Applied Food Research 6 (2026) 101640

Contents lists available at ScienceDirect

Applied Food Research

journal homepage: www.elsevier.com/locate/afres

Strategies to Improve the Oxidative Stability and Shelf Life of Sacha Inchi oil in Pharmaceutical Applications

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ARTICLE INFO

Keywords:
Sacha Inchi *(Plukenetia volubilis* L.*)*
Encapsulation
Co-microencapsulation
Nanoemulsion
Oxidative Stability

ABSTRACT

Sacha Inchi (Plukenetia volubilis L.) oil, abundant in polyunsaturated fatty acids (PUFAs), presents significant nutritional and therapeutic promise for traditional formulations; yet, it is highly susceptible to oxidation, compromising its stability and reducing shelf life. Diverse modification approaches, including encapsulation, co-microencapsulation (especially with natural antioxidants), and nanoemulsions, have demonstrated substantial improvements in oxidative stability and shelf life relative to conventional systems. Techniques for preparation, including spray drying, freeze-drying, ultrasonic emulsification, and high-pressure homogenization, along with optimization through Response Surface Methodology (RSM), provide stringent control of essential parameters to improve quality, safety, and performance. This study consolidates recent advancements in techniques for Sacha Inchi oil and delineates future potential for safer and more effective solutions.

1. Introduction

The Sacha Inchi plant *(Plukenetia volubilis* L.*)* belongs to the Euphorbiaceae family and is indigenous to South America, namely the Amazon region encompassing parts of Peru and northwestern Brazil Brasil (Cárdenas Sierra et al., 2021; Supriyanto et al., 2022). This plant is considered a sustainable substitute for conventional vegetable oils since its seeds are abundant in omega-3, omega-6, and omega-9 fatty acids, superior proteins, and bioactive substances (Yeritsyan et al., 2024). Sacha Inchi seeds are rich in polyunsaturated fatty acids, especially α-linolenic acid, high-quality protein, essential amino acids, tocopherols (vitamin E), phytosterols, phenolic compounds, and minerals (Mhd Rodzi & Lee, 2022). The oil contains up to 92 % polyunsaturated fats, while the pulp remaining after oil extraction is a valuable source of protein and antioxidants (Bueno-Borges et al., 2018).

Because seeds are highly valued in both domestic and foreign markets, small-scale farmers in the Amazon enjoy a steady income. Sacha Inchi exhibits considerable medicinal promise owing to its remarkable nutritional profile. Multiple investigations have shown that the oil possesses various pharmacological qualities, including antioxidant, anti-inflammatory (Wu et al., 2024), hypolipidemic, antidiabetic, and neuroprotective benefits. The elevated levels of polyphenols, phytosterols (Valencia et al., 2024), and tocopherols (vitamin E) (Muna et al., 2024) endorse its prospective use in formulating health supplements and preventive treatments for degenerative disorders (Andayani et al., 2023; Cárdenas et al., 2021). The oil can serve as an edible oil, a nutritious supplement and in pharmaceutical (Zhang et al., 2023), and cosmetics products in diverse processed items, and a replacement for animal fat. Furthermore, this oil can function as an excipient and active ingredient in various dosage forms, such as creams, emulsions, and capsules (Cordero-Clavijo et al., 2024). By using it as an excipient and active ingredient, particularly in emulsions and microencapsulations, formulations can improve stability, extend shelf life, and mask undesirable flavors or aromas (Lu et al., 2025). Moreover, the utilization of gelatin capsules or alternative biopolymers has demonstrated an improvement in the release and absorption of important fatty acids during digestion (Otálora et al., 2020). This oil is extensively utilized in skincare formulations for its emollient, antioxidant, and non-irritating characteristics, serving as a moisturizer, anti-aging agent, and skin protector. Oils abundant in essential fatty acids are frequently encapsulated because to

Abbreviations: API, Active Pharmaceutical Ingredient; EPI, Emulsification Phase Inversion; EE, Efficiency Encapsulation; AG, Gum Arabic; HLB, Hydrophilic-Lipophilic Balance; MD, Maltodextrin; Na-Cas, Maltodextrin and Sodium Caseinate; OLP, Olive Leaf Phenolics; OVA, Ovalbumin; PV, Peroxide Value; PEC, Pectin; PEG, Polyethylene Glycol; PUFAs, Polyunsaturated Fatty Acids; RSM, Response Surface Methodology; SIO, Sacha Inchi Oil; TA, Tannic Acid; TBARS, Thiobarbituric Acid Reactive Substances; UHPH, Ultra-High-Pressure Homogenization; W/O, Water-in-Oil; WPC, Whey Protein Concentrate.

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https://doi.org/10.1016/j.afres.2025.101640
Received 10 October 2025; Received in revised form 8 December 2025; Accepted 25 December 2025
Available online 28 December 2025

their vulnerability to breakdown in the gastrointestinal tract. This method improves the efficacy of oil extraction. Sacha Inchi oil sustains skin hydration, suppleness, and regeneration by enhancing collagen synthesis, shielding the skin from free radical damage, and maintaining the dermal architecture to avert wrinkles and premature aging (Lourith et al., 2024).

Sacha Inchi oil (*Plukenetia volubilis* L.) is recognized as a plant-derived source abundant in polyunsaturated fatty acids, notably omega-3 (alpha-linolenic acid) and omega-6 (linoleic acid), which constitute over 80 % of its total fatty acd composition (Cordero-Clavijo et al., 2024; Muangrat et al., 2018). Nonetheless, its limited stability against oxidation poses a significant problem for its storage and utilization. The oil is particularly prone to lipid peroxidation because of the molecular characteristics of polyunsaturated fatty acids (PUFAs), which possess numerous double bonds. The peroxidation of polyunsaturated fatty acid double bonds can be initiated by exposure to oxygen, light, and heat (Jacobsen et al., 2021; Madhujith & Sivakanthan, 2018). This process generates free radicals and primary peroxide molecules, including hydroperoxides (Castejón et al., 2021). Thereafter, these hydroperoxides breakdown into secondary chemicals, including ketones and aldehydes (Maya et al., 2023). Lipid peroxidation results in rancid odors, undesirable flavors, alterations in color, and a decrease in beneficial compounds, such as polyphenols (Rana et al., 2022) and vitamin E (Chasquibol et al., 2023). This oxidation also reduces sensory quality and health advantages, as the important fatty acids and antioxidants present in the substance are depleted (Avendaño et al., 2025). Prior to alterations, various traditional methods were employed to preserve the quality of this oil. A straightforward solution involves storing in opaque, airtight containers to reduce exposure to light and oxygen, which can hasten lipid oxidation (Martínez-Ávila et al., 2022; Redjeki et al., 2025). Furthermore, the incorporation of natural antioxidants, including Butylated Hydroxyanisole (BHA), ethylenediaminetetraacetic acid (sEDTA), butylated hydroxytoluene (BHT), tocopherols (vitamin E), rosemary extract, or ascorbic acid, is employed to prevent the development of prooxidant compounds and prolong shelf life. Concerns exist with the administration of synthetic antioxidants at elevated doses; hence, their application is frequently restricted to concentrations below 200 ppm (Feizollahi et al., 2018).

The oxidation of Sacha Inchi oil results in a decline in its sensory attributes (including scent, flavor, and color) and reduces its health benefits due to the breakdown or loss of key fatty acids and antioxidants (Avendaño et al., 2025). Prior to undergoing any modification, various conventional methods have been employed to preserve the quality of this oil (Pagano et al., 2021). Among the simplest approaches is storage in dark, airtight containers, which minimizes exposure to light and oxygen two factors known to accelerate lipid oxidation (Redjeki et al., 2025). Natural antioxidants counteract free radicals and inhibit lipid oxidation, which initiates the production of pro-oxidant compounds. Substances such as tocopherols, ascorbic acid, and polyphenols accomplish this by donating hydrogen atoms and chelating pro-oxidant metals. The synergistic action of diverse antioxidants in preventing oxidation further enhances shelf life (Castro et al., 2020; Herman et al., 2020). Neutralization and filtering of oils eliminate solid particulates, water, and bacteria, while diminishing volatile chemicals that produce undesirable aromas and flavors. This procedure improves oxidative stability, prolongs shelf life, and fortifies the barrier against moisture and oxygen. It obstructs lipid oxidation, suppresses microbial proliferation, and diminishes the generation of volatile chemicals. Storing at low temperatures (<25 °C) has been demonstrated to reduce the rate of oxidation. This approach has not yet achieved widespread industrial adoption (Ramos-Escudero et al., 2021). Conventional storage methods, such as using dark and airtight containers (Tsao et al., 2021), can slow down the oxidation process, however, the protection provided is passive and not entirely effective. The oil, which is rich in polyunsaturated fatty acids, remains highly susceptible to oxidation because oxygen exposure can still occur due to temperature variations or when the packaging is opened. Therefore, to effectively maintain the oxidative stability of the oil, active packaging strategies are required, such as the use of modified atmosphere packaging or oxygen scavengers (Abbattista et al., 2020; Cisneros et al., 2014; Dias et al., 2015).

Sacha Inchi oil is recognized for its extensive health advantages, and several technical innovations, including nanoemulsions, microencapsulation, and co-microencapsulation, have been created to improve its bioactive efficacy and stability (George et al., 2021). The concept of active compound delivery techniques used in this study requires a clear distinction between encapsulation and co-microencapsulation technologies, as both employ different mechanisms, objectives, and advantages. Encapsulation is a technique in which a single type of active compound is coated with a wall material to form stable micro- or nanoparticles, thereby reducing degradation caused by exposure to oxygen, light, heat, or moisture, and enabling regulated release profiles (controlled release) (Choudhury et al., 2021; Mehta et al., 2022). In contrast, co-microencapsulation is an advanced approach that involves encapsulating two or more active compounds within a single system through a combination of coating materials, resulting in multilayer protection and synergistic interactions. This approach ultimately enhances encapsulation efficiency, oxidative stability, and functional performance, particularly for highly sensitive materials such as plant oils rich in unsaturated fatty acids (Niño-vásquez et al., 2022). These procedures not only maintain the oil's nutritional integrity but also enhance its bioavailability, facilitating more effective absorption by the body compared to traditional formulations (Alarcón et al., 2020; Elgegren et al., 2019; Suwannasang et al., 2021). Co-microencapsulation is one of the most effective methods for prolonging the shelf life of Sacha Inchi oil. This approach, when combined with natural antioxidants, can maintain the levels of omega-3 fatty acids and β-sitosterol. It also improves oxidative stability, antioxidant efficacy, and the product's overall shelf life (Chasquibol et al., 2024). Nanoemulsion technology markedly improves the bioavailability (Jafari, 2017) of the oil by minimizing particle size, enhancing stability, and facilitating targeted release inside the digestive system. This renders the technique very beneficial for functional and nutraceutical applications (Herazo et al., 2019). Encapsulation, microencapsulation, and nanoemulsion techniques are particularly efficacious in diminishing the oxidation rate of the oil, safeguarding its omega-3 content, and prolonging its shelf life. Consequently, these technologies may be employed in functional food products and dietary supplements (Adali et al., 2020; Herazo et al., 2019; Pisano et al., 2019).

Technologies including microencapsulation, co-microencapsulation, and nanoemulsion have been devised to overcome these constraints and enhance stability, delivery efficiency, and controlled release of active chemicals (Norhazlindah et al., 2023). This paper aims to analyze different modification techniques and bioactive delivery mechanisms utilized for the oil. This evaluation examines the operational effectiveness and possible applications of these methods. To maintain the relevance and originality of the information, publications examined have been prioritized from the last decade. The publications were obtained from premier scientific databases including Scopus, PubMed, and ScienceDirect.

2. Methods

This study employs a comprehensive and systematic approach to gather and analyze pertinent information regarding the use of modification techniques to Sacha Inchi oil. Fig. 1 demonstrates the research's application of the terms "modification" and "Sacha Inchi oil" to do a comprehensive literature search inside the PubMed, Scopus, and ScienceDirect databases. The research is confined to academic publications released from 2011 to 2025. Rigorous inclusion criteria were devised, emphasizing research that have undergone peer review and exhibit substantial progress in the technique of Sacha Inchi oil modification.

1. Inclusion and Exclusion Criteria

The Inclusion criteria included studies discussing encapsulation, co-

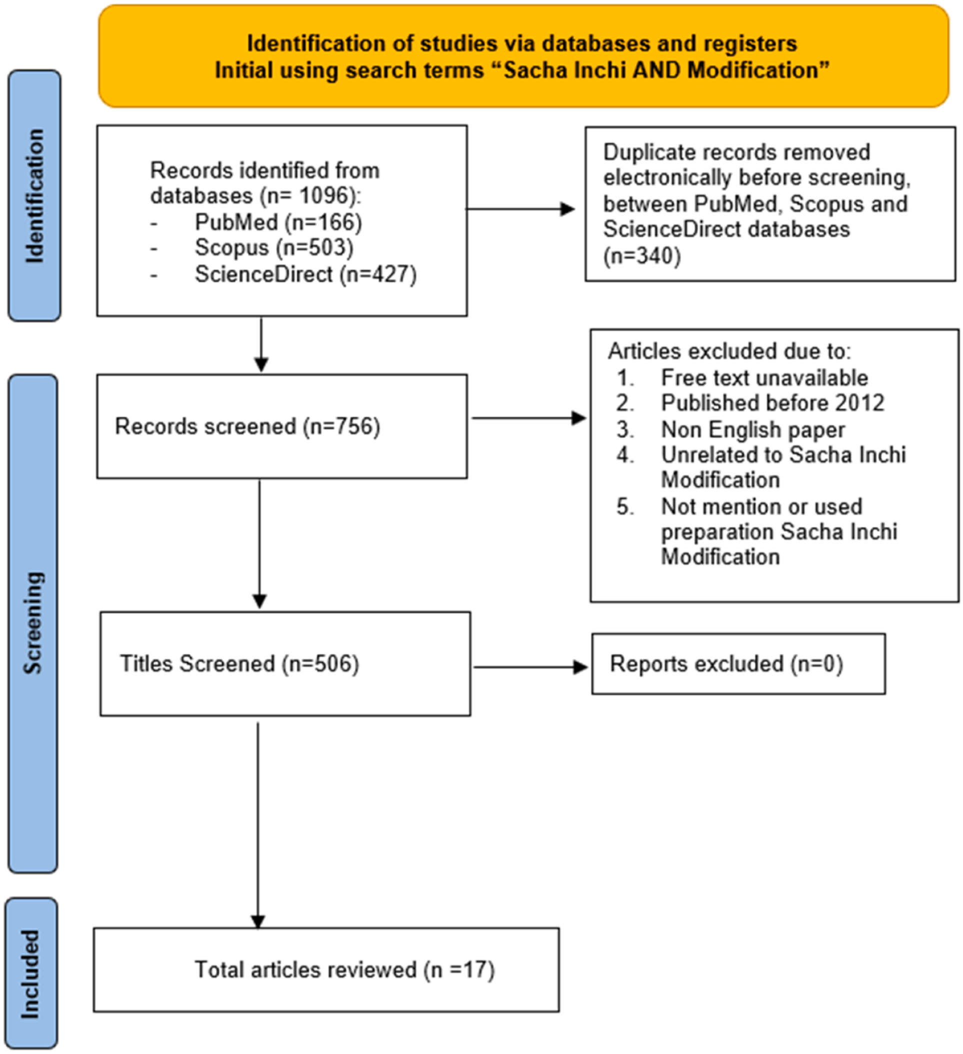

Fig. 1. The article screening followed the PRISMA Guidelines.

microencapsulation, and nanoemulsion techniques, particularly those focused on pharmaceutical formulations aimed at improving oxidative stability and extending the shelf life of Sacha Inchi oil. Exclusion criteria included papers not focused on encapsulation, co-microencapsulation, and nanoemulsions, studies not relevant to Sacha Inchi oil formulation, and articles published in languages other than English.

2. Selection Criteria

Duplicate articles were systematically classified according to title, abstract, and full text. Seventeen papers from the final evaluation about the therapeutic formulation of Sacha Inchi oil were chosen. The paper selection technique adhered to the PRISMA criteria, with pertinent papers discovered via title and abstract evaluation. The complete text of the chosen articles was analyzed. The documents chosen for this research were organized utilizing the Mendeley reference management software.

3. Data Extraction

The data gathered for this review encompassed the author's name, publication year, the methodology employed for formulation production, and the factors influencing the application of encapsulation, co-microencapsulation, and nanoemulsion techniques. The gathered data were systematically arranged in a table, facilitating comparison and assessment of the chosen studies.

4. Result

A comprehensive search using PubMed, Scopus, and ScienceDirect revealed 1096 publications published between 2011 and 2025. We methodically conducted a manual review of duplicate publications, including titles, abstracts, and full text. Seventeen papers were selected from the final screening, pertaining to modified encapsulation, co-microencapsulation, and nanoemulsion techniques, as illustrated in Fig. 1. The evaluation included additional components, including inclusion and exclusion criteria, in addition to the results. The studies selected for this study primarily focused on the encapsulation, co-microencapsulation, and nanoemulsion of Sacha Inchi oil.

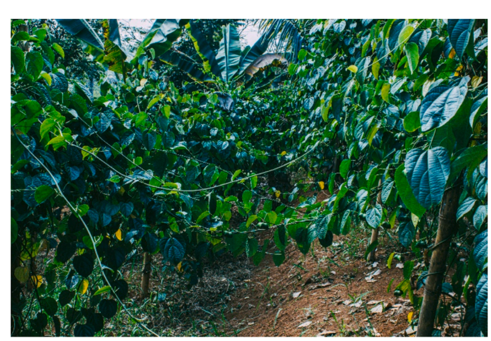

Fig. 2. Sacha Inchi plant *(Plukenetia volubilis* L.*)*.

3. Sacha Inchi

Fig. 2 demonstrates that Plukenetia volubilis is a plant indigenous to the Amazon region and has been utilized since the era of the Incas. This plant, belonging to the *Euphorbiaceae* family, is recognized for its oil- and protein-rich seeds and possesses considerable potential for advancement as a functional food crop worldwide (Supriyanto et al., 2022).

Sacha Inchi (*Plukenetia volubilis* L.) has morphological traits typical of this dioecious climbing species, reaching heights of up to two meters, featuring heart-shaped leaves and diminutive, unisexual flowers. The plant generates star-shaped capsules that enclose 4–7 seeds, each measuring around 1.5–2 cm in diameter (Brishti et al., 2025). A report has been generated on the morphological diversity of Plukenetia volubilis, encompassing variations in leaf morphology, stem dimensions, and fruit morphology among populations. This plant possesses climbing stems, or lianas, and huge, cordate leaves with oil-rich seeds. In comparison to agroforestry (Cardoso et al., 2015) or intercropping methods, Sacha Inchi growing in open areas demonstrates superior seed productivity. The total unsaturated fatty acid content stays elevated throughout all conditions, however essential fatty acid levels exhibit minor variations among cultivation techniques. Sacha Inchi (*Plukenetia volubilis* L.) exhibits significant tolerance to warm, humid tropical climates. It flourishes in diverse growing systems; nevertheless, research indicates that open-field cultivation produces the highest seed output, rendering it the optimal approach for commercial oil production. Although agroforestry systems may exhibit elevated omega-3 fatty acid levels, total seed yield is superior in open-field farming (Supriyanto et al., 2022).

Fig. 3 illustrates the seeds of The oil derived from Sacha Inchi seeds comprises roughly 52 % omega-3 fatty acids, about 34 % omega-6, and approximately 8 % omega-9 (Salimi et al., 2025) It is abundant in natural antioxidants, including tocopherols, along with several bioactive components that enhance its potential health benefits and biological activity (Lu et al., 2025; Muna et al., 2024).

Sacha Inchi, abundant in protein and high-quality vegetable oil, has been utilized by indigenous Peruvians, including the Incha, as a food source and traditional remedy for an extended period. This herb has long been utilized for its multifaceted and health-enhancing attributes to bolster immunity and avert numerous chronic ailments (Li et al., 2022; Panpa et al., 2024). Table 1 delineates several benefits and conventional use of the oil.

Sacha Inchi oil has been employed in pharmaceuticals and provides numerous advantages in cosmetic, medicinal, and nutraceutical domains. This is due to its fatty acid profile, mostly consisting of omega-3 and omega-6 fatty acids, which collectively comprise over 80 % of its total fatty acid content. Essential fatty acids significantly reduce the risk of cardiovascular illnesses (Alayón et al., 2018), chronic inflammation, and metabolic disorders (Lourith et al., 2024; Rodríguez et al., 2021). He oil contains tocopherols, particularly γ-tocopherol, which functions as a natural antioxidant (Szewczyk et al., 2021), present in amounts ranging from 120 to 140 mg per 100 g. The oil is an effective element in the prevention and mitigation of chronic diseases, as these tocopherols aid in preventing cellular damage and diminishing oxidative stress (Lupi et al., 2025; Reys et al., 2021). Furthermore, it comprises several phytosterols, such as stigmasterol and β-sitosterol (Sun et al., 2020), which assist in regulating blood pressure and reducing cholesterol levels. This renders it possibly beneficial in averting diabetes, coronary heart disease, and numerous other metabolic illnesses (Fanali et al., 2011). The oil serves as a valuable functional dietary component, particularly in breads and plant-based beverages. It is frequently designated as a superfood because to its elevated nutritional value. Moreover, owing to its hydrating attributes and capacity to foster healthy skin, this oil is extensively utilized in cosmetics (Lu et al., 2025; Norhazlindah et al., 2023).

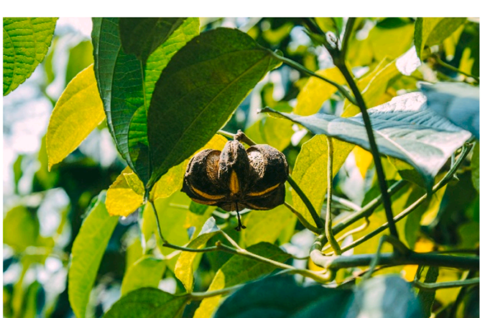

Fig. 3. Sacha Inchi seeds (*Plukenetia volubilis* L.).

Table 1
The advantages of Sacha Inchi oil.

Aspect	Advantage	Traditional usage	Reference
High Nutritional Composition	Rich in omega-3 fatty acids (α-linolenic acid), omega-6, and omega-9	It helps cardiovascular and metabolic health.	(Goyal et al., 2022; Wang et al., 2018)
Antioxidant content	Contains high levels of tocopherols (γ and δ) and phenolics.	It functions as a natural antioxidant	(Lourith et al., 2024; Rodríguez et al., 2021)
Pharmacological properties	Phenolic and Flavonoid	As an antimicrobial and prevents chronic inflammation.	(Lupi et al., 2025; Silalahi, 2022)
Cosmetic usage	-	Its oil content can be used to hydrate the skin.	(Wang et al., 2018)
As a functional food	-	Developed as a "superfood" due to its fiber, protein, and bioactive compounds	(Silalahi, 2022)

Sacha Inchi *(Plukenetia volubilis* L.) oil is abundant in α-linolenic acid (omega-3) and linoleic acid (omega-6), both of which confer health benefits; yet, it is particularly prone to lipid oxidation, potentially compromising its quality. Consequently, to preserve the oil's stability and safeguard its bioactive components from oxidative degradation, transformation technologies such as microencapsulation, co-microencapsulation, and nanoemulsion are essential (Otálora et al., 2020). Further constraints are delineated in Table 2.

The cold-pressing procedure is often employed to maintain the nutritional content and stability of Sacha Inchi oil. This technique prevents elevated temperatures during the pressing process, hence ensuring a stable composition of unsaturated fatty acids (Mehta et al., 2024) and preserving the levels of tocopherols and polyphenols (Nguyen et al., 2020; Redjeki et al., 2025). The oil poses considerable difficulties because to its pronounced vulnerability to lipid oxidation and its potent fragrance. Consequently, to enhance its stability and prolong its shelf life (Lonnie et al., 2020), transformation technologies such as encapsulation, microencapsulation, and nanoemulsion are essential. These technologies can be applied across multiple sectors, including food, pharmaceuticals, cosmetics, and as raw materials for sustainable enterprises (Garcia Pallo et al., 2025; Torres Sánchez et al., 2023).

The main aim of utilizing encapsulation, co-microencapsulation, and nanoemulsion technologies for Sacha Inchi oil (*Plukenetia volubilis* L.), as demonstrated in Table 3, is to mitigate issues associated with lipid oxidation stability, prolong shelf life, and improve the bioavailability of the oil's bioactive compounds.

4. Variations in Sacha Inchi modification techniques

Sacha Inchi oil, abundant in α-linolenic acid (omega-3) and natural

Table 2
The drawbacks of Sacha Inchi oil before modification.

Drawback	Explanation	Reference
Prone to oxidation	The high content of unsaturated fatty acids makes this oil prone to deterioration if not stored properly.	(Otálora et al., 2020)
Low storage stability	Techniques such as encapsulation are needed to extend shelf life and preserve its nutritional composition	(Garcia Pallo et al., 2025; Torres Sánchez et al., 2023)
Production costs are relatively high for environmentally friendly extraction methods	Methods such as supercritical CO_2 and enzymatic extraction are more expensive and require specialized technology	(Nguyen et al., 2020; Redjeki et al., 2025)
Strong aroma and flavor	Crude oil has a distinct smell and taste that may not be liked by all consumers, limiting its use in certain food products	(Otálora et al., 2020)
Short shelf life	Without protective technology, bioactive compounds such as tocopherols and polyunsaturated fatty acids (PUFAs) degrade quickly during storage	(Rodríguez et al., 2021)

antioxidants, holds significant significance as an ingredient in health (Poomanee et al., 2024), cosmetic, and nutraceutical goods; nonetheless, it need technical preservation to enhance its stability against lipid oxidation. Nonetheless, its oxidative instability continues to pose a significant obstacle that restricts its wider utilization. Various modification procedures have been devised to improve the stability of the oil and prolong its shelf life. Table 4 delineates the modification approaches, which comprise encapsulation, co-microencapsulation, and nanoemulsion. Each of these methodologies provides distinct benefits in enhancing oxidative protection and extending the shelf life of Sacha Inchi oil.

4.1. Modification techniques

4.1.1. Encapsulation

Encapsulation is the process of enclosing an active pharmaceutical ingredient (API) within a protective medium, including polymers, lipids, or natural biopolymers (Fig. 4). The primary objectives of encapsulation are to protect the medication from external environmental factors (e.g., light, heat, humidity, acidic media), enhance its stability, control its release, mask unpleasant taste or odor of the activeingredient, and facilitate targeted delivery within the organism (Henrique et al., 2020; Klojdová et al., 2023; Yan & Kim, 2024).

Sacha Inchi oil is a plant-derived lipid rich in polyunsaturated fatty acids, including alpha-linolenic acid (omega-3), linoleic acid (omega-6), and oleic acid (omega-9). Despite its high nutritional value, this oil is especially susceptible to oxidative degradation, leading to a decline in sensory quality, nutritional content, and functional stability. Thus, encapsulation technique is crucial for preserving the chemical and physical stability of the oil during storage and its use in final products. Various encapsulation techniques and materials have been employed to improve encapsulation efficiency, oxidative stability, and the release profile of the active constituents in the oil.

1. Spay Drying

Spray-drying encapsulation use elevated temperatures, generally over 100 °C, to convert a liquid solution into powder by atomizing it into a current of hot air. This method is frequently employed to generate microcapsules encapsulating active substances for use in food or nutraceutical products, providing regulated particle size and morphology (Zhang et al., 2020). The benefits of the spray drying technique encompass industrial scalability, economic efficiency, elevated production rates, compatibility with diverse coating materials, and the capacity to process thermolabile compounds owing to the brief drying duration (Valková et al., 2022). The quality of spray-dried microcapsules is significantly influenced by the established operational parameters (Aghbashlo et al., 2013; Emami et al., 2018).

The spray drying process demonstrated that maltodextrin and sodium caseinate (Na-Cas) as carrier materials effectively preserved the oxidative and thermal stability of Sacha Inchi oil while retaining sensory quality. The p-anisidine value (1.43) and TBARS value (2.62) on day 15 indicate that the microcapsules were effective in suppressing the formation of secondary oxidation compounds and maintaining oil quality. The FTIR analysis revealed characteristic peaks of the –O–H group (3300 cm^{-1}), –C–H groups (2927 and 2855 cm^{-1}), and –C=O (1746 cm^{-1}), confirming the presence of encapsulated oil, as well as amide I (1650 cm^{-1}), amide II (1517 cm^{-1}), 1158 cm^{-1}, and 1025 cm^{-1} peaks, which demonstrate the functional roles of sodium caseinate and maltodextrin as wall materials. The absence of new peaks confirms that no chemical interactions occurred and that the microcapsule structure remained stable. These findings are based on a single study and therefore cannot yet be generalized to all the oil spray-drying systems (Avendaño et al., 2025).

To enhance the reproducibility of this study, additional information has been provided regarding the general conditions of the spray-drying process, which typically operates at an inlet temperature of 150–250 °C and an outlet temperature of 50–80 °C. This process produces particles ranging from nanometers to several hundred micrometers in size, depending on the preparation method and the type of wall material used. Encapsulation in food applications requires food-grade wall materials capable of protecting the core substances, such as synthetic polymers or natural biomaterials. The evaluation of spray-dried products is commonly conducted through FTIR analysis, morphological characterization using SEM/TEM, and physical and chemical stability assessments to ensure the integrity of the microencapsulation (Mohammed et al., 2020).

The combination of camu-camu and mango peel extracts with gum arabic via spray-drying demonstrates enhanced oxidative protection relative to the synthetic antioxidant BHT (Landines Vera et al., 2024). This formulation markedly diminishes the degradation of omega-3 fatty acids during storage. The findings suggest that natural bioactive chemicals from fruit peels serve as potent antioxidants within the oil microencapsulation mechanism (Alarcón et al., 2020).

A different formulation utilizing maltodextrin (MD), gum arabic (AG), and whey protein concentrate (WPC) by spray-drying has yielded

Table 3
The purpose of modification techniques.

Modification Techniques	Objective	Expected Results	Reference
Encapsulation	Protecting the oil from oxidation and light.	Maintaining stability and extending shelf life.	(Otálora et al., 2020)
Co-microencapsulation	Combining two or more protective materials to enhance the effectiveness of protection and release.	Synergistic effect in oil stabilization and enhancement of bioactive efficiency	(Chasquibol et al., 2024)
Nanoemulsion	Converting the oil into nano-sized droplets to enhance absorption in the body and topical products	Higher bioavailability, better physical and chemical stability	(Vu et al., 2024)

Table 4
Variation of Sacha Inchi modification methods.

Modification Techniques	Active Ingredients	Coating Material	Preparation Methods	Results	Reference
Encapsulation	Sacha Inchi Oil	Lecithin and Tween 80	Freeze drying	Encapsulation efficiency of 59.94–72.29 %, particles <3.27 μm, high oxidative stability, and shelf life up to 21 days	(Suwannasang et al., 2021)
	Sacha Inchi Oil	Non-ionic surfactant, poloxamer 407, chitosan, and alginate	Ultrasonic Emulsification	Successfully encapsulated Sacha Inchi oil with high stability and controlled release, making it suitable as a drug delivery system.	(Elgegren et al., 2019)
	Sacha Inchi Oil	Sodium alginate, Tween 20, and Tween 80	Emulsification (Low-Energy Emulsification)	It results in an encapsulation efficiency of over 99 % with improved oxidative stability, reducing the Peroxide Value (PV) from 132 to 44 meq O_2/kg	(Silva et al., 2019)
	Sacha Inchi Oil	Maltodextrin, sodium caseinate (Na Cas)	Spray Drying	Sacha Inchi Oil (SIO) microencapsulation with maltodextrin and sodium caseinate (ratio 1.7:0.2) shows the best thermal and oxidative stability (p-AN: 1.43; TBARS: 2.62 on day 15), without chemical interaction between components. It is suitable for functional food applications.	(Avendaño et al., 2025)
	Sacha Inchi oil, camu-camu skin, and mango	Gum arabic	Spray Drying	Microcapsules with fruit peel extract provide better oxidative protection for Sacha Inchi oil compared to BHT, with lower $\omega-3$ loss	(Alarcón et al., 2020)
	Sacha Inchi Oil	Maltodextrin (MD), gum arab (AG), konsentrat protein whey (WPC)	Spray Drying	SIO microcapsules show high encapsulation efficiency, low moisture content, small particle size, and optimal oxidative stability	(Landoni et al., 2020)
	Sacha Inchi Oil	Ovalbumin, Xanthan Gum, Pektin (PEC)	Freeze drying	SIO microencapsulation with Ova, pectin, and xanthan gum through emulsification and freeze-drying enhances the thermal and structural stability of omega-3. The SIO-Ova-Pec and SIO-Ova-XG formulations effectively protect omega-3 during digestion simulation, making them potential candidates for nutraceutical applications	(Vicente et al., 2017)
	Sacha Inchi Oil	Ovalbumin (OVA), Tannic Acid (TA), Pectin (PEC)	Coacervation Technique	SIO microencapsulation using complex coacervation with OVA, TA, and PEC results in microcapsules with an EE% of 70–80 %, high thermal stability, and no changes in chemical composition. TA enhances the nutritional value of the capsules	(da Silva Soares et al., 2021)
	Sacha Inchi Oil	Lycopodium clavatum spores	Spray Drying	Lycopodium clavatum spores are used as natural microcapsules to encapsulate SIO with an efficiency of 51.2 % and a loading capacity of 29.3 %. The microcapsules exhibit antioxidant activity, rapid SIO release under pressure, and high cell viability (88 %), making them a promising candidate for cosmetic applications	(Khann et al., 2023)
	Sacha Inchi Oil	Zein, maltodextrin, Tween 80	Freeze Drying	SIO microencapsulation in yogurt using SDSOM (maltodextrin + modified starch) results in better physicochemical stability, lower syneresis, and higher free fatty acid release compared to non-encapsulated SIO. SDSOM is more suitable for fortifying functional yogurt	(Suwannasang et al., 2022a)
Co-Microencapsulation	Sacha Inchi Oil with natural antioxidant extract	Gum Arabic, maltodextrin, whey protein isolate	Spray Drying	Shows better protection against oxidation compared to synthetic antioxidants	(Chasquibol et al., 2023)
	Sacha Inchi oil with grape pomace and ají chili	Gum Arabic, cushuro polysaccharide	Spray drying	Co-microencapsulation of cushuro with grape pomace extract and ají charapita chili results in microcapsules with better oxidative stability and shelf life compared to the synthetic antioxidant BHT.	(Chasquibol et al., 2024)
Nanoemulsion	Sacha Inchi Oil	Steareth 2 and Steareth 20	Ultra-turrax homogenizer Ultra High 40.000 psi	The optimum HLB is HLB 8, which results in lower viscosity, smaller droplet size, and a more homogeneous system	(Rave et al., 2020)
	Sacha Inchi oil with fish scale collagen	Tween 80, polyethylene glycol, Collagen Peptide	Response Surface Methodology (RSM) method	High stability and potential for delivering nutraceuticals and vitamins	(Vu et al., 2024)
	Sacha Inchi oil and avocado oil	Lecithin, glycerol monostearate	Ultra-turrax homogenizer at 4000 rpm for 10 min	The oleogel formulation of avocado oil/SIO (80:20) with glycerol monostearate exhibits a semisolid pseudoplastic character, two melting points (−20.15 to −18.94 °C and 40.25 to 61.04 °C), and the best rheological stability with high consistency and tan $\delta < 0.5$	(Herazo et al., 2019)
	Sacha Inchi oil and phenolic compounds from olive leaves	Span 80 surfactant	magnetic stirring 30 °C for 15 min	W/O nanoemulsion based on SIO with olive leaf phenolics (OLP) (droplet size ~2.15 nm) exhibits high stability for 30 days and effectively enhances the oxidative stability of SIO, prolonging the induction time and protecting PUFAs and tocopherols from oxidation	(Liu et al., 2018)
	Sacha Inchi Oil	Span 80, Cremophor RH40, Tween 20	Inversion Phase Emulsification (EPI) low energy method	Sacha Inchi nanoemulsion for cosmetic applications was successfully developed using the EPI method. The smallest droplet size (41.43 nm) and high stability were achieved under optimal surfactant conditions and SOR ratio	(Tunkam & Satirapipathkul, 2016)

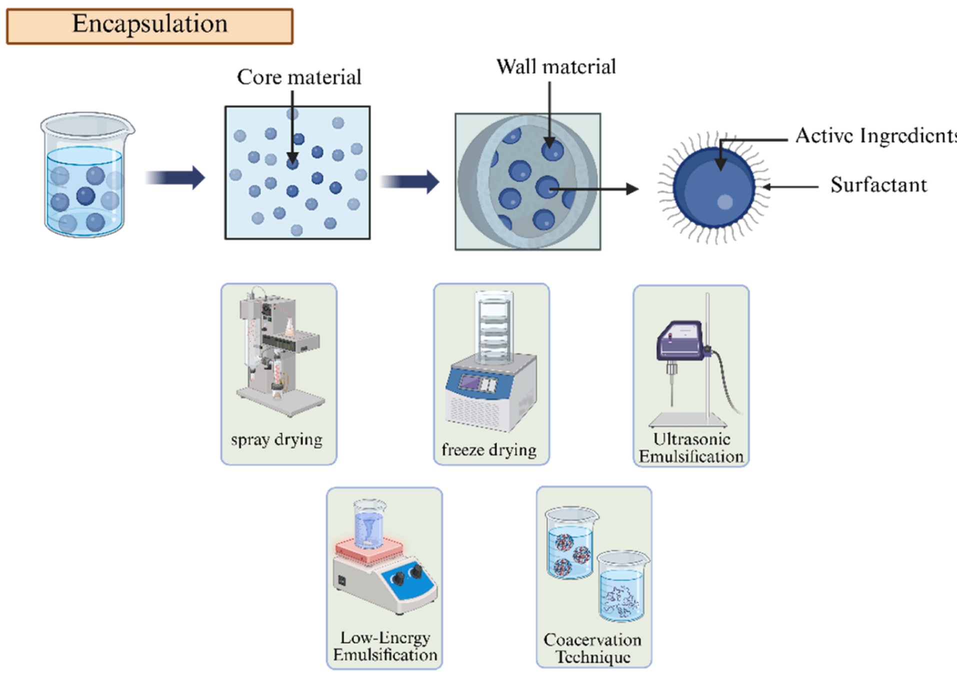

Fig. 4. The procedural framework of the encapsulation technique (Created in BioRender, https://biorender.com/pg8jjpu).

microcapsules with enhanced physicochemical properties, such as elevated encapsulation efficiency, reduced moisture content, and diminutive particle size. The amalgamation of carbs and proteins creates a uniform protective matrix that maintains stability during spray-drying, rendering it suitable for functional food applications necessitating prolonged shelf life (Landoni et al., 2020; Šavikin et al., 2021).

A distinctive method utilizes Lycopodium clavatum spores as natural capsules by spray-drying. Despite a relatively low encapsulation effectiveness of 51.2 %, this system has a substantial loading capacity of 29.3 %, quick release properties under pressure, and a high cell survival rate of 88 %. These findings underscore its potential for cosmetic applications, where fast release and dermal safety are essential issues (Khann et al., 2023).

2. Freeze drying

Encapsulation using the freeze-drying method is employed to enhance the stability and shelf life of Sacha Inchi oil. This process involves freezing the oil emulsion, followed by the sublimation of water vapor under vacuum conditions. The technique can produce particles with smaller sizes and more uniform distribution, thereby improving encapsulation efficiency. Conversely, freeze drying is a dehydration technique that yields high-quality products characterized by exceptional stability and ease of handling (Camacho et al., 2018). Nonetheless, it possesses disadvantages, such as elevated expenses and prolonged processing durations (Stratta et al., 2020).

Freeze-drying is generally conducted at a freezing temperature of −20 to −50 °C under vacuum pressure below the triple point of water (~610 Pa) to allow sublimation, followed by primary drying at −10 to +20 °C and secondary drying at 20–40 °C (Bakry et al., 2016). The sublimation process requires approximately 2885 kJ/kg of energy, necessitating careful heat supply control to prevent ice melting and collapse of the capsule structure (Nowak, 2020). Encapsulation evaluation was performed by comparing unencapsulated Sacha Inchi oil with oil encapsulated using various wall materials (maltodextrin, gum arabic, and proteins) and two drying methods (freeze-drying and spray-drying). The assessment criteria included encapsulation efficiency (EE%), particle size and morphology (SEM/TEM), moisture content, and oxidative stability (PV, TBARS, p-anisidine). Studies reported that freeze-drying achieved EE% values of 51.22–85.71 %, whereas spray-drying reached 77.38–90.74 % (Koo et al., 2023). However, freeze-drying was superior in preserving the stability of heat-sensitive compounds, exhibiting lower TBARS and PV values compared to unencapsulated oil (Zhao et al., 2025). By including detailed process parameters and comparative controls, this study provides a more comprehensive evaluation of encapsulation efficiency and oxidative stability, while also supporting reproducibility and comparability in future studies.

In a previous study, the use of a combination of lecithin and Tween 80 in the freeze-drying process resulted in encapsulation efficiencies ranging from 59.94 to 72.29 %, with microscopic particle sizes (<3.27 μm). Although this efficiency is considered moderate, the system demonstrated the ability to maintain oxidative stability and extend shelf life for up to 21 days, indicating its capacity to slow oxidation by minimizing direct contact with oxygen. Nevertheless, the suboptimal efficiency suggests the need for further formulation development or process condition adjustments to enhance overall encapsulation performance (Suwannasang et al., 2021).

The combination of ovalbumin, pectin, and xanthan gum using the freeze-drying method has shown a significant improvement in the thermal and structural stability of omega-3 fatty acids. This formulation not only effectively preserves the integrity of the fatty acids during storage but also demonstrates protective effects during simulated digestion. Therefore, this system holds strong potential for development in nutraceutical applications that require controlled release within the gastrointestinal tract (Vicente et al., 2017).

In the context of food fortification, microencapsulation of Sacha Inchi oil (SIO) using the freeze-drying method with zein, maltodextrin, and Tween 80 particularly in the form of SDSOM (a combination of maltodextrin and modified starch) has been shown to enhance the physicochemical stability of yogurt, reduce syneresis, and improve the release of free fatty acids. These findings indicate that encapsulation not only protects bioactive components but also improves the textural and sensory properties of the final product, which is essential for the development of functional yogurt (Suwannasang et al., 2022a; Yan et al., 2022).

3. Ultrasonic Emulsification

Ultrasonic emulsification is a technique that employs ultrasonic waves to produce a stable emulsion of Sacha Inchi oil. Ultrasonic waves operating at 20–40 kHz generate acoustic cavitation, which facilitates the dispersion of oil within the aqueous phase and results in extremely small and stable oil droplets. This approach is highly effective for nanoparticle formation, making it valuable for various medicinal applications.

(Sinsuebpol & Changsan, 2020).

This process breaks oil droplets into extremely small droplets with a homogeneous distribution, thereby enhancing encapsulation efficiency. Typical processing conditions include a power of 200–500 W, an amplitude of 30–70 %, and a duration of 5–15 min, with the temperature maintained below 30 °C to prevent thermal degradation. Previous studies have reported consistent findings (Gurumoorthi, 2023). demonstrated that ultrasonication at 20 kHz for 15 min produced chia oil nanoemulsions with an encapsulation efficiency of approximately 93 % and droplet sizes below 200 nm (Wang et al., 2022). reported that a power input of 400 W resulted in droplet sizes of ~167.77 nm and an encapsulation efficiency of 86.26 % (Perrin et al., 2022). further confirmed that ultrasonication reduces polydispersity and increases zeta potential, thereby improving emulsion stability. Performance evaluation typically includes droplet size, encapsulation efficiency (EE%), morphology (SEM/TEM), zeta potential, and oxidative stability parameters (PV, TBARS, p-anisidine). Overall, ultrasonication offers advantages such as shorter processing time, smaller particle size, and better oxidative protection compared to conventional emulsification methods.

Ultrasonic emulsification utilizing chitosan, alginate, and the nonionic surfactant Poloxamer 407 in the development of delivery systems has shown benefits for nanoparticle size, physical stability, and controlled release properties. Chitosan and alginate form a stable polyelectrolyte complex, whereas Poloxamer 407 improves the interfacial stability between the oil and aqueous phases. This technology is well-suited for pharmaceutical applications as a drug delivery strategy due to its capacity to increase bioavailability and efficiently transport active compounds to specified biological targets (Elgegren et al., 2019).

4. Low Energy Emulsification

Low energy emulsification facilitates the production of nanoemulsions without substantial mechanical energy input, such as high-speed mixing or high-pressure homogenization. This method employs spontaneous thermodynamic processes resulting from alterations in the system's composition (e.g., the ratios of oil, surfactant, and air) or from variations in external factors such as temperature and pH. As such, it is highly suitable for heat- or shear-sensitive substances, including pharmaceuticals and certain food ingredients (Anton & Vandamme, 2009).

The low-energy emulsification method involves mixing two phases (water and oil) with minimal mechanical input. Surfactants are typically employed to help maintain emulsion stability, making the process simpler and more energy-efficient. A combined approach utilizing low-energy emulsification and ionic gelation with sodium alginate and the surfactants Tween 20 and 80 has demonstrated exceptionally high encapsulation efficiency (>99 %). The reduction in peroxide value from 132 to 44 meq O_2/kg indicates significant protection against primary oxidation. The advantages of this method lie not only in its high efficiency but also in its simplicity and energy-saving nature, making it particularly suitable for industrial-scale production where cost-effectiveness and process sustainability are critical considerations (Silva et al., 2019).

5. Coacervation Technique

Coacervation is a process wherein two liquid phases contact and adhere to create small droplets that can encapsulate active substances, such as Sacha Inchi oil. This method is commonly employed for encapsulating active chemicals within polymer systems, where an oil-containing liquid phase is combined with a polymer or binding agent (Amiruddin et al., 2023; Sponton et al., 2017)(Tavares & Noreña, 2020).

The coacervation technique employing ovalbumin (OVA), pectin (PEC), and tannic acid (TA) yielded microcapsules with encapsulation efficiency ranging from 70 to 80 percent. This formulation exhibited significant thermal stability, preserved the chemical makeup of Sacha Inchi oil, and increased its nutritional value by the incorporation of TA as a bioactive phenolic molecule (da Silva Soares et al., 2021).

The choice of carrier materials and encapsulation techniques substantially influences the microencapsulation of Sacha Inchi oil. Methods based on proteins and polysaccharides have demonstrated superior oxidative and thermal protection, especially when combined with natural bioactive substances. Meanwhile, the application of the delivery system must be tailored to its intended end use, including cosmetic products, nutritional supplements, and food items. Therefore, the development of an appropriate encapsulation system is crucial in determining the effectiveness of the oil utilization within bioactive product industries.

4.2. Co-microencapsulation

Co- In general, co-microencapsulation is a method that enables two or more bioactive compounds to be encapsulated within a single microparticle to enhance the stability, efficacy, and controlled release of these compounds (Fig. 5). Its fundamental principle is similar to that of single-compound microencapsulation; however, co-microencapsulation offers the added advantage of synergistic interactions between active compounds and encapsulating materials, allowing for extended shelf life and a reduction in the amount of active ingredients required (Arenas-Jal et al., 2020; Chawda et al., 2017).

The co-microencapsulation of Sacha Inchi oil with natural antioxidant extracts, using a combination of gum arabic, maltodextrin, and whey protein isolate as carrier materials through the spray drying process, has been shown to provide superior oxidative protection compared to the use of synthetic antioxidants. This amalgamation of carrier materials functions as a physical matrix that protects the oil from light and oxygen while fostering a synergistic interaction between the oil and phenolic antioxidant chemicals. Gum arabic and maltodextrin augment the efficacy and stability of microencapsulation by enhancing film-forming ability and viscosity. Whey protein isolate facilitates the development of an elastic and thermally stable capsule network (N. Chasquibol et al., 2023; Lam et al., 2017).

The co-microencapsulation approach has been established in prior research utilizing orujo grape extract, aji charapita pepper, and cushuro polysaccharide, a natural biopolymer derived from microalgae, as wall components in the spray-drying process. This formulation, in comparison to BHT as a synthetic antioxidant, has demonstrated an improvement in the oxidative stability and shelf life of Sacha Inchi oil (SIO). The polysaccharide content and bioactive compounds in cushuro strengthen the microcapsule matrix, while the phenolic compounds from orujo and capsaicin from aji charapita chili augment overall antioxidant activity, offering dual protection: physical protection via the polymer matrix and psychological protection through the silver matrix (N. Chasquibol et al., 2024).

The second finding indicated that co-microencapsulation markedly enhanced the stability of Sacha Inchi oil while integrating the nutritional advantages of natural bioactive compounds. The efficacy of this treatment illustrates that co-microencapsulation is an effective technique for safeguarding and augmenting nutritional content. The utilization of indigenous materials like cushuro polysaccharides and aji charapita reinforces the notion of plenty and creates prospects for the advancement of local enterprises dependent on bioresources (Eadmusik et al., 2024).

Consequently, spray drying co-microencapsulation techniques that integrate polysaccharides and proteins as protective agents with natural antioxidant compounds may constitute an innovative and efficient strategy for maintaining the functional integrity of the oil. This method holds potential for application in the functional food and lipid-based health product industries, while also aligning with global trends toward replacing synthetic additives with natural compounds.

4.3. Nanoemulsion

Nanoemulsion is a dispersion of one liquid within another in which

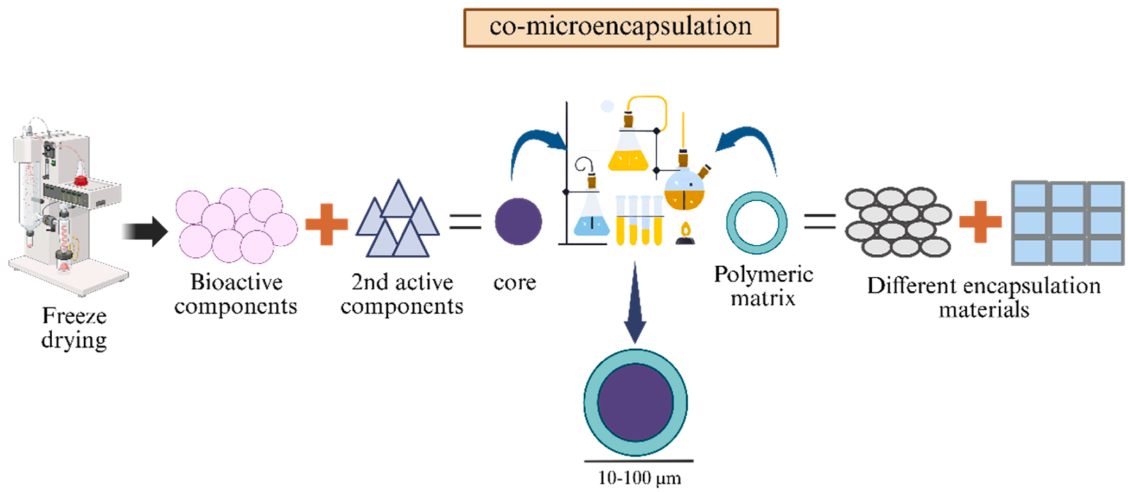

Fig. 5. The process scheme of the co-microencapsulation method (Created in BioRender, https://biorender.com/t7hy3xz).

the droplet size typically ranges from 20 to 500 nanometers, stabilized by emulsifiers or surfactants (Fig. 6) (Jaiswal et al., 2015; K. & Kumar, 2022). Nanoemulsions are widely utilized in the pharmaceutical, food, cosmetic, and other material-related industries due to their unique properties, such as optical transparency, physical stability, and large surface area (Chavda et al., 2024; Shao & Tang, 2014). Nanoemulsions can enhance the stability, bioavailability, and solubility of active compounds that are poorly soluble in water, such as drugs or nutrients (Ozogul et al., 2022). In the manufacturing process, high-energy methods (such as high-pressure homogenization, ultrasonication) or low energy methods (such as phase inversion, spontaneous emulsification) can be utilized. The method chosen depends on the intended purpose and desired characteristics, such as stability and quality of the nanoemulsion. The formulation, dimensions, droplet charge, and surfactant type employed also affect the quality of the nanoemulsion (Chavda et al., 2024; K. & Kumar, 2022).

Creating a nanoemulsion system for Sacha Inchi oil (SIO) is a strategic method to improve stability, bioavailability, and variety of application in functional food, cosmetics, and pharmaceuticals. Owing to the inherent characteristics of SIO, which is abundant in unsaturated fatty acids, a uniform, stable, and safeguarded dispersion mechanism is essential.

The study utilized ultra-high-pressure homogenization (UHPH) technology at 40,000 psi to mix the surfactants steareth-2 and steareth-20. The findings indicated that the optimal Hydrophilic-Lipophilic Balance (HLB) value is 8, signifying reduced viscosity, enhanced homogeneity, and minimized droplet size. The diminutive droplet size is essential for improving physical stability and prolonging the emulsion's shelf life (Rave et al., 2020)

A supplementary formulation incorporating Tween 80, collagen peptides, and polyethylene glycol (PEG) was created via response surface methodology (RSM). This formulation has exceptional physical stability, rendering it the optimal selection for the delivery of active compounds such as vitamins and minerals. Moreover, the collagen content in the system augments its value through bioactive properties and excellent biocompatibility, rendering it ideal for medicinal and

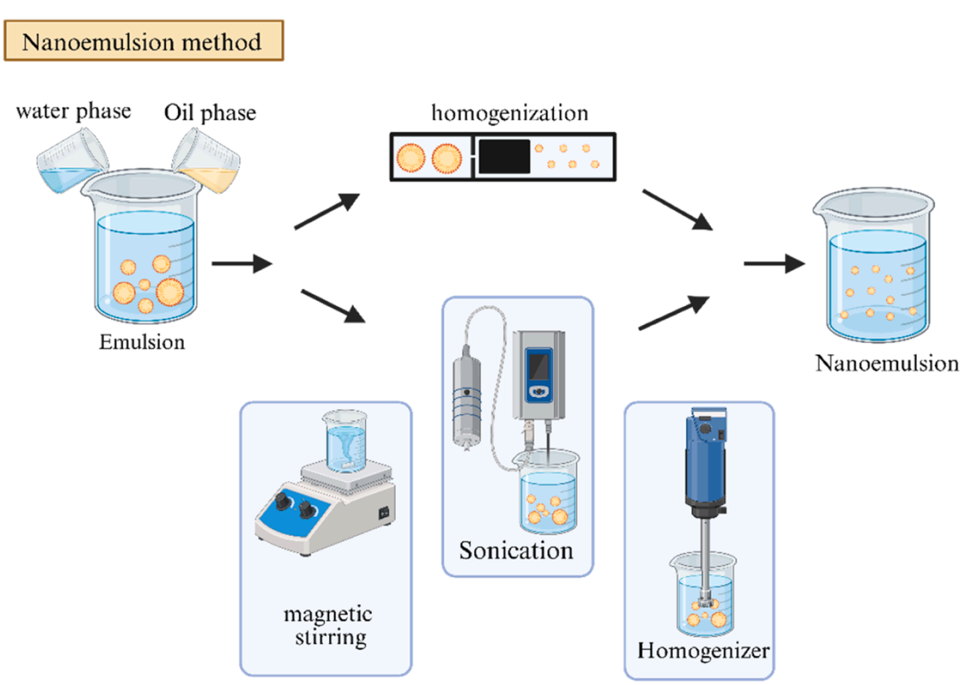

Fig. 6. The procedural framework of the nanoemulsion technique (Created in BioRender, https://biorender.com/i9z7md9).

cosmetic applications (Vu et al., 2024).

Oleogel, composed of Sacha Inchi oil (SIO) and a minor proportion of avocado (80:20), integrates glycerol monostearate and lecithin as structural components. The semi-solid oleogel, demonstrating pseudoplastic rheology and two distinct melting temperatures (−20.15 to −18.94 °C and 40.25 to 61.04 °C), is generated by the ultra-turrax homogenization process at 4000 rpm. A tan value of 0.5 signifies high viscoelastic stability. This oleogel is advantageous for integrating healthy fats into culinary dishes or semi-solid salads (Herazo et al., 2019).

This work utilized olive leaf phenolics (OLP), Span 80 surfactant, and a water-in-oil (W/O) nanoemulsion. This nanoemulsion was formed using magnetic stirring for 15 min at 30 °C. The resultant droplet size was notably diminutive, roughly 2.15 nm. The emulsion exhibited significant stability for 30 days and improved protection against the oxidation of tocopherol and polyunsaturated fatty acids (PUFA). An extended oxidation induction time suggests that olive leaf phenolics function as natural antioxidants in the oil phase (Fanali et al., 2011; Liu et al., 2018).

The findings indicated that the optimal surfactant ratio yielded a stable system with a droplet size of 41.43 nm. Span 80, Cremophor RH40, and Tween 20 served as surfactants in the low-energy phase inversion emulsification method. This nanoemulsion can be utilized in cosmetic items due to its ability to preserve its physical quality throughout storage (Tunkam & Satirapipathkul, 2016).

The surfactant type, emulsification technique, and intended application affect the creation of Sacha Inchi oil nanoemulsions. Ultra-high pressure homogenization (UHPH) and phase inversion emulsification (EPI) techniques facilitate the production of sub-nanoparticle sizes with enhanced stability. The incorporation of collagen and natural phenolic compounds enhances the system's functional value and prolongs its oxidative stability. Oleogel renders this oil appropriate for incorporation into semi-solid formulations with regulated rheological characteristics (Lei et al., 2020).

The nanoemulsion method for Sacha Inchi oil (SIO) functions as a physical dispersion mechanism and a delivery platform. This secondary role facilitates the amalgamation of several technical and health advantages.

5. Challenges in modification and future prospects

The challenges in modifying Sacha Inchi oil is particularly prone to lipid oxidation because of its elevated unsaturated fatty acid composition. This presents a significant obstacle in its alteration by encapsulation, co-microencapsulation, and nanoemulsion techniques. Therefore, to preserve its quality and stability (Sanchez-Reinoso & Gutiérrez, 2017). The modification of oil through encapsulation, co-microencapsulation, and nanoemulsion technologies presents several technical challenges due to its high content of polyunsaturated fatty acids, which makes the oil highly susceptible to oxidation.

Previous studies report that microencapsulation can reduce oxidation rates; however, lipid degradation still occurs, with omega-3 losses of approximately 6 % and tocopherol reductions of up to 30 % during processing and storage (Rodríguez-Cortina et al., 2022). Encapsulation efficiency (EE%) varies considerably depending on the technique used. Freeze-drying typically yields EE values ranging from 55 to 75 %, whereas spray-drying results in higher efficiencies of 75–90 %, and nanoemulsification can achieve 85–95 % with droplet sizes below 200 nm (Gurumoorthi, 2023; Koo et al., 2023; Wang et al., 2022). In terms of oxidative stability, non-encapsulated oil shows peroxide value (PV) increases up to two- or three-fold within 14–30 days, while microencapsulation significantly slows oxidation, reducing PV accumulation by 50–70 % (Zhao et al., 2025). Nanoemulsion systems further enhance stability, with reductions in droplet polydispersity and increases in zeta potential that inhibit coalescence (Perrin et al., 2022).

The choice of wall materials including maltodextrin, gum arabic, whey proteins, pectin, and biopolymer composites influences EE, particle size, and storage stability. Recent advances demonstrate that composite biopolymers such as pectin–alginate or maltodextrin–gum arabic can improve EE beyond 90 % and decrease oxidation rates by up to 40 % compared to single-polymer systems. Future opportunities include optimizing energy-efficient drying processes, improving polymer–bioactive interactions, and adapting encapsulation technologies for industrial scalability, as laboratory-scale performance often fails to translate directly to large-scale production. These approaches have been extensively employed to improve the stability and bioavailability of the oil. Nonetheless, numerous constraints frequently result in suboptimal outcomes, including a reduction in omega-3 fatty acid content by as much as 6 % and a fall in tocopherol levels by up to 30 %. The selection and combination of coating materials substantially influence encapsulation efficiency; for example, employing whey protein isolate (WPI) (Ingrassia et al., 2019) may reduce efficiency and result in unfavorable cholesterol levels (Chasquibol et al., 2019; Landoni et al., 2020; Suwannasang et al., 2022a).

While encapsulation may improve oxidative stability, many formulations continue to suffer oxidation of unsaturated fatty acids, resulting in rancid aromas or flavors. The co-microencapsulation of natural antioxidants can enhance stability; nevertheless, additional research is required to understand the interactions between bioactive components and the coating matrix, particularly for industrial-scale applications (Chasquibol et al., 2023, 2024). Nonetheless, nanoemulsions and nanoparticle encapsulation can provide particles characterized by diminutive diameters and enhanced stability. Nonetheless, their procedures and formulations are often intricate and susceptible to variations in surfactant concentration and processing conditions (Elgegren et al., 2019). The choice and combination of polymers such as maltodextrin, gum arabic, proteins, pectin, or other polymers significantly influence the encapsulation efficiency, oxidative stability, particle size, and the product's shelf life (N. Chasquibol et al., 2023; da Silva Soares et al., 2021; Suwannasang et al., 2022a). In co-microencapsulation with the addition of natural antioxidants, another challenge is ensuring synergistic interactions between the oil and bioactive compounds without compromising stability or bioavailability (N. Chasquibol et al., 2023). Controlling particle size to maintain stability, preventing aggregation, and ensuring controlled release of active substances in biological environments are key challenges in nanoemulsions (Elgegren et al., 2019).

Drying processes such as spray drying or freeze drying must also be optimized to prevent damage to sensitive components and to produce capsules with the desired morphology and physical properties (Landoni et al., 2020; Suwannasang et al., 2022a). Industrial-scale production also presents its own challenges, as formulations that are optimal in the laboratory may not be stable or efficient when produced on a large scale. Therefore, the modification of the oil in encapsulation systems requires a multidisciplinary approach to address challenges related to stability, efficiency, material interactions, and scalability (Sanchez-Reinoso & Gutiérrez, 2017).

The future prospects of Sacha Inchi oil modification are highly promising, particularly for enhancing stability, bioavailability, and expanding applications in the food, pharmaceutical, and cosmetic industries. Innovations in environmentally friendly extraction techniques, such as enzymatic extraction and supercritical CO2 extraction, are expected to yield high-quality oil with optimal omega-3 content and minimal chemical residues (Nguyen et al., 2020).

The advancement of microencapsulation and co-microencapsulation technologies remains centered on safeguarding oil against oxidation, prolonging shelf life, and regulating the release of active compounds in functional and medicinal goods. Furthermore, chemical alterations like epoxidation and structured lipid synthesis create new prospects for utilizing the oil as a raw material for eco-friendly lubricants and bioepoxies, while also increasing its value in nonfood sectors (Garcia Pallo et al., 2025).

Sacha Inchi oil has limitations in storage due to its high sensitivity to oxidation. It must be stored in dark, tightly sealed containers and kept at low or cool temperatures to prevent exposure to light, oxygen, and elevated temperatures that can accelerate degradation. In addition, storage under low-humidity conditions and the incorporation of antioxidants are required to maintain stability throughout its shelf life.

6. Conclusion

Sacha Inchi Oil (SIO), abundant in polyunsaturated fatty acids (PUFAs), possesses considerable nutritional and medicinal significance but is prone to oxidation, leading to diminished stability and shelf life. Diverse modification strategies have been established; encapsulation significantly prolongs shelf life and maintains bioactivity, whilst co-microencapsulation improves protection using natural antioxidants, rendering it appropriate for clean-label applications. Nanoemulsions significantly enhance bioavailability and facilitate regulated distribution, especially in medicinal and cosmetic compositions. Encapsulation is somewhat more appropriate for food goods; co-microencapsulation enhances value via antioxidant synergy, whilst nanoemulsions present the most promising platform for contemporary bioactive delivery.

Ethical statement for *applied food research*

Hereby, I am Patihul Husni consciously assure that for the manuscript **Strategies to Improve the Oxidative Stability and Shelf Life of Sacha Inchi Oil in Pharmaceutical Applications** the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

Ethics approval were waived for this study because no patients' data were reported

The violation of the Ethical Statement rules may result in severe consequences.

I agree with the above statements and declare that this submission follows the policies of Applied Food Research as outlined in the Guide for Authors and in the Ethical Statement.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist in proofreading and improving the readability of the initial manuscript draft. After using this tool, the author(s) carefully reviewed and edited the content as needed and take full responsibility for the content of the published article.

Funding sources

This research is part of the first author's master study, Indonesia Endowment Fund for Education (LPDP) under the Ministry of Finance, Republic of Indonesia, for its scholarship funding support.

CRediT authorship contribution statement

Nur Aisyah: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Feggy Yustika Sitinjak:** Writing – review & editing, Visualization. **Sriwidodo:** Writing – review & editing, Validation, Supervision, Conceptualization. **Patihul Husni:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The Author expresses sincere gratitude to Universitas Padjadjaran for supporting the publication of this article.

Data availability

No data was used for the research described in the article.

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