetá association in the Municipality of Doncello, Caquetá, for supplying the sacha inchi seeds. The authors are grateful to Minciencias for the Young Researchers and Innovators Scholarship 891 in 2020.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

- Ruiz, S.L.; Sánchez, E.; Tabares Villareal, E.; Prieto, A.; Arias, J.C.; Gómez, R.; Castellanos, D.; García, P.; Chaparro, S. *Diversidad Biológica y Cultural Del Sur De La Amazonia Colombiana-Diagnóstico-Diversidad Biológica Y Cultural Del Sur De La Amazonia Colombiana-Diagnóstico*; Coporamazonia, Instituto Humboldt, Instituto Sinchi: Bogotá, Colombia, 2007. Available online: <http://repository.humboldt.org.co/handle/20.500.11761/34605> (accessed on 24 July 2023).
- Jumbo, V.F.E.; Pita, M.D.L.A.B.; Veiga, D.; Herrera, A.M. Effect of Altitudinal Floors on Antioxidant Capacity in Sacha Inchi Plants *Cita Sugerida* (APA, Séptima Edición). *Rev. Científica Agroecosistemas* **2022**, *10*, 124–133.
- Gutiérrez, L.F.; Rosada, L.M.; Jiménez, Á. Chemical Composition of Sacha Inchi (*Plukenetia Volubilis* L.) Seeds and Characteristics of Their Lipid Fraction. *Grasas Aceites* **2011**, *62*, 76–83. [[CrossRef](#)]
- Kittibunchakul, S.; Hudthagosol, C.; Sanporkha, P.; Sapwarobol, S.; Temviriyankul, P.; Suttisansanee, U. Evaluation of Sacha Inchi (*Plukenetia volubilis* L.) By-Products as Valuable and Sustainable Sources of Health Benefits. *Horticulturae* **2022**, *8*, 344. [[CrossRef](#)]
- Expert Market Research Global Sacha Inchi Market: By Type: Natural, Organic; By Form: Powder, Oil, Seeds, Others; By Application: Pharmaceuticals, Cosmetics, Personal Care, Food and Beverages, Dietary Supplements, Others; Regional Analysis; Historical Market and Forecast (2018–2028); Competitive Landscape; Industry Events and Developments. Available online: <https://www.expertmarketresearch.com/reports/sacha-inchi-market> (accessed on 12 July 2023).
- Minagricultura CADENA DE SACHA INCHI Indicadores e Instrumentos; 2019. Available online: <https://sioc.minagricultura.gov.co/Pasifloras/Documentos/2019-06-30%20Cifras%20Sectoriales%20SACHA%20INCHI.pdf> (accessed on 8 May 2023).
- Muñoz Muriel, M.E. De La Coca al Sacha Inchi (*Plukenetia Volubilis* L.): El Surgimiento de Un Proceso Autónomo, Gestado Por Productores de Coca, Durante El Periodo 2010–2017, En Puerto Caicedo, Putumayo, Colombia. Master's Thesis, Pontificia Universidad Javeriana, Bogotá, Colombia, 2019.
- Kodahl, N.; Sørensen, M. Sacha Inchi (*Plukenetia volubilis* L.) Is an Underutilized Crop with a Great Potential. *Agronomy* **2021**, *11*, 1066. [[CrossRef](#)]
- Chirinos, R.; Zuloeta, G.; Pedreschi, R.; Mignolet, E.; Larondelle, Y.; Campos, D. Sacha Inchi (*Plukenetia volubilis*): A Seed Source of Polyunsaturated Fatty Acids, Tocopherols, Phytosterols, Phenolic Compounds and Antioxidant Capacity. *Food Chem.* **2013**, *141*, 1732–1739. [[CrossRef](#)]
- Kodahl, N. Sacha Inchi (*Plukenetia volubilis* L.)—From Lost Crop of the Incas to Part of the Solution to Global Challenges? *Planta* **2020**, *251*, 80. [[CrossRef](#)]
- Del-Castillo, Á.M.R.; Gonzalez-Aspajo, G.; de Fátima Sánchez-Márquez, M.; Kodahl, N. Ethnobotanical Knowledge in the Peruvian Amazon of the Neglected and Underutilized Crop Sacha Inchi (*Plukenetia volubilis* L.). *Econ. Bot.* **2019**, *73*, 281–287. [[CrossRef](#)]
- Torres Sánchez, E.G.; Hernández-Ledesma, B.; Gutiérrez, L.F. Sacha Inchi Oil Press-Cake: Physicochemical Characteristics, Food-Related Applications and Biological Activity. *Food Rev. Int.* **2021**, *39*, 148–159. [[CrossRef](#)]
- Fanali, C.; Dugo, L.; Cacciola, F.; Beccaria, M.; Grasso, S.; Dachà, M.; Dugo, P.; Mondello, L. Chemical Characterization of Sacha Inchi (*Plukenetia volubilis* L.) Oil. *J. Agric. Food Chem.* **2011**, *59*, 13043–13049. [[CrossRef](#)]
- Kim, D.S.; Joo, N. Nutritional Composition of Sacha Inchi (*Plukenetia volubilis* L.) as Affected by Different Cooking Methods. *Int. J. Food Prop.* **2019**, *22*, 1235–1241. [[CrossRef](#)]

15. Wang, S.; Zhu, F.; Kakuda, Y. Sacha Inchi (*Plukenetia volubilis* L.): Nutritional Composition, Biological Activity, and Uses. *Food Chem.* **2018**, *265*, 316–328. [[CrossRef](#)]
16. Wang, K.; Liu, X.; Zhang, X. Isolation and Identification of Lipid-Lowering Peptides from Sacha Inchi Meal. *Int. J. Mol. Sci.* **2023**, *24*, 1529. [[CrossRef](#)]
17. Ruiz, C.; Díaz, C.; Anaya, J.; Rojas, R.; Cayetano Heredia ALINAP SAC, P. Análisis Proximal, Antinutrientes, Perfil Ácidos Grasos y de Aminoácido de Semillas y Tortas de 2 Especies de Sacha Inchi (*Plukenetia volubilis* y *Plukenetia huayllabambana*). *Rev. Soc. Quím. Perú* **2013**, *79*, 29–36.
18. Kim, D.S.; Joo, N. Feasibility of Elder-Friendly Food Applications of Sacha Inchi According to Cooking Method: Focusing on Analysis of Antioxidative Activity and Brain Neuron Cell Viability. *Foods* **2021**, *10*, 2948. [[CrossRef](#)]
19. Cisneros, F.H.; Paredes, D.; Arana, A.; Cisneros-Zevallos, L. Chemical Composition, Oxidative Stability and Antioxidant Capacity of Oil Extracted from Roasted Seeds of Sacha-Inchi (*Plukenetia volubilis* L.). *J. Agric. Food Chem.* **2014**, *62*, 5191–5197. [[CrossRef](#)]
20. Trox, J.; Vadivel, V.; Vetter, W.; Stuetz, W.; Scherbaum, V.; Gola, U.; Nohr, D.; Biesalski, H.K. Bioactive Compounds in Cashew Nut (*Anacardium occidentale* L.) Kernels: Effect of Different Shelling Methods. *J. Agric. Food Chem.* **2010**, *58*, 5341–5346. [[CrossRef](#)]
21. Król, K.; Gantner, M.; Piotrowska, A.; Hallman, E. Effect of Climate and Roasting on Polyphenols and Tocopherols in the Kernels and Skin of Six Hazelnut Cultivars (*Corylus avellana* L.). *Agriculture* **2020**, *10*, 36. [[CrossRef](#)]
22. Peng, M.; Lu, D.; Liu, J.; Jiang, B.; Chen, J. Effect of Roasting on the Antioxidant Activity, Phenolic Composition, and Nutritional Quality of Pumpkin (*Cucurbita pepo* L.) Seeds. *Front. Nutr.* **2021**, *8*, 647354. [[CrossRef](#)]
23. Bueno-Borges, L.B.; Sartim, M.A.; Gil, C.C.; Sampaio, S.V.; Rodrigues, P.H.V.; Regitano-d’Arce, M.A.B. Sacha Inchi Seeds from Sub-Tropical Cultivation: Effects of Roasting on Antinutrients, Antioxidant Capacity and Oxidative Stability. *J. Food Sci. Technol.* **2018**, *55*, 4159–4166. [[CrossRef](#)]
24. Wołosiak, R.; Drużyńska, B.; Derewiaka, D.; Piecyk, M.; Majewska, E.; Ciecierska, M.; Worobiej, E.; Pakosz, P. Verification of the Conditions for Determination of Antioxidant Activity by Abts and Dpph Assays—A Practical Approach. *Molecules* **2022**, *27*, 50. [[CrossRef](#)]
25. Shantha, N.C.; Decker, E.A. Rapid, Sensitive, Iron-Based Spectrophotometric Methods for Determination of Peroxide Values of Food Lipids. *J. AOAC Int.* **1994**, *77*, 421–424. [[CrossRef](#)]
26. Thewes, F.R.; Both, V.; Thewes, F.R.; Brackmann, A.; Wagner, R.; Ribeiro, S.R.; Ludwig, V.; Rossato, F.P. Pecan Storage: Effects of 1-MCP on the Overall Quality and Volatile Compounds Profile of Shelled and Unshelled Pecans. *Food Sci. Technol.* **2021**, *145*, 111298. [[CrossRef](#)]
27. Zeb, A.; Ullah, F. A Simple Spectrophotometric Method for the Determination of Thiobarbituric Acid Reactive Substances in Fried Fast Foods. *J. Anal. Methods Chem.* **2016**, *2016*, 9412767. [[CrossRef](#)]
28. Abuzaytouna, R.; Shahid, F. Oxidative Stability of Flax and Hemp Oils. *J. Am. Oil Chem. Soc.* **2006**, *83*, 855–861. [[CrossRef](#)]
29. Yate, A.V.; Narváez, P.C.; Orjuela, A.; Hernández, A.; Acevedo, H. A Systematic Evaluation of the Mechanical Extraction of *Jatropha Curcas* L. *Oil Biofuels Prod. Food Bioprod. Process.* **2020**, *122*, 72–81. [[CrossRef](#)]
30. El-Beltagi, H.S.; Maraie, R.W.; El-Ansary, A.E.; Rezk, A.A.; Mansour, A.T.; Aly, A.A. Characterizing the Bioactive Ingredients in Sesame Oil Affected by Multiple Roasting Methods. *Foods* **2022**, *11*, 2261. [[CrossRef](#)]
31. Pellegrini, N.; Serafini, M.; Colombi, B.; Del Rio, D.; Salvatore, S.; Bianchi, M.; Brighenti, F. Nutrient Requirements Total Antioxidant Capacity of Plant Foods, Beverages and Oils Consumed in Italy Assessed by Three Different In Vitro Assays 1. *J. Nutr.* **2003**, *133*, 2812–2819. [[CrossRef](#)]
32. Suri, K.; Singh, B.; Kaur, A.; Singh, N. Impact of Roasting and Extraction Methods on Chemical Properties, Oxidative Stability and Maillard Reaction Products of Peanut Oils. *J. Food Sci. Technol.* **2019**, *56*, 2436–2445. [[CrossRef](#)]
33. Xu, B.; Chang, S.K.C. Total Phenolics, Phenolic Acids, Isoflavones, and Anthocyanins and Antioxidant Properties of Yellow and Black Soybeans as Affected by Thermal Processing. *J. Agric. Food Chem.* **2008**, *56*, 7165–7175. [[CrossRef](#)]
34. Suri, K.; Singh, B.; Kaur, A.; Yadav, M.P.; Singh, N. Impact of Infrared and Dry Air Roasting on the Oxidative Stability, Fatty Acid Composition, Maillard Reaction Products and Other Chemical Properties of Black Cumin (*Nigella sativa* L.) Seed Oil. *Food Chem.* **2019**, *295*, 537–547. [[CrossRef](#)]
35. Berk, E.; Hamzaloglu, A.; Gökmen, V. Investigations on the Maillard Reaction in Sesame (*Sesamum indicum* L.) Seeds Induced by Roasting. *J. Agric. Food Chem.* **2019**, *67*, 4923–4930. [[CrossRef](#)]
36. Guo, S.; Na Jom, K.; Ge, Y. Influence of Roasting Condition on Flavor Profile of Sunflower Seeds: A Flavoromics Approach. *Sci. Rep.* **2019**, *9*, 11295. [[CrossRef](#)]
37. Liu, H.M.; Han, Y.F.; Wang, N.N.; Zheng, Y.Z.; Wang, X. De Formation and Antioxidant Activity of Maillard Reaction Products Derived from Different Sugar-Amino Acid Aqueous Model Systems of Sesame Roasting. *J. Oleo Sci.* **2020**, *69*, 391–401. [[CrossRef](#)]
38. Waszkowiak, K.; Siger, A.; Rudzińska, M.; Bamber, W. Effect of Roasting on Flaxseed Oil Quality and Stability. *JAOCS J. Am. Oil Chem. Soc.* **2020**, *97*, 637–649. [[CrossRef](#)]
39. Zou, Y.; Gao, Y.; He, H.; Yang, T. Effect of Roasting on Physico-Chemical Properties, Antioxidant Capacity, and Oxidative Stability of Wheat Germ Oil. *LWT-Food Sci. Technol.* **2018**, *90*, 246–253. [[CrossRef](#)]
40. Djikeng, F.T.; Teyomnou, W.T.; El Tenyang, N.; Tiencheu, B.; Morfor, A.T.; Arnaud, B.; Touko, H.; Houketchang, S.N.; Boungo, G.T.; Sri, M.; et al. Effect of Traditional and Oven Roasting on the Physicochemical Properties of Fermented Cocoa Beans. *Heliyon* **2018**, *4*, e00533. [[CrossRef](#)]

41. Zuleta, E.C.; Rios, L.A.; Benjumea, P.N. Oxidative Stability and Cold Flow Behavior of Palm, Sacha-Inchi, Jatropha and Castor Oil Biodiesel Blends. *Fuel Process. Technol.* **2012**, *102*, 96–101. [[CrossRef](#)]
42. Sanchez-Reinoso, Z.; Gutiérrez, L.F. Effects of the Emulsion Composition on the Physical Properties and Oxidative Stability of Sacha Inchi (*Plukenetia volubilis* L.) Oil Microcapsules Produced by Spray Drying. *Food Bioproc. Technol.* **2017**, *10*, 1354–1366. [[CrossRef](#)]
43. Hamaker, B.R.; Valles, C.; Gilman, R.; Hardmeier, R.M.; Clark, D.; Garcia, H.H.; Gonzales, A.E.; Kohlstad, I.; Castro, M.; Valdivia, R.; et al. Amino Acid Fatty Acids Profiles of Tge Inca Peanut (*Plukenetia volubilis*). *Cereal Chem.* **1992**, *69*, 461–463.
44. Lee, Y.C.; Oh, S.W.; Chang, J.; Kim, I.H. Chemical Composition and Oxidative Stability of Safflower Oil Prepared from Safflower Seed Roasted with Different Temperatures. *Food Chem.* **2004**, *84*, 1–6. [[CrossRef](#)]
45. Durmaz, G.; Gökmen, V. Changes in Oxidative Stability, Antioxidant Capacity and Phytochemical Composition of Pistacia Terebinthus Oil with Roasting. *Food Chem.* **2011**, *128*, 410–414. [[CrossRef](#)] [[PubMed](#)]
46. Keawkim, K.; Na Jom, K. Metabolomics and Flavoromics Analysis of Chemical Constituent Changes during Roasting of Germinated Sacha Inchi (*Plukenetia volubilis* L.). *Food Chem. X* **2022**, *15*, 100399. [[CrossRef](#)] [[PubMed](#)]
47. Ewy, M.W.; Patel, A.; Abdelmagid, M.G.; Mohamed Elfadil, O.; Bonnes, S.L.; Salonen, B.R.; Hurt, R.T.; Mundi, M.S. Plant-Based Diet: Is It as Good as an Animal-Based Diet When It Comes to Protein? *Curr. Nutr. Rep.* **2022**, *11*, 337–346. [[CrossRef](#)]
48. Burns-Whitmore, B.; Froyen, E.; Heskey, C.; Parker, T.; Pablo, G.S. Alpha-Linolenic and Linoleic Fatty Acids in the Vegan Diet: Do They Require Dietary Reference Intake/Adequate Intake Special Consideration? *Nutrients* **2019**, *11*, 2365. [[CrossRef](#)]
49. Ahn, J.-M.; Kassees, K.; Lee, T.-K.; Manandhar, B.; Yousif, A.M. Strategy and Tactics for Designing Analogs: Biochemical Characterization of the Large Molecules. In *Comprehensive Medicinal Chemistry III*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 66–115.
50. Metges, C.; Yu, Y.-M.; Cai, W.; Lu, X.-M.; Wong, S.; Regan, M.M.; Ajami, A.; Young, V. Oxoproline Kinetics and Oxoproline Urinary Excretion during Glycine- or Sulfur Amino Acid-Free Diets in Humans. *Physiol. Endocrinol. Metab.* **2000**, *278*, E868–E876. [[CrossRef](#)] [[PubMed](#)]
51. Diana, M.; Quílez, J.; Rafecas, M. Gamma-Aminobutyric Acid as a Bioactive Compound in Foods: A Review. *J. Funct. Foods* **2014**, *10*, 407–420. [[CrossRef](#)]
52. Xia, C.; Wen, P.; Yuan, Y.; Yu, X.; Chen, Y.; Xu, H.; Cui, G.; Wang, J. Effect of Roasting Temperature on Lipid and Protein Oxidation and Amino Acid Residue Side Chain Modification of Beef Patties. *RSC Adv.* **2021**, *11*, 21629–21641. [[CrossRef](#)]
53. Wei, F.; Tanokura, M. Chemical Changes in the Components of Coffee Beans during Roasting. In *Coffee in Health and Disease Prevention*; Elsevier Inc.: Amsterdam, The Netherlands, 2015; pp. 83–91; ISBN 9780124167162.
54. Keawkim, K.; Lorjaroenphon, Y.; Vangnai, K.; Jom, K.N. Metabolite–Flavor Profile, Phenolic Content, and Antioxidant Activity Changes in Sacha Inchi (*Plukenetia volubilis* L.) Seeds during Germination. *Foods* **2021**, *10*, 2476. [[CrossRef](#)]
55. Yanti, S.; Agrawal, D.C.; Saputri, D.S.; Lin, H.Y.; Chien, W.J. Nutritional Comparison of Sacha Inchi (*Plukenetia volubilis*) Residue with Edible Seeds and Nuts in Taiwan: A Chromatographic and Spectroscopic Study. *Int. J. Food Sci.* **2022**, *2022*, 9825551. [[CrossRef](#)]
56. Ginz, M.; Balzer, H.H.; Bradbury, A.G.W.; Maier, H.G. *Formation of Aliphatic Acids by Carbohydrate Degradation during Roasting of Coffee*; Springer: Berlin/Heidelberg, Germany, 2000; Volume 211.
57. Drabińska, N.; Siger, A.; Jeleń, H. Comprehensive Two-Dimensional Gas Chromatography-Time of Flight Mass Spectrometry as a Tool for Tracking Roasting-Induced Changes in the Volatilome of Cold-Pressed Rapeseed Oil. *Anal. Bioanal. Chem.* **2022**, *415*, 2523–2534. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.