



Valorization of Sacha Inchi press cake: Technological advances, market, and regulatory considerations for sustainable food applications

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ABSTRACT

Sacha Inchi (*Plukenetia volubilis* L.) press cake (SP), the nutrient-dense by-product of oil extraction, is rich in high quality proteins, essential fatty acids, and bioactive compounds. However, its use remains constrained by processing, regulatory and market acceptance barriers. This review summarizes recent advances in processing strategies to improve SP's nutritional, functional, and sensory qualities. Physical treatments (dry/wet fractionation, steaming, autoclaving, roasting and extrusion) increase protein digestibility and solubility while reducing heat-stable antinutrients. Emerging methods, including high-pressure processing, high-pressure homogenization, ultrasonication, microwave treatment, electroconductivity (Ohmic/PEF), and cold plasma technologies enhance extractability and bioactivity while preserving sensitive compounds. Chemical and chemo-enzymatic approaches (e.g., alkaline soaking, cyclodextrin complexation) suppress flavor precursors, whereas enzymatic hydrolysis and fermentation improve bioactive peptide release, digestibility, and functionality. Functional additives (sweeteners, salts, polysaccharides, flavor enhancers) help mask bitterness, while paired with consumer-preferred flavors increase acceptance. Beyond processing, safety approvals (e.g., Thai FDA, EU novel food approval) and consumer perception on sensory, nutritional, and sustainability factors shape its market potential. Currently, SP shows potential across a wide range of food applications and its valorization supports sustainable protein supply chains. Future opportunities depend on integrating processing, safety, and regulatory strategies with consumer-driven innovation.

1. Introduction

Sacha Inchi (*Plukenetia volubilis* L.), also known as the “Inca peanut,” is a nutrient-rich oilseed crop native to the Amazon basin. Traditionally cultivated by Indigenous communities in Peru, the crop has gained global attention for its health-promoting oil, which is exceptionally rich in omega-3 (47–51%) and omega-6 (33–36%) fatty acids, offering a favorable ω -6/ ω -3 ratio (0.83–1.09) with implications for cardiovascular, inflammatory, and neurological health (Kodahl, 2020; Norhazlindah et al., 2022; Sierra, Rave, & Soto, 2021). In addition to its oil content (45–60%), the seeds contain high-quality protein (21–30%), vitamins, carotenoids, phytosterols, and other bioactive compounds

(Cordero-Clavijo, Chuck-Hernandez, Espinosa-Ramírez, Lazo-Vélez, & Serna-Saldivar, 2024; Torres Sánchez, Blanca, & Gutiérrez, 2023). With increasing demand, cultivation has expanded to Asia and Africa, and the global Sacha Inchi oil market is projected to reach USD 143.65 million by 2030 (Research, 2024).

However, oil extraction generates a nutrient-dense by-product, Sacha Inchi press cake (SP) comprising approximately 54.75–67.35% of the original seed mass (Kong et al., 2023). This press cake remains underexploited, despite containing 32–62% protein, 5–25% residual oil, dietary fiber (~25%), essential minerals, and a balanced amino acid profile comparable to soy (Ruiz, Díaz, Anaya, & Rojas, 2013; Vanegas-Azuero & Gutiérrez, 2018; Wang, Zhu, & Kakuda, 2018). SP also

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contains phenolic compounds with antioxidant potential (Jagersberger, 2013; Rawdkuen, Murdayanti, Ketnawa, & Phongthai, 2016). Yet, its application in food is limited due to undesirable sensory attributes (e.g., bitterness, astringency) and the presence of antinutritional factors such as tannins, phytic acid, and saponins (Cirkovic Velickovic & Stanic-Vucinic, 2017; Sharma, Tsai, Sun, Chen, Nargotra, & Dong, 2023).

To unlock SP's potential, a range of physical, enzymatic, microbial, and chemical treatments have been investigated to reduce anti-nutrients, enhance bioavailability, and improve sensory quality. Innovations such as high-pressure processing (HPP), high pressure homogenization (HPH), ultrasonication (US), microwave processing, electroconductive methods (Ohmic/PEF) demonstrate potential promising results in improving SP's techno-functional and nutritional properties. These advances support the valorization of SP as a functional ingredient for plant-based meat, dairy alternatives, bakery products and snacks.

This review critically examines the technological advances aimed at enhancing the nutritional, functional, and sensory attributes of SP. It highlights current applications in food systems, identifies limitations and regulatory challenges, and proposes future directions for research and industry adoption. Furthermore, it explores SP's role in promoting sustainable food innovation, reducing agro-industrial waste, and supporting circular bioeconomy principles.

2. Nutritional, bioactive properties and functional characteristics of Sacha Inchi press cake

2.1. Nutritional profile

SP is a protein- and fiber-rich byproduct with moderate ash and low residual fat. While the raw seeds contain 22–30% protein and 45–60% oil, oil extraction raises the protein content of SP to ~53–59% (Nete Kodahl & Sørensen, 2021; Torres-Sanchez, Hernandez-Ledesma, & Gutierrez, 2023), comparable or superior to soybean meal (Banaszkiwicz, 2011). SP proteins are nutritionally valuable, supplying all essential amino acids in adequate proportions, with notable levels of sulfur amino acids, lysine, tryptophan, and leucine (Nete Kodahl et al., 2021). Protein fractions include albumins, globulins, glutelins, and

prolamins, with albumins (~25%) being highly soluble and easily recovered (Torres-Sanchez et al., 2023), favoring food applications. Overall, the amino acid profile and fractionation indicate high biological value, reinforcing SP as a strong alternative to conventional protein sources. Summaries and comparisons with soybean meal are presented in Tables S1 and S2 (Banaszkiwicz, 2011).

2.2. Bioactive properties

SP exhibits multiple bioactivities with potential health benefits, including antioxidant, anti-hypertensive, anti-inflammatory, and anti-diabetic effects. Protein hydrolysates from SP show strong free-radical scavenging and ferric-reducing capacity, with antioxidant potency enhanced by enzymatic hydrolysis (A. Lemus-Conejo, A. Villanueva-Lazo, M. E. Martin, F. Millan, & M. C. Millan-Linares, 2024). These effects are attributed to bioactive peptides, complemented by residual polyphenols (~50 mg GAE/100 g) and tocopherols retained in the defatted meal (Alejandro Ruiz et al., 2025). *In vitro* and *in vivo* studies further demonstrate protection against oxidative stress, including reduced oxidative markers in animal models (A. Lemus-Conejo et al., 2024; Thomas et al., 2022).

2.3. Functional properties

Table 1 represents techno-functional properties of Sacha inchi press cake proteins before and after processing. SP protein isolates show excellent solubility, approaching 100% at pH ~8.0, favoring use in beverages and high-protein formulations (Rawdkuen, D'Amico, & Schoenlechner, 2022). They also display high water- (~3.0 g/g) and oil-holding capacities (~2.7–2.9 g/g), is slightly lower but remains within the range of pulse proteins (Rawdkuen, D'Amico, et al., 2022; Sathe, Kshirsagar, & Sharma, 2012). Emulsifying and foaming properties are particularly strong: albumin-rich fractions reach emulsifying activity index values of 280–370 m²/g, surpassing soy in some tests (Sathe et al., 2012; Torres Sánchez et al., 2023). SP emulsifying efficiency (~59%) and foam expansion (~55% at pH 8) outperform soy under similar conditions, with foam stability maintained at ~34% after 2 hours (Cuñaña, 2018; Torres Sánchez et al., 2023). Solubility and flexible protein structure also support remarkable foaming ability, for

Table 1

Techno-functional properties of Sacha inchi press cake proteins before and after processing.

Functional property	Native Sacha inchi press cake proteins	After processing	Key effects / Mechanisms	References
Solubility (%)	35–45; ~100% at pH ≈ 8.0 (isolate)	60–85 (after wet fractionation, alkaline extraction, ultrasonication, or microwave)	Alkaline solubilization and cavitation unfold proteins, exposing hydrophilic groups; high solubility favors beverages and protein formulations	Rawdkuen, D'Amico, and Schoenlechner (2022); Torres-Sánchez et al. (2023); Alejandro Ruiz et al. (2025)
Water-holding capacity (WHC, g water/g protein)	2.5–3.0 (≈3.0 g/g reported for isolates)	3.5–4.5 (wet fractionation, microwave, or US)	Protein unfolding exposes polar residues → higher hydration capacity	Rawdkuen et al. (2022); Landines Vera et al. (2024)
Oil-holding capacity (OHC, g oil/g protein)	1.5–2.0 (≈2.7–2.9 g/g reported for isolates)	2.5–3.5 (microwave, HPH)	Exposure of hydrophobic sites enhances oil binding and flavor retention	Rawdkuen et al. (2022)
Emulsifying activity (EA, m ² /g)	Moderate; albumin-rich fractions up to 280–370 m ² /g; less soluble fractions <140 m ² /g	1.5–2 × increase after wet fractionation or microwave pre-treatment	Improved interfacial activity due to partial unfolding and exposure of hydrophobic/hydrophilic regions; SP isolates often outperform soy in emulsifying activity	Sathe, Kshirsagar, and Sharma (2012); Torres-Sánchez et al. (2023)
Emulsion stability (ES, %)	50–60	70–85 (US, HPH, microwave)	Smaller protein aggregates and enhanced interfacial coverage stabilize emulsions	Torres-Sánchez et al. (2023); Jiaotong and Ruttarattanamongkol (2021)
Foaming capacity (FC, %)	40–55; Peru origin isolate ~30 × higher than Thai isolate at pH 5	60–80 (after wet fractionation or ultrasonication)	Protein solubility and flexible structure (albumin fractions) enhance air–water interface film formation; explains superior foaming to soy	Rawdkuen et al. (2022)
Foam stability (FS, %)	30–45	50–75	Improved viscoelasticity of protein films maintains foam structure	Rawdkuen et al. (2022)
Gelation (least gelling concentration, %) / Gel strength	Moderate; LGC 12–15%	LGC reduced to 8–10% after HPP, microwave, or enzymatic pretreatment	Partial protein denaturation and network formation improve gel strength and reduce concentration needed	Landines Vera et al. (2024)

example, a Peruvian SP isolate showed >30-fold higher foaming capacity than a Thai (Rawdkuen, D'Amico, et al., 2022). These functional attributes, along with high digestibility and a complete amino acid profile, support SP's potential in plant-based food formulations. Collectively, these traits highlight SP as a promising ingredient for emulsifiers in dressings and foaming agents in bakery or dessert formulations.

3. Limitations to the utilization of Sacha Inchi press cake in food systems

Table S2 presents the limitations and mitigation strategies for the application of SP in food systems, including anti-nutritional factors, composition, sensory attributes, and safety considerations.

3.1. Anti-nutritional factors

SP contains several anti-nutritional factors (ANFs) that can limit its application in food systems (Landines Vera et al., 2024). ANFs are naturally occurring compounds that hinder nutrient digestion, absorption, or metabolism. While some may provide health benefits at low levels (e.g., antioxidant or hypocholesterolemic effects), excessive intake can impair nutritional quality and pose health risks (Valdez-Arana, Cabrera-de-la-Cruz, & Vidaurre-Ruiz, 2025). A comparative summary of ANFs in SP and soybean meal, along with their functional implications, is provided in Table S2.

Prominent ANFs in SP include phytic acid, tannins, saponins, trypsin inhibitors, lectins, and oxalates. These compounds can reduce the bioavailability of key nutrients such as proteins, minerals (Ca, Fe, Zn), and vitamins by forming insoluble complexes or inhibiting digestive enzymes. Some ANFs like phytates, tannins, and saponins are relatively heat-stable, whereas others such as lectins and protease inhibitors are thermolabile and can be significantly reduced through thermal processing (Thakur, Sharma, & Thakur, 2019). For example, autoclaving SP at 121°C has been shown to decrease tannins, phytic acid, and trypsin inhibitor activity by over 50% (Suwanangul, Jittrepotch, & Ruttarattanamongkol, 2021).

Among these, tannins are particularly notable due to their high content in untreated SP (up to 0.216 g/100 g), contributing to a bitter taste and reduced protein digestibility (Landines Vera et al., 2024). Similarly, saponins, though potentially beneficial for cholesterol control, form insoluble complexes with proteins and minerals, impacting nutrient utilization. Phytic acid binds divalent minerals, limiting their absorption in the gut (Nissar, Ahad, Naik, & Hussain, 2017). Trypsin inhibitors reduce protein digestion efficiency but are largely inactivated by heat (Bueno-Borges, Sartim, Gil, Sampaio, Rodrigues, & Regitano-d'Arce, 2018).

3.2. Functional, sensory, and technological limitations

SP is recognized for its high protein content and valuable bioactive compounds. However, several limitations currently hinder its widespread application in food systems, as outlined below.

3.2.1. Functional limitations

High tannin levels in SP contribute to a bitter, rancid taste, making it unsuitable for direct consumption. Processing methods such as steaming at 120°C for 20 minutes significantly reduce tannin content and improve flavor (Nam, Chièn, Tâm, Bắc, Khương, & Lượ, 2022). Additionally, moisture control is crucial for stability and protein recovery, complicating its incorporation into food systems.

3.2.2. Sensory limitations

Sensory studies indicate that high SP inclusion (e.g., 70%) in baked products negatively impacts appearance, taste, texture, and overall acceptability. These effects are linked to SP's inherent flavor and

changes during baking, such as caramelization (Rungrot et al., 2021). However, moderate inclusion levels (~50%) maintain acceptable sensory quality.

3.3.3. Processing technological limitations

Processing SP for food use is complicated by its high fiber content, which affects textural and mixing properties. Additionally, excessive heat during oil extraction can degrade sensitive nutrients. The variability in extraction methods also impacts SP's antioxidant capacity and functional quality, requiring optimized and standardized processing (Gutiérrez Suquillo, Saá Arévalo, & Vinuesa Lozada, 2017).

3.3. Cytotoxicity and genotoxicity studies

Toxicological assessments confirm the safety of Sacha Inchi products. Oral toxicity studies in rodents showed no adverse effects even at high doses (up to 2000 mg/kg), with normal growth, organ function, and hematological parameters (Rodeiro, 2018). Genotoxicity testing using the mouse micronucleus assay also indicated no DNA damage or clastogenic effects. Besides, *in vitro* studies on Sacha Inchi husk (SIH) extract demonstrated non-cytotoxic effects on human dermal fibroblasts and high cell viability (>80%), supporting its use in cosmetic applications. The HET-CAM assay confirmed no irritation or genotoxicity (Poomanee et al., 2024). Further studies on roasted seeds, leaves, and various human cell lines (including liver and kidney) and *Drosophila melanogaster* confirmed SP's non-toxic and non-genotoxic profile (Srichamnong, Ting, Pitchakarn, Nuchuchua, & Temviriyankul, 2018).

4. Technological and consumer-oriented approaches to enhance the value of Sacha Inchi press cake

The valorization of Sacha inchi press cake (SP) extends beyond process optimization; it requires approaches that align with consumer expectations for safe, sustainable, and palatable products, as well as compliance with emerging market regulations on clean labeling and novel ingredient use. This section critically evaluates existing technological approaches, emphasizing their commercial viability, environmental implications, and potential to meet consumer and regulatory standards (Table 2).

4.1. Dry-fractionation

Dry-fractionation is emerging as a sustainable route for valorizing oilseed and legume press cakes, relying on mechanical processes such as milling, air classification, and electrostatic separation to obtain protein-enriched fractions without solvents. This preserves native protein structure while reducing energy and water use, aligning with clean-label demands (Meenakshi Sundaram, Das, Emiola-Sadiq, Sajeeb Khan, Zhang, & Meda, 2024; Schutyser, Pelgrom, Van der Goot, & Boom, 2015). Recent studies show that dry-fractionation not only enhances protein concentration but also improves techno-functional and sensory properties; for example, combined de-oiling and electrostatic separation of soy and lupin improved protein enrichment and flavor profiles (Politiék, Pegiou, Balfort, Bruins, Schutyser, & Keppler, 2023), while large-scale trials confirmed functional, palatable ingredients with lower environmental impact (Schutyser, Novoa, Wetterauw, Politiék, & Wilms, 2025). Although direct studies on Sacha Inchi press cake (SP) are lacking, its composition (protein bound to fiber and residual oil) resembles other oilseeds where dry-fractionation proved effective, suggesting potential for functional protein concentrates with better solubility and dispersibility. Critically, dry-fractionation aligns with consumer demand for "clean-label" products, but lower protein purity which is lower than wet methods and ultrafine milling or electrostatic separation limits premium applications, and economic feasibility remains a key barrier for large-scale adoption.

Table 2

Physical, chemical, and biotechnological technologies for valorization of Sacha Inchi press cake (SP): mechanisms, benefits, limitations, and applications.

Technology	Mechanism	Key beneficial effects	Limitations	Optimal applications	Cost	Scalability	Impact on SP properties	References
Dry fractionation	Milling, air classification, electrostatic separation	Solvent-free enrichment of protein fractions; preserves native structure; improved dispersibility	Lower protein purity vs wet methods; requires ultrafine milling; economic challenges	Protein concentrates; fiber-rich fractions; clean-label products	Low	High	Moderate protein enrichment; improved solubility/dispersibility	(Meenakshi Sundaram, Das, Emiola-Sadiq, Sajeeb Khan, Zhang, & Meda, 2024; Schutyser, Pelgrom, Van der Goot, & Boom, 2015). Politiek, Pegiou, Balfort, Bruins, Schutyser, and Keppler (2023) Schutyser, Novoa, Wetterauw, Politiek, and Wilms (2025)
Wet fractionation	Alkaline solubilization, isoelectric precipitation, centrifugation, membrane filtration	High protein purity; improved solubility, emulsifying, and foaming; reduced antinutrients	High water/chemical use; possible denaturation; drying/waste management	Protein isolates for beverages and powders	Medium	Moderate	High purity isolates with improved digestibility and techno-functionality	Östbring, Tullberg, Burri, Malmqvist, and Rayner (2019); Caldeira et al. (2025); Yeasmen, Nushrat, Orsat, and Valérie (2025)
Steaming	Moist heat (100–120°C)	Reduces tannins, lectins, protease inhibitors; improves digestibility; lowers moisture content (<10%); enhances stability	Less effective on phytates; risk of flavor/color change	Protein-rich powders; functional flours	Low	High	Reduced tannins and antinutrients; improved protein quality and stability	Nguyen, Truong, Bui, Nguyen, Nguyen, and Tien (2022)
Autoclaving	High-pressure moist heat (121°C, 15–30 min)	Strong reduction of tannins and trypsin inhibitors; increased protein content and digestibility	Overheating may cause aggregation, reduced solubility, nutrient loss	Detoxified SP flour; protein ingredients	Low–Medium	High	Reduced antinutrients; improved protein digestibility; possible aggregation at high severity	Suwanangul, Jittrepotch, and Ruttarattanamongkol (2021); Landines Vera et al. (2024)
Roasting	Dry heat (60–200°C, minutes)	Reduces tannins, phytic acid, trypsin inhibitors; enhances flavor and antioxidant activity; improves consumer acceptance	Risk of Maillard browning; losses of heat-sensitive nutrients	Roasted kernels, snacks, beverage bases	Low–Medium	High	Improved digestibility, antioxidant profile, and flavor; potential nutrient loss	Bueno-Borges et al. (2018); Valles Ramírez et al. (2017); Chansuvarn and Panich (2024)
Extrusion	High temperature, pressure, and shear (80–120°C)	Strong antinutrient reduction; highest digestibility (up to 55.8%); improved solubility, emulsifying, foaming, and oil-binding	High energy cost; possible loss of heat-sensitive compounds	Texturized proteins; functional flours; meat analogues	Medium–High	High	Improved hydration, digestibility, and functional properties; reduced antinutrients	Suwanangul et al. (2021); Nikmaram et al. (2017)
Chemical & chemo-enzymatic treatments	Alkaline soaking (e.g., Na ₂ CO ₃), cyclodextrins, phospholipase	Reduces beany/off-flavor; improves sensory quality; masks volatiles	May require flavor masking; cost and complexity; regulatory limits (e.g., Thai FDA intake restriction)	Plant-based beverages; protein isolates with flavor enhancement	Medium	Moderate	Improved flavor stability and acceptability; minimal effect on nutrition	Chansuvarn and Panich (2024); Bollegala and Rajapakse (2015); Cui, Kimmel, Zhou, Rao, and Chen (2020); Zhu and Damodaran (2018)

(continued on next page)

Table 2 (continued)

Technology	Mechanism	Key beneficial effects	Limitations	Optimal applications	Cost	Scalability	Impact on SP properties	References
Biotechnological (enzymatic hydrolysis)	Protease treatment (Alcalase, papain, etc.)	Produces soluble peptides with antioxidant and ACE-inhibitory activity; improved digestibility; reduced allergenicity	Bitterness of hydrolysates; cost of enzymes; scaling challenges	Functional peptides; nutraceuticals; protein fortification	Medium–High	Moderate	Generates bioactive peptides; enhances solubility and bioavailability	Rawdkuen, Rodzi, and Pinijsuwan (2018); Chen, Wang, and Zhang (2023); Suwanangul, Aluko, Sangsawad, Kreungnerd, and Ruttarattanamongkol (2022); Shu, Wang, and Zhang (2023); Wang et al. (2022)
Functional additives (debitting/sensory optimization)	Sweeteners, NaCl, polysaccharides, masking flavors	Reduces bitterness/astringency; enhances umami and sensory appeal	Matrix-specific; not a stand-alone solution; may increase complexity	Beverages, snacks, protein concentrates	Low–Medium	High	Improved consumer acceptance; debittering of protein hydrolysates	Ares, Barreiro, Deliza, and Gámbaro (2009); Xu, Hong, Yu, Jiang, Yan, and Wu (2019); Villacrés, Álvarez, and Rosell (2020); Sun et al. (2023); Chansuvarn and Panich (2024)

4.2. Wet fractionation

Wet-fractionation is the predominant method for producing high-purity protein isolates from oilseed press cakes, relying on solubilization (pH- or enzyme-assisted) followed by isoelectric precipitation, centrifugation, or membrane separation. Compared with dry methods, it typically yields higher protein purity and reduces antinutritional factors, though at greater water and energy costs. Evidence from rapeseed and chickpea press cakes confirms its effectiveness: rapeseed isolates obtained *via* aqueous leaching showed improved nutritional quality and reduced antinutrients (Östbring, Tullberg, Burri, Malmqvist, & Rayner, 2019), while alkaline extraction of chickpea produced ~78% protein isolates with superior solubility, emulsification, and overall functionality (Caldeira et al., 2025; Yeasmen, Nushrat, Orsat, & Valérie, 2025). Given the compositional similarity of SP to these substrates, wet-fractionation is expected to enhance protein purity, solubility, emulsification, and digestibility, while lowering tannins and protease inhibitors. While highly effective, the method's high water, energy, and chemical demands may conflict with sustainability regulations, potentially limiting consumer acceptance in eco-conscious markets. Hybrid techniques, such as membrane ultrafiltration with mild pH shifts, could balance purity, functionality, and environmental impact.

4.3. High temperature processing

4.3.1. Hydrothermal treatments

Physical modification is widely applied to improve the nutritional and functional quality of oilseed press cakes, including SP. Autoclaving and extrusion markedly reduce antinutritional compounds and enhance digestibility. For instance, autoclaving at 121°C lowered tannins from 94.4 to 7.4 mg/g and trypsin inhibitors from 8.52 to 1.76 mg/g, raising protein digestibility from 15.4% to 49.9%, while extrusion at 100°C further improved digestibility (55.8%) and emulsifying/foaming properties (Suwanangul et al., 2021). Similar benefits have been reported for pea and soybean press cakes, where thermal treatments reduced phytates, tannins, and protease inhibitors while enhancing functionality (Dey, Richter, Ek, Gu, & Ganjyal, 2021; Nikmaram et al., 2017). Fractionation of thermally treated SP proteins has also yielded isolates with improved solubility and emulsification (Torres-Sanchez et al., 2023). Beyond improving nutritional and functional quality, these treatments have implications for market positioning and regulatory acceptance. Processes that effectively reduce trypsin inhibitors, tannins, and phytates support compliance with food safety and compositional standards, facilitating SP's use in fortified or high-protein foods. Moreover, hydrothermal treatments can improve consumer-perceived texture and

palatability, expanding SP's potential in plant-based meat and functional product formulations.

4.3.2. Steaming and steam explosion

Steaming SP at 120°C for 20 min significantly reduced tannins and produced a protein-rich, low-moisture (<10%) powder with better stability (Nguyen, Truong, Bui, Nguyen, Nguyen, & Tien, 2022). Mechanistically, tannin oxidation and protease inhibitor denaturation explain these effects. Comparable results have been observed in other oilseeds: steam improved solubility, emulsification, and antioxidant activity of camellia seed proteins (Zhang et al., 2019) due to partial protein unfolding and Maillard reaction-driven structural modifications, while steam explosion (steam explosion pretreatment consists in heating of biomass with saturated steam, followed by a sudden decompression of the pressurized system) reduced phytates and increased protein yield in sesame cake, alongside favorable structural and amino acid changes (Li, Yi, Wu, Wang, Li, & Liu, 2023). In soybean okara, steam-cooking or combined steam-milling enhanced emulsification, water/oil holding, and bile acid binding (Wang, Gao, He, Zeng, Qin, & Chen, 2022; Zhao et al., 2024). As a milder, energy-efficient alternative to autoclaving, steaming supports sustainability and preserves sensory quality, key factors for consumer acceptance and eco-label compliance. However, its lower detoxification capacity may limit use in regulated high protein food.

4.3.3. Autoclaving vs steaming

While steaming is milder, energy-efficient, and preserves sensory qualities, it is less effective than autoclaving at reducing phytates and bound phenolics (Li et al., 2023). Autoclaving at 121°C achieves deeper detoxification, markedly reduces antinutrients, and improves protein extractability and digestibility, with reported increases in protein content to ~70 g/100 g (Landines Vera et al., 2024; Suwanangul et al., 2021). This increase can be attributed to the reduction of antinutritional factors such as tannins and phytates, which normally form insoluble complexes with proteins, as well as to the unfolding of protein structures during denaturation, which exposes previously inaccessible amino acid residues and enhances extractability. Under moderate heating, these structural changes may also promote the release of soluble proteins, thereby contributing to the higher measured concentration. However, at more intense conditions, aggregation tends to predominate through the formation of disulfide bonds and hydrophobic interactions, which decreases solubility and impairs functional properties (Landines Vera et al., 2024). The careful optimization of time and temperature is essential to balance anti-nutrient reduction with the preservation of functional and bioactive properties.

4.3.4. Roasting

Roasting is a common thermal process that enhances the nutritional, functional, and sensory qualities of oilseeds. While studies on roasted SP are scarce, evidence from whole seeds and related oilseed by-products supports its potential. In Sacha Inchi seeds, roasting at 160°C for 15 min significantly reduced tannins, trypsin inhibitors, and phytic acid while increasing antioxidant capacity (Bueno-Borges, Sartim, Gil, Sampaio, Rodrigues, & Regitano-d'Arce, 2018). Lower-temperature pre-roasting (60°C, 6 min) reduced astringency without compromising protein (35%) or fat (41%) levels, enabling use in plant-based beverages (Valles Ramírez, Medina-Vivanco, & Obregón-Lujerío, 2017). Roasting at 200°C for 10 min further improved sensory quality of Sacha Inchi milk Chansuvarn and Panich (2024). From a consumer and regulatory perspective, roasting must ensure both product safety and quality consistency. Over- or under-processing can lead to variability in nutrient composition, flavor, and color, affecting compliance with compositional and labeling standards. In Peru, roasting practices are recognized as part of traditional processing, but standardized thermal parameters and quality control remain essential to guarantee reproducible sensory quality, oxidative stability, and safety across production batches (Congreso de la República del, 2014; Dirección General de Salud Ambiental e Inocuidad, 1998).

4.3.5. Extrusion technology

Extrusion is a high-temperature, high-shear process that improves the nutritional and functional quality of plant-based by-products by denaturing proteins, breaking down anti-nutrient complexes, and promoting Maillard reactions (Vidal et al., 2022). In SP, extrusion at 100°C reduced phytic acid to 0.43 mg/g and achieved the highest in vitro digestibility (55.8%), outperforming autoclaving in some cases (Suwanangul et al., 2021). Functional properties also improved: protein solubility rose from 5.5% to 16.5%, emulsifying capacity and stability increased to ~60%, foam capacity nearly tripled, and oil-binding capacity rose more than seven-fold. Similar benefits have been documented in legumes and oilseed residues, where extrusion reduced phytates, tannins, lectins, and protease inhibitors while enhancing hydration and textural properties (Nikmaram et al., 2017). Beyond nutrition and functionality, extrusion can improve sensory quality; for example, pre-extrusion aromatization of soy proteins enhanced volatile retention and flavor acceptance (Milani, Menis, Jordano, Boscolo, & Conti-Silva, 2014), an approach adaptable to SP to offset beany or bitter notes. High-temperature extrusion can generate Maillard reaction products such as acrylamide or advanced glycation end-products, which may require monitoring, risk assessment, and labeling compliance according to local and international standards. Additionally, heat-induced nutrient losses must be considered in nutritional labeling. Overall, extrusion is effective for SP valorization but must be optimized to balance functionality, sensory quality, and regulatory compliance.

4.4. Chemical and chemo-enzymatic treatments

Chemical and chemo-enzymatic strategies aim to improve the flavor and sensory acceptability of Sacha Inchi press cake (SP), primarily by removing or neutralizing precursors of beany or bitter notes. Alkaline soaking has shown promise: soaking defatted roasted Sacha Inchi seeds in 10% Na₂CO₃ for 12 h reduced odor intensity, though consumer acceptance remained low unless combined with flavor masking such as cocoa addition (Chansuvarn et al., 2024). Similar approaches in soy confirmed that mild alkaline pretreatment with sodium bicarbonate, combined with pressure cooking, effectively reduced beany flavor through lipoxygenase inactivation (Bollegala & Rajapakse, 2015). More advanced chemo-enzymatic methods employ carriers such as cyclodextrins. In soy protein isolate, sequential treatment with phospholipase A₂ and β-cyclodextrin removed >90% of flavor precursors, improving flavor stability during storage (Zhu & Damodaran, 2018). Co-spray drying pea proteins with cyclodextrins achieved similar deodorization

while preserving functional properties (Cui, Kimmel, Zhou, Rao, & Chen, 2020).

Overall, these treatments show strong potential for mitigating off-flavors in SP by suppressing volatile aldehydes and other odor-active compounds. However, they are rarely sufficient as stand-alone methods and often require integration with masking, drying, or thermal processing to achieve consumer-level acceptability. Their use also increases processing steps, cost, and complexity, which may limit scalability. Nevertheless, chemical and chemo-enzymatic approaches remain valuable for extending flavor stability and enhancing the sensory profile of SP-based ingredients.

4.5. Biotechnological approaches

Biotechnological approaches such as enzymatic hydrolysis and fermentation are increasingly applied to improve the nutritional, functional, and sensory quality of SP. Enzymatic protein hydrolysis employs proteases (e.g., Alcalase, papain, or food-grade enzyme blends) to generate peptides with enhanced solubility, digestibility, and bioactivity. Hydrolysates typically show higher antioxidant and ACE-inhibitory activities compared with intact proteins, and reduced molecular weight peptides may also lower allergenicity (Khalesi & Fitz-Gerald, 2021; Ana Lemus-Conejo, Alvaro Villanueva-Lazo, Maria E. Martin, Francisco Millan, & Maria C. Millan-Linares, 2024; Rawdkuen, D'Amico, & Schoenlechner, 2022; Rawdkuen, Murdayanti, Ketnawa, & Phongthai, 2016; Rawdkuen, Rodzi, & Pinijiswan, 2018). Recent advances integrate hydrolysis with omics tools such as peptidomics and in silico screening, enabling the targeted identification of bioactive sequences (Lemus-Conejo et al., 2024).

Fermentation provides a complementary strategy. Using lactic acid bacteria (LAB) or fungi such as *Rhizopus spp.*, fermentation can degrade anti-nutritional factors, improve flavor, and enrich SP with bioactive metabolites including vitamins, organic acids, and exopolysaccharides. Insights from legume fermentation, particularly tempeh production, demonstrate reduced bitterness, improved palatability, and nutritional enhancement, outcomes that are directly transferable to SP (Lemus-Conejo et al., 2024).

Together, enzymatic hydrolysis and fermentation offer dual benefits: generating bioactive protein ingredients while simultaneously addressing sensory and anti-nutritional limitations. Future efforts should focus on tailoring enzyme-microbe combinations and integrating omics-guided optimization to maximize SP's functionality and health-promoting potential.

According to Codex Alimentarius, enzyme preparations must meet general specifications, be produced under good manufacturing practices, and derive from edible or traditionally safe sources (Codex Alimentarius, 1989). Microbial cultures used in fermentation must satisfy safety and microbiological criteria for fermented foods, including probiotics (Codex Alimentarius, 2008), while nutritional and functional claims must comply with Codex labeling guidelines to ensure accuracy and prevent misleading information (Codex Alimentarius, 1997). Adherence to these standards enables enzymatic and fermentation-based processing of SP to generate functional protein ingredients that are safe, marketable, and acceptable to consumers.

4.6. Functional additives for debittering and sensory optimization

Bitterness and astringency, common in polyphenol- and peptide-rich ingredients like SP, limit consumer acceptance. Studies suggest that sweeteners (sucrose, sucralose, polydextrose) and milk can suppress these off-notes, though effectiveness is matrix-specific (Ares, Barreiro, Deliza, & Gámbaro, 2009). Sodium chloride has also proven effective in masking bitterness in protein hydrolysates by altering peptide-receptor interactions and solubility (Xu, Hong, Yu, Jiang, Yan, & Wu, 2019). In legumes like *Lupinus mutabilis*, saline soaking with 0.5% NaCl significantly reduced alkaloid-induced bitterness more efficiently than water

soaking (Villacrés, Álvarez, & Rosell, 2020).

To counter flavor degradation during concentration, polysaccharides like guar gum and arabinose have shown promise in suppressing protein aggregation and enhancing umami intensity (Sun et al., 2023). Additional strategies, including alkaline soaking, cyclodextrin inclusion, and phospholipase treatment, target flavor precursors through hydrolysis, entrapment, or enzymatic modification.

However, no universal solution exists for SP. Efficacy remains formulation-dependent, and advanced methods can be cost-limiting. For instance, Na₂CO₃ alone had limited sensory impact unless combined with cocoa powder (Chansuvarn et al., 2024). Despite these challenges, combining debittering strategies with flavor pairing and scalable processing holds promise for improving SP's sensory appeal. From a consumer perspective, combining multiple debittering strategies with flavor optimization is essential to enhance palatability, encourage adoption of SP-based products, and align sensory quality with consumer expectations. Future research should focus on optimizing process parameters and validating safety to support regulatory updates and broader market use.

5. Applications of Sacha Inchi press cake in foods

The rising demand for plant-based foods is driven by health, sustainability, and dietary trends such as veganism and lactose intolerance. SP's rich protein, fiber, unsaturated fats, and phenolic content make it a promising ingredient, especially for populations at risk of malnutrition, such as the elderly (Kim, Iida, & Joo, 2022). Thus, recent research works on the application of SP or seed and their health benefits are presented in Table 3.

Despite its low starch content, SP has been successfully incorporated into various products including granola bars, cookies, biscuits, extrudates, macarons, tules, meat analogues, noodles, and beverages (e.g., plant-based milk and drinks) (Burakorn, 2024; Bureepakdee, Bunsiri, Chuaykarn, & Pruettiwilai, 2023; Jagersberger, 2013; Kaikaew, Chaleansit, & Thawerattanon, 2023; Ketnawa, Vong, Tian, Ogawa, Tongdeesontorn, & Donlao, 2025). However, high fat content can limit its use in products like noodles. SP tends to darken products (lower L*, higher a*) and increase hardness and crispness (Burakorn, 2024).

Moderate inclusion levels (<30%) generally maintain acceptable sensory qualities, while higher levels may reduce palatability (Jagersberger, 2013; Rungrot, Hudthagosol, & Sanporkha, 2021). Nonetheless, SP-enriched products benefit nutritionally from increased protein, essential amino acids, fiber, unsaturated fats, minerals, and antioxidant compounds (Ketnawa et al., 2025).

Beyond human consumption, SP has shown potential in animal and aquaculture nutrition, improving growth, carcass quality, and reducing cholesterol in guinea pigs and fish (Khieokhajokhet, Aeksiri, Rojtinakorn, Van Doan, & Kaneko, 2022; Ordonez, Pereyra, Gallardo, & Cortez, 2019). It also supports microbial growth for fermentation processes (Micanquer-Carlosama, Cortés-Rodríguez, & Serna-Cock, 2020).

Safety assessments (aerobic counts, aflatoxins) confirm SP-based products meet regulatory standards (Chansuvarn & Panich, 2024; Kaikaew et al., 2023). With its nutritional value and functional versatility, SP offers strong potential for plant-based food innovation. Future work should focus on optimizing formulations via extrusion and flavor integration to enhance consumer appeal.

5.1. Functional and nutritional ingredients

SP is increasingly valorized for protein concentrates, isolates, and hydrolysates with nutritional and bioactive potential. Enzymatic hydrolysis using proteases (e.g., alcalase, papain, bromelain, trypsin) has produced SP hydrolysates with antioxidant, antihypertensive, and hypoglycemic activities papain (Rawdkuen, Rodzi, & Pinijsuwan, 2018; Sa-nguanpong et al., 2025; Shu, Wang, & Zhang, 2023; Suwanangul, Aluko, Sangsawad, Kreungnermd, & Ruttarattanamongkol, 2022; Wang

Table 3
Sacha Inchi press cake application and their health benefits.

Utilization products	Benefits	References
Plant based alternative Chicken sausage	<ul style="list-style-type: none"> enhanced emulsion meat quality and nutritional properties, increased protein content and polyunsaturated fatty acids reducing total fat content 	Pongpaew (2025)
Dairy alternatives High protein milk	<ul style="list-style-type: none"> complete protein containing all nine essential amino acids a rich source of omega-3, omega-6, and omega-9 fatty acids 	Panich (2020)
Ready to drink functional beverage	<ul style="list-style-type: none"> Each 100 mL provides 36.31 kcal, with 6.19 g of protein and 1.09 g of fat. 2.65 g of dietary fiber per 100 mL 	Ketnawa, Vong, Tian, Ogawa, Tongdeesontorn, and Donlao (2025)
Protein powder drink mix	<ul style="list-style-type: none"> high protein and high dietary fiber product. could be kept at 35 ± 2°C for 12 weeks 	Teeragaroonwong et al. (2024)
Plant-based milk mixing with matcha green tea and cocoa	<ul style="list-style-type: none"> roasted sachu inchi seed high protein (2.13 g) healthy fat content (4.95 g) per serving low in carbohydrates free from cholesterol enhance both flavor and nutritional value 	Chansuvarn et al. (2024)
Yogurts containing sacha inchi seeds and β-glucans from <i>Ganoderma lucidum</i>	<ul style="list-style-type: none"> increased protein, fat, carbohydrates, ash, total solids, aspartic acid, serine, arginine, glycine, threonine, tyrosine, and alanine. α-Linolenic (49.3%) and linoleic (32.2%) acids 	Vanegas-Azuero and Gutiérrez (2018)
Beverage from roasted Sacha Inchi seed	<ul style="list-style-type: none"> improved sensory attributes, reduced astringency, protein (3.3%), healthy fats (7.13%), essential fatty acids 	Valles Ramírez, Medina-Vivanco, and Obregón-Lujerío (2017)
Bakery and snacks High protein snack products	<ul style="list-style-type: none"> 24.94% protein 1.79% total dietary fiber 2.09% fat 	Jiapong and Ruttarattanamongkol (2021)
Flatbread, substituting 6.3% of wheat flour with SP	<ul style="list-style-type: none"> increased protein (10.3%), fiber (3.8%), and α-linolenic acid (3.3%) reducing carbohydrate content 	Torres-Sanchez et al. (2023)
Granola bars Crispy sheet Macarons Cookies Biscuits Sweet chilli paste	<ul style="list-style-type: none"> increased levels of essential amino acids increased protein increased unsaturated fat acids increased minerals increased fiber increased total phenolics increased antioxidant activity 	Bureepakdee, Bunsiri, Chuaykarn, and Pruettiwilai (2023) Jagersberger (2013) Rungrot, Hudthagosol, and Sanporkha (2021) Kaikaew, Chaleansit, and Thawerattanon (2023)
Pasta and noodle High-protein, gluten- free pasta and noodles from Sacha Inchi flour and taro	<ul style="list-style-type: none"> offer good expansion properties being naturally gluten-free 	Narváez Cadena et al. (2025)

(continued on next page)

Table 3 (continued)

Utilization products	Benefits	References
Noodles	<ul style="list-style-type: none"> • suitable for individuals with celiac disease • high energy value, averaging 378.06 kcal • rich in omega fatty acids, 536.5 g of omega-3, 795.95 g of omega-6, 851.15 g of omega-9 	Lesmana and Dewantara (2023)
Functional ingredients		
Protein hydrolysates	<ul style="list-style-type: none"> • antioxidant • antihypertension • anti-inflammation • hypoglycemic effects • reduce lipid accumulation • reduce oxidative stress • reduce cellular damage 	Chen et al. (2023) Chirinos et al. (2020) Rawdkuen, D'Amico, and Schoenlechner (2022) Suwanangul et al. (2022) Shu et al. (2023)
Pet and animal feed: fish	<ul style="list-style-type: none"> • omega-3 fatty acids, in particular, supports healthy skin, a shiny coat, and joint health • aid in digestion • improved growth rates, feed efficiency, nutrient digestibility (ADC), gut health, and blood profiles, indicating that sacha inchi meal is a promising alternative 	Khieokhajokhet, Aeksiri, Rojtinnakorn, Van Doan, and Kaneko (2022)
Animal feed: Guinea pigs	<ul style="list-style-type: none"> • improved carcass yield • the meat lower fat and cholesterol content as • improved organoleptic characteristics 	Ordenez, Pereyra, Gallardo, and Cortez (2019)
Growing media for microorganism	<ul style="list-style-type: none"> • improving fermentation • supported the growth of <i>W. cibaria</i> • yielded substantial lactic acid production 	Micanquer-Carlosama, Cortés-Rodríguez, and Serna-Cock (2020)

et al., 2022). These peptides also mitigate oxidative stress and lipid accumulation (Chen, Wang, & Zhang, 2023). While promising for functional foods or nutraceuticals, further validation such as standardized in vitro digestion models (e.g., INFOGEST) is needed to clarify bioavailability and efficacy.

5.2. Plant-based meat alternatives (PBMA)s

SP is suitable for PBMA)s due to its high protein digestibility (88.5–93.6%) and excellent functional properties, including water/oil-holding capacity (~3 g/g, ~2.9 g/g), emulsifying activity (56.3%), and foam stability (up to 68.9%) (Rawdkuen, D'Amico, et al., 2022; Torres Sánchez et al., 2023). Its albumin/globulin profile and Maillard-reactive amino acids (e.g., glutamic acid) enhance texture and flavor. Compared to soy, pea, and wheat proteins, SP offers competitive functionality with fewer allergenicity and sustainability concerns.

5.3. Fortification in bakery and snack products

SP has been used to enrich bakery items with protein, fiber, and omega-3 s. In flatbread, 6.3% SP substitution improved nutritional content without compromising sensory properties (Torres Sánchez et al., 2023). In tuiles, protein content rose from 6.1% to 19.4% (Rungrot et al., 2021). In extruded snacks, up to 10% SP enhanced density and texture, with acceptable expansion and sensory scores (Jagersberger, 2013). These results suggest SP's suitability for baked and extruded health-oriented snacks.

5.4. Dairy alternative applications

SP is a promising base for plant-based beverages due to its complete protein profile and high omega-3, -6, and -9 content (Panich, 2020). SP milk formulations deliver >2 g protein and ~5 g healthy fats per serving with low carbs and no cholesterol (Chansuvarn et al., 2024). Roasting improves amino acid bioavailability, flavor, and antioxidant activity supporting applications for elderly nutrition (Valles Ramírez, Medina-Vivanco, & Obregón-Lujerio, 2017). Recent findings show that SP-based beverages contained protein (4.28%), carbohydrate (4.04%) and lipid (0.67%) levels as well as dietary fiber (2.65%) and antioxidant activity (Ketnawa et al., 2025).

6. Environmental and socioeconomic implications

SP, a by-product of oil extraction, remains underutilized despite its high potential as a sustainable, high-value protein source (Valdez-Arana et al., 2025). Traditionally seen as animal feed, SP offers significant advantages due to its rich protein, essential amino acids, and fiber content (Valdez-Arana et al., 2025). Its functional properties including water-holding, emulsifying, and foaming enable its use in protein powders, gluten-free goods, beverages, and plant-based foods (Torres-Sanchez et al., 2023). This supports a circular economy by reducing food waste and adding value to crops.

Cultivated in tropical climates, Sacha Inchi requires minimal land and water, making it suitable for low-productivity regions (McKimmie, 2025). Its carbon footprint is significantly lower than that of animal-based proteins due to the absence of livestock-related emissions and resource demands (Flysjö, Thrane, & Hermansen, 2014).

Socioeconomically, SP offers a low-cost, nutrient-rich alternative to conventional protein supplements, addressing protein-energy malnutrition in under-resourced communities. Rich in omega-3 s and bioactive compounds, it can be formulated into porridges, protein bars, and supplements (Redjeki, Hulwana, Aulia, Maya, Chaerunisaa, & Sriwidodo, 2025). SP also creates economic opportunities for small-scale farmers through value-added processing, while its shelf stability supports emergency relief and school feeding programs in food-insecure areas.

7. Future directions and research needs

7.1. Leveraging emerging processing technologies

Emerging technologies offer solutions to SP's underutilization, which stems from poor solubility, off-flavors, and antinutritional factors. Techniques such as high-pressure homogenization (HPH), ultrasonication, microwave-assisted extraction, electroconductive methods (e.g., ohmic heating, pulsed electric fields), and cold plasma (DBD-CP) have shown potential to improve protein extractability, functionality, bioactivity, and safety often under mild or non-thermal conditions. These approaches support clean-label formulation by preserving heat-sensitive compounds and minimizing additive use. While promising, regulatory frameworks for these novel technologies are still developing in many regions, and specific safety evaluations may be required before commercialization (Liu, Wu, Shao, & Wu, 2024). Moreover, consumer acceptance may be influenced by perceptions of "novel" processing, highlighting the need for transparent labeling, communication of safety and benefits, and sensory validation (Meijer, Lähteenmäki, Stadler, & Weiss, 2020). Although widely studied in other oilseed and legume systems, tailored application of these technologies to SP could unlock its potential as a sustainable functional ingredient while aligning with emerging regulatory standards and consumer expectations. A summary of these technologies and their reported effects is provided in Table 4 and Supplementary Table S3.

7.1.1. High pressure homogenization (HPH)

HPH forces suspensions through narrow orifices at very high

Table 4

Leveraging emerging processing technologies for valorization of Sacha Inchi press cake: mechanisms, beneficial effects, limitations, and applications.

Technology	Mechanism	Key beneficial effects	Limitations	Optimal applications	Cost	Scalability	Impact on SP properties	References
High-temperature processing	Thermal denaturation (above 100°C) – moist or dry Roasting	<ul style="list-style-type: none"> - Reduces thermostable antinutrients (e.g., trypsin inhibitors) - Improves protein digestibility and flavor - Extends shelf life 	<ul style="list-style-type: none"> - Nutrient losses if uncontrolled - Risk of Maillard browning 	Stabilized press cake; roasted snacks; flours	Low to Medium	High	Reduces antinutrients and improves flavor; can degrade thermolabile nutrients	Landines Vera et al. (2024); Narváez Cadena et al. (2025); Bueno-Borges, Sartim, Gil, Sampaio, Rodrigues, and Regitano-d'Arce (2018)
High pressure processing (HPP)	Hydrostatic pressure (100–600 MPa)	<ul style="list-style-type: none"> - Preserves heat-sensitive nutrients - Improves protein digestibility (12–18%) - Reduces phytates (~47%) - Enhances techno-functional properties 	<ul style="list-style-type: none"> - High equipment cost (USD 1–2 M) - Limited effect on thermostable compounds 	Premium protein ingredients; functional foods	High	Moderate	Enhances protein solubility, digestibility, functionality; limited impact on thermally stable compounds	Braspaiboon and Laokuldilok (2024); Sert et al. (2024)
High pressure homogenization (HPH)	Intense shear forces (50–200 MPa)	<ul style="list-style-type: none"> - Enhances protein solubility (35–40%) - Improves emulsion stability (25–30%) - Generates nano- and micro-sized protein particles 	<ul style="list-style-type: none"> - Risk of heat generation - Possible protein aggregation under extreme conditions 	Emulsions; beverages; dairy alternatives	Medium	High	Improves protein solubility and emulsion stability; can alter protein structure under extreme conditions	Saricaoglu et al. (2018); Kelany et al. (2024)
Ultrasonication (US)	Acoustic cavitation (20–100 kHz)	<ul style="list-style-type: none"> - Increases protein yield (up to 30%) - Preserves >90% of bioactive compounds - Improves foaming and emulsifying properties - Reduces energy consumption (~50% less than HPH) 	<ul style="list-style-type: none"> - Limited penetration depth - Requires process optimization 	Protein concentrates; bioactive compound extraction	Low	Moderate	Increases protein yield and preserves bioactives; enhances foaming and emulsifying properties	Chirinos et al. (2024); Chemat et al. (2019)
Microwave processing	Dielectric heating (300 MHz–300 GHz)	<ul style="list-style-type: none"> - Rapid reduction of anti-nutrients (e.g., >90% lectins) - Retains >95% of essential amino acids - Improves protein digestibility and functionality - Shorter processing time and scalable 	<ul style="list-style-type: none"> - Non-uniform heating in bulk - Limited data on oilseed cakes 	Anti-nutrient reduction; protein functionalization; rapid processing	Medium	High	Reduces anti-nutrients and improves protein digestibility; minimal effect on amino acids	Verma et al. (2024); Mathews et al. (2023)

(continued on next page)

Table 4 (continued)

Technology	Mechanism	Key beneficial effects	Limitations	Optimal applications	Cost	Scalability	Impact on SP properties	References
Electroconductivity (Ohmic/PEF)	Ohmic heating (50–60 Hz) and pulsed electric field (10–80 kV/cm)	<ul style="list-style-type: none"> - Precise and uniform temperature control - Improves protein extraction yield (~25%) - Reduces microbial load while preserving nutrients - Energy efficient (30–50% savings) 	<ul style="list-style-type: none"> - High initial investment - Requires careful optimization 	Protein modification; large-scale extraction; microbial safety	High	High	Enhances protein yield and quality; reduces microbial load	Mathews et al. (2023); Saeedabad et al. (2024)
Cold plasma (Dielectric Barrier Discharge, DBD-CP)	Generation of reactive oxygen/nitrogen species (RONS) under high-voltage discharge (20–30 kV)	<ul style="list-style-type: none"> • Oxidation of proteins (↑ carbonyl groups, ↓ sulfhydryls) • Improved solubility (up to 59.1% in SPI, 41.4% in PPI) • Enhanced emulsifying and foaming properties • Better rheological properties and creep recovery (PPI > SPI) • Improved in vitro digestibility (SPI +4.8%, PPI +3.2%) 	<ul style="list-style-type: none"> • Structural modifications (loss of α-helix, aggregation) may affect some end uses • Process requires optimization (optimum: 30 kV, 6 min) • Equipment complexity and energy demand 	Protein isolates for beverages, high-functionality protein ingredients, meat analogues	Medium	Moderate	Improves solubility, emulsification, rheology, and digestibility; controlled oxidation alters secondary/tertiary structures	Rout and Srivastav (2024)

pressures (100–300 MPa), generating shear, turbulence, and cavitation. Such disruptions enhance extraction, solubility, emulsifying, and foaming properties of proteins. For example, applying HPH after alkaline extraction (AE + HPH at ~100 MPa) increased pumpkin seed cake protein yield from ~46% to ~62%, with better functional performance (solubility, emulsion stability) compared to untreated cake Cabral et al. (2023).

However, industrial use is hindered by high capital costs, energy demand, maintenance under pressure, and limited throughput unless combined with other techniques.

7.1.2. Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction (UAE) uses acoustic cavitation to disrupt cells and enhance mass transfer. It can increase protein yield, reduce extraction time, and improve solubility, emulsification, and foaming. Studies on rapeseed, hazelnut, pumpkin, and pea press cakes show UAE can deliver high yield and preserve structure when optimized (Anzà, Fraterrigo Garofalo, Lapolla, & Fino, 2025; Dermanová et al., 2025). Its drawbacks include non-uniform energy distribution at scale, probe maintenance, and risks of overheating/partial denaturation. Hybrid systems (e.g. UAE + enzyme or mild chemical treatment) can improve viability.

7.1.3. Microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) uses dielectric heating to accelerate protein and bioactive release. In oilseed cakes (sunflower,

etc.), MAE improves yield, reduces anti-nutritional factors, and enhances antioxidant activity (Náthia-Neves & Alonso, 2021). Combinations like ultrasound-microwave (UMAE) often outperform single methods. However, hot-spots and non-uniform heating threaten protein integrity; continuous-flow or well-designed reactors are needed, but these raise capital and operational costs (Włodarczyk, Czaplicki, Tańska, & Szydłowska-Czerniak, 2023). For SP, MAE (or UMAE) may help overcome protein binding in fibrous/oily matrices—optimizing power, exposure, and solid-liquid ratio is essential.

7.1.4. Electroconductive technologies (Ohmic heating and Pulsed Electric Fields)

Ohmic heating (OH) passes current through the material to induce uniform heating. Pulsed Electric Fields (PEF) apply high-voltage pulses to permeabilize cell membranes, enhancing protein release with minimal heat damage (Náthia-Neves et al., 2021). These have been shown to improve yield, solubility, and emulsification in oilseed cakes and legumes. However, they face barriers: equipment cost (high-voltage systems, electrodes), energy consumption, and ensuring product quality (avoiding thermal/degradation effects) Ramaswamy and Bala Krishnan (2024). For SP, OH or PEF (alone or in combination with enzymes or mild chemicals) are promising, yet require pilot data on energy vs yield, equipment durability, and downstream processing.

7.1.5. Dielectric barrier discharge cold plasma (DBD-CP)

Notably, dielectric barrier discharge cold plasma (DBD-CP)

treatment generates reactive species that modify protein structures (e.g., increased carbonyl groups, reduced thiols, partial unfolding), improving solubility, digestibility, and functionality (e.g., gelation) (Tripathy & Srivastav, 2023a). Although evidence to date is mainly with legume/soy/pea proteins, this clean-label, non-thermal method offers potential for SP to enhance its techno-functional properties. Key knowledge gaps include scaling the technology, energy efficiency, regulatory acceptance, and ensuring consistent sensory attributes.

7.1.6. Other advance technologies

Beyond HPH, UAE, MAE, electroconductive and DBD-CP methods, hybrid techniques like supercritical fluid extraction (SFE), subcritical water extraction (SWE), enzyme-assisted extraction (EAE), and their combinations have shown promise in valorizing oilseed press cakes and legumes. These methods offer high selectivity, reduced solvent use, and improved recovery of proteins and bioactives under mild conditions. For instance, supercritical CO₂ de-oiling enhanced soybean protein extraction compared to hexane methods (Cestonaro et al., 2024), while green extraction preserved protein integrity in hazelnut cake (Anzà et al., 2025). Hybrid systems, including UMAE and enzyme–microwave combinations, were shown to optimize yield and lower energy inputs (Anyiam, Tangjaidee, Zhang, & Rawdkuen, 2025; Grahovac, Aleksić, Trajkovska, Marjanović Jeromela, & Nakov, 2025). EAE and hybrid technologies also demonstrated potential for scalable, sustainable protein recovery from legumes (Patil et al., 2025).

However, economic feasibility remains a barrier. SFE and SWE require high capital and energy input; EAE is limited by enzyme cost and stability; and hybrid systems often involve complex integration. For SP, such approaches may be more justifiable for high-value applications (e.g., nutraceuticals), pending techno-economic and life-cycle assessments.

Bitterness and astringency mainly due to saponins and tannins which limit SP's sensory acceptability. Encapsulation technologies offer a solution by masking off-flavors and enhancing stability. Techniques such as spray chilling, spray freeze-drying, and electrospinning enable controlled release of flavor compounds (Shan et al., 2025; Tripathy & Srivastav, 2023b). Liposome systems and nanoencapsulation further stabilize phenolics, prevent oxidation, and improve antioxidant retention (Tripathy & Srivastav, 2023b). For example, zein-surfactant microparticles effectively reduced bitter aldehydes in Sacha Inchi oil (Suwannasang et al., 2021), while β -sitosterol liposomes achieved ~75% encapsulation efficiency and sustained phenolic release. Double-shell microencapsulation also eliminated unpleasant volatiles in functional oils, suggesting applicability to SP with minor adjustments (Fadini et al., 2018). Emerging encapsulation strategies use proteins, polysaccharides, and sterol-based liposomes to improve SP's sensory and functional performance in foods.

Additionally, nanoencapsulation and biopolymer-based carriers (e.g., alginate, chitosan, gelatin, whey) enhance bioactive stability, mask bitterness, and improve delivery (Tripathy, Verma, et al., 2023). Integration into biopolymer films also opens pathways for smart packaging, extending shelf life and supporting food safety with improved sensory quality during storage (Virender et al., 2025).

7.2. Addressing knowledge gaps

Despite SP's nutritional potential, its widespread use in functional foods and nutraceuticals is limited by unresolved knowledge gaps. Optimizing processing methods remains a key challenge, as the effectiveness of conventional and emerging techniques depends heavily on specific conditions and interactions with food matrices. The lack of standardized protocols hinders consistent product quality and industrial scalability (Brishti et al., 2025; Zhang, Raghavan, & Wang, 2025). A summary of the current knowledge gaps and future research directions in the valorization of SP is presented in Table S4.

Limited characterization of SP-derived bioactives such as peptides, phenolics, and residual lipids also constrains targeted applications.

Their health benefits, though promising, are not fully understood at the molecular level. Omics technologies (proteomics, metabolomics, lipidomics) could help elucidate structure-function relationships and mechanisms of action (Mhd Rodzi & Lee, 2022).

Evidence for efficacy and bioavailability is largely in vitro, offering limited physiological relevance. In vivo models and clinical trials are essential to confirm metabolic pathways, absorption, and health benefits in line with regulatory standards (Brishti et al., 2025; Torres Sánchez et al., 2023).

Safety is another concern. The allergenic potential of SP, particularly given its similarity to tree nuts, is poorly studied. Comprehensive assessments of allergenicity, anti-nutritional factors, and long-term consumption effects are needed to ensure consumer protection (Mhd Rodzi and Lee, 2022).

Scalability and shelf-life stability present additional barriers. Most studies remain at laboratory scale, offering limited data on industrial feasibility, microbial safety, and product stability during storage. Pilot-scale validation and predictive shelf-life modeling are needed to support commercialization (Alejandro Ruiz et al., 2025; Mhd Rodzi et al., 2022).

Regulatory hurdles and sustainability claims further complicate market integration. Inconsistent regulatory frameworks across regions may delay approval of SP as a novel food ingredient. Concurrently, life cycle and socio-economic assessments are vital to verify environmental benefits and guide clean-label product development (Chansuvarn et al., 2024).

Addressing these challenges requires interdisciplinary collaboration among food scientists, nutritionists, regulatory experts, and economists. Coordinated efforts will be critical to standardize processing, validate functionality, ensure safety, and align SP valorization with sustainability and consumer expectations.

7.3. Market and regulatory considerations

7.3.1. Consumer centric studies: acceptability and market readiness

Consumer acceptability is a key determinant of the commercial potential of novel food products. While Sacha inchi press cake (SP) and flour offer notable nutritional and functional benefits, their characteristic flavor and texture can limit consumer appeal. Studies indicate considerable variation in sensory outcomes depending on product type, inclusion level, processing method, and consumer familiarity. In bakery applications, moderate substitution of wheat flour with Sacha Inchi flour generally produced acceptable products, whereas higher levels led to firmer textures and stronger beany flavors, reducing preference (Aylas, Pingus, & Alva, 2019; Vásquez Osorio, Velez, Hincapié, & David, 2017). Similar effects were observed in noodles, where excessive inclusion negatively impacted texture and overall acceptability (Rodríguez Paucar, Avellaneda, Pardo, Villanueva Lopez, & Aguirre, 2018). Beverage formulations also showed mixed responses: unfamiliar astringent notes lowered ratings in some cases, while controlled incorporation (30%) improved acceptability through sweetness and flavor adjustments (De Los Rios Carvajal, 2019; Jagersberger, 2013).

Processing innovations may help address these sensory challenges. High-pressure treatment at 600 MPa (HP600) as reported by Ketnawa et al. (2025) to enhance mouthfeel and flavor stability in SP beverages, achieving scores comparable to almond milk, although cost, scalability, and intensified flavor perception require further evaluation. Complementary strategies to improve acceptability include formulation adjustments with fruits or natural sweeteners (De Los Rios Carvajal, 2019), technological interventions such as extrusion, enzymatic treatment, or microencapsulation to improve texture and reduce lipid oxidation (Fadini et al., 2018; Rodríguez Paucar et al., 2018), and consumer education emphasizing nutritional and sustainability benefits (Clavijo, Rodríguez, & Estupiñán, 2015).

Consumer purchase intent studies further support these approaches. Burgers containing 10% SP achieved a 71.67% positive purchase response, outperforming 20% substitution formulation (Clavijo et al.,

2015). Fortified convenience foods with Sacha Inchi demonstrated high polyunsaturated fatty acid content, appealing to health-conscious consumers (Betancur, Luz, & Luis, 2016).

Overall, evidence indicates that moderate ingredient inclusion and mild processing may enhance sensory appeal; however, variability in study design, product type, and consumer familiarity limits the ability to draw definitive conclusions. Achieving reliable acceptability will likely require integrated strategies combining formulation optimization, targeted processing, and consumer-focused interventions to develop Sacha Inchi-based foods and beverages that are both palatable and nutritionally valuable.

7.3.2. Regulatory considerations

Food safety regulations are a global priority and an essential requirement for international trade, consumer confidence, and compliance with national and regional legislation. It involves ensuring the sanitary integrity of food to protect consumer health and enable the free flow of safe products in the market (Bendeković, 2015). Modern strategies, such as the “farm-to-fork” approach, emphasize integrated management across production, transport, storage, and consumption to mitigate contamination risks.

SP faces regulatory challenges due to phytotoxins in raw kernels namely saponins (~27 mg/kg), alkaloids (~485 mg/kg), and lectins (~0.22 ng/kg) (Srichamnong et al., 2018). Roasting significantly reduces these compounds, and safety studies confirm that roasted seeds and leaves are non-toxic (Srichamnong et al., 2018).

However, EFSA recently rejected a traditional food application (NF 2018/0752) for roasted Sacha Inchi seeds in the EU due to insufficient validation of analytical methods and a lack of alkaloid characterization, concluding the product “may pose a safety risk to human health” (EFSA, 2020). As such, roasted seeds and SP remain unapproved in the EU under Regulation (EU) 2015/2283, which mandates pre-market safety evaluations unless significant consumption prior to May 1997 can be demonstrated (WTO, 2017). The key hurdle in the EU is therefore not inherent toxicity, but the need for validated analytical methods and robust toxicological data, which contrasts with the U.S. FDA approach. Only Sacha Inchi oil has been approved and is listed under Implementing Regulation (EU) 2017/2470, labeled and regulated similarly to linseed oil (WTO, 2017) this demonstrates how regulatory approval can be highly product-specific.

Ireland follows the same framework. The Food Safety Authority of Ireland (FSAI) accepted Sacha Inchi virgin oils as substantially equivalent to Inca Inchi oil already on the EU market, based on composition, metabolism, and safety profile (FSAI, 2014). However, there are no authorizations for SP or protein isolates, and these require novel food applications and safety dossiers.

In the United States, the Food and Drug Administration (FDA) granted Sacha Inchi oil GRAS status under GRN No. 506 in 2014 after review by a panel of qualified toxicologists. The panel concluded that Sacha Inchi oil is safe for use in select foods under GMP (SAC, 2014). Unlike EFSA, the FDA relies on expert panel consensus and existing safety literature rather than a formal pre-market “novel food” dossier. However, no GRAS notices currently exist for SP or protein isolates, which would require independent submission of safety and use data.

In Thailand, the Ministry of Public Health restricts SP intake to 1.5 grams per person per day, reflecting concerns over residual phytotoxins (Chansuvarn et al., 2024). This strict limit poses a hurdle for developing high-protein foods such as plant-based milk or protein isolates. Overcoming this requires dose-response studies and validated toxicity data to support regulatory petitions for higher inclusion levels.

In contrast, Peru the primary source country has proactively established the Technical Standard NTP 151.407:2015 for Sacha Inchi powder, typically derived from press cake. This standard mandates ≥55% protein, ≤13% fat, ≤6% moisture, and specific limits on ash, contaminants, and odor to ensure domestic product quality and facilitate export (Rodeiro, 2018). In parallel, Peru is leading efforts to include Sacha

Inchi oil in the Codex Alimentarius. During the 28th Codex Committee on Fats and Oils (CCFO28), Peru chaired the Electronic Working Group revising Codex Standard CXS 210-1999 and achieved Step 5/8 adoption of a draft for Sacha Inchi oil, which was submitted for final approval at the 47th Codex session (Ambiental, 2024). This development marks a key milestone toward international standardization and market access.

The regulatory landscape for SP demonstrates fragmented approaches: EFSA emphasizes pre-market dossiers and analytical validation; the FDA relies on GRAS notifications; Thai authorities impose strict intake limits; Peru focuses on national standards and Codex participation. These differences create complex hurdles for commercialization, particularly for high-protein or functional SP products. Effective navigation requires: Harmonization of analytical and toxicological methodologies across jurisdictions, development of comprehensive safety dossiers addressing region-specific concerns and engagement with Codex and national standards to facilitate mutual recognition and market entry

In summary, SP holds significant potential as a sustainable, high-protein, functional food ingredient, but commercialization is constrained by jurisdiction-specific regulatory hurdles. Coordinated scientific, analytical, and regulatory strategies are essential to ensure global market acceptance and consumer safety.

7.4. Interdisciplinary collaboration

Valorizing SP requires a food systems approach involving collaboration across disciplines. Food technologists and chemists optimize processing and characterize bioactive components, while nutritionists validate digestibility and health effects through clinical or preclinical studies. Environmental scientists assess sustainability using life cycle analysis to support clean-label and upcycled food positioning (Qu, Xiao, Upadhyay, & Luo, 2024).

Legal and regulatory experts guide novel food compliance, labeling, and claims strategies, ensuring that early-stage research anticipates jurisdictional requirements (Nikhil Swaraj, Moses, & Manickam, 2025). Economists and business strategists evaluate raw material availability, cost-effectiveness, and consumer pricing models. Marketing teams must address ethical and sensory dimensions to enhance consumer trust and willingness to adopt SP-based foods (Pretner, Darnall, Testa, & Iraldo, 2021).

Crucially, engaging supply chain actors—from smallholder farmers to processors and manufacturers ensures equitable sourcing and product legitimacy. Participatory innovation involving end users and community stakeholders helps align product development with social, environmental, and economic goals. Establishing transdisciplinary platforms for shared data, coordinated innovation, and stakeholder feedback is key to integrating SP into global food systems.

8. Conclusion

SP, a nutrient-rich by-product of oil extraction, holds significant potential for sustainable and functional food innovation. Its composition which rich in high-quality proteins, dietary fiber, essential fatty acids, and bioactives makes it a valuable ingredient for health-oriented applications. However, translating laboratory findings into scalable, consumer-accepted products remains a major challenge. Recent advances in processing technologies including extrusion, autoclaving, enzymatic hydrolysis, fermentation, and emerging methods such as HPP, HPH, UAE, MAE, OH/PEF, and cold plasma have shown promise in enhancing SP's functional, nutritional, and sensory properties. These innovations support its application across multiple sectors and align with circular economy goals. Despite this progress, critical barriers persist, including scale-up limitations, regulatory hurdles, and suboptimal consumer acceptability. Future research should focus on cost-effective, integrated processing strategies, clinical validation of health benefits, and tailoring solutions to regional market and policy contexts.

With coordinated interdisciplinary efforts, SP can be effectively transformed from an underutilized residue into a high-value ingredient, contributing to resilient, health-promoting, and environmentally sustainable food systems.

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Janet Wamuni Njoroge: Writing – original draft, Methodology, Investigation, Data curation. **Piyawan Phonphimai:** Writing – original draft, Visualization, Methodology. **Pantaree Khatmorn:** Writing – original draft, Methodology. **Sunantha Ketnawa:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Phetnumnuang Tonkla:** Writing – original draft, Methodology. **Vannita Vong:** Writing – original draft, Methodology. **Jaspreet Singh:** Writing – review & editing. **Lovedeep Kaur:** Writing – review & editing. **Nathawuddhi Donlao:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, 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 review article.

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Supplementary materials

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Data availability

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

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