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Effects of roasting temperature and time on the quality of cold-pressed Sacha Inchi oil from industrial practices in Thailand

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ABSTRACT

This study aimed to determine the effects of roasting temperature (60°C and 80°C) and time (10, 20, and 30 min) on the quality, oxidative stability, and antioxidant properties of cold-pressed Sacha Inchi oil. Oil samples were evaluated for chemical composition, total phenolic content (TPC), antioxidant activity (DPPH and ABTS assays), peroxide and p-anisidine values, tocopherol and phytosterol contents, and color parameters under different roasting conditions. The results showed that moderate roasting (80°C, 20 min) significantly increased TPC and antioxidant activity ($p < 0.05$), while extended roasting (80°C, 30 min) led to the loss of polyunsaturated fatty acids (PUFAs), tocopherols, and increased secondary oxidation. Phytosterol levels remained stable across all treatments, indicating resistance to thermal degradation. Roasting also caused increased yellowness (b*) and decreased lightness (L*) due to the Maillard reaction and phenolic oxidation. These findings suggest that roasting at 80°C for 20 min is optimal for improving antioxidant capacity and oxidative stability while preserving the functional components. The results provide a practical approach for improving oil quality in industrial processing by optimizing roasting conditions to enhance the functional and nutritional properties of cold-pressed Sacha Inchi oil.

Contribution/Originality: This study is the first to evaluate the combined effects of industrial-scale roasting temperature and time on the antioxidant properties, oxidative stability, color, and bioactive compounds of cold-pressed Sacha Inchi oil using multiple analytical methods relevant to real processing conditions.

1. INTRODUCTION

Sacha inchi (Plukenetia volubilis L.) is an oilseed crop indigenous to South America and is extensively produced in Thailand due to its nutritional and functional attributes. Sacha Inchi has gained significant relevance in health and nutrition for both the oil and the protein extracted from the seeds due to their high amounts of polyunsaturated fatty acids (PUFAs), mainly α-linolenic acid (ω-3) and linoleic acid (ω-6) (Carrillo et al., 2018) along with bioactive compounds (tocopherols and phytosterols) that impart an array of health benefits (Lemus-Conejo, Villanueva-Lazo, Martin, Millan, & Millan-Linares, 2024; Redjeki et al., 2025). Nevertheless, the oxidative stability of cold-pressed

Sacha Inchi oil is a significant issue, as PUFAs are prone to oxidation, which leads to rancidity and decreases the quality, flavor, and nutritional value of the oil (Kong et al., 2023).

Cold pressing is a mechanical method of oil extraction that does not use high temperatures or chemical solvents; it is touted as a more environmentally sound and human-safe alternative to common solvent-based extraction methods (Durazzo, Fawzy Ramadan, & Lucarini, 2022). This process helps maintain the oil's inherent bioactive substances, sensitive fatty acid composition, and sensory properties while preventing unwanted trans fats and oxidation products from developing (Chandra, Kumar, Dwivedi, & Shinde, 2020). However, the lack of thermal refining makes cold-pressed oils more susceptible to oxidative degradation, necessitating strategies aimed at their stability and shelf life.

Roasting is commonly employed as a pre-treatment used in the oilseed industry to augment flavor, aroma, and the release of bioactive compounds, while possibly increasing the efficiency of oil extraction (Li et al., 2023). As described for other oilseeds (sesame, peanut, and flaxseed), the heat treatment can be adjusted for oil components such as antioxidant activity, phenolic compound composition, and lipid oxidation stability (El Hanafi et al., 2023; Wang et al., 2024). Prolonged exposure to elevated temperatures, especially when oil is industrially processed or cooked, can cause degradation of tocopherols, oxidation of fatty acids, and generation of undesirable oxidation products, which overall affect the oil quality. The optimization of roasting conditions is important to achieve a balance between enhancing the antioxidant potential and avoiding the oxidative deterioration of raw cold-pressed Sacha Inchi oil.

Some studies have linked moderate roasting with increased TPC and antioxidant activity, indicating that prolonged exposure to heat may induce lipid peroxidation and the elimination of certain significant bioactive compounds (Thepthanee, Li, Wei, Prakitchaiwattana, & Siriamornpun, 2024). However, studies on the effects of roasting temperature and time on the quality and stability of Sacha Inchi oil in an industrial processing setting are limited.

The present work investigates the impact of roasting at 60°C and 80°C for 10, 20, and 30 minutes on the chemical composition, antioxidant activity, oxidative stability, and color of cold-pressed Sacha Inchi oil. Through the examination of these parameters, this study reveals essential information to determine suitable roasting conditions, considering the functional properties of Sacha Inchi oil in its use and stability, allowing for the improvement of industrial processing to obtain Sacha Inchi oil with high-quality functional properties.

2. MATERIALS AND METHODS

2.1. Materials and Sample Preparation

In this study, the Sacha Inchi seeds (Plukenetia volubilis L.) were obtained from community enterprises in Chiang Mai province, Thailand, in accordance with the processes of industrial practice. Each batch of seeds was cleaned manually and sealed in polyethylene bags and stored in a refrigerator until processing.

Roasting was conducted in a stainless-steel tray dryer (Unique Tools Co. Ltd., Chachoengsao, Thailand). To assess the effect of different roasting conditions, seeds were roasted at 60 °C and 80 °C for 10, 20, and 30 minutes. Control: Unroasted seeds were used (unroasted seeds). The roasting batches consisted of 2.5 kg of seeds evenly distributed in a drying tray for uniform heat distribution. The roasted seeds were cooled to room temperature prior to oil extraction.

2.2. Extraction of Cold-Pressed Oils

A mini screw press (T3Pro, Nature Health and Innovation Co. Ltd., Saraburi, Thailand) was used and operated at 50 rpm (maximum capacity of 6 L/h) to extract oil. The cold-pressed oil extracted was filtered using a 10 µm filter paper to remove solid residues and then stored in 1,000 mL polyethylene (PE) bottles at -18°C until further analysis.

2.3. Acid and Iodine Values Determination

The acid value (AV) was measured according to the AOCS official method Cd 3d-63. Three grams of oil samples were dissolved in ethanol-diethyl ether (1:1, v/v) and titrated with KOH solution (with phenolphthalein as an indicator) at 20 °C. Results are reported as mg KOH/g oil.

The iodine value (IV) was determined following AOCS Cd 1-25 (Wijs method). Iodine monochloride solution was added to the oil samples, which were subsequently titrated with sodium thiosulfate solution. Data were reported as g I_2/100 g of oil.

2.4. Analysis of Fatty Acid Composition

Fatty acid methyl esters (FAMEs) were derived according to AOCS Ce 2b-11 using methanolic sodium hydroxide (NaOH) and boron trifluoride (BF_3) methanol. Analysis of FAMEs was performed using a Shimadzu GC-17A (Japan) gas chromatograph coupled to a DB-Wax column (30 m × 0.25 mm i.d., 0.25 μm film thickness) and a flame ionization detector (FID). The carrier gas was helium at 1 mL/min. The fatty acids were identified by comparing their retention times with those of the Supelco 37 Component FAME Mix (Sigma-Aldrich, USA).

2.5. Values of Peroxide and P-Anisidine

The peroxide value (PV) was determined according to AOCS Cd 8-53. A defined amount of the oil samples was dissolved in acetic acid-chloroform (3:2, v/v) and titrated with sodium thiosulfate solution in the presence of potassium iodide (KI) and starch indicator. For the analysis, results were expressed as meq O_2/kg oil.

The AOCS Cd 18-90 method was used to determine the p-anisidine value (AnV). Oil samples were added to isooctane and mixed with the p-anisidine reagent, and the absorbance was measured at 350 nm using a UV-Vis spectrophotometer (Lambda EZ201, PerkinElmer, USA).

2.6. Tocopherol Analysis

The tocopherols (α-, γ-, δ-tocopherol) were determined based on AOCS Ce 8-89 using high-performance liquid chromatography (HPLC, Agilent 1100 series, USA) with a C18 GP column (4.6 × 250 mm, 3 μm, Kanto Chemical, Japan). A mixture of methanol, acetonitrile, and dichloromethane (50:44:6, v/v/v) was used as the mobile phase at a flow rate of 1 mL/min. Fluorescence detection was performed at 295/330 nm of excitation/emission wavelength.

2.7. Determination of Phytosterols

Phytosterols were analyzed as previously described by Duchateau et al. (2002) using gas chromatography (GC-FID). The unsaponifiable fraction was retrieved through liquid-liquid partitioning. In brief, 100 mg of oil was saponified with 1.0 mL of ethanolic KOH at 70°C for 50 minutes and extracted with n-heptane (total 14 mL). After drying the organic phase over anhydrous Na_2SO_4, the extract was homogenized and injected into a Shimadzu GC-17A with a Perkin-Elmer Elite-225 column and FID-2014 detector. The temperature of the column was set to rise from 250°C to 285°C at a rate of 25°C/min, and the temperature was held at 285°C for 32 minutes. Phytosterols were isolated and quantified by comparing the retention times of unknown samples with the retention times of authenticated standards, and results were expressed in terms of the area under the chromatogram.

2.8. Total Phenolic Content (TPC)

TPC was determined by the Folin-Ciocalteu method (Singleton, Orthofer, & Lamuela-Raventos, 1999). The oil extracts were combined with Folin-Ciocalteu reagent and sodium carbonate (Na_2CO_3) and incubated for 2 hours; thereafter, the absorbance at 765 nm was recorded using a UV-Vis spectrophotometer. Results were reported as mg of gallic acid equivalents (GAE) per 100 g of oil.

2.9. Antioxidant Activity (DPPH and ABTS)

DPPH Radical Scavenging Activity: the DPPH assay was conducted according to the method of Thaipong, Boonprakob, Crosby, Cisneros-Zevallos, and Byrne (2006) with some modifications. Oil extracts and DPPH solution (0.1 mM in methanol) were mixed and incubated in the dark at room temperature for 2 hours; then, the absorbance was measured at 515 nm using a UV-Vis spectrophotometer. The antioxidant activity was measured using a Trolox standard curve, and the results were represented as μg Trolox equivalents (TE) per gram of oil (μg TE/g oil). Each sample was measured in triplicate, and values were expressed as mean ± SD.

ABTS Radical Scavenging Activity: the ABTS method was performed based on the modified procedure by Christodouleas, Fotakis, Nikokavoura, Papadopoulos, and Calokerinos (2015). ABTS radical cation ($ABTS^{+}$•) was produced by mixing 7.0 mM ABTS diammonium salt and 2.45 mM potassium persulfate in a 10 mL volumetric flask. The dark incubation at room temperature for 12–16 hours was to ensure that ABTS was fully oxidized to its radical form. The $ABTS^{+}$• working solution was diluted in ethanol to give an absorbance of 1.0 at 734 nm.

For the assay, the oil extract (0.50 mL) was diluted in 1-butanol and mixed with 2.00 mL of the $ABTS^{+}$• working solution. The change in absorption at 734 nm was recorded after 15 min using a UV-Vis spectrophotometer (Lambda EZ201, PerkinElmer, USA). The antioxidant activity was assessed based on a gallic acid standard curve and was expressed as mg gallic acid equivalent (GAE) per gram of oil (mg GAE/g oil). Each sample was processed in triplicate, and values were indicated as mean ± SD.

2.10. Statistical Analysis

All experiments were conducted in triplicate (n = 3), and data were presented as mean ± standard deviation (SD). Statistical analysis was determined by one-way analysis of variance (ANOVA) with Tukey's post hoc test, $p < 0.05$. Statistical analysis was performed using SPSS software (Version 26, IBM, USA).

3. RESULTS AND DISCUSSION

3.1. Acid and Iodine Values

Table 1 presents the acid value (AV) and iodine value (IV) of cold-pressed Sacha Inchi oil subjected to different roasting conditions. The AV, which indicates the level of free fatty acids (FFA), increased significantly with both roasting time and temperature ($p < 0.05$). The unroasted oil exhibited the lowest AV (1.25 ± 0.11 mg KOH/g oil), while the highest AV (1.86 ± 0.23 mg KOH/g oil) was observed in oil roasted at 80°C for 30 minutes. This increase suggests a higher degree of hydrolysis or oxidation of triglycerides during roasting.

Table 1. Acid value and iodine value of oil samples under different roasting treatments.

Treatment	Time (min)	Acid value (mg KOH/g)	Iodine value (g I_2/100 g oil)
Unroasted	-	1.25 ± 0.11^{a}	202.25 ± 1.56
Roasted at 60°C	10	1.26 ± 0.13^{a}	199.14 ± 2.88
	20	1.38 ± 0.15^{ab}	198.33 ± 2.67
	30	1.64 ± 0.16^{b}	197.24 ± 2.43
Roasted at 80°C	10	1.35 ± 0.12^{a}	198.34 ± 2.23
	20	1.69 ± 0.22^{b}	197.36 ± 3.12
	30	1.86 ± 0.23^{c}	196.02 ± 2.86

Note: Values are presented as mean ± standard deviation. Different superscript letters (a, b, c) in the same column indicate significant differences ($p < 0.05$).

Conversely, the IV, which reflects the degree of unsaturation in the oil, showed a slight decreasing trend with increasing roasting time and temperature. The IV of unroasted oil was 202.25 ± 1.56 g I_2/100 g oil, whereas roasting at 80°C for 30 min resulted in an IV of 196.02 ± 2.86 g I_2/100 g oil. However, the differences in IV among treatments were not statistically significant ($p > 0.05$), indicating that roasting did not substantially affect the degree of unsaturation in the oil.

Roasting may also have caused greater lipolysis here; triglycerides are hydrolyzed by circulating esterase enzymes into free fatty acids because of thermal stress.(Sharma & Jain, 2015) As evidenced by the increase in AV, researchers found that roasted sesame and peanut oils also showed similar trends, where heating for extended periods resulted in increased AV due to cleavage in lipid structures.(Arab et al., 2022; Zhang, Li, Cao, Wang, & Xue, 2020) The increased AV at 80°C for 30 min, which is significantly higher than other treatments, suggests that excessive roasting could hasten hydrolysis and oil quality degradation.

The decline in IV means that the level of unsaturation is lower, which could be associated with thermal degradation of polyunsaturated fatty acids (PUFAs) or due to oxidation reactions (Nagy, Iacob, Bodoki, & Oprean, 2024). This effect has occurred in the case of flaxseed and sunflower oils, where the IV has decreased upon heating at high temperatures due to oxidative polymerization or cleavage of double bonds (Mukhametov, Dautkanova, Kazhymurat, Yerbulekova, & Aitkhozhayeva, 2023; Sun et al., 2021). The decline in IV at 80 °C in 30 minutes revealed that prolonged roasting may cause the loss of bioactive unsaturated fatty acids, resulting in a decrease in oil quality.

The results show that roasting has a strong effect on cold-pressed Sacha Inchi oil's acid and iodine values. For example, mild roasting (at 60°C for between 10 and 20 minutes) resulted in some degradation, but extensive heating (80°C for 30 minutes) increased free fatty acids and reduced unsaturation. This indicates that high levels of roasting are linked with decreased oil stability and nutritional quality, thus highlighting the need for future studies focused on specific roasting temperatures that yield higher-quality oil.

3.2. Fatty Acid Composition

The fatty acid composition of cold-pressed Sacha Inchi oil at different roasting conditions is summarized in Table 2. This unroasted oil had 5.11 ± 0.32% of palmitic acid (C16:0); 3.04 ± 0.11% of stearic acid (C18:0); 12.46 ± 0.78% of oleic acid (C18:1, ω-9); 38.03 ± 0.82% of linoleic acid (C18:2, ω-6); and 40.11 ± 0.69% of α-linolenic acid (C18:3, ω-3). The SFA and PUFA had total values of 8.15 ± 0.19% and 78.14 ± 0.64%, respectively.

The fatty acid composition was not significantly different ($p > 0.05$) in most cases, with only slight differences for roasts at 60°C and 80°C for 10–20 min. On the other hand, a long roasting time of 30 min at 80°C facilitated a remarkable increase in SFA (11.23 ± 0.19%) and a decrease in PUFA (74.87 ± 0.55%). Most importantly, the concentration of linoleic acid (C18:2, ω-6) and α-linolenic acid (C18:3, ω-3) at 80°C was significantly reduced ($p < 0.05$) after 30 min, suggesting that the thermal effect led to the decrease of unsaturated fatty acids.

The minor changes in fatty acid composition that occurred at milder roasting temperatures (60°C and 80°C for ≤ 20 min) were consistent with those reported for roasted flaxseed and sesame oils, where heat treatment had a limited effect on lipid stability (Arab et al., 2022; Moknatjou et al., 2015). The dramatic increase of SFA and decrease of PUFA at 80°C for 30 min implies that longer roasting at high temperatures leads to thermal degradation and oxidation of polyunsaturated fatty acids (Chan, Chiu, Li, & Lu, 2024).

At high roasting temperatures, linoleic acid and α-linolenic acid generally decrease, likely because these ω-6 and ω-3 fatty acids are highly prone to degradation induced by heat through oxidation and polymerization reactions (Wang, Xiao, Lyu, Chen, & Wei, 2023). Roasted chia and perilla oils have demonstrated the same responses, where oils excessively exposed to heat show a reduction in essential PUFA contents (Al-Juhaimi et al., 2024; Lee, Lee, Sung, & Shin, 2015). Overall data indicate that roasting certainly enhances Sacha Inchi oil taste and various other oil properties, but high temperatures may also affect the nutritional profile by significantly decreasing the PUFA content.

The results show that Sacha Inchi oil's fatty acid profile was relatively well-preserved during roasting at 60°C and during short-term exposure to temperatures of 80°C, while roasting at this temperature for 30 minutes led to a significant increase in SFA and a decrease in PUFA levels. This implies that when oil is roasted at high temperatures, it may deplete its nutritional content, especially ω-3 and ω-6 fatty acids. Optimum processing conditions to better preserve oil quality should be evaluated in future studies by further investigating the oxidative stability and bioavailability of fatty acids under different roasting conditions.

Table 2. Fatty acid composition of oil samples under different roasting treatments.

Treatment	Time (Min)	Palmitic acid	Stearic acid	Oleic acid	Linoleic acid	□-Linolenic acid	SFA	PUFA
Unroasted	-	5.11 ± 0.32^{b}	3.04 ± 0.11^{b}	12.46 ± 0.78^{a}	38.03 ± 0.82^{a}	40.11 ± 0.69^{a}	8.15 ± 0.19^{b}	78.14 ± 0.64^{a}
Roasted 60 ^{O}C	10	5.09 ± 0.22^{b}	3.12 ± 0.14^{b}	12.51 ± 0.88^{a}	37.72 ± 0.59^{a}	40.51 ± 0.53^{a}	8.21 ± 0.23^{b}	78.03 ± 0.92^{a}
	20	5.22 ± 0.24^{b}	3.11 ± 0.19^{b}	12.37 ± 0.75^{a}	37.99 ± 0.92^{a}	40.06 ± 0.64^{a}	8.32 ± 0.25^{b}	78.05 ± 0.77^{a}
	30	5.28 ± 0.27^{b}	3.24 ± 0.12^{b}	12.45 ± 0.38^{a}	37.71 ± 0.86^{a}	40.07 ± 0.53^{a}	8.52 ± 0.27^{b}	77.13 ± 0.55^{a}
Roasted 80 ^{O}C	10	5.15 ± 0.12^{b}	3.11 ± 0.11^{b}	12.23 ± 0.43^{a}	38.11 ± 0.71^{a}	40.05 ± 0.31^{a}	8.26 ± 0.18^{b}	78.16 ± 0.62^{a}
	20	5.09 ± 0.11^{b}	3.21 ± 0.09^{b}	12.47 ± 0.36^{a}	37.99 ± 0.69^{a}	39.99 ± 0.41^{a}	8.30 ± 0.11^{b}	77.98 ± 0.61^{a}
	30	6.98 ± 0.12^{a}	4.25 ± 0.16^{a}	12.38 ± 0.29^{a}	36.05 ± 0.58^{b}	38.82 ± 0.37^{b}	11.23 ± 0.19^{a}	74.87 ± 0.55^{b}

Note: The data are presented as mean ± standard deviation (n = 3). Values within the same column bearing different superscript letters (a, b) indicate statistically significant differences ($p < 0.05$).

3.3. Peroxide and P-Anisidine Values

Cold-pressed Sacha Inchi oil peroxide value (PV) and p-anisidine value (p-AV) are shown in Table 3 under various roasting conditions. A single unroasted oil had the lowest PV (1.56 ± 0.08 meq O_2/kg oil), whereas the highest PV was with oil roasted at 80°C for 10 min (3.99 ± 0.18 meq O_2/kg oil). PV values fell to 2.56 ± 0.15 meq O_2/kg oil when the roasting time was increased to 30 min (80°C). On the other hand, the secondary oxidation product, p-AV, remained stable in the range of 0-60°C for 30 min, but increased significantly (3.76 ± 0.25) at 80°C for 30 min ($p < 0.05$).

Table 3. Effect of roasting on peroxide and p-anisidine values.

Treatment	Time (Min.)	Peroxide value (meqO_2/kg oil)	p-anisidine value
Unroasted	-	1.56 ± 0.08^{d}	1.66 ± 0.14^{c}
Roasted 60 ^{O}C	10	2.55 ± 0.12^{c}	1.72 ± 0.16^{c}
	20	3.45 ± 0.11^{b}	1.75 ± 0.08^{c}
	30	3.95 ± 0.13^{a}	1.84 ± 0.18^{c}
Roasted 80 ^{O}C	10	3.99 ± 0.18^{a}	1.79 ± 0.12^{c}
	20	3.28 ± 0.14^{b}	2.66 ± 0.21^{b}
	30	2.56 ± 0.15^{c}	3.76 ± 0.25^{a}

Note: The data are presented as mean ± standard deviation (n = 3). Different superscript letters (a, b, c, d) within the same column indicate statistically significant differences ($p < 0.05$).

This increase in PV at shorter roasting times indicates that oxidative rancidity of lipids develops more rapidly during the first heating stage due to the availability of oxygen and the formation of hydroperoxide (Yoon et al., 2024). Similar trends were observed in roasted sesame and sunflower oils, where moderate heat exposure increased PV due to enhanced lipid peroxidation (Cai et al., 2021). Nonetheless, the observed decrease in PV at 80 °C for 30 min indicates that hydroperoxides break down into secondary oxidation products, which can be converted to p-AV (Abeyrathne, Nam, & Ahn, 2021).

The large increase in p-AV at 80°C for 30 min is consistent with the findings of others who investigated the effect of various oils during high-temperature processing of seed oils, where prolonged heating resulted in the breakdown of peroxides with subsequent formation of aldehydes and ketones, which increased the levels of secondary oxidation markers (Valdés García et al., 2021). This indicates that longer roasting times do not necessarily increase primary oxidation but can increase secondary oxidative degradation.

Roasting triggers lipid peroxidation, as evident in greater PV at 80°C for 10 minutes; however, prolonged exposure results in secondary oxidation, signified by higher p-AV at 80°C for 30 minutes. Thus, although roasting improves the oil stability of Sacha Inchi oil, excessive roasting could lead to oxidative deterioration and, therefore, affect the overall quality of Sacha Inchi oil. Future studies should assess the storage stability and oxidative shelf life of roasted oil to better understand its potential utility over time.

3.4. Tocopherol Contents

Table 4 shows the tocopherol contents (α-, γ-, and δ-tocopherol) of cold-pressed Sacha Inchi oil roasted under different conditions. The levels of α-tocopherol, γ-tocopherol, and δ-tocopherol in the unroasted oil were 4.58 ± 0.17 mg/100 g oil, 148.03 ± 2.53 mg/100 g oil, and 86.95 ± 1.02 mg/100 g oil, respectively. Roasting at 60°C and 80°C resulted in an initial decrease followed by a gradual loss of α- and γ-tocopherol, while δ-tocopherol remained relatively unaffected. The greatest losses occurred at 80 °C for 30 min, with α-tocopherol amounting to 3.37 ± 0.15 mg/100 g oil and γ-tocopherol amounting to 135.97 ± 1.85 mg/100 g oil ($p < 0.05$).

Table 4. Effect of roasting on tocopherol content.

Treatment	Time (Min)	α-tocopherol (mg/100 g oil)	γ-tocopherol (mg/100 g oil)	δ-tocopherol (mg/100 g oil)
Unroasted	-	4.58 ± 0.17^{a}	148.03 ± 2.53^{a}	86.95±1.02
Roasted 60 ^{O}C	10	4.32 ± 0.15^{ab}	146.54 ± 2.01^{a}	86.88±1.21
	20	4.07 ± 0.13^{b}	143.46 ± 1.85^{ab}	86.92±1.31
	30	3.88 ± 0.16^{bc}	138.39 ± 1.78^{bc}	86.74±1.58
Roasted 80 ^{O}C	10	4.13 ± 0.11^{b}	145.21 ± 2.39^{ab}	86.78±1.87
	20	3.76 ± 0.14^{c}	140.83 ± 1.81^{b}	86.59±1.69
	30	3.37 ± 0.15^{d}	135.97 ± 1.85^{c}	86.82±1.94

Note: The data are presented as mean ± standard deviation (n = 3). Values within the same column with different superscript letters (a, b, c, d) indicate statistically significant differences ($p < 0.05$).

Consistent with the degradation of tocopherols due to thermal oxidation and volatilization from previous studies of roasted seed oils, a gradual decrease of α- and γ-tocopherol was also observed in roasted seed oils (Şimşek, Özcan, Arslan, Ünver, & Kanbur, 2015). Among tocopherols, α-tocopherol is the most fat-soluble vitamin in terms of temperature degradation, consistent with the literature reporting that α-tocopherol is less stable than γ- and δ-tocopherol at high temperatures (Wagner, Isnardy, & Elmadfa, 2004).

The stability of δ-tocopherol in all treatments indicates that the δ-tocopherol may be more resistant to thermolytic degradation, which has also been observed for peanut and sesame oils. (Arab et al., 2022; Idrissi et al., 2024) In fact, the considerable reduction of γ-tocopherol at 80 °C for 30 min demonstrated that prolonged roasting results in oxidative losses that affect the antioxidant potential of the oil. This loss of tocopherols is of special concern as tocopherols function as natural antioxidants to prevent lipid peroxidation of oil. (Athanasiadis et al., 2023).

The results show that tocopherol content was reduced by roasting, with maximum losses at a temperature of 80°C for 30 min. Therefore, tocopherols were reduced at high temperatures in the mild (60°C for 10–20 min) roasting of oilseeds, which maintain most of the tocopherols, whereas prolonged roasting significantly reduces tocopherols, α- and γ-tocopherol being affected. This means that roasting conditions must be optimized to guarantee the bioactive properties, as well as the stability, of Sacha Inchi oil. Future studies should investigate the functional role of the residual tocopherols in the stability of roasted oil during storage and oxidative protection.

3.5. Phytosterol Contents

Table 5 shows the cold-pressed Sacha Inchi oil phytosterol contents (β-sitosterol, stigmasterol, and campesterol) at the various roasting treatments. The unroasted oil had 62.41 ± 1.84 mg/100 g oil of β-sitosterol, 23.45 ± 0.98 mg/100 g oil of stigmasterol, and 13.17 ± 0.06 mg/100 g oil of campesterol. Results showed that the roasting process did not significantly affect phytosterols ($p > 0.05$), with only slight differences depending on treatments. After roasting followed by extraction, β-sitosterol, stigmasterol, and campesterol contents were stable with final values of 62.36 ± 1.84; 23.16 ± 1.65; and 13.14 ± 0.04 mg/100 g oil at 80 °C for 30 min.

Table 5. Effect of roasting on phytosterol content.

Treatments	Time (min)	β-sitosterol (mg/100 g oil)	Stigmasterol (mg/100 g oil)	Campesterol (mg/100 g oil)
Unroasted	-	62.41 ± 1.84	23.45 ± 0.98	13.17±0.06
Roasted 60 ^{O}C	10	63.28 ± 1.95	22.95 ± 1.07	13.11±0.04
	20	62.18 ± 2.45	23.14 ± 1.13	13.12±0.08
	30	62.32 ± 1.66	23.27 ± 0.95	13.04±0.05
Roasted 80 ^{O}C	10	62.33 ± 2.37	23.11 ± 1.53	13.15±0.09
	20	62.44 ± 1.99	23.40 ± 1.09	13.16±0.09
	30	62.36 ± 1.84	23.16 ± 1.65	13.14±0.04

Note: The data are presented as mean ± standard deviation (n = 3). Different superscript letters within the same column denote statistically significant differences ($p < 0.05$).

Since phytosterols did not undergo thermal degradation during roasting, these compounds are relatively resistant to heat under moderate roasting conditions (Oehrl, Hansen, Rohrer, Fenner, & Boyd, 2001), consistent with studies on sesame (Arab et al., 2022), rapeseed (Rękas et al., 2017), and cocoa beans (Oracz, Nebesny, & Żyżelewicz, 2014) oils. Sacha Inchi oil is rich in β-sitosterol, and its low degradation shows that roasting at 60–80°C does not significantly alter its content.

Potential natural variability in oil composition overheat degradation for stigmasterol and campesterol. Although such trends have been observed neither in the case of canola nor rapeseed oil, where phytosterol contents remained almost constant after roasting at high temperatures (Rękas et al., 2017; Siger, Michalak, & Rudzińska, 2016). Studies have demonstrated that phytosterols are stable up to 150°C, suggesting that very little change would be expected beyond this temperature range (Oehrl et al., 2001).

These results demonstrate that the phytosterol contents of Sacha Inchi oil were stable during roasting at a temperature range of 60–80°C, confirming its robustness as a potential bioactive component. In contrast to tocopherols and polyunsaturated fatty acids, which are much more readily degraded by heat, phytosterols seem to be more resistant to the effects of roasting, further supporting their health-beneficial role within roasted oil products.

3.6. Phenolic Content, DPPH and ABTS

Figures 1, 2, and 3 show the influence of roasting on the total phenolic content (TPC) and antioxidant activities of Sacha Inchi oil obtained through the cold-pressing method, as evaluated via the DPPH and ABTS radical scavenging assays. The TPC of unroasted oil was 3.36 ± 0.29 mg GAE/100 g oil; DPPH and ABTS activities were 55.27 ± 2.88 μg TE/g oil and 1.38 ± 0.12 mg GAE/g oil, respectively. Roasting resulted in a considerable enhancement for the parameters evaluated, peaking at 80°C for 20 min (TPC: 9.88 ± 0.59 mg GAE/100 g oil; DPPH: 79.45 ± 3.17 μg TE/g oil; ABTS: 2.01 ± 0.19 mg GAE/g oil). In contrast, extending the roasting time to 30 min at 80°C caused a minor decrease in all measurements (TPC: 8.50 ± 0.47 mg GAE/100 g oil; DPPH: 75.14 ± 2.82 μg TE/g oil; ABTS: 1.91 ± 0.18 mg GAE/g oil). Different lowercase letters above bars indicate significant differences among treatments in Figures 1, 2, and 3 ($p < 0.05$).

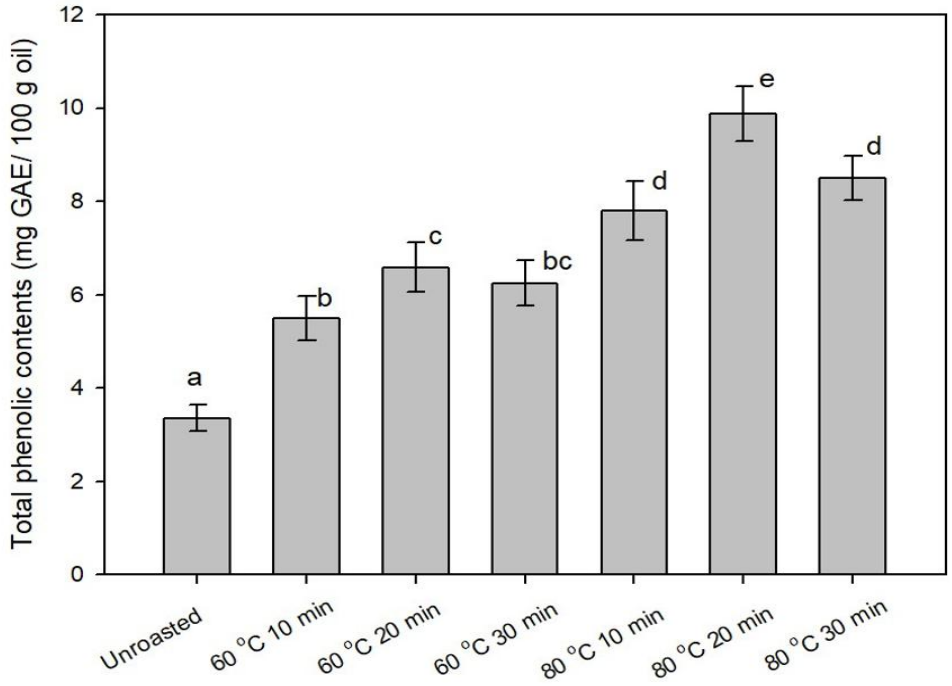

Figure 1. Total phenolic content (TPC) of Sacha Inchi oil (mg GAE/100 g oil) under different roasting conditions.
Note: Bars represent the mean ± standard deviation (SD) from three independent measurements. Different lowercase letters (a, b, c, d, e) above bars indicate significant differences between treatments ($p < 0.05$).

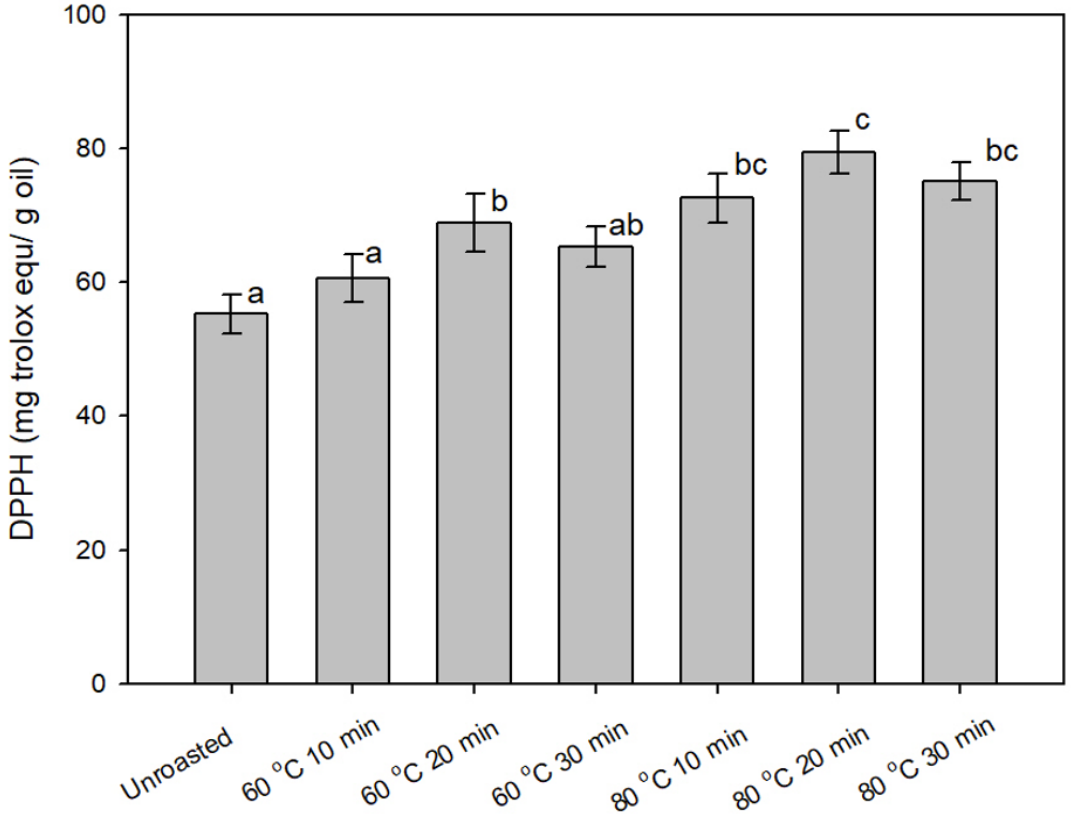

Figure 2. DPPH radical scavenging activity of Sacha Inchi oil (mg Trolox equivalent/g oil) under different roasting conditions.
Note: Bars represent the mean ± standard deviation (SD) from three independent measurements. Different lowercase letters (a, b, c) above bars indicate significant differences between treatments ($p < 0.05$).

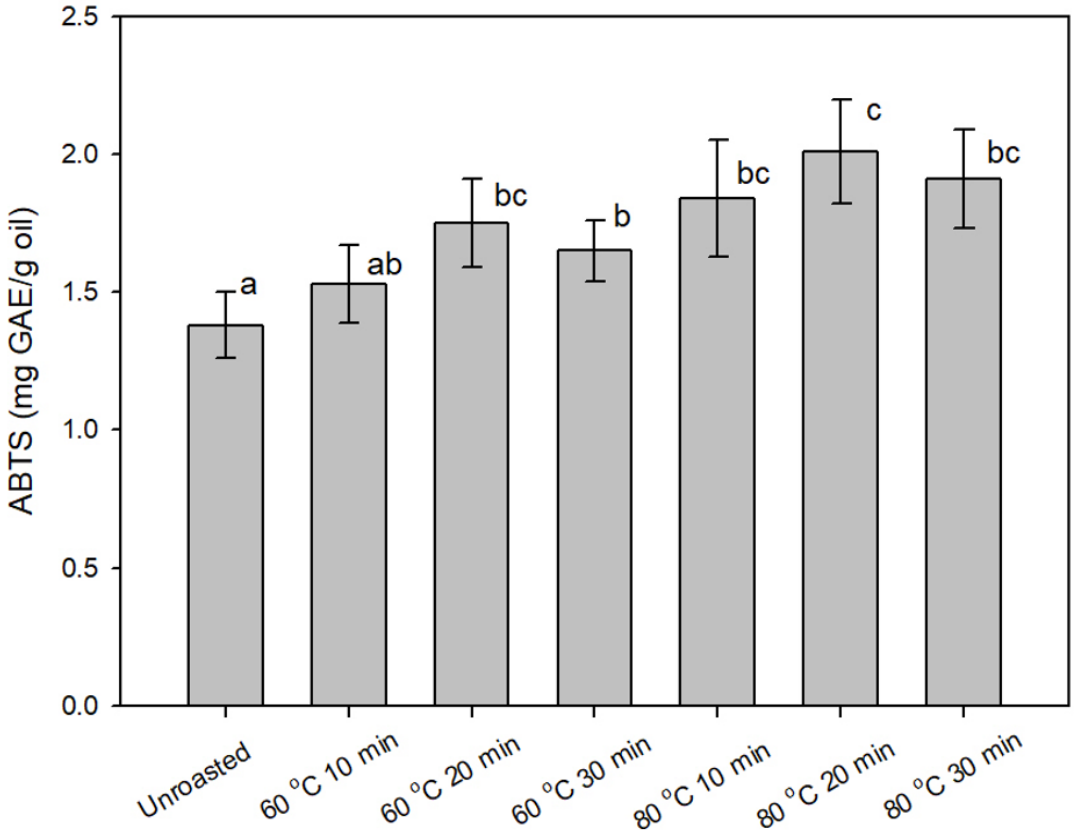

Figure 3. ABTS radical scavenging activity of Sacha Inchi oil (mg GAE/g oil) under different roasting conditions.
Note: Bars represent the mean ± standard deviation (SD) from three independent measurements. Different lowercase letters (a, b, c) above bars indicate significant differences between treatments ($p < 0.05$).

The observed rise of TPC upon roasting is due to the thermal liberation of bound phenolic moieties, akin to that reported for sesame and peanut oils, where moderate heating enhanced the depolymerization of phenolic glycosides, thus improving extractability to the oil phase (Arab et al., 2022; Ciou, Chen, Chen, & Yang, 2021). The TPC attained under the aforementioned conditions (9.88 mg GAE/100 g oil at 80 °C for 20 min) surpasses values described for unroasted cold-pressed Sacha Inchi oil, suggesting that under optimized conditions, roasting could enhance the oil's antioxidant profile. On the other hand, excessive heat treatment (for example, 80°C for 30 min) may lead to the oxidation and polymerization of polyphenols, thus contributing to a decrease in extractable phenolic concentration.

The scavenging activity towards DPPH and ABTS radicals exhibited the same trend in relation to TPC, supporting the hypothesis that improved extraction results in increased antioxidant activity through enhanced phenolic isolation. As has also been related in the roasted sesame study (Nasirullah, Jeyarani, & Rakshitha, 2009) and the flaxseed oil study (Ahmed, Değerli, Özcan, & Babiker, 2023) moderate roasting indeed has beneficial effects on antioxidant activity, while it can result in oxidative degradation of phenolics and tocopherols, further decreasing the radical-scavenging efficiency when exposed to long roasting times (Kadoma & Fujisawa, 2011).

A possible explanation for the trends observed is the Maillard reaction, which produces intermediate compounds that display antioxidant behavior (Al-Abbasy, Younus, Rashan, & Ahmad, 2024). At moderate roasting temperatures, these reaction products could also contribute to the overall antioxidant capacity. At extended roasting times, the degradation of polyphenols and Maillard reaction products may exceed the antioxidant advantages, thus reducing the overall radical scavenging capacity (Lin, Choong, & Chu, 2021; Siah, Konczak, Wood, Agboola, & Blanchard, 2014).

This study elucidates that roasting at 80°C for 20 minutes successfully increased the antioxidant activity of cold-pressed Sacha Inchi oil due to an increase in phenolic content and radical scavenging activity. Prolonged roasting increases the degradation of crucial bioactive compounds. In future work, the long-term oxidative stability of roasted Sacha Inchi oil and the bioavailability of phenolic compounds concerning human metabolism should be clarified.

3.7. Color Changes

Figure 4 illustrates the impact of roasting on the color parameters (Hunter L, a, and b) in cold-pressed Sacha Inchi oil. The lightness (L value) decreased ($P < 0.05$) significantly with the increase of roasting temperature and time from 94.23 ± 2.89 in unroasted oil to 76.54 ± 3.98 after roasting at 80°C for 30 min. The redness (a value) changed from negative to positive and increased from -2.01 ± 0.11 (greenish hue) in unroasted oil to 1.31 ± 0.12 before 80°C for 30 min, shifting it to an increasingly slightly redder tone. On the other hand, the yellowness (b value) also increased (from 50.36 ± 3.78 in unroasted oil to 58.97 ± 3.47 after being heated for 30 min at 80°C), indicating a strong yellowness. Additionally, different lowercase letters over data points shown in Figure 4 indicate significant differences between treatments ($p < 0.05$).

The significant differences in Hunter L, a, and b values recorded for the control and roasted oils (Figure 4) are consistent with previous work on roasted oils, where thermal treatment resulted in darkening attributed to Maillard reaction products and pigment oxidations (Shrestha & De Meulenaer, 2014). The decrease in L value is mainly due to non-enzymatic browning reactions like the Maillard reaction and caramelization at higher temperatures (Zamora & Hidalgo, 2005). Similar trends have been observed for roasted sesame and peanut oils, showing a reduction in lightness and an increase in yellowness with prolonged heating (Ji, Liu, Shi, Wang, & Wang, 2019; Zhang et al., 2022).

The rise in an aspect (moving towards red) in the example is likely due to the warming degradation of chlorophylls and carotenoids, generating materials with more red pigments (Dini, Khanamani Falahati-Pour, Behmaram, & Sedaghat, 2019). Similar effects were observed in roasted sunflower oil, where prolonged heat significantly enriched the oil in redness (Ji, Zhang, Wang, Wang, & Jie, 2023). On the other hand, the increase in b value (yellow color) could be related to the release of lipophilic pigments and Maillard-derived chromophores, which lead to a more intense yellow coloration (Noda & Murata, 2017).

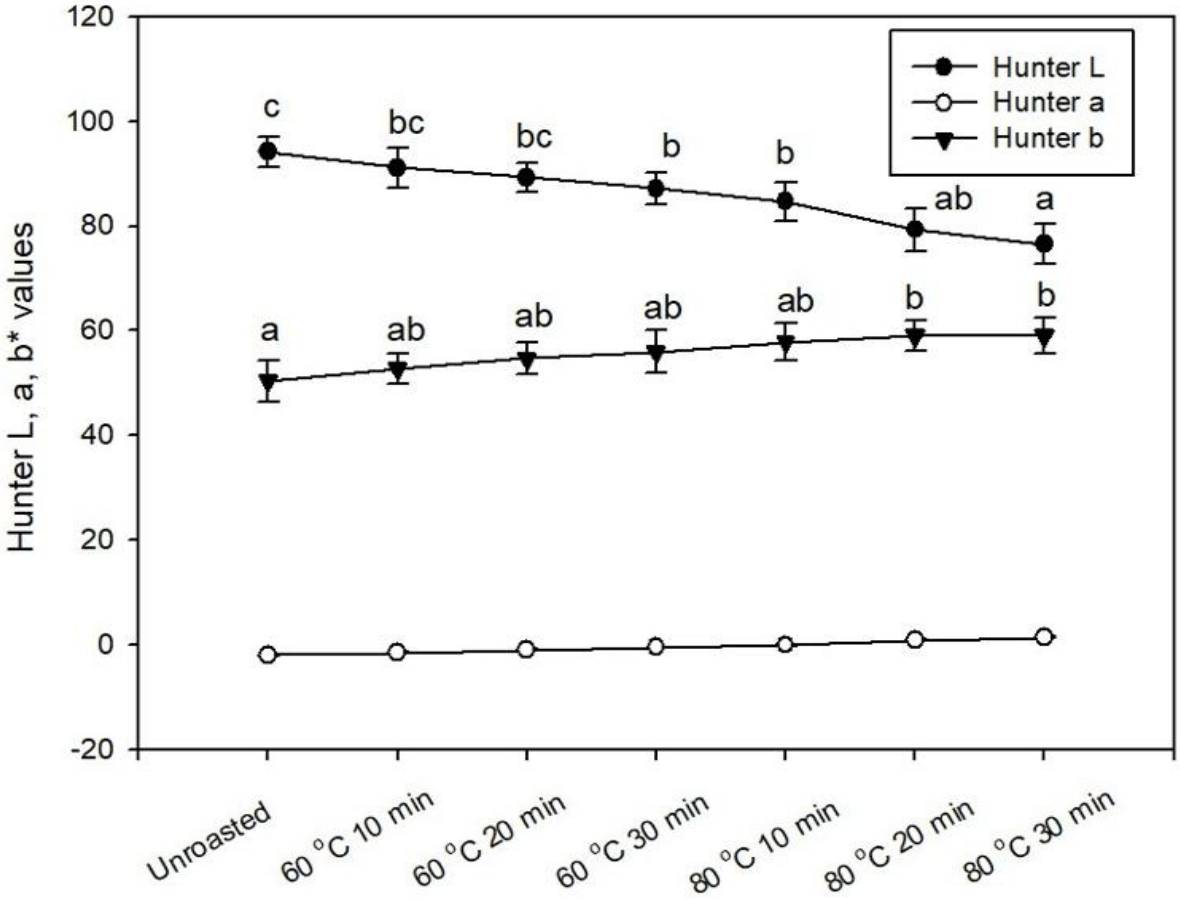

Figure 4. Hunter L, a*, and b* values of Sacha Inchi oil under different roasting conditions.

Note: Data represents the mean ± standard deviation (SD) from three independent measurements. Different lowercase letters (a, b, c) indicate significant differences between treatments ($p < 0.05$).

Remarkably, at 80°C for 20 minutes, the highest b value (58.99 ± 2.98) was reached; however, for the longer roasting duration of 30 minutes at 80°C, the value stabilized at a slightly lower value (58.97 ± 3.47), indicating possible degradation or pigment transformation during extended roasting.

This study revealed that color profiles of cold-pressed Sacha Inchi oil were highly colored due to roasting and that increasing roasting temperature and time resulted in darker oil with more yellow coloring; however, there was a marginal increase in red. These colors might affect consumer perception and oil quality; thus, sensory attributes and consumer preferences for roasted Sacha Inchi oil deserve further study.

4. CONCLUSION

In this study, cold-pressed Sacha Inchi oil was roasted at 60°C and 80°C for 10–30 min, and its chemical composition, antioxidant activity, and color parameters were evaluated. Roasting was found to modify oil quality, having a generally positive impact on some parameters and a negative impact on others, according to the data. Mild roasting at 60°C for ≤ 20 min did not significantly alter the oil's fatty acid composition, phytosterol, and tocopherol contents, but increased phenolic compounds and antioxidant activity (DPPH and ABTS values). However, prolonged roasting at 80°C for 30 min again showed an increase in acid value, a decrease in iodine value, and a loss of polyunsaturated fatty acids (PUFAs) and tocopherols, especially α- and γ-tocopherol due to thermal degradation. The total phenolic contents and antioxidant activities reached their highest point when extracts were heated at 80°C for 20 min, and they slightly decreased at 80°C for 30 min, possibly mediated by the oxidative degradation of phenolics. The peroxide value increased during the first 30 minutes of roasting at 60°C and 20 minutes of roasting at 80°C, indicating the formation of primary oxidation products. However, prolonged roasting led to a decline in peroxide

value, suggesting the degradation of primary oxidation products into secondary oxidation products, as evidenced by the rising p-anisidine value.

On the other hand, phytosterols remained constant among all the treatments, demonstrating their ability to resist thermal degradation. Color analysis indicated a continuous decrease in lightness (L) and an increase in yellowness (b) with increasing roasting time, consistent with the known effects of Maillard reaction products and the oxidation of phenolics.

Based on the results, it can be concluded that the optimal conditions for maximizing phenolic content and the associated antioxidant activity, while balancing nutritional quality and oxidative stability, are roasting at 80°C for 20 minutes. Most importantly, roasting at 80°C for 30 minutes caused degradation of some key bioactive compounds and negatively affected oil stability. Future research should assess the long-term oxidative stability, sensory properties, and functional uses of roasted Sacha Inchi oil to explore the potential of incorporating this oil into food applications and nutraceutical formulations.

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Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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