Food Analytical Methods (2026) 19:81
https://doi.org/10.1007/s12161-026-02994-0

RESEARCH

Extraction of Fixed Oils from Sacha Inchi (*Plukenetia volubilis*) Seeds via Ohmic Heating: Optimization and Comparative Study

Muhammad Hazwan Hamzah[1,2] · Nur Fatihah Jamaludin[2] · Adila Fazliyana Aili Hamzah[2] · Mohd Zuhair Mohd Nor[3] · Abd Halim Md Ali[4] · Maimunah Mohd Ali[5] · Hasfalina Che Man[1,2]

Received: 3 October 2025 / Accepted: 17 January 2026

Abstract

Sacha inchi (*Plukenetia volubilis*) is a nutrient-rich oilseed valued for its high content of polyunsaturated fatty acids, particularly omega-3 and linoleic acid. Conventional extraction techniques such as steam distillation (SD) and hydro distillation (HD) are limited by low yields and high energy demands, reducing both efficiency and sustainability. This study evaluates ohmic-heated extraction (OHE), an electrically driven green technology, as an alternative method for oil recovery from sacha inchi seeds. Response surface methodology (RSM) was employed to optimize key parameters: reaction time, voltage, and solvent-to-solid ratio for maximizing oil yield. OHE performance was compared with SD and HD based on oil yield, energy efficiency, and physicochemical, antimicrobial, and morphological properties. The optimal OHE conditions were determined to be 70 V, 30 min, and a solvent-to-solid ratio of 7.06:1, resulting in a yield of 23.16%, significantly higher than that obtained by HD (10.6%) and SD (0.04%). Under these conditions, OHE produced a substantially higher oil efficiency of 225.89 mL/kWh with energy consumption of only 0.141 kWh, representing up to 91.21% savings compared with SD and HD. The oil obtained through OHE exhibited a light-yellow color and a refractive index of 1.48, comparable to conventionally extracted oils, although its specific gravity was slightly lower. Gas chromatography–mass spectrometry (GC–MS) analysis identified 17 chemical constituents, with linoleic acid methyl ester, hexadecanoic acid methyl ester, and methyl stearate as the dominant components across all extraction methods, reflecting the characteristic fatty acid composition of sacha inchi oil. Scanning electron microscopy further revealed pronounced structural disruption of seed tissues, indicative of enhanced cell wall breakdown and oil release. Overall, OHE demonstrates high efficiency, significant energy savings, and the ability to produce high-quality sacha inchi oil, highlighting its potential for sustainable applications in the food and cosmetic industries.

Keywords Sacha inchi · Fixed oil · Extraction · Ohmic heating · Response surface methodology

✉ Muhammad Hazwan Hamzah
hazwanhamzah@upm.edu.my

Nur Fatihah Jamaludin
nfatihahjamal@gmail.com

Adila Fazliyana Aili Hamzah
adilafazliyana28@gmail.com

Mohd Zuhair Mohd Nor
zuhair@upm.edu.my

Abd Halim Md Ali
abd.halim@utm.my

Maimunah Mohd Ali
maimunahmma@ukm.edu.my

Hasfalina Che Man
hasfalina@upm.edu.my

1 SMART Farming Technology Research Centre, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

2 Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

3 Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

4 Department of Chemical and Environmental Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

5 Department of Food Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, UKM, 43600 Bangi, Selangor, Malaysia

Introduction

Sacha inchi (*Plukenetia volubilis*), also known as mountain peanut or Incha nut, belongs to the Euphorbiaceous family and is native to the Amazon rainforest (Mhd Rodzi and Lee 2022). The seeds require a warm climate (10–36 °C) and annual rainfall ranging from 850 to 1000 mm for optimal germination (Redjeki et al. 2025). Given its significant economic potential, sacha inchi is now being cultivated in various regions around the world, including Southeast Asia. Sacha inchi seeds are a valuable source of health-promoting lipids and proteins, containing 35 to 60 wt% oils and 25 to 30 wt% proteins (Gutiérrez et al. 2011; Jitpinit et al. 2022). The sacha inchi's rich nutritional compounds make it a valuable bioresource, employed in a wide range of industries, including medicine, cosmetics, dietary supplements, functional foods, and personal care products (Cárdenas et al. 2021). Sacha inchi oil, a fixed oil, is predominantly composed of polyunsaturated fatty acids, accounting for approximately 85–93% of the total fatty acid content, with α-linolenic acid (omega-3) and linoleic acid (omega-6) being the most abundant components (Follegatti-Romero et al. 2009; Fanali et al. 2011; Niu et al. 2014). These fatty acids are primarily present as non-volatile triacylglycerols, while volatile compounds occur only in trace amounts (Zanqui et al. 2016), mainly as aroma-active constituents such as alcohols, aldehydes, acids, ketones, and terpenoids (Ramos-Escudero et al. 2021). The processing of sacha inchi oil has become an important area of research, as variations in process configuration can alter its physical, chemical, and biological characteristics, thereby influencing quality, functionality, and potential applications.

Currently, several conventional methods are used to extract oil and other chemical constituents from sacha inchi seeds, including cold pressing (Supriyanto et al. 2022; Kong et al. 2023), solvent extraction (Bueno-Borges et al. 2018; Cordero-Clavijo et al. 2025), aqueous enzymatic extraction (Nguyen et al. 2020), gamma-irradiation (Gutiérrez et al. 2017), and screw pressing (Muangrat et al. 2018). In the food industry, triacylglycerols are primarily extracted from seeds using hexane or other organic solvents, such as petroleum ether, ethyl ether, methanol, and chloroform (Zanqui et al. 2016). These conventional approaches have some limitations, in which solvent extraction methods are time-consuming and require large quantities of harmful organic solvents (Jackson et al. 2024). The aqueous enzymatic extraction process generally results in low yield recovery and requires a prolonged processing time (Gao et al. 2024). Mechanical extraction stands out among other extraction techniques because of its simple setup, lower investment cost, absence of hazardous solvents, and shorter processing time, making it more advantageous than solvent extraction (Ofori-Boateng et al. 2012). The main drawbacks of mechanical extraction are excessive heat generation and higher operational costs. Gamma-irradiation extraction poses health risks to operators from radiation exposure (D'Orsi et al. 2024) and can induce alterations in product quality (Mahdi Navehsi et al. 2024).

Emerging technologies applied to the extraction of sacha inchi oil include supercritical fluid extraction (Follegatti-Romero et al. 2009; Jitpinit et al. 2022) and subcritical extraction with n-propane (Zanqui et al. 2016). Among these, ohmic-heated extraction (OHE) has been regarded as particularly promising due to its efficiency in oil recovery and its potential to enhance the overall extraction process. There is no evidence in the existing literature of sacha inchi oil extraction being investigated through the ohmic heating concept. OHE has attracted growing interest as a green processing technique due to its rapid and uniform volumetric heating (Khalid et al. 2024), which minimizes thermal gradients and preserves thermally sensitive fatty acids like α-linolenic and linoleic acids. Furthermore, with an appropriate power control system design, the heat generated can be precisely regulated (Silva et al. 2017), ensuring that only the energy required to facilitate oil release and induce electroporation is applied, in alignment with its release from the seed cellular matrix. However, the performance of OHE depends strongly on process conditions, material characteristics, and scale limitations (Bakhshabadi et al. 2025). Its practical application is constrained by several challenges, including scale-up and industrial implementation, electrode corrosion or fouling, electrical safety considerations, and uncertainties in energy efficiency at large throughputs. Unlike supercritical fluid extraction, which requires high pressure carbon dioxide (Cui et al. 2024), or enzymatic extraction, which involves lengthy incubation under strict pH and temperature control (Sharma et al. 2017), OHE can be performed with minimal or no solvents, thereby offering a more environmentally sustainable approach.

Volatile essential oils and non-volatile fatty oils from sacha inchi are extracted using different principles due to their chemical properties. In the present work, water was used as the extraction medium in OHE. Steam distillation (SD) and hydro distillation (HD) were included as reference techniques because they likewise rely on water-based extraction. HD and SD, which are types of azeotropic distillation, are widely used to extract volatile essential oil constituents (Machado et al. 2022). These methods vaporize the compounds with steam, allowing them to be carried and subsequently condensed as essential oils. Triacylglycerols, the main components of lipid-rich vegetable oils, are non-volatile, high-boiling compounds that do not vaporize under normal distillation conditions. Because of their low volatility, these fixed oils are typically extracted by cold pressing or non-polar solvent-based methods rather than by SD or HD (Piras et al. 2021). OHE can enhance the release of non-volatile compounds such as phenolics and oils through rapid internal heating and electric field-induced cell disruption (Sánchez et al. 2023), while it also affects the volatile aroma compounds, indicating that the retention of volatiles depends on processing conditions (Pavón-Vargas et al. 2025). However, qualitative comparisons of OHE and traditional distillation methods in extracting both volatile and non-volatile compounds from sacha inchi remain scarce, highlighting a clear knowledge gap.

This study aims to evaluate the potential of OHE for producing sacha inchi oil of high yield and quality. The specific objectives are as follows: (1) to optimize the reaction time, voltage, and solvent-to-solid ratio of OHE using response surface methodology (RSM) and (2) to compare the performance of OHE with conventional methods, hydro distillation (HD) and steam distillation (SD), in terms of oil yield, energy efficiency, and the physical, chemical, antimicrobial, and morphological properties.

Materials and Method

Sample Preparation

Sacha inchi seeds were obtained from a local supplier, imported from West Java, Indonesia. Mature, defect-free seeds were selected, ensuring the absence of mold or contamination. Sample preparation followed the method with modifications (Muangrat et al. 2018). Upon arrival, the seeds were stored at 4 °C in a cold room. Prior to drying, the seeds were washed with water, and larger debris such as kernels was manually removed. The cleaned seeds were arranged on trays and dried in a hot-air oven (WS 30, WA, USA) at 60 °C for 3 days. The shell-free seeds were then ground using a domestic blender (Panasonic 1.0 L Blender MX-EX1001WSK, Osaka, Japan) to reduce kernel size. Then, the powder was re-dried at 60 °C for 24 h to remove residual moisture introduced during blending, which caused clumping or agglomeration, ensuring a free-flowing, homogeneous material for subsequent processes (Jung et al. 2018). The drying temperature was chosen to balance effective moisture removal with minimal thermal exposure. The moderate temperature and relatively short reheating period were expected to limit thermo-oxidative degradation of heat-sensitive lipids such as polyunsaturated fatty acids (Ninčević Grassino et al. 2025). The dried material was sieved through a 2-mm mesh sieve (Retsch Test Sieve, 200 × 50 mm) (Mohd Fuad and Mat Don 2016). Finally, the sacha inchi powder was stored in sealed and airtight containers at 4 °C until further use.

Setup and Optimization of Ohmic-Heated Extraction Process

Ohmic-Heated Extraction (OHE)

The experimental setup was carried out in a specialized ohmic cell equipped with a voltage controller, thermocouple probe, main switch, and titanium electrodes (19 cm × 2.1 cm) positioned on opposite sides (Hamzah et al. 2025b). Power cables were connected to the left and right electrodes to ensure optimal operation. The amount of sacha inchi powder used was determined based on the selected solvent-to-solid ratio, and the powder was mixed with water to obtain a total volume of 500 mL. The OHE systems require a mixture of sample with a minimum of 1200 µS/cm electrical conductivity to allow current to pass through. The mixture of sacha inchi powder with water was 250–300 µS/cm depending on the solvent-to-solid ratio. Thus, to enhance electrical conductivity, 0.2 g of sodium chloride (NaCl) was dissolved in the solution, ensuring that conductivity exceeded 1200 µS/cm. The addition of NaCl allows the electrical conductivity of the mixture to be around 1200 to 1600 µS/cm. The temperature and voltage were then raised to their predetermined set values, with automated controllers maintaining stable operating conditions throughout the reaction. After the specified reaction time, liquid–liquid extraction was performed to obtain sacha inchi oil. The experimental setup for the OHE process is illustrated in Fig. 1.

Sacha Inchi Oil Recovery

After OHE, the water–oil mixture was separated from the solid residue and transferred into a clean beaker for the next extraction step (Samadi et al. 2020). Liquid–liquid extraction was performed using n-hexane (J.T. Baker™, USA) at a 1:1 ratio. One part of n-hexane (455 mL) was used for 455 mL water–oil mixture (1 part of mixture) recovered from OHE. The mixture was placed in a separatory funnel, securely stoppered, and inverted 10 times to ensure thorough mixing. This shaking process was triplicated. After mixing, the aqueous layer at the bottom of the separatory funnel was drained, leaving the oil–n-hexane solution. The liquid–liquid extraction was repeated twice to make sure that there was no oil left in the water (Samadi et al. 2020). The solution was transferred to a round-bottom flask, sealed with plastic wrap to minimize solvent loss, and subjected to vacuum rotary evaporation (Heidolph Laborota 4000, Germany) at 60 °C to remove n-hexane. To ensure the solvent recovery efficiency and to completely remove excess moisture from the oil, the recovered oil was further dried in an oven at 60 °C for 24 h to eliminate residual solvent, then weighed and collected in a receiving flask. Drying temperatures below 60 °C are often recommended by the literature to prevent the loss of the

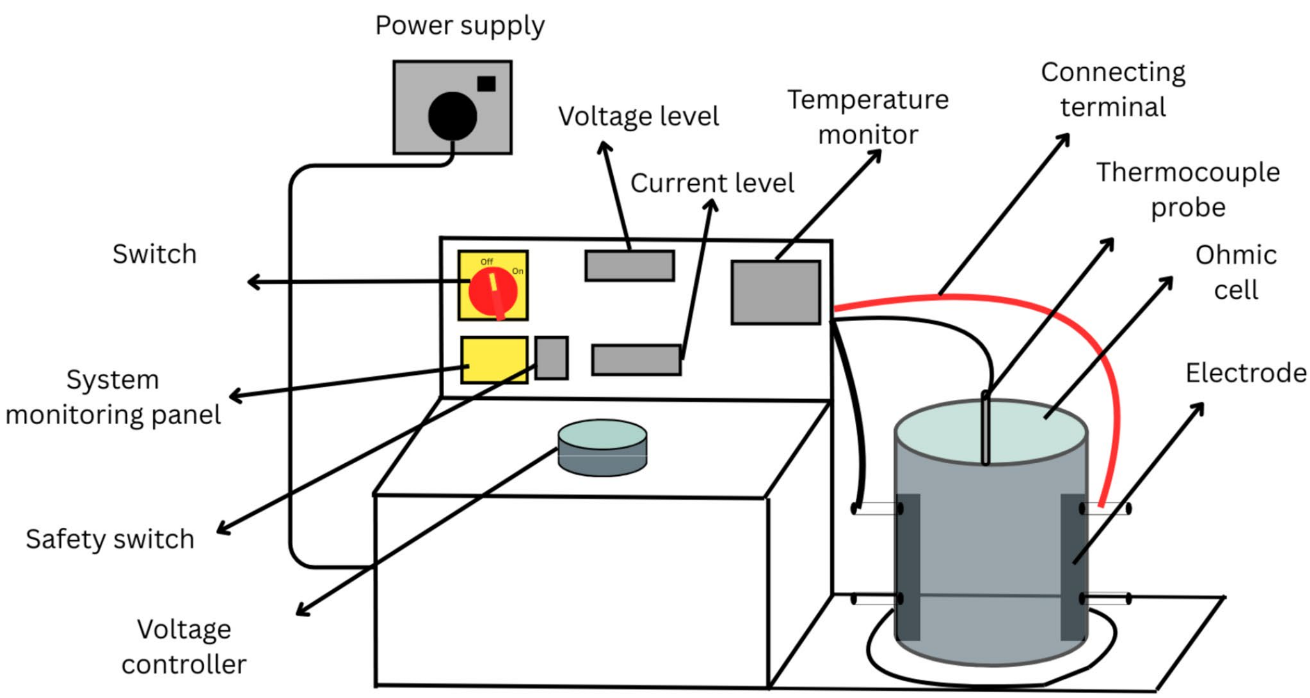

Fig. 1 Schematic diagram of OHE

bioactive components (Laoretani et al. 2014; Hamzah et al. 2024). The sacha inchi oil yield was calculated using Eq. (1).

$$\text{Sacha inchi oil yield (\%)} = \frac{\text{Mass of oil recovered (g)}}{\text{Mass of solid used (g)}} \times 100\% \quad (1)$$

Response Surface Methodology (RSM) Optimization of Sacha Inchi Oil Extraction

The extraction parameters influencing sacha inchi oil yield were optimized using Central Composite Design (CCD) in Design-Expert® software (version 11.1.2, Stat-Ease Inc., Minneapolis, USA). RSM served as a tool for experimental design, statistical analysis, and optimization of extraction parameters (Dao et al. 2021a). The study evaluated the interaction effects and determined optimal values for voltage, reaction time, and solvent-to-solid ratio during OHE. Table 1 summarizes the variable parameter with different coded levels ranging from −1 (lowest), 0 (center), and +1 (highest), with additional intermediate levels represented by +α and −α. The OHE experiments were conducted at voltages of 70 to 105 V, reaction times of 15 to 30 min, and solvent-to-solid ratios of 5:1 to 10:1.

Table 2 presents the 20 experimental runs, each carried out in triplicate to ensure accuracy. Statistical analysis was performed using analysis of variance (ANOVA). Model adequacy was assessed using post-estimation statistics, including R^2, adjusted R^2, predicted R^2, the F-value, and lack-of-fit tests (Nguyen-Kim et al. 2021). The regression coefficients served as the foundation for creating 2D and 3D response surface plots. The 3D plots enable a better understanding of how independent variables affect process properties and assist in predicting the optimal values according to the target function (Dao et al. 2021b).

RSM optimization identified the set of OHE conditions that maximized oil yield while minimizing temperature, reaction time, and applied voltage. Multiple possible solutions were generated, and the set with the highest desirability was selected. The optimal parameters were validated through OHE experiments, with hydro distillation (HD) and steam distillation (SD) serving as reference methods.

Table 1 Experimental data of independent variables and their coded levels for the RSM

Label	Variable parameters	Coded levels				
		$-\alpha$	−1	0	1	$+\alpha$
A	Solvent-to-solid ratio	3.3:1	5:1	7.5:1	10:1	11.7:1
B	Voltage, V	58.1	70	87.5	105	116.9
C	Reaction time, min	9.9	15	22.5	30	35.1

Table 2 The independent variables and sacha inchi oil yield (experimental and predicted)

Independent variables				Sacha inchi oil yield (%)	
Run Order	Factor 1	Factor 2	Factor 3	Actual value	Predicted value
	A: Solvent-to-solid ratio	B: Voltage (V)	C: Reaction time (minutes)		
1	11.7:1	87.5	22.5	4.02	1.97
2	5:1	70.0	15.0	2.19	4.80
3	7.5:1	87.5	35.1	21.23	21.91
4	7.5:1	87.5	22.5	11.32	10.92
5	7.5:1	58.1	22.5	15.87	12.46
6	7.5:1	87.5	22.5	11.50	10.92
7	5:1	70.0	30.0	17.30	17.76
8	7.5:1	87.5	22.5	11.87	10.92
9	3.3:1	87.5	22.5	3.66	2.98
10	7.5:1	87.5	22.5	7.33	10.92
11	5:1	105.0	15.0	0.49	0.96
12	5:1	105.0	30.0	9.77	8.94
13	10:1	105.0	30.0	9.53	8.85
14	10:1	70.0	30.0	14.20	15.66
15	7.5:1	116.9	22.5	2.83	3.51
16	7.5:1	87.5	9.9	8.56	5.14
17	7.5:1	87.5	22.5	11.25	10.92
18	10:1	70.0	15.0	0.92	3.68
19	10:1	105.0	15.0	0.38	1.85
20	7.5:1	87.5	22.5	11.76	10.92

Hydro Distillation

HD was performed following a modified method (Taiwo et al. 2024). A 7:1 ratio of distilled water to solid sample was prepared to reach a total volume of 500 mL and placed in a flask. Distillation was carried out using a Clevenger-type apparatus with a 500 W heating mantle for conditions equivalent to those of the OHE process, with the time to reach boiling recorded at the start. After completion, the mixture was subjected to solvent extraction for oil recovery, and the sacha inchi oil yield was calculated.

Steam Distillation

SD was performed using a 20-L stainless steel–copper boiler distiller, following a modified procedure based on the manufacturer's operating manual (Hamzah et al. 2025a). A solvent-to-solid ratio of 7:1 was applied, with the sample secured in a filter bag and placed inside the distillation bucket. Water was added at the same ratio, ensuring the combined volume of solids and liquid did not exceed 70% of the container's capacity. The bucket was sealed, connected to the steaming tower, and heated using an induction cooker (Khind IC1600, Malaysia) at 1600 W power setting to ensure boiling at 100 °C. Steam carrying vaporized sacha inchi oil was condensed and collected, together with the residual solution. Following distillation, the solution was subjected to solvent extraction for oil recovery.

Energy Analysis

During the OHE, the voltage, temperature, and current were recorded every 2 min throughout the extraction duration. For the energy evaluation, two key parameters were considered: electrical input and heating duration. The time required to reach the boiling point and the corresponding electric current (A) were recorded to enable comparison among OHE, HD, and SD. Energy consumption (J) was calculated using Eq. (2), where electrical power (W) was multiplied by the total extraction time (hours) (Phillips 2019).

$$E = P \times t \tag{2}$$

where E = energy (joules), P = power (watts), and t = time (hours).

The power input during the extraction process was estimated using Eq. (3) (Thyagarajan et al. 2000). In this context, power represents the rate of work performed over time. The work done was calculated from the applied voltage and the corresponding electrical charge, where the total charge was obtained by multiplying the current by the extraction time, as expressed in the following equation:

$$\text{Power} = \frac{\text{Work done}}{\text{Time}} = \frac{\text{Voltage} \times \text{Charge}}{\text{Time}} \quad (3)$$

$$\text{Power} = \frac{\text{Voltage} \times \text{Current} \times \text{Time}}{\text{Time}} \quad (4)$$

Based on the relationships established in Eqs. (3) and (4), the power input was subsequently determined using Eq. (5).

$$\text{Power} = \frac{V \times I \times t_s}{t_1} + \frac{V \times I \times t_b}{t_2} \quad (5)$$

where P = power (kWh), V = voltage used (volt), I = current (A), t_s = time taken any time before boiling point (hours), t_b = time taken any time after boiling point (hours), t_1 = time taken to reach boiling point (hours), and t_2 = time taken from boiling point to the end of extraction (hours). While the power for the induction cooker used for SD was 1600 W and 500 W was used for the heating mantle for HD, it was used for energy consumption using Eq. 2. Energy savings of OHE and HD were calculated relative to steam distillation (SD) as the benchmark, following the method (Genc 2024) using Eq. (6).

$$\text{Total energy saving (\%)} = \frac{\text{Energy}_0 - \text{Energy}_{\text{system}}}{\text{Energy}_0} \times 100 \quad (6)$$

In this analysis, energy$_0$ refers to the energy consumed by SD, while energy$_{\text{system}}$ denotes the energy used by either OHE or HD, both measured in kilowatts (kW). The cost of extraction of sacha inchi oil using OHE, SD, and HD was estimated by their respective energy usage. An electricity tariff of 0.2703 MYR/kWh (approximately 0.062 USD/kWh) in Malaysia was used as the standard for calculating energy-related costs (Tenaga Nasional Berhad 2025). The electricity cost of the extraction process was calculated using Eq. (7) (Jeon et al. 2019), which considers the total energy consumption (kWh) and the applicable electricity tariff, thereby estimating the operational energy cost for each extraction method.

$$Electricity\ cost\ (USD) = Power\ (kW) \times Time\ (h) \times Price\ (USD\ per\ kWh) \quad (7)$$

where power (kW), time = total time taken to complete the extraction (hours), and price = in USD according to the electricity rate in Malaysia.

Physical Analysis

Color

The color of sacha inchi oil was measured using a colorimeter (Konica Minolta Chroma Meter CR-400, USA), following a modified method (Chirinos et al. 2024). The instrument was calibrated with a white reference tile, and measurements were taken in triplicate under room conditions (20 °C) with illuminant C and a 2° standard observer. Results were expressed in CIE Lab coordinates: L^* (lightness), a^* (green to red), and b^* (blue to yellow).

Refractive Index

The refractive index of sacha inchi oil obtained by OHE, HD, and SD was measured at 20 °C using a refractometer (ATAGO PAL-α Pocket Refractometer, Japan) (Aktar and Adal 2019).

Specific Gravity

The specific gravity of oils obtained by OHE, HD, and SD was measured at 20 °C (Ong et al. 2021). The density of water is equivalent to 0.998 g/mL at 20 °C. Values were calculated using Eq. (8).

$$\text{Specific gravity} = \frac{\text{Mass of sacha inchi oil (g)/Volume of sacha inchi (mL)}}{\text{Density of water } \left(\frac{\text{g}}{\text{mL}}\right)} \quad (8)$$

Optical Rotation

The optical rotation was measured at 20 °C in accordance with ISO 592:1998 (The International Organization for Standardization 1998), using an automatic polarimeter (AUTOPOL VI, Rudolph Research Analytical, NJ, USA).

Gas Chromatography–Mass Spectrometry (GC–MS) Analysis

The composition of sacha inchi oil was analyzed as fatty acid methyl esters (FAME) using gas chromatography–mass spectrometry (GC–MS) following the transesterification of the oils with 2 N methanolic KOH, in accordance with Standard Method 2.302 as outlined by Rodríguez et al. (2022). Fifty microliters of oil was added to 10-mL screw-cap test tubes. Subsequently, 5 mL of n-hexane was added, and the mixture was subjected to vortex mixing for 60 s. Then, 50 µL of methanolic 2 N KOH was added to the solution, and the mixture was vortexed for an additional 60 s. The tube should be allowed to stand at room temperature for a few minutes to facilitate phase separation. The upper layer, which contains the FAME, is carefully withdrawn and subsequently utilized for GC–MS analysis.

Chemical composition of sacha inchi oil extracted by OHE, SD, and HD was analyzed using a GC–MS system (Agilent 7890B GC coupled with a 5977B MSD). Separation was achieved on an HP-5Q Ultra Low-Bleed capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness), with helium as the carrier gas at a constant flow rate of 1 mL/min. Oil samples were diluted in n-hexane, and 1 µL aliquots were injected with a 50:1 split ratio. The GC oven was programmed from 50 °C (2 min hold), ramped at 3 °C/min to 250 °C, and held for 10 min. Injector and transfer line temperatures were set at 250 °C and 280 °C, respectively. Mass spectral data were collected in scan mode across a mass-to-charge ratio (m/z) range of 30–500, with a solvent delay of 4 min to prevent early interference. Compound identification was performed by comparison of mass spectra with the National Institute of Standards and Technology (NIST) library, and only peaks with a spectral similarity score ≥ 80% were accepted, consistent with established methodologies reported in the literature (Sola Martínez et al. 2020). Peak areas of identified FAMEs were integrated and expressed as relative area percentages of the total identified FAMEs (Lacey et al. 2021), providing semi-quantitative estimates of fatty acid composition rather than absolute concentrations.

Antimicrobial Activity

The antimicrobial activity was evaluated using the agar well diffusion method on Mueller–Hinton Agar (MHA) plates, following a modified procedure described in the literature (Shrestha et al. 2021). Test organisms included *Staphylococcus aureus* (Gram-positive), *Escherichia coli*, and *Klebsiella pneumoniae* (Gram-negative), with suspensions adjusted to 0.5 McFarland standard (~ 10^6–10^8 CFU/mL). The standardized inocula were evenly spread over MHA plates using sterile cotton swabs and allowed to stand for 15 min to facilitate adhesion. Wells (6 mm diameter) were aseptically prepared, and 100 µL of each oil sample was added. Plates were pre-incubated at room temperature for 2 h to allow optimal diffusion, then incubated under strain-specific conditions following Clinical and Laboratory Standards Institute (CLSI 2020) guidelines: 35 ± 2 °C for 24 h for *S. aureus* and 18 h for *E. coli* and *K. pneumoniae*. After incubation, inhibition zones were measured in millimeters using a digital caliper, and antimicrobial efficacy was assessed by comparing the inhibition zones across different extraction methods.

Morphological Analysis

The structural characteristics of sacha inchi powder were examined using scanning electron microscopy (SEM, S-6400, Jeol, Japan) (Aili Hamzah et al. 2024). Samples were gold-coated for 180 s with an SCD 005 sputter coater (Bal-Tec, Switzerland) before imaging. SEM was conducted under vacuum at 5 kV accelerating voltage and ×1500 magnification. Structural differences between raw powder and samples extracted by OHE, HD, and SD were evaluated to determine the physical disruption induced by each method.

Results and Discussion

Response Surface Methodology (RSM) Optimization of Sacha Inchi Oil Extraction

Table 2 summarizes the predicted and experimental oil yield values for sacha inchi oil extracted using the OHE method. The lowest yield (0.38%) was recorded in the 19th trial at a 10:1 solvent-to-solid ratio, 105 V, and 15 min. The findings demonstrated that a high solvent-to-solid ratio, when paired with increased voltage and a short reaction time, may substantially reduce oil yield, as evidenced in the 19th run. Nonetheless, this effect does not apply in all cases, as extending the reaction time under similar conditions (13th and 14th run) led to significantly higher yields. This shows that the reaction time used for extraction is a key factor in balancing out the impacts of high solvent-to-solid ratios and voltage. This reduction in the 19th is likely due to insufficient extraction duration, which limits solvent penetration into the cellular matrix and restricts the mobilization of intracellular oil. Extending extraction time improves oil recovery by enhancing solvent–sample interaction and facilitating mass transfer from plant cells to the solvent (Bhadange et al. 2024). Conversely, inadequate extraction time compromises these mechanisms and lowers overall extraction efficiency.

In contrast, the maximum oil yield was achieved in the 3rd run at a 7.5:1 solvent-to-solid ratio, 87.5 V, and 30.1 min. These results suggest that moderate levels of solvent-to-solid ratio, voltage, and extraction time promote efficient recovery of sacha inchi oil. The synergistic effect of these parameters enhances extraction by increasing solvent–matrix contact, enabling controlled cell membrane disruption, and allowing sufficient time for oil diffusion (Che-U-Bong et al. 2025). Nevertheless, determining the optimal extraction duration is critical, as prolonged processing may reduce yield quality by degrading sensitive bioactive compounds (Handayani et al. 2025).

Several runs, specifically runs 4, 6, 8, 10, 17, and 20, were conducted using the same parameters: 87.5 V, 22.5 min, and a 7.5:1 solvent-to-solid ratio. The oil yields for these runs generally ranged between 7.33 and 11.87%. However, run 10 stands out with a noticeably lower yield of just 7.33%, which deviates significantly from the others despite identical set parameters. Similar to earlier observations in extraction studies, even under controlled process parameters (Gil-Martín et al. 2022; Ponphaiboon et al. 2023), sample heterogeneity such as particle size, moisture content, and chemical or biological degradation can lead to lower than expected extraction yields.

OHE operates by passing an electric current directly through the material, generating heat internally due to electrical resistance. As the applied voltage increases, the electric field strength rises, influencing both the rate and uniformity of temperature increase within the sample (Astráin-Redín et al. 2024). Simultaneously, temperature changes affect the electrical conductivity of the material, resulting in a coupled voltage–temperature interaction (Srivastav and Roy 2014). In this study, water was used as the solvent with a boiling point of 100 °C. Therefore, the applied voltage was set at predetermined levels based on the experimental design matrix and evaluated for its effects on heating behavior and extraction efficiency, while ensuring operation within the solvent's thermal limits. Further studies could investigate the influence of electric field strength on the OHE process. Overall, the efficiency of sacha inchi oil extraction in the study is governed not by a single parameter but by the combined effects of voltage, extraction time, and solvent-to-solid ratio.

Interaction Effects of Independent Factors on Sacha Inchi Oil Yield

Figure 2a–c graphically presents the 3D surface plots and 2D contour plots used to identify the optimal values of each variable for oil extraction from sacha inchi seeds. The effects of parameters such as voltage, reaction time, and solvent-to-solid ratio are discussed in the following section.

Effect of Voltage and Reaction Time (B × C) on Oil Yield

Figure 2a illustrates the interaction between reaction time and voltage during the oil extraction process. A high oil yield was obtained by applying lower voltage over a longer extraction period. Inversely, oil yield decreased when high voltage was paired with shorter extraction times. These results are consistent with the observations of Che Sulaiman et al. (2017); extending the extraction time at 80 °C may degrade bioactive compounds through thermal effects. A similar outcome may occur in OHE, as the applied voltage generates heat that can damage heat-sensitive compounds during extended extraction. Nevertheless, prolonged contact between the solvent and the matrix can also enhance extraction efficiency by allowing more time for solute diffusion under controlled conditions. Thus, optimizing extraction time requires careful consideration of its interplay with both the solvent-to-solid ratio and voltage. Hashemi et al. (2019) found that in ohmic-assisted hydro distillation, applying higher voltages shortened extraction time while simultaneously improving oil yield and quality, suggesting that the voltage–time relationship may vary depending on the extraction system and target compounds.

Oil extraction generally occurs in two stages: an initial rapid release of oil from easily accessible regions, followed by a slower phase in which oil must diffuse through more rigid cell walls (Ramos et al. 2024) (transitioning from the blue to the red zone in Fig. 2a). Under the optimized conditions of a 7.5:1 solvent-to-solid ratio, 87.5 V, and a maximum reaction time of 35.1 min, the highest oil yield observed was 21.23%. However, previous studies have reported that extending extraction time beyond this point leads to a progressive decline in the rate of oil recovery, eventually reaching a plateau (Suttiarporn et al. 2024; Molina et al. 2024). This indicates that the process has approached mass transfer equilibrium, where most of the oil from weaker cell structures has already been extracted, while the remaining oil is confined within more robust seed cell walls and becomes increasingly inaccessible to the solvent. Prolonging the extraction beyond this stage offers limited benefit and can even be detrimental. Excessive extraction time may degrade heat-sensitive compounds such as antioxidants, reduce oil quality, increase solvent loss through evaporation, and restrict solvent penetration into oil-rich regions (Yim et al. 2013; Bhadange et al. 2024). These findings underscore the importance of carefully selecting an appropriate extraction duration to maximize oil yield while preserving oil quality and process efficiency.

The 2D and 3D plot in Fig. 2a clearly shows that increasing extraction time at lower voltage in OHE leads to higher oil yield. This is evident in run 3, which achieved a high oil yield of 21.23% at 87.5 V and 35.1 min. This condition aligns well with electroporation theory. This happens when an electric field strong enough passes through plant cells, causing temporary openings or pores to form in their membranes. These pores make the cell walls more permeable, allowing the oil trapped inside to come out more easily (Ranjha et al. 2021). According to Shorstkii et al. (2023), this phenomenon, referred to as electro-permeabilization or pulsed electric field treatment, has been observed in both single cells and entire plant tissues. In individual cells, the treatment induces temporary pores in the membrane that increase permeability, while in whole tissues, the cumulative effect of many permeabilized cells leads to structural softening and improved release of intracellular compounds.

Effect of Solvent-to-Solid Ratio and Reaction Time (A × C) on Oil Yield

Figure 2b illustrates the effect of varying solvent-to-solid ratios and reaction times on the oil yield percentage of sacha inchi oil. The plot shows that sustaining a moderate solvent-to-solid ratio of around 7.5:1 at higher reaction time (30 min) resulted in significant oil recovery. The results

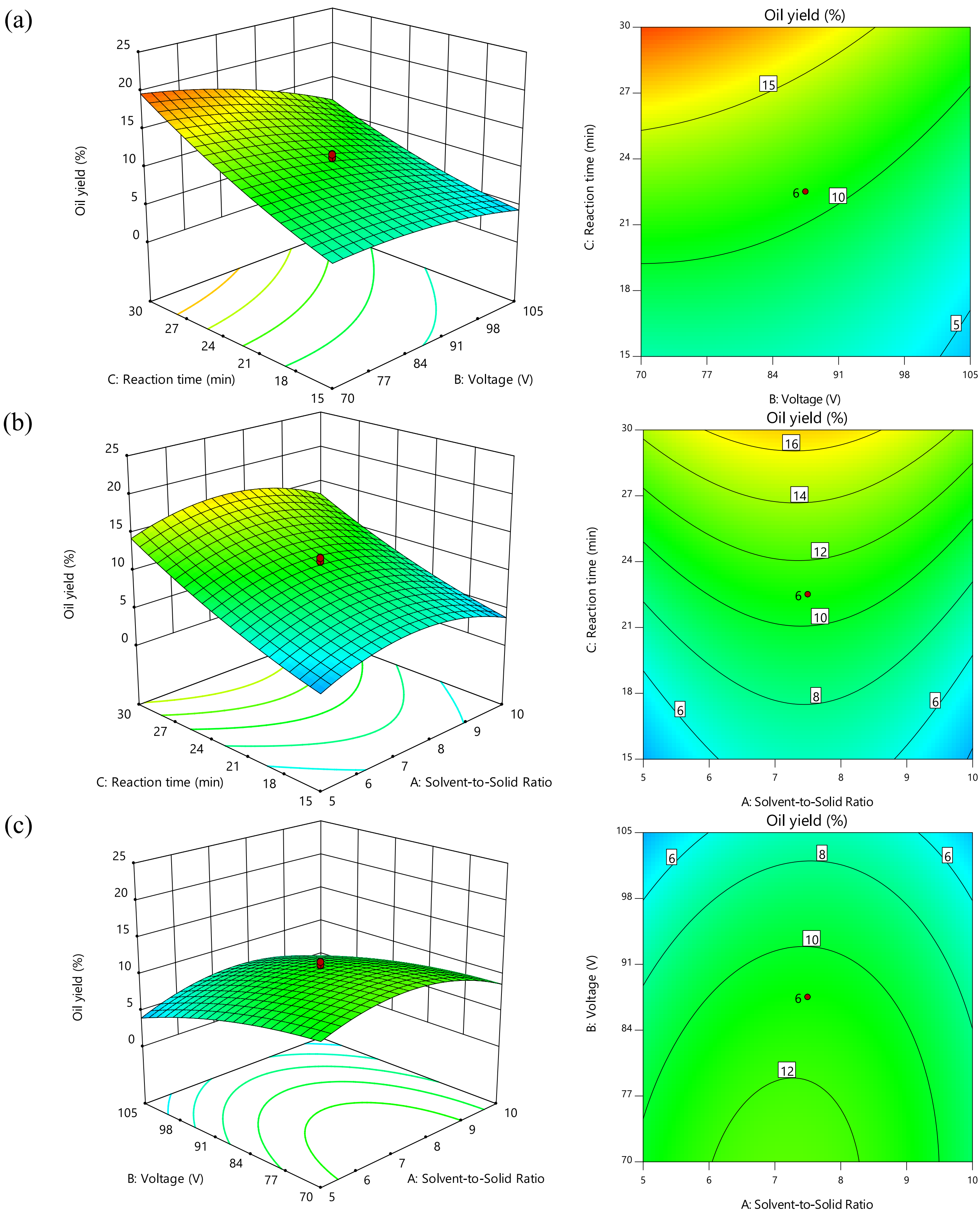

Fig. 2 The 3D surface graph and contour response plot of sacha inchi oil; interaction between **a** voltage and reaction time, **b** solvent-to-solid ratio and reaction time, and **c** solvent to-solid ratio and voltage

reveal that both parameters significantly influence oil yield, with a noticeable interaction between solvent-to-solid ratio and reaction time. As shown in the plots, oil yield increases with higher solvent-to-solid ratios and longer extraction times, reaching a maximum when the solvent-to-solid ratio is approximately 7.5 to 8.0:1 and reaction time is around 27 to 30 min.

The 3D surface plot clearly reveals a peak region, indicating that beyond a certain threshold of extraction time or solvent ratio, further increases yield minimal gains. This suggests a saturation point or possible quality and stability deterioration at extended conditions (Ishak et al. 2025). The color gradient provides a visual representation of the oil yield response, ranging from blue (low yield, 0.38%) to yellow (high yield, 21.23%). The contour plot shows elliptical-shaped lines, which suggest that the solvent-to-solid ratio and reaction time affect each other. This suggests that the effect of one variable on oil yield depends on the level of the other, highlighting a significant interplay between the two factors.

Effect of Solvent-to-Solid Ratio and Voltage (A × B) on Oil Yield

The 3D surface and contour plot in Fig. 2c show the response plot interaction between solvent-to-solid ratio and voltage on oil yield. A high oil yield of sacha inchi is obtained at lower voltage levels. The optimal conditions for maximum oil recovery are a solvent-to-solid ratio of 7.5:1 and a voltage range between 70 and 90 V. Additionally, Gumustepe et al. (2023) reported that there is an optimal voltage for ohmic heating-based avocado leaves valorization, beyond which further increases in voltage do not enhance the extraction yield. Another researcher highlighted that ohmic heating can be optimized to enhance oil yield and energy efficiency, but increasing voltage beyond a certain threshold offers no further improvement (Sivashankari et al. 2024). The results in Fig. 2c confirm that voltage and solvent-to-solid ratio interaction significantly influence sacha inchi oil yield.

While the present results emphasize the interaction between voltage and solvent-to-solid ratio, other studies have highlighted additional influential parameters under different extraction systems. Kautkar et al. (2025) optimized ohmic heating conditions for enzymatically hydrolyzed rapeseed slurry and reported oil yields ranging from 63.69 to 89.54%. Regression analysis revealed that the voltage gradient and holding time had a stronger influence on oil yield than temperature. Several studies have also shown that increasing solvent volume enhances oil yield by improving solvent–solid contact and mass transfer, thereby increasing extraction efficiency (Sayyar et al. 2009; Ntalikwa 2021). However, this effect is limited to an optimal point, beyond which the yields plateau or decline due to solvent saturation and mass transfer equilibrium. Overall, the results in Fig. 2c show that voltage and solvent-to-solid ratio have a considerable impact on oil yield, with maximum recovery occurring at moderate voltage and balanced solvent loading. Hence, although not dominant, the solvent-to-solid ratio remains an important factor when optimized in combination with voltage and reaction time.

Statistical Analysis and Validation

A second-order polynomial model was employed to accurately describe the data and evaluate the interactions among the independent variables: solvent–solid ratio (A), voltage (B), and reaction time (C). The following is the regression model based on coded components A, B, and C.

$$\begin{aligned} \textit{Oil yield}\ (\%) = {} & 10.92 - 0.3016A - 2.66B + 4.99C \\ & + 0.5025AB - 0.2450AC - 1.24BC \\ & - 2.99A^2 - 1.04B^2 + 0.9246C^2 \end{aligned} \tag{9}$$

where A = solvent-to-solid ratio; B = voltage (v); C = reaction time; AB, AC, BC = interaction factors; and A^2, B^2, C^2 = second-order effects of the respective variables.

The encoded model predicts oil yield based on the coded levels of the independent variables, where the highest and lowest factor levels are represented by +1 and −1, respectively. This standardized format allows direct comparison of factor coefficients and facilitates assessment of each variable's relative influence. Model significance was evaluated using ANOVA. As shown in Table 3, the model exhibited a significant fit ($F = 10.60$, $p < 0.001$), indicating a very low probability of error. A quadratic model was selected under RSM due to the importance of higher-order terms and the absence of aliasing. Among the parameters, reaction time (C) had the highest influence ($F = 52.86$), followed by voltage (B, $F = 15.06$), while solvent-to-solid ratio (A) had only a minor effect ($F = 0.1930$). These results highlight reaction time as the dominant factor in oil yield, with voltage exerting a secondary effect and solvent ratio contributing minimally.

The coefficient of variation (CV), which expresses the standard deviation as a percentage of the mean, was calculated to be 28.82%, with a mean oil yield of 8.80% and a standard deviation of 2.54%. This value indicates acceptable model reliability and data consistency (Medina et al. 2020; Dide-Agossou et al. 2022). Model terms with p-values below 0.05 were considered statistically significant; these include B (voltage), C (reaction time), and A^2 (quadratic effect of solvent-to-solid ratio). By contrast, terms such as AB, AC, BC, B^2, and C^2 had p-values greater than 0.05 and were therefore not significant contributors to the model.

Adequate precision (signal-to-noise ratio) was calculated as 11.6882, surpassing the desired threshold of 4, confirming that the model has a strong signal and is capable of

Table 3 ANOVA test for a quadratic model of extracted sacha inchi oil

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	613.76	9	68.20	10.60	0.0005	Significant
A—Solvent-to-solid ratio	1.24	1	1.24	0.1930	0.6698	
B—Voltage	96.82	1	96.82	15.06	0.0031	
C—Reaction time	339.94	1	339.94	52.86	< 0.0001	
AB	2.02	1	2.02	0.3141	0.5875	
AC	0.4802	1	0.4802	0.0747	0.7902	
BC	12.40	1	12.40	1.93	0.1951	
A^2	128.62	1	128.62	20.00	0.0012	
B^2	15.54	1	15.54	2.42	0.1511	
C^2	12.28	1	12.28	1.91	0.1971	
Residual	64.31	10	6.43			
Lack of fit	49.25	5	9.85	3.27	0.1097	Not significant
Pure error	15.06	5	3.01			
Cor total	678.07	19				
Std. Dev	2.54			R^2	0.9052	
Mean	8.80			Adjusted R^2	0.8198	
C.V. %	28.82			Predicted R^2	0.4170	
				Adeq precision	11.6882	

effectively navigating the experimental design space. The model can explain 90.52% of response variability, according to the study's R^2 value of 0.9052. The adjusted R^2 value of 0.8198 and the predicted R^2 value of 0.4170 differed more than the recommended 0.2 range, potentially indicating issues such as a strong block effect or other model inconsistencies. To address this, suggestions include investigating influential data points, applying response transformations, or simplifying the model (Chen and Chen 2025). Every empirical model must undergo a confirmation run to ensure its reliability. Therefore, a validation experiment using the optimal parameter set identified by RSM should be conducted to assess the model's predictive accuracy.

The lack-of-fit test for this model resulted in a p-value of 0.1097, exceeding the 0.05 threshold, which implies that the model fits the data well without a significant lack of fit. This suggests that the regression model adequately captures the variation in the response surface data. Supporting this, the residual sum of squares was 64.31, with a mean square of 6.43 across 10 degrees of freedom, representing the random error expected in experimental conditions. Additionally, the pure error variation observed from replicates under identical conditions was relatively low at 15.06, showing good repeatability of the experimental setup. Finally, the corrected total sum of squares was 678.07, indicating the full variation across all experimental runs. These statistics collectively demonstrate that the model sufficiently captures the variation in the data, with the remaining variability attributed primarily to experimental noise, thus validating the model's robustness for prediction and optimization.

The scatter plot from the RSM regression analysis is observed in Fig. 3a and b. The colored markers illustrate the oil yield values, while the straight line on the graph represents the predicted outcomes based on the regression model. In Fig. 3a, the normal probability plot of residuals shows points closely aligned along the diagonal line, indicating that the residuals are approximately normally distributed. This confirms that the assumption of normality is reasonably satisfied, and the observed errors are mainly due to random variation rather than systematic bias or systematic issues. Figure 3b depicts the residuals versus predicted oil yield, with data points scattered evenly around the diagonal, indicating minimal bias in predictions and good model fit. The residuals exhibit no apparent trends or systematic deviations, supporting the reliability of the model for predicting oil yield within the tested range. Using this model, numerical optimization was performed using Design-Expert® software to determine the optimal conditions for maximum oil yield (Table 4).

From a total of 59 potential solutions, the optimal parameter combination was selected based on the highest desirability score of 0.977. The optimal parameters identified were 70 V, 30 min, and a solvent-to-solid ratio of 7.06:1. Experiments validated the model prediction, yielding an oil output of 23.16 ± 2.02%, compared to the predicted value of 19.796%. The resulting deviation corresponded to a 3.36% error, which falls well within the generally accepted threshold of below 5% (Mabayo et al. 2018). Additionally, the desirability value of 0.977, which is very close to 1, confirms the effectiveness of the optimization process. Several optimization studies have highlighted that desirability values

Table 4 A numerical optimization solution was obtained using RSM and the predicted sacha inchi oil yield was compared with the experimental yield under the optimized conditions

Numerical optimization solution generated by RSM					
Voltage (V)	Reaction time (min)	Solvent-to-solid ratio (:)	Sacha inchi oil yield (%)	Desirability	
70	30	7.06:1	19.796	0.977	Selected
Comparison between predicted and corresponding experimental sacha inchi oil yield based on optimal parameters (validation)					
Predicted sacha inchi oil yield (%)			19.796		
Experimental sacha inchi oil yield (%)			23.160 ± 2.02		
Percentage of absolute error (%)			3.364		

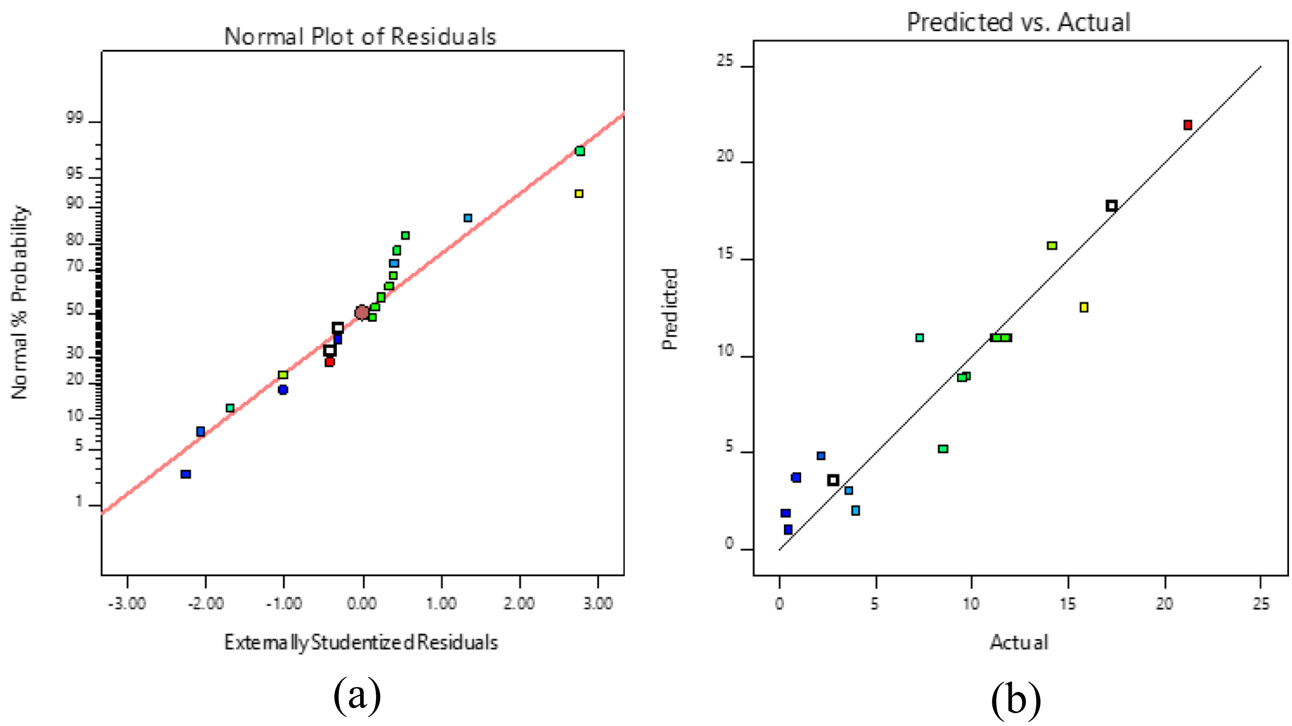

Fig. 3 Graph of **a** normal plot and **b** predicted versus actual plot

approaching 1 serve as strong indicators of reliable and valid model predictions (Chauca-Cerrutti et al. 2024; Aili Hamzah et al. 2024; Eddaoudi et al. 2025). Therefore, these findings confirm the success of the RSM model in optimizing sacha inchi oil extraction.

Comparison Study Between Ohmic-Heated Extraction, Hydro Distillation, and Steam Distillation

Sacha Inchi Oil Yield

Oil extracted from sacha inchi seeds using the OHE method yielded a significantly higher amount (23.16%) compared to HD (10.6%) and SD (0.04%), as shown in Fig. 4. For HD and SD, almost no oil was recovered in the distillate, which can be explained by the oil composition of sacha inchi seeds, consisting predominantly (93%) of fatty oils rather than volatile essential oils (Yanti et al. 2022). A previous study has shown that HD is primarily suitable for extracting volatile and aromatic compounds that can evaporate with steam (Pandey et al. 2023). In contrast, fatty oils such as those in sacha inchi are non-volatile and cannot be transported by steam, thereby limiting the effectiveness of HD and SD for such matrices. Consequently, instead of collecting oil from the distillate, the residual material solvent was analyzed to determine the oil content, which yielded 10.6% for HD and 0.04% for SD.

OHE has been reported to be particularly effective for seeds with high fatty oil content. For example, Kautkar et al.

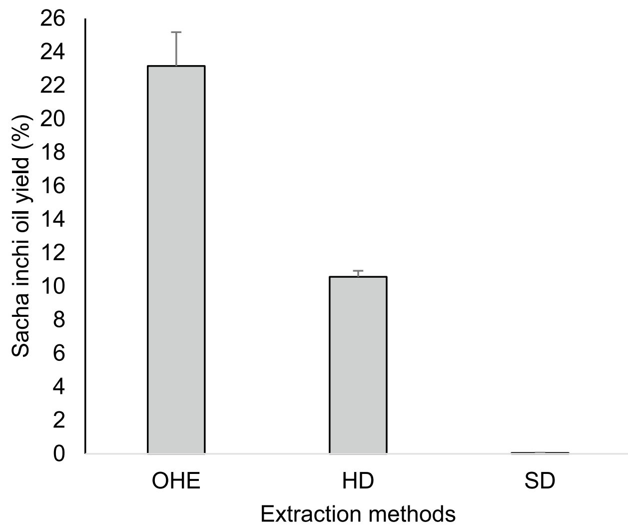

Fig. 4 Comparison of sacha inchi oil yield for OHE, HD, and SD

() showed that combining ohmic heating with enzymatic hydrolysis in rapeseed slurry improved oil yield while maintaining oil quality. The mechanism of OHE is explained by Joule's law, where electrical energy is converted into thermal energy inside the matrix (Ding et al. 2021). As a result, cell membranes become more permeable, proteins denature, and the seed structure softens, enabling the efficient recovery of non-volatile fatty oils that conventional distillation techniques fail to extract effectively. Moreover, OHE is recognized as a green and sustainable technology, offering precise temperature control, shorter processing times, and reduced energy consumption (Maspeke et al. 2025).

In contrast, HD and SD rely on external heating with boiling water or steam to extract volatile compounds. These methods are well suited for essential oils from plants such as coriander, lavender, and citrus peels, which are light, aromatic, and readily vaporized. Fatty oils from seeds and nuts, however, are predominantly composed of triglycerides that are heavy and non-volatile with high boiling points (Yusof et al. 2002). Consequently, such oil cannot be efficiently carried by steam, and the inherently low yields observed with HD and SD are an expected outcome (Ara et al. 2015; Fagbemi et al. 2021) rather than a reflection of technological limitation. This principle is illustrated in sacha inchi seeds, from which only 10.6% and 0.04% of oil were obtained using HD and SD, respectively.

In the present study, the oil yield was therefore calculated on a wet basis, using the total mass of the solid material without correction for moisture content. The initial moisture content of the seeds was not measured and was not included in the yield calculation. As a result, the reported oil yields represent apparent yields based on the original sample mass rather than dry-matter-based yields. This approach was applied consistently across all extraction methods to ensure comparability under identical experimental conditions. Moisture content can influence extraction efficiency and yield normalization (Colucci Cante et al. 2021; Aicher and Engelberth 2025). Future work will include the determination of initial moisture content and the calculation of oil yield on a dry basis, which will enable more accurate comparison with literature data and a more rigorous assessment of extraction performance.

Energy Analysis

Table 5 presents the energy analysis of sacha inchi oil extracted using three methods: OHE, HD, and SD. HD was the fastest, reaching the boiling point (t_1) in just 0.267 h (16 min) with a total extraction time ($t_1 + t_2$) of 0.767 h (46 min). SD followed, taking 30 min to reach the boiling point (t_1) and 60 min ($t_1 + t_2$) overall, while OHE required the longest, with 44 min to reach boiling (t_1) and 74 min ($t_1 + t_2$) total. Such differences are critical for industrial-scale production, where shorter cycles are advantageous. Despite its longer duration, OHE achieved the second-highest oil produced (31.76 mL), slightly lower than HD (25.73 mL), while SD produced markedly less (0.18 mL). However, these results should be interpreted cautiously, considering yield relative to energy consumption.

Gavahian and Chu (2022a) indicated that increasing voltage and extending extraction time can enhance oil yield. Among the methods compared, OHE consumed the least energy, requiring only 0.114 kW of power with a total energy usage of 0.141 kWh. In contrast, SD demanded the highest power and energy, at 1.6 kWh, while HD used 0.5 kW and 0.384 kWh. These substantial differences underscore the potential implications for both cost and environmental impact, particularly in large-scale operations (Gavahian and Chu 2022b). Furthermore, OHE achieved greater total energy savings (91.21%) compared to HD (76.03%) while also yielding more oil, demonstrating superior efficiency in both energy consumption and extraction performance.

Significant energy savings have also been reported in green extraction technologies. For *Mentha piperita* oils, ohmic-assisted HD consumed only 64% of the energy required by microwave-assisted HD and 20% of that used in HD (Gavahian et al. 2015). Ohmic-accelerated SD outperformed conventional SD in both speed and energy efficiency, with a total extraction time of 50.3 min versus 112.7 min and energy consumption of 0.4 kWh versus 0.9 kWh per 1 mL of oil (Gavahian and Chu 2018). As shown in Table 5, OHE, HD, and SD differ markedly in energy efficiency and electricity cost. OHE is the most energy-efficient method, achieving 91.21% energy savings by consuming only 0.141 kWh and incurring an electricity cost of 0.01 USD. HD consumes 0.384 kWh, costing 0.02 USD in electricity, representing 76.03% energy savings but still less efficient

Table 5 The process parameters of OHE, SD, and HD

Parameter/method	OHE	SD	HD
Time taken to reach boiling point (hr), t_1	0.733 (44 min)	0.5 (30 min)	0.267 (16 min)
Time taken from boiling point to the end of extraction (hr), t_2	0.5 (30 min)	0.5 (30 min)	0.5 (30 min)
Total extraction time (t_1+t_2) (hr)	1.233 (74 min)	1.0 (60 min)	0.767 (46 min)
Power (kW)	0.114	1.6	0.5
Energy (kWh)*	0.141	1.6	0.384
Total energy saving (%) **	91.210	0	76.030
Electricity cost (USD)	0.009	0.099	0.024
Average oil yield (%), g/g***	23.16	0.04	10.6
Average oil weight (g)	14.360	0.205	19.810
Average oil volume (mL)****	31.76	0.18	25.73
Oil extraction efficiency (mL/kWh)	225.89	0.11	67.09

*According to Eq. 4 (power × total extraction time); **the energy consumed in the SD was determined as the reference for total energy saving calculation; ***optimized oil yield; ****conversion using specific gravity information in Eq. (8)

than OHE. SD is the least efficient, requiring 1.6 kWh, with an electricity cost of 0.100 USD, making it both the most energy-intensive and least cost-effective method.

Similarly, SD and HD are not only more expensive but also considerably less predictable in cost compared to supercritical fluid extraction, clearly highlighting SD and HD as the least economically viable extraction methods (Kant and Kumar 2022). When considering oil productivity (mL) per kilowatt-hour (kWh), OHE clearly outperforms all methods, achieving the highest percentage yield (23.16%) and the greatest efficiency at 225.89 mL/kWh, despite a longer processing time of 74 min due to lower applied voltage. HD achieved moderate efficiency at 67.09 mL/kWh, while SD was the least efficient at 0.11 mL/kWh. These results highlight OHE as a highly energy- and cost-efficient method, making it particularly attractive for industrial-scale essential oil production. However, future studies should perform full techno-economic assessments of OHE-based extraction, explicitly including solvent costs, solvent recovery, labor, maintenance, and equipment amortization, to compare true operating cost per gram of oil with conventional methods.

Physical Analysis

Table 6 compares the physical attributes of oils extracted via OHE, HD, and SD, focusing on aspects like color, refractive index, specific gravity, and optical rotation. There is currently no specific International Organization for Standardization (ISO) standard dedicated exclusively to sacha inchi oil. The physical properties of sacha inchi oil can vary depending on the extraction method.

Color is an important physical parameter, influencing consumer perception and marketability. Visually, sacha inchi oil ranges from light to dark yellow. As shown in Table 6, oils extracted via OHE, HD, and SD all fall within this

Table 6 The physical properties of the sacha inchi oil

Physical characteristics		OHE	SD	HD
Color	*L*	71.88	70.47	73.64
	a	−0.69	−0.3133	0.06
	b	17.23	15.68	12.58
Refractive index		1.4804	1.4830	1.4830
Color appearance		Pale yellow	Dark yellow	Very light pale yellow
Specific gravity*		0.729	0.757	0.770
Density (g/mL)		0.728	0.756	0.769
Optical rotation (°)		0.039	−0.195	−7.190

*Density of water equivalent to 0.998 g/mL at 20 °C

yellowish range. Cold-pressed sacha inchi oil appears as a thick yellow liquid with a distinct, strong odor (Maya et al. 2023). Lab measurements for OHE, *L* (71.88), *a* (−0.69), and *b* (17.23), indicate a bright oil with a soft yellow hue and minimal red or green tones, suggesting that OHE preserves the natural color with minimal pigment loss. These findings are consistent with previous reports linking positive b values to yellow tones maintained through gentle heat treatment (Narwojsz et al. 2025). Studies on ohmic heating, including those by various researchers (Aguilar-Machado et al. 2017; Rascón et al. 2020; Jafarpour and Hashemi 2022), reported that color changes in foods during ohmic heating can occur due to electrochemical reactions and thermal exposure, which may lead to pigment degradation or browning. However, because ohmic heating delivers rapid and uniform heat throughout the material, it generally results in less color degradation compared to conventional heating methods. Careful control of process parameters is essential to optimize color retention and minimize adverse electrochemical effects during ohmic heating.

Differences in oil color were observed among the extraction methods. Oil color is influenced by natural pigments such as carotenoids and chlorophylls, as well as by thermal exposure and oxidation during processing (Chen and Sun 2023). In this study, color was considered a visual attribute rather than a direct indicator of extraction efficiency or chemical quality. Although no direct correlation with chemical quality parameters was established, the results suggest that extraction conditions influence oil appearance.

Sacha inchi oil extracted using SD appears darker yellow, with colorimeter values of *L* (70.47), *a* (−0.31), and *b* (15.68). Compared to the brighter yellow oil obtained via OHE, SD oil shows a slightly lower lightness, a very slight green tint, and a noticeable yellow hue. The darker yellow appearance of SD oil relative to HD oil can be attributed to the direct application of steam and heat, which may cause pigment breakdown or minor browning reactions (Alejandro Ruiz et al. 2025). Similarly, HD and SD extraction methods tend to produce deeper yellow or orange tones, as they not only extract more pigments but may also induce slight heat-related color changes during the process (Ngamwonglumlert et al. 2017).

The refractive index of sacha inchi oil obtained using all three extraction methods ranged from 1.4804 to 1.4830. This aligns well with literature values; for example, Gutiérrez et al. () reported a refractive index of 1.4791, consistent with typical vegetable oils. Similarly, a comprehensive characterization of sacha inchi oil indicated a refractive index of 1.4784, further confirming this range (Jitpinit et al. 2022). The refractive index serves as a reliable indicator of oil quality and purity. OHE shows a slightly lower refractive index, yet it remains within the acceptable range, confirming that the oil's integrity is well preserved during extraction.

The density of sacha inchi oil varied depending on the extraction method, measuring 0.728 g/mL for OHE, 0.756 g/mL for SD, and 0.769 g/mL for HD. This indicates that OHE yields slightly lighter oil compared to the denser oils obtained through HD and SD. A study by Kyaw et al. (2019) reported a density of 0.9160 g/mL at 30 °C for sacha inchi oil extracted using Soxhlet extraction. Triana-Maldonado et al. (2017) reported a density of 0.9211 g/mL for sacha inchi oil obtained via supercritical carbon dioxide extraction, which is notably higher than the previously reported range of 0.7731 to 0.8965 g/mL for the same method (Jitpinit et al. 2022). This difference is attributed to variations in the supercritical carbon dioxide extraction conditions, particularly the temperature and pressure applied. Overall, the observed deviations in density relative to reported literature values can be attributed to differences in extraction techniques, processing parameters as well as variations in the oils' fatty acid composition (Salimi et al. 2025).

The optical rotation of sacha inchi oil varied by extraction method: 0.039° for OHE, −0.195° for SD, and −7.190° for HD, indicating nearly neutral, slightly levorotatory, and strongly levorotatory oils, respectively. For example, Eibler and Vetter (2017) highlight that short-chain 4-alkyl-branched fatty acids, which are chiral, can influence both the aroma and optical properties of oils. These compounds can exist as enantiomers, each exhibiting distinct optical rotations, thereby affecting the overall optical activity of the oil. Further analysis using GC–MS is recommended to identify and quantify the specific compounds responsible for these variations.

Gas Chromatography–Mass Spectrometry Analysis

The GC–MS analysis identified several constituents of sacha inchi oil, as presented in Table 7. Linoleic acid methyl ester, hexadecanoic acid methyl ester, and methyl stearate were identified as the major constituents of sacha inchi oil across all extraction methods, while other compounds were present at levels below 4%.

Linoleic acid (C18:2, omega-6) is an essential polyunsaturated fatty acid with a mild oily taste, recognized for its nutritional and therapeutic properties, particularly its cardioprotective effects (Jackson et al. 2024). Vegetable oils high in linoleic acid have been reported to significantly mitigate ultraviolet B-induced reactive oxygen species generation, cellular damage, and photoaging of skin, as demonstrated in keratinocyte models (Manosalva et al. 2024). This result

Table 7 Chemical constituents of sacha inchi oil

Chemical constituents	OHE (%)	HD (%)	SD (%)
Linoleic acid, methyl ester	49	66.56	44.94
Hexadecanoic acid, methyl ester	22.55	14.80	23.20
Methyl stearate	16.38	11.50	17.89
Oleic acid, methyl ester	3.85	n.s	n.s
9-Octadecen-12-ynoic acid, methyl ester	n.s	n.s	3.82
3-Dodecen-1-yne, (Z)-	n.s	2.16	n.s
11-Eicosenoic acid, methyl ester	2.32	1.44	2.23
Linolenic acid, ethyl ester	1.59	1.15	1.34
Eicosanoic acid, methyl ester	1.03	n.s	0.95
2-Monolinolenin	0.91	0.85	1.09
Erucylamide	n.s	0.85	0.50
Butyl 9,12-octadecadienoate	0.90	0.69	0.82
γ-Sitosterol	0.81	n.s	0.67
cis-11,14-Eicosadienoic acid, methyl ester	0.66	n.s	0.52
Heptadecanoic acid, methyl ester	n.s	n.s	0.79
cis-10-Heptadecenoic acid, methyl ester	n.s	n.s	0.51
Linolein, 2-mono-	n.s	n.s	0.73

is consistent with the findings of Ramos-Escudero et al. (2019), who reported linoleic acid levels in sacha inchi oil ranging from 33 to 53%. Similarly, Gutiérrez et al. reported that linoleic acid accounted for approximately 33.4% of the total fatty acids in sacha inchi oil, with notable prominence in the lipid fraction (Gutiérrez et al. 2011).

Hexadecanoic acid methyl ester, also known as palmitic acid methyl ester, exhibits a mild, waxy, and fatty character with low aroma intensity and was detected in considerable amounts, particularly in SD (23.2%) and OHE (22.55%). Palmitic acid methyl ester has demonstrated anti-inflammatory (Abdel Jaleel et al. 2021), antifibrotic and hepatoprotective (Sharawy et al. 2013), gastroprotective (Arab et al. 2019), and immunomodulatory (Zhang et al. 2019) properties in preclinical studies. Methyl stearate, a saturated fatty acid methyl ester characterized by an oily and waxy aroma and flavor, was detected in notable amounts, accounting for 17.89%, 16.38%, and 11.50% in the SD, OHE, and HD samples, respectively. Methyl stearate has been shown to play an important role across diverse industrial applications. In the food industry, it is employed to modify the physicochemical properties of edible oils through interesterification processes (Xie et al. 2015). In addition, methyl stearate serves as a valuable feedstock to produce long-chain alcohols, which are widely utilized in surfactants and lubricants (Shuang et al. 2021).

Minor yet noteworthy constituents were identified, including oleic acid methyl ester in OHE, 3-dodecen-1-yne (Z) in HD, and 9-octadecen-12-ynoic acid methyl ester in SD. Oleic acid, an unsaturated fatty acid with distinctive nutritional and functional properties compared to other vegetable oils, has been highlighted as a promising ingredient for advanced formulations in the cosmetic, pharmaceutical, and food industries (Penagos-Calvete et al. 2019). 3-Dodecen-1-yne has also been reported as a minor component in the GC–MS profile of *Eryngium triquetrum* oil (De Carvalho Augusto et al. 2020; Merad et al. 2021). Additionally, 9-octadecen-12-ynoic acid methyl ester has been identified in oils derived from *Angelica sinensis* (Peng et al. 2024) and *Apium graveolens* (Nagella et al. 2012). 11-Eicosenoic acid methyl ester, 2-monolinolenin, and butyl 9,12-octadecadienoate were consistently detected across oils extracted by all three methods. 11-Eicosenoic acid methyl ester has been reported to stimulate the immune system and promote the production of inflammatory metabolites, indicating a role in modulating immune responses (Alqarni et al. 2019). Similarly, 2-monolinolenin has shown antibacterial activity against specific strains, highlighting its potential as a natural antimicrobial agent with relevance in managing inflammation-related conditions (Kusumah et al. 2020). Butyl 9,12-octadecadienoate has been identified in peanut oil (Al-Rajhi et al. 2025) and carrot powder (Kamel et al. 2023), and its occurrence in the hexane fraction of *Achillea wilhelmsii* has been reported to exhibit antileishmanial activity (Achakzai et al. 2019).

GC–MS analysis revealed that minor constituents, including linolenic acid ethyl ester, eicosanoic acid methyl ester, and cis-11,14-eicosadienoic acid methyl ester, were present in oils from OHE and SD but absent in HD. Erucylamide was detected in SD and HD. Unique compounds such as heptadecanoic acid methyl ester, cis-10-heptadecenoic acid methyl ester, and 2-mono-linolein were detected exclusively in SD. These variations may be attributed to differences in extraction methods, solvent polarity, and the stability of minor compounds, which can affect the solubility, degradation, or formation of specific constituents (Zhang et al. 2018; Zarrinmehr et al. 2022).

Antimicrobial Properties

Table 8 summarizes the antimicrobial activity of sacha inchi extracts obtained via different extraction methods, along with comparative data from previous studies. A clear trend emerges showing that the type of extract strongly influences bioactivity, reflecting differences in chemical composition. The seed protein extract exhibited the highest antimicrobial potency, generating the largest inhibition zones against both *E. coli* and *Micrococcus luteus*. This suggests that specific bioactive peptides or protein components are primarily responsible for antibacterial effects (Zin et al. 2024). In contrast, seed shell extracts showed moderate activity, particularly against *Staphylococcus aureus* and MRSA strains. However, higher concentrations were required to achieve inhibition, indicating a lower potency or reduced bioavailability of active compounds in the shells (Al-Hamoud et al. 2025).

Ozonated sacha inchi oil displayed measurable antimicrobial activity, notably antifungal effects against *Candida albicans*, indicating that oxidative modification can generate bioactive compounds and enhance the activity of otherwise inactive oils (Llaque-Bardales and García-Rupaya 2024). In contrast, oils extracted via OHE, HD, or SD showed no antibacterial effects, highlighting that these oils lack effective antimicrobial constituents. These results demonstrate that both chemical composition and extraction or post-processing methods determine antimicrobial activity (Campos et al. 2022). Protein-rich extracts are most effective against bacteria, while oxidatively modified oils show selective antifungal activity. Practically, this suggests that natural antimicrobial formulations should focus on protein-rich extracts for antibacterial applications (Al Akeel et al. 2014) and consider ozonated oils for antifungal purposes (Augello et al. 2024). Overall, understanding the relationship between extraction method, chemical composition, and bioactivity enables the design of targeted natural antimicrobial agents tailored for specific pathogens and applications.

Table 8 Antimicrobial properties of sacha inchi

Material/extract	Extraction type/treatment	Microorganisms tested	Assays tested	Key findings of inhibition	References
Seed protein extract	Ammonium sulfate precipitation and dialysis	*Escherichia coli*, *Micrococcus luteus*, *Colletotrichum gloeosporioides*	Agar diffusion	• *E. coli* = 30.5 mm • *M. luteus* = 33 mm • Suppressing the growth of *C. gloeosporioides* at inhibitory concentration percentages (IC%) of 1.5 ± 0.12%, 5.85 ± 3.89%, and 5.90 ± 1.98% after 2, 3, and 4 days of incubation	Zin et al. (2024)
Seed shell extracts	70% ethanol Aqueous extracts	*S. aureus* (ATCC29213), *S. aureus* (clinical) isolate, andmethicillin-resistant *S. aureus* (MRSA)	Agar diffusion	• *S. aureus* = 17 mm • *S. aureus* = 20 mm • MRSA = 17 mm • *S. aureus* = 14 mm • *S. aureus* = 14 mm • MRSA = 15 mm • All showed minimum inhibitory concentration values of 250 mg/mL	Al-Hamoud et al. (2025)
Ozonated oil from seed	Sacha inchi oil ozonated for 6 h	*Enterococcus faecalis*, *Candida albicans*	Agar diffusion	• *E. faecalis*: 13.4 mm • *C. albicans*: 18.97 mm	Llaque-Bardales and García-Rupaya (2024)
Oil from seed	Extracted via OHE, HD, SD	*Staphylococcus aureus*, *Escherichia coli*, and *Klebsiella pneumoniae*	Agar diffusion	No observable inhibition zones	Current study

Morphology Analysis

SEM images of sacha inchi powder under four conditions: raw, after OHE, SD, and HD, are presented in Fig. 5, illustrating distinct microstructural modifications induced by each treatment and their implications for extraction performance.

In Fig. 5a, the raw powder exhibits a smooth surface with largely intact cell structures, along with traces of oily residue. In the raw or untreated powder, the plant tissue has not been subjected to intensive thermal or electrical treatments that would cause extensive cell wall rupture (Jiang et al. 2020). Drying, especially at mild or low temperatures, mainly removes free and bound moisture but does not completely destroy the cellular matrix, while the traces of surface oil result from partial cell rupture in an inherently oil-rich matrix. Studies of oil seed powders and high-oil plant materials demonstrate that even mild processing like grinding or drying can begin to break some cells, releasing small amounts of oil that remain on particle surfaces and are visible as surface residues under microscopy (Adhikari et al. 2025).

Following OHE-treatment (Fig. 5b), the microstructure shows extensive rupture and degradation of cell walls, with no visible residual oil coating the surface. This pronounced structural disruption is primarily attributed to the passage of electric current through the moist plant matrix, resulting in rapid internal heating and localized temperature gradients. The applied electric field induces charge accumulation across cell membranes, leading to membrane polarization, water vaporization, and subsequent rupture of oil-bearing structures and pore formation (Astráin-Redín et al. 2024). In addition to thermal effects, electrically induced mechanical stresses further increase membrane permeability, accelerating oil release and enhancing mass transfer (Aydın and Eser 2024). These combined effects account for the higher extraction yield and more efficient oil removal achieved by OHE compared with conventional water-based methods.

The HD-treated sample (Fig. 5c) displays a flattened and swollen morphology with noticeable residual oil coating the surface. Although pores and ruptures are present, they are less extensive than those observed after OHE. Prolonged exposure to boiling water during HD promotes cell swelling and gradual weakening of cell walls, increasing permeability

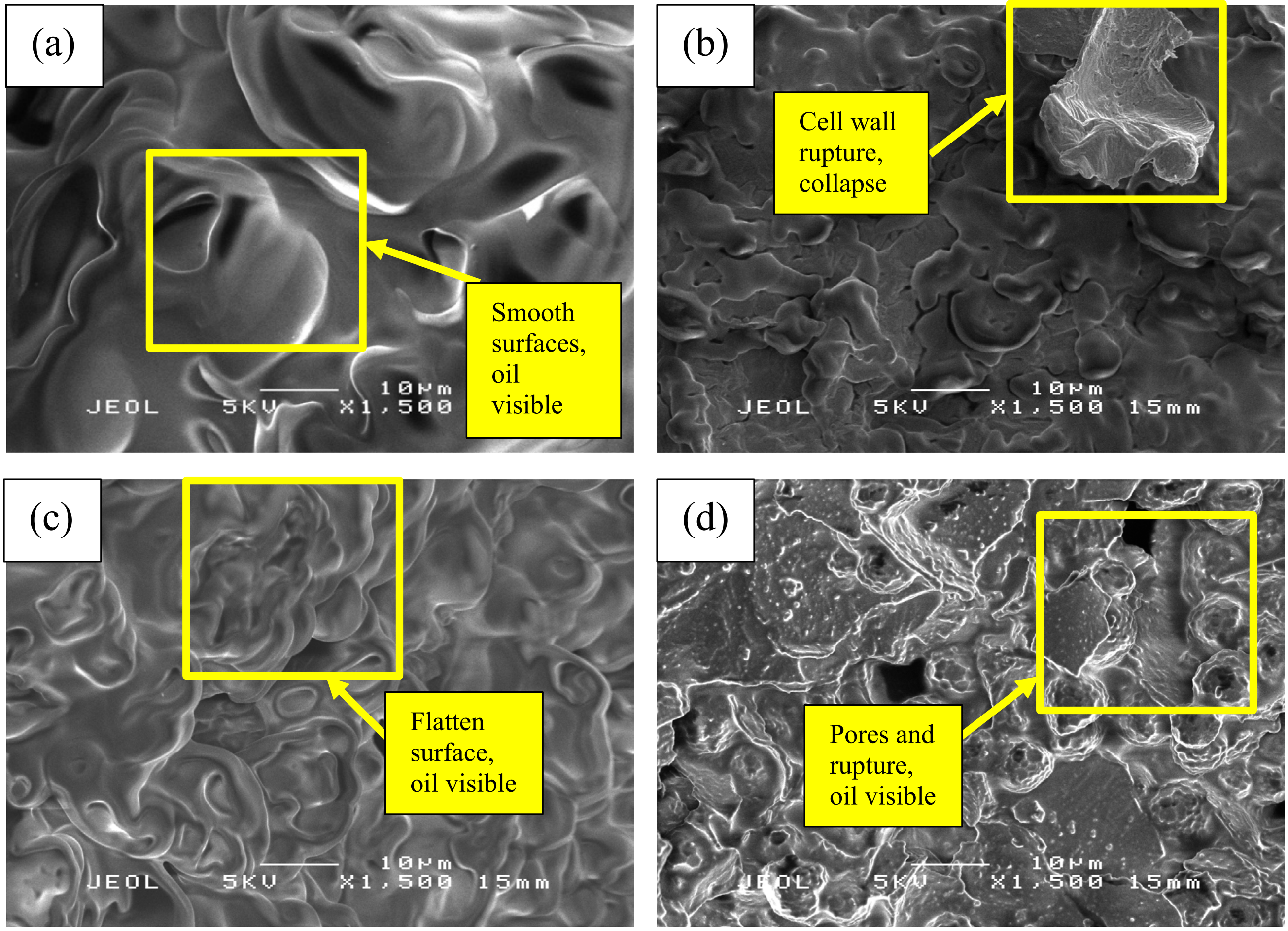

Fig. 5 SEM images of sacha inchi powder **a** raw sample, **b** after OHE, **c** after HD, and **d** after SD

and facilitating oil diffusion. However, heat transfer during HD occurs mainly via conduction and convection from the surface toward the interior, resulting in slower and less uniform heating compared with volumetric heating techniques. Consequently, cell disruption is more gradual, leading to partial oil release and lower extraction efficiency (Gavahian et al. 2011; Akhbari et al. 2018).

In contrast, the SD-treated sample (Fig. 5d) exhibits a more agglomerated structure, with particle surfaces coated by residual oil. This oily layer is likely derived from non-volatile, high-molecular-weight lipid fractions that do not vaporize with steam and therefore remain trapped within the plant matrix. Previous studies have reported similar surface smearing and agglomeration due to the retention of non-volatile constituents during steam-based extraction (Pandey et al. 2023). As SD relies solely on indirect steam heating, it imparts limited thermal and mechanical stress to plant tissues, resulting in minimal cell wall rupture. Moreover, insufficient residence time further restricts mass transfer, leaving much of the cellular structure intact and reducing oil recovery.

Overall, the SEM observations correlate strongly with the physical properties and extraction efficiencies obtained under different treatments. Extensive cell wall rupture and pore formation in OHE-treated samples enhance mass transfer and oil release. The mild structural changes in HD and SD limit cell disruption, making them theoretically unsuitable for fixed oil extraction, as shown by their low yields of 10.6% and 0.04% versus 23.16% for OHE. These findings highlight the importance of microstructural disruption in governing oil extraction performance and underscore the advantage of OHE as an internally driven heating method for lipid-rich matrices.

Conclusion

In conclusion, this study identified the optimal OHE conditions for extracting sacha inchi oil as 70 V, 30 min, and a 7.06:1 solvent-to-solid ratio. Under these conditions, OHE outperformed both SD and HD, achieving an oil efficiency of 225.89 mL/kWh compared to 0.11 mL/kWh (SD) and 67.09 mL/kWh (HD). OHE consumed only 0.141 kWh, achieving up to 91% energy savings over conventional methods. As expected, HD and SD were unsuitable for extracting fixed oils, resulting in lower extraction efficiencies. These methods are better suited for volatile compounds, while the non-volatile, triacylglycerol-rich oils in sacha inchi remain largely trapped due to limited cell disruption. The oil obtained by OHE exhibited comparable physical characteristics to those from SD and HD, while GC–MS analysis confirmed the presence of major constituents such as linoleic acid methyl ester, hexadecanoic acid methyl ester, and methyl stearate. SEM analysis further revealed significant structural modifications in OHE-treated samples relative to SD and HD. Overall, these results highlight OHE as a promising and energy-efficient method for enhancing both yield and quality of sacha inchi oil.

Acknowledgements The work also received assistance from the Faculty of Engineering, Universiti Putra Malaysia, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia and Faculty of Science and Technology, Universiti Kebangsaan Malaysia.

Author Contribution Muhammad Hazwan Hamzah: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Writing-original draft. Nur Fatihah Jamaludin: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing-original draft. Adila Fazliyana Aili Hamzah: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing-review and editing. Mohd Zuhair Mohd Nor: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing-review and editing. Abd Halim Md Ali: Investigation, Methodology, Supervision, Validation, Writing-review and editing. Maimunah Mohd Ali: Investigation, Methodology, Supervision, Validation, Writing-review and editing. Hasfalina Che Man: Funding acquisition, Methodology, Project administration, Supervision, Writing-review and editing.

Funding Open access funding provided by The Ministry of Higher Education Malaysia and Universiti Putra Malaysia. The authors gratefully acknowledge the financial support provided by Universiti Putra Malaysia through the Geran Putra Berimpak (GP-GPB) grant (No. GPB/2023/9783600).

Data Availability All data generated or analyzed during this study are included in published article.

Declarations

Ethics Approval and Consent to Participate This article contains no studies with human participants or animals performed by any authors.

Competing interests The authors declare no competing interests.

References

Abdel Jaleel GA, Azab SS, el-Bakly WM, Hassan A (2021) 'Methyl palmitate attenuates adjuvant induced arthritis in rats by decrease of CD68 synovial macrophages. Biomed and Pharmacotherapy 137:111347. https://doi.org/10.1016/j.biopha.2021.111347

Achakzai JK, Anwar Panezai M, Kakar AM et al (2019) In vitro antileishmanial activity and GC-MS analysis of whole plant hexane fraction of *Achillea wilhelmsii* (WHFAW). J Chem 2019:5734257. https://doi.org/10.1155/2019/5734257

Adhikari S, Bhattarai RR, Al-Salami H, Dhungana P (2025) Innovative formulations using spray-drying technology for plant-based high-oil powders: physicochemical and micro-structural analyses. Sustain Food Technol 3:1569–1579. https://doi.org/10.1039/d5fb00251f

Aguilar-Machado D, Morales-Oyervides L, Contreras-Esquivel JC et al (2017) Effect of ohmic heating processing conditions on color stability of fungal pigments. Food Sci Technol Int 23:338–348. https://doi.org/10.1177/1082013216689514

Aicher E, Engelberth AS (2025) Comparing extraction conditions for favorable yield of lutein and zeaxanthin from distiller's grains. Discover Food 5:14. https://doi.org/10.1007/s44187-025-00287-9

Aili Hamzah AF, Hamzah MH, Nurulhuda K et al (2024) Utilization of subcritical water for improving methane production from oil palm empty fruit bunch by anaerobic co-digestion: process optimization, compositional, chemical, and morphological analysis. Renew Energy 231:121013. https://doi.org/10.1016/j.renene.2024.121013

Akhbari M, Masoum S, Aghababaei F, Hamedi S (2018) Optimization of microwave assisted extraction of essential oils from Iranian *Rosmarinus officinalis* L. using RSM. J Food Sci Technol 55:2197–2207. https://doi.org/10.1007/s13197-018-3137-7

Aktar T, Adal E (2019) Determining the Arrhenius kinetics of avocado oil: oxidative stability under rancimat test conditions. Foods 8:236. https://doi.org/10.3390/foods8070236

Al Akeel R, Al-Sheikh Y, Mateen A et al (2014) Evaluation of antibacterial activity of crude protein extracts from seeds of six different medical plants against standard bacterial strains. Saudi J Biol Sci 21:147–151. https://doi.org/10.1016/j.sjbs.2013.09.003

Alejandro Ruiz FE, Ortega Jácome JF, Mora JR et al (2025) Comprehensive characterization and valorization potential of Amazonian sacha inchi (*Plukenetia volubilis* L.) seeds, oil, and oilcake by-products for sustainable food applications. Front Nutr 12:1597300. https://doi.org/10.3389/fnut.2025.1597300

Al-Hamoud GA, Amina M, Alrashoudi RH et al (2025) Unveiling phenolic content, antibacterial, and antibiofilm potential of sacha inchi (*Plukenetia volubilis* L.) seed shell extracts against *Staphylococcus aureus*. PeerJ 13:e19524. https://doi.org/10.7717/peerj.19524

Alqarni AM, Dissanayake T, Nelson DJ et al (2019) Metabolomic profiling of the immune stimulatory effect of eicosenoids on PMA-differentiated THP-1 cells. Vaccines 7:142. https://doi.org/10.3390/vaccines7040142

Al-Rajhi AMH, Abdelghany TM, Selim S et al (2025) Phytochemical characterization of peanut oil and its ozonized form to explore

biological activities in vitro. AMB Express 15:76. https://doi.org/10.1186/s13568-025-01849-x
Ara KM, Jowkarderis M, Raofie F (2015) Optimization of supercritical fluid extraction of essential oils and fatty acids from flixweed (*Descurainia sophia* L.) seed using response surface methodology and central composite design. J Food Sci Technol 52:4450–4458. https://doi.org/10.1007/s13197-014-1353-3
Arab HH, Salama SA, Eid AH et al (2019) Targeting MAPKs, NF-κB, and PI3K/AKT pathways by methyl palmitate ameliorates ethanol-induced gastric mucosal injury in rats. J Cell Physiol 234:22424–22438. https://doi.org/10.1002/jcp.28807
Astráin-Redín L, Ospina S, Cebrián G, Álvarez-Lanzarote I (2024) Ohmic heating technology for food applications, from ohmic systems to moderate electric fields and pulsed electric fields. Food Eng Rev 16:225–251. https://doi.org/10.1007/s12393-024-09368-4
Augello S, Cameli V, Montanari A et al (2024) The antifungal potential of ozonated extra-virgin olive oil against *Candida albicans*: mechanisms and efficacy. Biomolecules 14:1472. https://doi.org/10.3390/biom14111472
Aydın C, Eser F (2024) Impact of ohmic heating extraction on the bioactive components of parsley: comparison with conventional and green extraction techniques. J Food Measure Charact 18:7575–7584. https://doi.org/10.1007/s11694-024-02749-7
Bakhshabadi H, Ganje M, Gharekhani M et al (2025) A review of new methods for extracting oil from plants to enhance the efficiency and physicochemical properties of the extracted oils. Processes 13:1124. https://doi.org/10.3390/pr13041124
Bhadange YA, Carpenter J, Saharan VK (2024) A comprehensive review on advanced extraction techniques for retrieving bioactive components from natural sources. ACS Omega 9:31274–31297. https://doi.org/10.1021/acsomega.4c02718
Bueno-Borges LB, Sartim MA, Gil CC et al (2018) Sacha inchi seeds from sub-tropical cultivation: effects of roasting on antinutrients, antioxidant capacity and oxidative stability. J Food Sci Technol 55:4159–4166. https://doi.org/10.1007/s13197-018-3345-1
Campos L, Seixas L, Dias S et al (2022) Effect of extraction method on the bioactive composition, antimicrobial activity and phytotoxicity of pomegranate by-products. Foods 11:992. https://doi.org/10.3390/foods11070992
Cárdenas DM, Rave LJG, Soto JA (2021) Biological activity of sacha inchi (*Plukenetia volubilis* linneo) and potential uses in human health: a review. Food Technol Biotechnol 59:253–266. https://doi.org/10.17113/ftb.59.03.21.6683
Chauca-Cerrutti A, Inga M, Pasquel-Reátegui JL et al (2024) Optimization of extraction in supercritical fluids in obtaining *Pouteria lucuma* seed oil by response surface methodology and artificial neuronal network coupled with a genetic algorithm. Front Chem 12:1491479. https://doi.org/10.3389/fchem.2024.1491479
Che Sulaiman IS, Basri M, Fard Masoumi HR et al (2017) Effects of temperature, time, and solvent ratio on the extraction of phenolic compounds and the anti-radical activity of *Clinacanthus nutans* Lindau leaves by response surface methodology. Chem Cent J 11:54. https://doi.org/10.1186/s13065-017-0285-1
Chen H-Y, Chen C (2025) A study of the response surface methodology model with regression analysis in three fields of engineering. Appl Syst Innov 8:99. https://doi.org/10.3390/asi8040099
Chen X, Sun S (2023) Color reversion of refined vegetable oils: a review. Molecules 28:5177. https://doi.org/10.3390/molecules28135177
Che-U-Bong W, Hongsprabhas P, Jaree A, Klinkesorn U (2025) Enhancing the recovery yield and quality of oil from coconut residue by ultrasound pretreatment-assisted ethanol extraction. J Agric Food Res 22:102133. https://doi.org/10.1016/j.jafr.2025.102133
Chirinos R, Scharff-Salinas R, Rodriguez-Diaz J et al (2024) Conventional and ultrasound-assisted extractions of protein from sacha inchi (*Plukenetia volubilis*) and their impact on the physicochemical and structural characteristics. Appl Food Research 4:100545. https://doi.org/10.1016/j.afres.2024.100545
Clinical and Laboratory Standards Institute (CLSI) (2020) Performance standards for antimicrobial susceptibility testing. CLSI supplement M100, 30th edn. Clinical and Laboratory Standards Institute, Wayne, PA
Colucci Cante R, Garella I, Gallo M, Nigro R (2021) Effect of moisture content on the extraction rate of coffee oil from spent coffee grounds using Norflurane as solvent. Chem Eng Res des 165:172–179. https://doi.org/10.1016/j.cherd.2020.11.002
Cordero-Clavijo LM, Mejía-Valdez D, Antunes-Ricardo M et al (2025) Evaluating sacha inchi (*Plukenetia volubilis*) oil stability and physicochemical properties: a comparison between conventional extraction and supercritical fluids. Food Chem 463:141132. https://doi.org/10.1016/j.foodchem.2024.141132
Cui W, Xu R, Li X et al (2024) Research on the supercritical CO_2 extraction process of Hetian rose essential oil. Processes 12:1396. https://doi.org/10.3390/pr12071396
D'Orsi B, Carcione R, Di Sarcina I et al (2024) Gamma irradiation for cultural heritage conservation: comparison of the side effects on new and old paper. J Cult Herit 70:335–344. https://doi.org/10.1016/j.culher.2024.10.009
Dao TP, Nguyen TV, Nhi Tran TY et al (2021a) Central composite design, kinetic model, thermodynamics, and chemical composition of pomelo (Citrus Maxima (Burm.) Merr.) essential oil extraction by steam distillation. Processes 9:2075. https://doi.org/10.3390/pr9112075
Dao TP, Quyen NTC, Nhi TTY et al (2021) Response surface methodology for optimization studies of hydro-distillation of essential oil from pixie mandarin (*Citrus reticulata* Blanco) peels. Polish J Chem Technol 23:26–34. https://doi.org/10.2478/pjct-2021-0034
De Carvalho Augusto R, Merad N, Rognon A et al (2020) Molluscicidal and parasiticidal activities of *Eryngium triquetrum* essential oil on *Schistosoma mansoni* and its intermediate snail host *Biomphalaria glabrata*, a double impact. Parasit Vectors 13:486. https://doi.org/10.1186/s13071-020-04367-w
Dide-Agossou C, Rossmassler K, Reid J et al (2022) MOVER approximated CV: a tool for quantifying precision in ratiometric droplet digital PCR assays. J Pharm Biomed Anal 212:114664. https://doi.org/10.1016/j.jpba.2022.114664
Ding X, Liu J, Xiong X et al (2021) Influence of ohmic heating on the electrical conductivity, volume, and rice quality of each component of the water–rice mixture. Innov Food Sci Emerg Technol 72:102757. https://doi.org/10.1016/j.ifset.2021.102757
Eddaoudi FE, Guezzane CE, El Moudden H et al (2025) Optimization of seed oil extraction from *Asphodelus tenuifolius* Cav. using response surface methodology. Plants 14:2298. https://doi.org/10.3390/plants14152298
Eibler D, Vetter W (2017) Enantioseparation and optical rotation of flavor-relevant 4-alkyl-branched fatty acids. J Chromatogr A 1505:87–95. https://doi.org/10.1016/j.chroma.2017.05.011
Fagbemi KO, Aina DA, Olajuyigbe OO (2021) Soxhlet extraction versus hydrodistillation using the clevenger apparatus: a comparative study on the extraction of a volatile compound from *Tamarindus indica* seeds. Sci World J 2021:1586. https://doi.org/10.1155/2021/5961586
Fanali C, Dugo L, Cacciola F et al (2011) Chemical characterization of sacha inchi (*Plukenetia volubilis* L.) oil. J Agric Food Chem 59:13043–13049. https://doi.org/10.1021/jf203184y
Follegatti-Romero LA, Piantino CR, Grimaldi R, Cabral FA (2009) Supercritical CO_2 extraction of omega-3 rich oil from sacha inchi (*Plukenetia volubilis* L.) seeds. J Supercrit Fluids 49:323–329. https://doi.org/10.1016/j.supflu.2009.03.010

Gao Y, Ding Z, Liu Y, Xu YJ (2024) Aqueous enzymatic extraction: a green, environmentally friendly and sustainable oil extraction technology. Trends Food Sci Technol 144:104315. https://doi.org/10.1016/j.tifs.2023.104315

Gavahian M, Chu YH (2018) Ohmic accelerated steam distillation of essential oil from lavender in comparison with conventional steam distillation. Innov Food Sci Emerg Technol 50:34–41. https://doi.org/10.1016/j.ifset.2018.10.006

Gavahian M, Chu R (2022) Ohmic heating extraction at different times, temperatures, voltages, and frequencies: a new energy-saving technique for pineapple core valorization. Foods 11:2015. https://doi.org/10.3390/foods11142015

Gavahian M, Chu R (2022) Design, development, and performance evaluation of an ohmic extractor to valorize fruit by-products based on Taguchi method: reduced energy consumption and enhanced total phenolics. J Food Process Eng 45:e13825. https://doi.org/10.1111/jfpe.13825

Gavahian M, Farahnaky A, Majzoobi M et al (2011) Ohmic-assisted hydrodistillation of essential oils from *Zataria multiflora* Boiss (Shirazi thyme). Int J Food Sci Technol 46:2619–2627. https://doi.org/10.1111/j.1365-2621.2011.02792.x

Gavahian M, Farahnaky A, Farhoosh R et al (2015) Extraction of essential oils from *Mentha piperita* using advanced techniques: microwave versus ohmic assisted hydrodistillation. Food Bioprod Process 94:50–58. https://doi.org/10.1016/j.fbp.2015.01.003

Genc A (2024) Extraction of *Origanum onites* L. using an industrial-type microwave-assisted distillation (MWAD) system: increasing energy saving and essential oil yield compared to conventional steam distillation. J Appl Res Med Aromat Plants 43:1–10. https://doi.org/10.1016/j.jarmap.2024.100575

Gil-Martín E, Forbes-Hernández T, Romero A et al (2022) Influence of the extraction method on the recovery of bioactive phenolic compounds from food industry by-products. Food Chem 378:131918. https://doi.org/10.1016/j.foodchem.2021.131918

Gumustepe L, Kurt N, Aydın E, Ozkan G (2023) Comparison of ohmic heating- and microwave-assisted extraction techniques for avocado leaves valorization: optimization and impact on the phenolic compounds and bioactivities. Food Sci Nutr 11:5609–5620. https://doi.org/10.1002/fsn3.3556

Gutiérrez LF, Rosada LM, Jiméneza Á (2011) Chemical composition of sacha inchi (*Plukenetia volubilis* L.) seeds and characteristics of their lipid fraction. Grasas Aceites 62:76–83. https://doi.org/10.3989/gya044510

Gutiérrez LF, Quiñones-Segura Y, Sanchez-Reinoso Z et al (2017) Physicochemical properties of oils extracted from γ-irradiated sacha inchi (*Plukenetia volubilis* L.) seeds. Food Chem 237:581–587. https://doi.org/10.1016/j.foodchem.2017.05.148

Hamzah MH, Zulkefli N, Hamzah AFA et al (2024) Optimization of process parameters using response surface methodology for essential oil extraction from *Canarium odontophyllum* kernels by subcritical water treatment. Food Anal Methods 17:910–929. https://doi.org/10.1007/s12161-024-02624-7

Hamzah MH, Aminudin NH, Hamzah AFA et al (2025) Towards higher yield and quality of essential oils extracted from lemon myrtle (*Backhousia citriodora*) leaves via ohmic heated extraction. J Food Meas Charact 19:3301–3318. https://doi.org/10.1007/s11694-025-03182-0

Hamzah MH, Dani Lalo OJ, Aili Hamzah AF et al (2025) Optimization of ohmic heated extraction using response surface methodology and quality attributes of dabai (*Canarium odontophyllum*) pulp oil. Food Anal Methods 18:1019–1038. https://doi.org/10.1007/s12161-025-02775-1

Handayani DP, Mahfud M, Kusuma HS (2025) Extraction technologies and bioactive applications of *ocimum basilicum*: a bibliometric and systematic review. Sustainable Chemistry for Climate Action 7:100119. https://doi.org/10.1016/j.scca.2025.100119

Hashemi SMB, Kamani MH, Amani H, Mousavi Khaneghah A (2019) Voltage and NaCl concentration on extraction of essential oil from *Vitex pseudonegundo* using ohmic-hydrodistillation. Ind Crops Prod 141:111734. https://doi.org/10.1016/j.indcrop.2019.111734

International Organization for Standardization (1998) ISO 592:1998 Essential oils — determination of optical rotation, 2nd edn. International Organization for Standardization, Geneva, Switzerland

Ishak I, Coorey R, Ghani MA et al (2025) Effects of different extraction methods on yield, polyunsaturated fatty acids, antioxidants, and stability improvement of chia seed oil: a review. Pertanika J Trop Agric Sci 48:237–257. https://doi.org/10.47836/pjtas.48.1.13

Jackson KH, Harris WS, Belury MA et al (2024) Beneficial effects of linoleic acid on cardiometabolic health: an update. Lipids Health Dis 23:296. https://doi.org/10.1186/s12944-024-02246-2

Jafarpour D, Hashemi SMB (2022) Ohmic heating application in food processing: recent achievements and perspectives. Foods and Raw Materials 10:216–226. https://doi.org/10.21603/2308-4057-2022-2-531

Jeon HW, Lee S, Wang C (2019) Estimating manufacturing electricity costs by simulating dependence between production parameters. Robot Comput Integr Manuf 55:129–140. https://doi.org/10.1016/j.rcim.2018.07.009

Jiang Y, Wang S, Yu M et al (2020) Ultrasonic-assisted ionic liquid extraction of two biflavonoids from *Selaginella tamariscina*. ACS Omega 5:33113–33124. https://doi.org/10.1021/acsomega.0c04723

Jitpinit S, Siraworakun C, Sookklay Y, Nuithitikul K (2022) Enhancement of omega-3 content in sacha inchi seed oil extracted with supercritical carbon dioxide in semi-continuous process. Heliyon 8:e08780. https://doi.org/10.1016/j.heliyon.2022.e08780

Jung H, Lee YJ, Yoon WB (2018) Effect of moisture content on the grinding process and powder properties in food: a review. Processes 6:69. https://doi.org/10.3390/pr6060069

Kamel DG, Hammam ARA, Nagm El-diin MAH et al (2023) Nutritional, antioxidant, and antimicrobial assessment of carrot powder and its application as a functional ingredient in probiotic soft cheese. J Dairy Sci 106:1672–1686. https://doi.org/10.3168/jds.2022-22090

Kant R, Kumar A (2022) Review on essential oil extraction from aromatic and medicinal plants: techniques, performance and economic analysis. Sustain Chem Pharm 30:100829. https://doi.org/10.1016/j.scp.2022.100829

Kautkar S, Pandey JP, Singh A et al (2025) Development and optimization of ohmic heating device for extraction of oil from enzymatically hydrolyzed rapeseedslurry using multilevel factorial design. Agriculture Association of Textile Chemical and Critical Reviews 13:483–489. https://doi.org/10.21276/aatccreview.2025.13.01.482

Khalid S, Hassan SA, Altemimi AB et al (2024) Recovery of valuable substances from food waste by ohmic heating assisted extraction -a step towards sustainable production. Future Foods 9:100365. https://doi.org/10.1016/j.fufo.2024.100365

Kong S, Keang T, Bunthan M et al (2023) Hydraulic cold-pressed extraction of sacha inchi seeds: oil yield and its physicochemical properties. ChemEngineering 7:69. https://doi.org/10.3390/chemengineering7040069

Kusumah D, Wakui M, Murakami M et al (2020) Linoleic acid, α-linolenic acid, and monolinolenins as antibacterial substances in the heat-processed soybean fermented with *Rhizopus oligosporus*. Biosci Biotechnol Biochem 84:1285–1290. https://doi.org/10.1080/09168451.2020.1731299

Kyaw T, Nwe TL, Myint O et al (2019) Studies on nutritional compositions of sacha inchi seed and physicochemical characteristics of sacha inchi oil. Int European Extended Enablement in Sci, Eng & Manage 7:111–119

Lacey RF, Sullivan-Hill BA, Deslippe JR et al (2021) The fatty acid methyl ester (FAME) profile of *Phytophthora agathidicida* and its potential use as diagnostic tool. FEMS Microbiol Lett 368:fnab113. https://doi.org/10.1093/femsle/fnab113

Laoretani D, Fernández M, Crapiste G, Nolasco S (2014) Effect of drying operating conditions on canola oil tocopherol content. Antioxidants 3:190–199. https://doi.org/10.3390/antiox3020190

Llaque-Bardales MI, García-Rupaya CR (2024) Antibacterial and antifungal effects of ozonated essential oil of sacha inchi, calcium hydroxide, and the combination of both against *Enterococcus faecalis* and *Candida albicans*: an in vitro study. Odovtos - Int J of Dental Sci 26:175–185. https://doi.org/10.15517/ijds.2024.61116

Mabayo VIF, Aranas JRC, Cagas VJB et al (2018) Optimization of oil yield from *Hevea brasiliensis* seeds through ultrasonic-assisted solvent extraction via response surface methodology. Sustain Environ Res 28:39–46. https://doi.org/10.1016/j.serj.2017.08.001

Machado CA, Oliveira FO, de Andrade MA et al (2022) Steam distillation for essential oil extraction: An evaluation of technological advances based on an analysis of patent documents. Sustainability 14:7119. https://doi.org/10.3390/su14127119

Mahdi Navehsi F, Abdossi V, Abbaszadeh B et al (2024) Effect of gamma rays on the essential oil and biochemical characteristics of the *Satureja mutica* Fisch & C. A. Mey. Sci Rep 14:7581. https://doi.org/10.1038/s41598-024-57989-w

Manosalva C, Bahamonde C, Soto F et al (2024) Linoleic acid induces metabolic reprogramming and inhibits oxidative and inflammatory effects in keratinocytes exposed to uvb radiation. Int J Mol Sci 25:10385. https://doi.org/10.3390/ijms251910385

Maspeke PNS, Salengke S, Muhidong J et al (2025) Potential application of ohmic heating in sugar palm (*Arenga pinnata*) sap processing. In: IOP conference series: earth and environmental science, vol 1471. Institute of Physics Publishing, Merauke, Indonesia, p 012064

Maya I, Winardi DO, Amalia E et al (2023) Physicochemical characteristics, fatty acid profile, and in vitro antioxidant activity evaluation of sacha inchi seed oil from Indonesia. Cosmetics 10:171. https://doi.org/10.3390/cosmetics10060171

Medina J, van der Velpen V, Teav T et al (2020) Single-step extraction coupled with targeted hilic-ms/ms approach for comprehensive analysis of human plasma lipidome and polar metabolome. Metabolites 10:495. https://doi.org/10.3390/metabo10120495

Merad N, Andreu V, Chaib S et al (2021) Essential oils from two apiaceae species as potential agents in organic crops protection. Antibiotics 10:636. https://doi.org/10.3390/antibiotics10060636

Mhd Rodzi NAR, Lee LK (2022) Sacha inchi (*Plukenetia volubilis* L.): recent insight on phytochemistry, pharmacology, organoleptic, safety and toxicity perspectives. Heliyon 8:e10572. https://doi.org/10.1016/j.heliyon.2022.e10572

Mohd Fuad F, Mat Don M (2016) Ultrasonic-assisted extraction of oil from *Calophyllum inophyllum* seeds: optimization of process parameters. J Teknol 78:2180–3722

Molina R, López-Santos C, Balestrasse K et al (2024) Enhancing essential oil extraction from *Lavandin grosso* flowers via plasma treatment. Int J Mol Sci 25:2383. https://doi.org/10.3390/ijms25042383

Muangrat R, Veeraphong P, Chantee N (2018) Screw press extraction of *sacha inchi* seeds: oil yield and its chemical composition and antioxidant properties. J Food Process Preserv 42:e13635. https://doi.org/10.1111/jfpp.13635

Nagella P, Ahmad A, Kim SJ, Chung IM (2012) Chemical composition, antioxidant activity and larvicidal effects of essential oil from leaves of *Apium graveolens*. Immunopharmacol Immunotoxicol 34:205–209. https://doi.org/10.3109/08923973.2011.592534

Narwojsz A, Sawicki T, Piłat B, Tańska M (2025) Effect of heat treatment methods on color, bioactive compound content, and antioxidant capacity of carrot root. Appl Sci 15:254. https://doi.org/10.3390/app15010254

Ngamwonglumlert L, Devahastin S, Chiewchan N (2017) Natural colorants: pigment stability and extraction yield enhancement via utilization of appropriate pretreatment and extraction methods. Crit Rev Food Sci Nutr 57:3243–3259. https://doi.org/10.1080/10408398.2015.1109498

Nguyen HC, Vuong DP, Nguyen NTT et al (2020) Aqueous enzymatic extraction of polyunsaturated fatty acid–rich sacha inchi (*Plukenetia volubilis* L.) seed oil: an eco-friendly approach. LWT 133. https://doi.org/10.1016/j.lwt.2020.109992

Nguyen-Kim MT, Truong QC, Nguyen MT et al (2021) Optimized extraction of polyphenols from leaves of Rosemary (*Rosmarinus officinalis* L.) grown in Lam Dong province, Vietnam, and evaluation of their antioxidant capacity. Open Chem 19:1043–1051. https://doi.org/10.1515/chem-2021-0061

Ninčević Grassino A, Karlović S, Dujmić F et al (2025) Effects of hot air, vacuum, and conductive drying on the fatty acid profile of *Cucurbita maxima* pulp and its processing by-products. Foods 14:57. https://doi.org/10.3390/foods14010057

Niu L, Li J, Chen MS, Xu ZF (2014) Determination of oil contents in *sacha inchi* (*Plukenetia volubilis*) seeds at different developmental stages by two methods: Soxhlet extraction and time-domain nuclear magnetic resonance. Ind Crops Prod 56:187–190. https://doi.org/10.1016/j.indcrop.2014.03.007

Ntalikwa JW (2021) Solvent extraction of jatropha oil for biodiesel production: effects of solvent-to-solid ratio, particle size, type of solvent, extraction time, and temperature on oil yield. J Renew Energy 2021:9221168. https://doi.org/10.1155/2021/9221168

Ofori-Boateng C, Keat Teong L, Jitkang L (2012) Comparative exergy analyses of *Jatropha curcas* oil extraction methods: solvent and mechanical extraction processes. Energy Convers Manag 55:164–171. https://doi.org/10.1016/j.enconman.2011.11.005

Ong TH, Hamzah MH, Che Man H (2021) Optimization of palm oil extraction from decanter cake using soxhlet extraction and effects of microwaves pre-treatment on extraction yield and physicochemical properties of palm oil. Food Res 5:25–32. https://doi.org/10.26656/fr.2017.5(S1).008

Pandey VK, Tripathi A, Srivastava S et al (2023) Exploiting the bioactive properties of essential oils and their potential applications in food industry. Food Sci Biotechnol 32:885–902. https://doi.org/10.1007/s10068-023-01287-0

Pavón-Vargas D, Simkova K, Puzović A et al (2025) Comparative analysis of aroma and phenolic compounds in strawberry nectar subjected to equivalent thermal, ohmic heating, high pressure, and pulsed electric fields processes at pilot scale. LWT 228:118066. https://doi.org/10.1016/j.lwt.2025.118066

Penagos-Calvete D, Duque V, Marimon C et al (2019) Glycerolipid composition and advanced physicochemical considerations of sacha inchi oil toward cosmetic products formulation. Cosmetics 6:70. https://doi.org/10.3390/COSMETICS6040070

Peng B, Zhou Z, Wang R et al (2024) Analysis of components and antioxidant activity of Angelica sinensis essential oil (AEO) extracted from supercritical carbon dioxide. J Food Bioactives 26:72–79. https://doi.org/10.31665/jfb.2024.18382

Phillips PR (2019) Electrical principles, 4th edn. Cengage Learning Australia, South Melbourne, Victoria, Australia

Piras A, Piras C, Porcedda S, Rosa A (2021) Comparative evaluation of the composition of vegetable essential and fixed oils obtained by supercritical extraction and conventional techniques: a chemometric approach. Int J Food Sci Technol 56:4496–4505. https://doi.org/10.1111/ijfs.15098

Ponphaiboon J, Krongrawa W, Aung WW et al (2023) Advances in natural product extraction techniques, electrospun fiber fabrication, and the integration of experimental design: a comprehensive review. Molecules 28:5163. https://doi.org/10.3390/molecules28135163

Ramos PR, Sponchiado J, Echenique JVF et al (2024) Kinetics of vegetable oils (rice bran, sunflower seed, and soybean) extracted by pressurized liquid extraction in intermittent process. Processes 12:1107. https://doi.org/10.3390/pr12061107

Ramos-Escudero F, Muñoz AM, Ramos Escudero M et al (2019) Characterization of commercial sacha inchi oil according to its composition: tocopherols, fatty acids, sterols, triterpene and aliphatic alcohols. J Food Sci Technol 56:4503–4515. https://doi.org/10.1007/s13197-019-03938-9

Ramos-Escudero F, Morales MT, Ramos Escudero M et al (2021) Assessment of phenolic and volatile compounds of commercial sacha inchi oils and sensory evaluation. Food Res Int 140:110022. https://doi.org/10.1016/j.foodres.2020.110022

Ranjha MMAN, Kanwal R, Shafique B et al (2021) A critical review on pulsed electric field: a novel technology for the extraction of phytoconstituents. Molecules 26:4893. https://doi.org/10.3390/molecules26164893

Rascón L, Cruz M, Rodríguez-Jasso RM et al (2020) Effect of ohmic heating on sensory, physicochemical, and microbiological properties of "aguamiel" of agave salmiana. Foods 9:1834. https://doi.org/10.3390/foods9121834

Redjeki SG, Hulwana AF, Aulia RN et al (2025) Sacha inchi (*Plukenetia volubilis*): potential bioactivity, extraction methods, and microencapsulation techniques. Molecules 30:160. https://doi.org/10.3390/molecules30010160

Rodríguez G, Aguirre E, Córdova-Chang A et al (2022) Modification of the nutritional quality and oxidative stability of lupin (*Lupinus mutabilis sweet*) and sacha inchi (*Plukenetia volubilis* L.) oil blends. Molecules 27:7315. https://doi.org/10.3390/molecules27217315

Salimi YK, Tungadi R, Liputo SA et al (2025) Physicochemical properties, fatty acid and amino acid profiles, and antioxidant activity of sacha inchi (*Plukenetia volubilis* L.) seed oil and press cake extracted using hydraulic press and soxhlet methods. Trends in Sciences 22:9690. https://doi.org/10.48048/tis.2025.9690

Samadi M, Zainal Abidin Z, Yoshida H et al (2020) Towards higher oil yield and quality of essential oil extracted from *Aquilaria malaccensis* wood via the subcritical technique. Molecules 25:3872. https://doi.org/10.3390/molecules25173872

Sánchez M, Ferreira-Santos P, Gomes-Dias JS et al (2023) Ohmic heating-based extraction of biocompounds from cocoa bean shell. Food Biosci 54:102886. https://doi.org/10.1016/j.fbio.2023.102886

Sayyar S, Abidin ZZ, Yunus R, Muhammad A (2009) Extraction of oil from *Jatropha* seeds-optimisation and kinetics. Am J Appl Sci 6:1390–1395. https://doi.org/10.3844/ajassp.2009.1390.1395

Sharawy MH, El-Agamy DS, Shalaby AA, Ammar ESM (2013) Protective effects of methyl palmitate against silica-induced pulmonary fibrosis in rats. Int Immunopharmacol 16:191–198. https://doi.org/10.1016/j.intimp.2013.04.007

Sharma HP, Patel H, Sugandha (2017) Enzymatic added extraction and clarification of fruit juices–a review. Crit Rev Food Sci Nutr 57:1215–1227. https://doi.org/10.1080/10408398.2014.977434

Shorstkii I, Stuehmeier-Niehe C, Sosnin M et al (2023) Pulsed electric field treatment application to improve product yield and efficiency of bioactive compounds through extraction from peels in kiwifruit processing. J Food Process Preserv 2023:1–11. https://doi.org/10.1155/2023/8172255

Shrestha B, Nath DK, Maharjan A et al (2021) Isolation and characterization of potential antibiotic-producing actinomycetes from water and soil sediments of different regions of Nepal. Int J Microbiol 2021:5586165. https://doi.org/10.1155/2021/5586165

Shuang Y, Tong Z, Xiaoyu T et al (2021) Octadecanol production from methyl stearate by catalytic transfer hydrogenation over synergistic Co/HAP catalysts. Energy Fuels 35:9970–9982. https://doi.org/10.1021/acs.energyfuels.1c00729

Silva VLM, Santos LMNBF, Silva AMS (2017) Ohmic heating: an emerging concept in organic synthesis. Chem Eur J 23:7853–7865. https://doi.org/10.1002/chem.201700307

Sivashankari M, Sadvatha RH, Karunanith S (2024) Ohmic heating and its impact on oil extraction from food processing by-products. In: Srivastav PP, Karunanithi S (eds) Emerging methods for oil extraction from food processing waste. CRC Press, pp 126–149

Sola Martínez RA, Pastor Hernández JM, Lozano Terol G et al (2020) Data preprocessing workflow for exhaled breath analysis by GC/MS using open sources. Sci Rep 10:22008. https://doi.org/10.1038/s41598-020-79014-6

Srivastav S, Roy S (2014) Changes in electrical conductivity of liquid foods during ohmic heating. Int J Agric Biol Eng 7:133–138. https://doi.org/10.3965/j.ijabe.20140705.015

Supriyanto S, Imran Z, Ardiansyah R et al (2022) The effect of cultivation conditions on sacha inchi (Plukenetia volubilis L.) seed production and oil quality (Omega 3, 6, 9). Agronomy 12:636. https://doi.org/10.3390/agronomy

Suttiarporn P, Seangwattana T, Srisurat T et al (2024) Enhanced extraction of clove essential oil by ultrasound and microwave assisted hydrodistillation and their comparison in antioxidant activity. Curr Res in Green and Sustainable Chem 8:100411. https://doi.org/10.1016/j.crgsc.2024.100411

Taiwo EA, Sanda O, Odesola OO et al (2024) Influence of enzymatic pretreatment and optimization on hydro distillation recovery of essential oils from *Allium cepa*. Chem Afr 7:1223–1233. https://doi.org/10.1007/s42250-023-00828-8

Tenaga Nasional Berhad (2025) Tariff Schedule & Rates. https://www.tnb.com.my/. Accessed 12 Sep 2025

Thyagarajan T, Chelvi KPSendur, Rangaswamy TR (2000) Engineering basics: electrical, electronics and computer engineering, 3rd edn. New Age International (P) Limited, New Delhi

Triana-Maldonado DM, Torijano-Gutiérrez SA, Giraldo-Estrada C (2017) Supercritical CO_2 extraction of oil and omega-3 concentrate from sacha inchi (*Plukenetia volubilis* L.) from Antioquia, Colombia. Grasas Aceites 68:e172

Xie W, Yang X, Zang X (2015) Interesterification of soybean oil and methyl stearate catalyzed by guanidine-functionalized SBA-15 silica. JAOCS, J of the American Oil Chemists' Society 92:915–925. https://doi.org/10.1007/s11746-015-2651-2

Yanti S, Agrawal DC, Saputri DS et al (2022) Nutritional comparison of sacha inchi (*Plukenetia volubilis*) residue with edible seeds and nuts in Taiwan: a chromatographic and spectroscopic study. Int J Food Sci 2022:9825551. https://doi.org/10.1155/2022/9825551

Yim HS, Chye FY, Rao V et al (2013) Optimization of extraction time and temperature on antioxidant activity of *Schizophyllum commune* aqueous extract using response surface methodology. J Food Sci Technol 50:275–283. https://doi.org/10.1007/s13197-011-0349-5

Yusof B, Dimitrios B, Frank DG et al (2002) Vegetable oils in food technology: composition, properties and uses. Blackwell Publishing, Boca Raton

Zanqui AB, da Silva CM, de Morais DR et al (2016) Sacha inchi (*Plukenetia volubilis* L.) oil composition varies with changes in temperature and pressure in subcritical extraction with n-propane. Ind Crops Prod 87:64–70. https://doi.org/10.1016/j.indcrop.2016.04.029

Zarrinmehr MJ, Daneshvar E, Nigam S et al (2022) The effect of solvents polarity and extraction conditions on the microalgal lipids yield, fatty acids profile, and biodiesel properties. Bioresour Technol 344:126303. https://doi.org/10.1016/j.biortech.2021.126303

Zhang QW, Lin LG, Ye WC (2018) Techniques for extraction and isolation of natural products: a comprehensive review. Chin Med 13:20. https://doi.org/10.1186/s13020-018-0177-x
Zhang L, Li HX, Pan WS et al (2019) Administration of methyl palmitate prevents non-alcoholic steatohepatitis (NASH) by induction of PPAR-α. Biomed Pharmacother 111:99–108. https://doi.org/10.1016/j.biopha.2018.12.059
Zin NHM, Wahab WA, Ahmad MN et al (2024) The investigation of bio-preservative properties in *Plukenetia volubilis* L. (sacha inchi) seeds protein extract for food spoilage prevention. Malays Appl Biol 53:87–96. https://doi.org/10.55230/mabjournal.v53i6.9