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Review

Supercritical Fluid Extraction of Amazonian Oils and Fats: Promising Species, Equipment, Yields, Composition, and Potential Uses

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Abstract: Amazonian oils and fats (AOFs) have promising composition and bioactive properties, and their processing with supercritical fluids presents several opportunities and challenges for the industry. Our review is dedicated to unraveling the advances in the application of supercritical fluid extraction (SFE) to produce these exceptional oils and fats from Amazonian raw materials, such as fruits, pulps, seeds, and industrial by-products. Our review found that Amazonian plant species produce lipid-rich raw materials and also grow naturally in other regions with similar climates. AOFs present high nutritional value and functional properties due to their content of bioactive compounds. The properties of AOFs are attributed to their major and minor components; lipid molecules represent the major fraction and some fat-soluble compounds, such as tocopherols, phytosterols, terpenes and others, constitute the minor fraction. The production of AOFs by SFE requires properly prepared raw materials and process optimization. Several scientific articles report on the production of AOFs by SFE, but application studies in product development are still scarce. The composition and technological properties of AOFs show a wide spectrum of opportunities for the development of nutritional and functional products. Aspects such as the scaling up of the SFE process, agroforestry or agronomic production, and product development require further studies to promote the AOFs industry in a way that contributes to sustainable development, food security, and the quality of life and health of the Amazonian populations.

Keywords: Amazonian fruits; edible oils; triacylglycerols; fat-soluble phytochemicals; supercritical fluid extraction

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1. Introduction

Oils and fats present a complex composition that includes fatty acids, acylglycerols, phospholipids, sphingolipids, and sterols [1]; this composition may vary depending on

the raw material. Lipids are an important source of energy in the human diet and play important roles in metabolic processes [2]. Currently, the lipids used in the industry for the manufacture of a wide range of products come from industrial crops and exotic tropical species [3]. A wide variety of tropical plant species thrive in the Amazon region [4]. This diversity stems from the presence of unique ecosystems along the banks of the Amazon River in South America [5]. The literature highlights the potential of Amazonian species for the production of oils and fats due to their yield and composition [3]. Some Amazonian raw materials produce fats with a higher content of saturated fatty acids, such as the seeds of *Theobroma grandiflorum* [6], which presents interesting bioactive compounds for the manufacture of food products for human [7] and animal [8] consumption. Cupuassu (*T. grandiflorum*) seeds are used to produce products similar to those derived from cocoa [9]; the liquor made from both seeds (cupuassu and cocoa) has a similar lipid content, but the liquor from cupuassu has a lower content of palmitic fatty acid [10]. Other Amazonian raw materials have a high content of oils rich in unsaturated and polyunsaturated fatty acids, such as the fruits of *Mauritia flexuosa* [11], *Oenocarpus distichus* [12], seeds of *Bertholletia excelsa* [13], and others. The composition of fatty acids, secondary metabolites, and physicochemical and thermodynamic properties of AOFs [7] offer a horizon of diverse opportunities for the development of new products, such as cosmetics, functional foods, pharmaceuticals, and biofuels [7,14,15]. On the other hand, some of these raw materials have managed to position themselves in local and international markets as minimally processed products and/or derivatives, contributing to the economy of the countries of the Amazon region [16]. However, the Amazon region offers a greater diversity of species that produce lipid-rich raw materials that are little known to date. In this context, the present review aims to describe the main scientific advances in the application of supercritical fluid technology to produce AOFs, highlighting new Amazonian species as potential for the oils and fats industry.

The processing of raw materials to obtain lipids involves unit operations based on conventional and/or emerging technologies. Conventional technologies include the Soxhlet method [17], the Bligh and Dyer method [18], dynamic maceration [19], and mechanical pressing [20,21]. The quality of lipids for use in products and responsibility to the environment are motivations that have driven scientific research for the development of unit operations using new technologies, such as SFE [22,23], ultrasound [20], microwave [24], and variations of the SFE method [25–28]. SFE is considered an emerging technology characterized by its extraction selectivity, low operating temperatures, no use of toxic solvents, and the use of GRAS (Generally Recognized as Safe) solvents as polarity modifiers to enhance the extraction of polar molecules [29]. Supercritical carbon dioxide ($scCO_2$) was more effective than the Soxhlet method with petroleum ether to obtain seed oil from *Virola surinamensis* [23]; $scCO_2$ yielded *Acrocomia aculeata* kernel oil with a higher content of phytosteroids and tocopherols compared to compressed propane and Soxhlet method with n-hexane [17]. *Renealmia petasites* Gagnep. seed oil with a higher composition of terpenes was obtained with $scCO_2$ compared to the Soxhlet methods with petroleum ether and maceration with hexane [19]. The yield and phytochemical content (tocopherols, volatile, and semi-volatile) of *Dipteryx alata* Vogel oil obtained with $scCO_2$ was superior compared to continuous expeller press [21]. In the literature, many scientific publications are available on the application of $scCO_2$ for the extraction of oils and fats from a wide variety of raw materials. The oils and fats of Amazonian origin can be obtained from fruits and seeds, from trees [7,15,30], palms [7,14,31], and other types of plants [7,19,32–34].

The present review article discusses the technological advancement of the application of $scCO_2$ in the production of lipid compounds from Amazonian raw materials. The composition of fatty acids and lipid-soluble compounds is addressed, highlighting promising

Amazonian species. The potential applications of the main fatty acids and lipid-soluble bioactive compounds are also described. In the following sections of the review, the SFE process for obtaining Amazonian oils and fats is described, highlighting the potential of this method in comparison to conventional methods. The potential of AOFs, especially those obtained by SFE, is highlighted in comparison to conventional methods. The diversity of Amazonian species studied to date using supercritical fluids is shown, highlighting the particularities of each raw material and the way of preparation. The composition of AOFs and their bioactive properties are analyzed and discussed as a basis for the development of the functional products industry and future perspectives.

2. Procedure of Search and Selection of Scientific Articles

The review period was from 2015 to 2024 in the SCOPUS database, using the keywords "Oil extraction by mechanical pressing", "Supercritical fluid extraction oilseeds", "SFE tropical oily fruit", "CO_2 extraction oil pulp fruit", "SFE fatty acid", "SFE bioactive compounds oilseeds", "SFE bioactive compounds oily fruit", "SFE Terpenes oilseeds", "SFE Phytosterols oilseeds", "SFE Carotenoids oilseeds", "SFE fat-soluble vitamins", "SFE oil: Validation", "SFE oil: Optimization", "SFE oilseeds: scale-up criteria", "SFE oilseeds: Industrial scale", and "Supercritical fluid extraction oil modeling". The articles were selected using two criteria: (1) the Amazonian origin of the raw materials used in the studies, and (2) the article should focus on SFE of oils or/and fats, SFE processing, and application of the lipid fraction and/or liposoluble compounds obtained by SFE. The first criterion was pre-selection; only original articles were considered, and the scientific name of the samples used in the studies was used to verify the Amazonian origin in the GBIF [35], Tropicos [36], and KEW [37] databases. Additionally, articles that used samples of species collected in countries that do not belong to the Amazon region were considered, but the species must occur naturally in the Amazon region. Finally, the articles used in the present review were selected using the second criterion to the articles pre-selected with the first criterion.

3. Amazonian Oleaginous Plants

The Amazon region has a great diversity of plant species with potential for the production of oils/fats, which can be obtained from seeds and fruit pulp produced by palms, trees, lianas, cactus, climbing shrubs, and other types of plants (Table 1).

Table 1. Oleaginous species from the Amazon region.

Species	Part of Plant	Oil/Fat	
	Palm		
Oenocarpus bacaba	Fruit	Oil	[15]
Elaeis oleifera	Fruit	Oil	[38]
Oenocarpus bataua Mart.	Fruit	Oil	[7,14,31]
Attalea speciosa Mart. (Synonym: *Orbignya phalerata*)	Seed	Oil	[7,14]
Euterpe oleracea	Fruit	Oil	[39]
Mauritia aculeata	Fruit	Oil	[39]
Barcella odora	Pulp	Oil	[39]
Astrocaryum acaule	Pulp	Oil	[39]
Bactris gasipaes	Pulp	Oil	[39,40]
Astrocaryum murumuru	Seed	Fat	[7]
Mauritia vinifera	Fruit	Oil	[7]
Euterpe edulis M.	Pulp	Oil	[41]

Table 1. *Cont.*

Species	Part of Plant	Oil/Fat	
Euterpe precatoria	Fruit	Oil	[31]
Oenocarpus distichus Mart.	Fruit	Oil	[12]
Maximiliana maripa	Fruit	Oil	[42]
Mauritiella armata Mart.	Fruit	Oil	[43]
Oenocarpus mapora H. Karst	Pulp	Oil	[20,22]
Mauritia flexuosa L.f.	Fruit	Oil	[11,30,31,39]
Astrocaryum vulgare	Pulp/Kernel	Oil	[30,44]
Acrocomia aculeata	Pulp	Oil	[45–47]
	Tree		
Platonia insignis	Fruit	Oil	[15]
Virola surinamensis	Seed	Fat	[7,30]
Carapa guianensis Aublet	Seed	Oil	[14]
Annona hypoglauca	Seed	Oil	[39]
Byrsonima crassifolia	Seed	Oil	[39]
Byrsonima coccolobifolia	Seed	Oil	[39]
Platonia insignis	Seed	Fat	[7]
Theobroma grandiflorum	Seed	Fat	[7]
Pentaclethra filamentosa	Seed	Oil	[7]
Copaifera langsdorffii	Stem	Oil	[7]
Carapa guianensis	Seed	Oil	[7]
Theobroma grandiflorum	Seed	Fat	[6]
Swietenia macrophylla King	Seed	Extract	[48]
Hevea brasiliensis	Seed	Oil	[30,49]
Terminalia catappa	Seed	Oil	[30,49]
Gustavia macarenensis	Fruit	Oil	[50]
Jatropha curcas L.	Seed	Oil	[51]
Moringa oleifera Lamarck	Seed	Oil	[52]
Persea americana Mill.	Pulp	Oil	[53]
Parinari pachyphylla Rusby	Seed	Oil	[54]
Pterodon spp.	Fruit	Oil	[55]
Pentaclethra macroloba	Seed	Oil	[6,56]
Geoffroea decorticans	Seed	Oil	[57]
Dipteryx alata Vogel	Seed	Oil	[21,25]
Theobroma cacao L.	Seed	Fat	[58]
Bertholletia excelsa	Seed	Oil	[7,13,15,18]
Pterodon emarginatus Vogel	Seed	Oil	[59]
Dipteryx lacunifera Ducke	Seed	Oil	[60]
Caryocar brasiliense Cambess.	Seed	Oil	[61,62]
	Subshrub or shrub		
Capsicum baccatum	Fruit	Apocarotenoids	[63]
Capsicum chinense	Fruit	Apocarotenoids	[63]
Ruellia angustiflora	Leaves	SFE extract rich in fat-soluble compounds	[64]
	Liana		
Passiflora edulis	Fruit	Oil	[30]
Passiflora spp.	Seed	Oil	[7]
	Cactus		
Hylocereus megalanthus	Seed	Oil	[34]
	Climbing shrub		
Plukenetia volubilis L.	Seed	Oil	[65]

Table 1. *Cont.*

Species	Part of Plant	Oil/Fat	
Rubus glaucus	Seed	Oil	[33]
Scrambling subshrub			
Solanum lycopersicum	Seed/peel	Oleoresin/Oil	[32,66]
Perennial or rhizomatous geophyte			
Renealmia petasites Gagnep.	Seed	Oil	[19]

3.1. Palms

Table 1 shows a total of twenty palm species that were reported to produce fruits, pulp, and seeds with potential for oil/fat production. A greater number of raw materials studied come from the Brazilian Amazon [7,12,14,15,39,41–45], followed by Colombia [31,40], Peru [11,20], and Costa Rica [38]. The processing of Amazonian palm fruits integrates usual unitary operations, such as selection, washing/disinfection, pulping (manual and/or mechanical), dehydration (forced convection drying and/or freeze-drying), and milling [11,12,20,31,38–40,42–45]. Some fruits (*O. mapora* and *O. distichus*) require heat treatment in order to soften the pulp and facilitate the separation of the pulp from the peel and seeds [12,20]. The fruits of Amazonian palms are gaining importance in the industry due to their composition, nutritional characteristics, and functional properties; in the most recent studies, the fruits that constitute the samples in scientific research come from the direct collection of the palms in natural environment [11,40,42,43], experimental centers [31,38,45], and germplasm bank [12], and were also acquired from markets [39,44] and processing companies [20,39,41]. At the industry level, palm fruits are processed to obtain oils and fats [7], and research laboratories evaluated the production of biodiesel from *O. bacaba* oil [15].

3.2. Trees

A total of twenty-six species of fruit-producing trees that have seeds and/or pulps with high lipid content were recently reported in the literature (Table 1). The studies used raw materials (fruits, seeds, and pulp) in natura collected from the field [25,48,50–54,57,59], experimental centers [49,60], agricultural fields [18,53,61], commercial centers [39,55], and processing companies [56]. Another set of the studies used derivatives of Amazonian raw materials from universities [15] and processing companies [6,7,30,58]. Based on the number of studies with Amazonian raw materials (in natura products and derivatives), the country that stood out most was Brazil [6,7,15,18,25,30,39,52,53,55,59–61], followed by Indonesia [49], Ecuador [50], Colombia [54], Malaysia [48], Chile [57], China [58], and India [51]. Although countries such as Indonesia, Malaysia, Chile, China, and India do not belong to the Amazon region, scientific studies conducted in those countries involved raw materials from species that grow in those countries [48,49,51,57] and that also grow in the Amazon region. It could also be observed that they used processed raw materials, probably from the Amazonian regions [58].

The processing of tree fruits presents some particularities due to the morphological characteristics of each species. Usually, the processing of Amazonian oils/fats is constituted by unitary operations such as selection, pulping, drying, and milling [25,50,53]. Some species produce fruits with a modified morphology and have no pulp (mesocarp), such as the fruits of *Pterodon* spp. [55], *G. decorticans* [57], and others, requiring shelling and dehulling operations, both mechanical unit operations performed manually [18,48,54,57].

3.3. Other Plants

Other Amazonian plants with high lipid potential include various classifications, such as liana, cactus, climbing shrub, scrambling subshrub, and rhizomatous geophyte (Table 1).

Table 1 shows seven oilseed-producing species from Brazil [7,19,30], Colombia [33,65], Ecuador [34], and Romania [32]. Some of the species of these groups are widely produced in the agricultural sector in several countries that do not even belong to the Amazon region, such as *S. lycopersicum* [32], *P. edulis* [30], *H. megalanthus* [34], and *P. volubilis* [65]. According to our review, it was verified that the scientific studies used nuts, seeds, and seed oils, which were acquired from processing companies; this allows us to deduce that there is an interesting level of industrialization for the productive sector.

AOFs have various properties and particularities that differentiate them from oils and fats obtained from conventional oilseeds. Some of these particularities are described below:

The oil obtained from *Oenocarpus bacaba*, *Platonia insignis*, *Bertholletia excelsa*, and *Elaeis guineensis* has great potential for the production of biodiesel; a negative aspect of these oils is the presence of metals, considered contaminants, which occur naturally or are produced in the catalysis reaction in the process of obtaining biodiesel [15]. The species *J. curcas* and *M. oleifera* Lamarck also have the potential for the production of biodiesel [51,52] due to their high content of monounsaturated fatty acids, especially oleic acid, although there are varieties of *J. curcas* that produce seeds with a higher content of linoleic acid [51]. On the other hand, the oil obtained from the seeds of *M. oleifera* was subjected to transesterification, obtaining 86% of an ester with technical characteristics of adequate quality for the production of biodiesel [52].

In a recent study, a variety of oil palm (*Elaeis oleifera* Quepos (CB9204)) has been reported to produce fruits with a higher content of tocotrienols (890 μg/g of oil) and vitamin E (892 μg/g of oil) compared to varieties of *E. guineensis*; the content of these compounds was evaluated in oil extracted by conventional methods [38]. On the other hand, *Acrocomia aculeata* is a widely distributed species in the Amazon region; the fruit of this palm has productivity and oil quality like palm oil and can be a substitute for this crop in the Amazon region. Its oil yield from the pulp is about 75%, and from the seeds is 65% [46]. The oils obtained from *C. guianensis*, *O. bataua*, and *A. speciosa* are also rich in vitamins (A and E) and unsaturated fatty acids, which gives them medicinal properties for the treatment of skin diseases, being used empirically in Amazon populations as natural cosmetics [14].

The use of AOFs in the formulation of functional foods is a promising alternative for the food industry because they contain fatty acids of various degrees of unsaturation. The degree of unsaturation of fatty acids gives oils and fats different indices of atherogenicity and thrombogenicity, which are important characteristics for the formulation of healthier foods. These characteristics were observed in the fat extracted from *T. grandiflorum*, and the oil from *P. macroloba* and *P. edulis* [6]. Also, the oil obtained from the pulp of *C. brasiliense* has medicinal and health-promoting potential because it is rich in unsaturated fatty acids, carotenoids, and phenolic compounds [62]. *H. megalanthus*, known as the dragon fruit, is cultivated in many Asian countries, as well as in several countries that belong to the Amazon region and other countries with a tropical climate; the oil from its seeds is an interesting source of linoleic acid, which represents 69% of the total composition of its fatty acids [34]. The oleic, linoleic, and linolenic acid composition of oil from *E. oleracea*, *A. hypoglauca*, *M. aculeata*, *Byrsonima crassifolia*, *B. coccolobifolia*, *B. odora*, *A. acaule*, *B. gasipaes* var. red, and *B. gasipaes* var. yellow was evaluated by nuclear magnetic resonance, all the oils presented a high content of oleic acid in relation to the other fatty acids, followed by linoleic acid, which was in higher concentration in the oil of three species (*A. hypoglauca, B. crassifolia*, and *B. coccolobifolia*), while linolenic acid was found in low concentration in the oil of all species, varying from 0.3 to 2.4% [39].

O. phalerata oil, *A. murumuru* fat, and *P. insiginis* fat have a higher content of saturated fatty acids, such as lauric and palmitic acid, a higher proportion of monounsaturated fatty acids was observed in *Mauritia vinifera* oil and *P. filamentosa*, and a high content of

polyunsaturated fatty acids was observed in the seeds of *Passiflora* spp.; the presence of unsaturated fatty acids present functional properties of great importance for the prevention of human health [7].

The AOFs, like the oils and fats of commercial oilseeds, have a higher composition of acylglycerides, made up of saturated, unsaturated and/or polyunsaturated fatty acids. Studies have shown that the fatty acid composition of the acylglycerides of oils and fats strongly influences the thermodynamic properties associated with phase transitions, which represent an important technological characteristic of food processing. Accordingly, it has been observed that the oil from the pulp of *A. vulgare* Mart. (Tucumã) is similar to the oil from the pulp of *M. flexuosa* Mart., the oil from the seed of *H. brasiliensis* is similar to the oil from the seed of *P. edulis*, and the oil from the seed of *A. vulgare* Mart is similar to the fat of the seeds of *V. surinamensis* [30].

AOFs contain other lipid or fat-soluble compounds that have biological activity of great interest for medical and/or pharmacological applications; in this group of compounds are fucosterol and β-sitosterol. Both compounds were detected in the ethereal extract obtained from the seeds of *S. macrophylla*; this species is used in Malaysia for the treatment of diabetes mellitus [48]. *S. macrophylla* is a species that is widely distributed in the Amazon region. Recently, the antihyperglycemic activity of seed extracts obtained with different organic solvents was studied, which showed a promising effect for the treatment of this condition [48].

The presence of bioactive compounds in AOFs may contribute to their functional properties. For example, in the case of oil obtained from the fruit of *G. macarenensis*, characterized by its higher fraction of unsaturated acids and the presence of bioactive compounds, the latter confer antioxidant properties [50].

While it is true that the raw materials of Amazonian origin that we present in this review are potential sources of oils rich in bioactive molecules, we should not ignore other macronutrients, such as proteins, for example, the seeds of *P. tetragonolobus*, *H. brasiliensis* and *T. catappa*, have an interesting protein content for the industry [49]. After the extraction of the oil from the seed of these three species, the solid by-product of the extraction process has a higher concentration of protein, which is ideal for incorporation in the formulation of feed rations for ruminants [49].

4. Conventional Extraction of Amazonian Oils/Fats

Tables 2 and 3 summarize some studies with Amazonian oleaginous raw materials extracted by conventional methods. The conventional methods used for the recovery of Amazonian oils/fats were grouped into mechanical methods (Table 2) and methods using organic solvents (Table 3).

Extraction with organic solvents allows for obtaining a higher yield compared to mechanical methods. This can be attractive for the industry, but studies show that the application of organic solvents affects the physicochemical and compositional characteristics of lipid extracts [31,52,67]. When hexane was used as an extraction solvent to obtain oil from *M. oleifera* seeds, the oil obtained presented a high acidity index (20.5 mg KOH/g oil) compared to the oil obtained by mechanical pressing (8.8 mg KOH/g oil); this indicates that the oil obtained with hexane is of lower quality than the oil obtained by mechanical pressing, due to the high content of free fatty acids [52]. Using hexane with two extraction methods (Soxhlet and maceration), the maceration method obtained a higher yield (30%) of oil from *P. edulis* seeds, but the yield decreased (19.9%) when replaced with ethanol; on the other hand, the acidity index of the oil obtained with ethanol was higher than the oil obtained with hexane [67]. On the other hand, when studying the extraction of oil from *E. precatoria*, *M. flexuosa*, and *O. bataua* pulps, it was observed that the acidity index was higher for oils obtained by mechanical pressing compared to the extraction method with organic

solvent [31]; this difference in relation to the other studies reported in the literature may be due to the type of mechanical pressing machine used and the type of organic solvent used. Extraction methods using organic solvents present a higher extraction yield than mechanical methods but can generate negative effects on the composition and quality of Amazonian oil that may limit its application in the natural products industry. Conventional methods using organic solvents to obtain oils are highly polluting. Alternatively, other emerging technologies can be applied, such as supercritical fluids [68], which will be described in the following section.

Table 2. Mechanical extraction of AOFs.

Raw-Material	Extraction Methods	Yield	
Moringa oleifera Lamarck	Mechanical pressing	11%	[52]
Caryocar brasiliense Camb	Hydraulic pressing Pressure: 0.5 ton/cm^2 Temperature: 30 °C	32%	[62]
	Hydraulic pressing + enzymatic treatment Pressure: 0.5 ton/cm^2 Temperature: 30 °C	39%	
Euterpe edulis Mart.	Cold pressing Temperature: 25 °C Raw-material moisture: 10%	10%	[41]
	Hot pressing Temperature: 50 °C Raw-material moisture: 10%	20%	
Persea americana Mill.	Cold pressing Pressing force: 9 tons Raw-material moisture: 5–6%	42%	[53]
Passiflora edulis	Mechanical pressing	19.5%	[67]
Jatropha curcas	Bielenberg press	26%	[69]
Jatropha curcas	Screw pressing Temperature: 80 °C Raw-material moisture: 4.5%	16.2%	[70]
Parinari pachyphylla Rusby	Hydraulic pressing	-	[54]
Euterpe precatoria	Expeller press	10%	[31]
Mauritia flexuosa	Temperature: 25–30 °C	22%	
Oenocarpus bataua	Particle size: 1 mm	28%	

Table 3. Extraction with organic solvents of AOFs.

Raw-Material	Extraction Conditions	Yield	
Jatropha curcas L.	Soxhlet Solvent: hexane Temperature: 70–80 °C Time: 8–10 h	13.7–54.4%	[51]
Moringa oleifera Lamarck	Soxhlet Solvent: hexane Time: 4 h	36%	[52]
Swietenia macrophylla king	Maceration Solvent: petroleum ether Temperature: 60–80 °C	8.6%	[48]
	Maceration Solvent: Chloroform Temperature: 60–80 °C	6.2%	
	Maceration Solvent: Methanol Temperature: 60–80 °C	5.4%	

Table 3. *Cont.*

Raw-Material	Extraction Conditions	Yield	
Psophocarpus tetragonolobus	Soxhlet Solvent: petroleum ether Time: 6 h Particle size: 1 mm	20%	[49]
Hevea brasiliensis		37.6%	
Terminalia catappa		52.1%	
Gustavia macarenensis Philipson	Soxhlet Solvent: hexane Time: 4 h Particle size: 1 mm	53.6%	[50]
Euterpe precatoria	Soxhlet Solvent: Petroleum benzene Temperature: 40–60 °C Particle size: 1 mm	18%	[31]
Oenocarpus bataua		62%	
Mauritia flexuosa		33%	
Euterpe oleracea		35.4%	
Annona hypoglauca		15%	
Oenocarpus bacaba		43.9%	
Mauritia flexuosa		23.2%	
Mauritia aculeata		26%	
Byrsonima crassifolia	Soxhlet Solvent: hexane Particle size: 0.84–0.42 mm	46.5%	[39]
Byrsonima coccolobifolia		38%	
Bactris gasipaes var. yellow.		17.1%	
Bactris gasipaes var. red		27.3%	
Barcella odora		12%	
Astrocaryum acaule		33.1%	
Acrocomia aculeata	Soxhlet Solvent: hexane Temperature: 69 °C Time: 8 h Raw-material moisture: 3.6% Particle size: 0.5 mm	25.6%	[47]
	Soxhlet Solvent: Dichloromethane Temperature: 40 °C Time: 8 h Raw-material moisture: 3.6% Particle size: 0.5 mm	26.8%	
Acrocomia aculeata	Soxhlet Solvent: hexane Temperature: 68 °C Time: 8 h Raw-material moisture: 3.3% Particle size: 0.841 mm	43.6%	[17]
Plukenetia volubilis L.	Soxhlet Solvent: hexane Temperature: 60 °C Time: 20 h Raw-material moisture: 2.36% Particle size: 1.51–2.01 mm	40.6%	[65]
Passiflora edulis	Soxhlet Solvent: hexane Time: 4 h	23.6%	[67]
	Maceration Solvent: hexane Time: 24 h	30%	
	Maceration Solvent: ethanol Time: 24 h	19.9%	

Table 3. *Cont.*

Raw-Material	Extraction Conditions	Yield	
Virola surinamensis (Rol. ex Rottb.) Warb.	Soxhlet Solvent: Petroleum ether Time: 4 h Raw-material moisture: 2.5% Particle size: 0.24 mm	61.4%	[23]
Cyphomandra betacea (Cav.) Sendtn.	Soxhlet Solvent: hexane Time: 6 h Raw-material moisture: 4.97% Particle size: 0.68 mm	24.1%	[71]

5. SFE-CO_2

5.1. Processes Parameters

SFE can be considered a unit operation in the production process of extracting oils and fats from different raw materials. The processing of oils and fats with supercritical fluids includes stages such as preparation/conditioning of raw material, preparation of the extraction unit with supercritical fluids prior to extraction, SFE extraction, and cleaning of the extraction unit.

Conditioning of Amazonian raw materials for the SFE process at the laboratory scale involves different unitary operations, such as dehulling, drying, and milling of *A. aculeatum* seeds [72], pulping to obtain passion fruit seeds and freeze-drying of seeds [73], pulping and freeze-drying of *A. vulgare* pulp [44]; these operations were implemented for in natura raw materials and depending on the type of source (seeds, pulp, other parts) of oils/fats these unit conditioning operations may vary for SFE extraction. The reader is referred to the articles cited in Table 4 for the unit operations implemented for various in natura feedstocks and some agro-industrial residues.

Based on our experience, preparing SFE equipment for laboratory and pilot-scale extraction is quite similar. In the first instance, we must point out that the SFE equipment requires auxiliary equipment for its operation, such as an air compressor to activate the CO_2 compression pump and a cooling bath to cool the head of the CO_2 compression pump. First, the two auxiliary units must be turned on. The air compression pump must reach 6 bar pressure, and the cooling bath should be -2 °C, adjustable as needed. Commercial pilot plants and industrial SFE equipment are usually equipped with electric CO_2 compression pumps. On the other hand, the extraction vessel is loaded with the previously conditioned raw material; depending on the configuration and dimensions of the vessel, the extraction bed can be filled completely or partially, and the empty space of the vessel can be filled with an inert material (such as glass beads), which allows a better economy of the solvent. Once the extraction vessel is ready, the operating conditions of temperature and pressure are conditioned. With the conditioning of pressure and temperature, the extraction of the components without CO_2 flow starts, commonly called static extraction and can have different durations (5 min [43], 30 min [12], 50 min [19], among others). After the static extraction, the dynamic extraction begins; in this stage, a constant extraction flow is established. Depending on the supercritical conditions and the oil and fat content of the raw material, the SFE process time may vary until complete extraction.

After the SFE extraction, the equipment must undergo cleaning for further extraction operation. Usually, the cleaning consists of passing a solvent (ethanol, water and a mixture of both) through the piping system and valves of the SFE equipment. Some oily extracts may have components that are difficult to clean with the mentioned solvents; in

that situation, it is possible to use cleaners recommended for the pharmaceutical industry, such as alkaline cleaners. However, conditions of use must be established, such as concentration, temperature, and volume of cleaner to be used depending on the raw material under extraction.

In general, the factors that can influence the yield and composition of oils and fats in the SFE process are particle size, CO_2 flux, type of polarity modifier (cosolvent), and cosolvent concentration, pressure, and temperature (Table 4). Thermodynamic parameters (temperature and pressure) influenced the oil extraction yield of *P. edulis* seeds [74], the fatty acid composition of *O. distichus* oil [12], the microbial activity of *V. surinamensis* seed oils [23], and the antioxidant activity of *B. gasipaes* oils [40]. When evaluating the effect of pressure, temperature, and mass flow on *P. volubilis* oil extraction, it was observed that they affected the yield, quality indexes, and oil composition [65]. The use of ethanol as a polarity modifier in the supercritical extraction of *M. maripa* oil increased the extraction yield and composition [42]. In *C. annuum* oil extraction, the parameters of temperature, pressure, extraction time, and particle size influenced the extraction yield [75]. The yield and composition of *D. alata* almond oil were influenced by the factors of pressure, temperature, cosolvent type, and cosolvent concentration [21]. On the other hand, scale-up studies to obtain AOFs by SFE are limited; the most recent study reports a new scale-up method based on a dimensionless number called Gama (Ga) [76]. This new method allowed the reproduction of similar oil extraction yields from *A. vulgare* pulp for small and large scale [76]. Another successful scale-up experience was carried out with *P. volubilis* seeds, the scaling technique was to keep constant the ratio between CO_2 flow (g/min) and raw material mass (g) [65]. These scale-up experiments are promising, but further studies are needed for other Amazonian raw materials, and other aspects such as stability, shelf life, and bioactive properties of AOFs should also be evaluated.

Table 4. SFE of AOFs.

Raw-Material	Extraction Conditions	Yield	
Passiflora edulis seeds	Temperature: 60 °C Pressure: 35 MPa Time: 2.5 h Raw-material moisture: 10%	15.7%	[74]
	Temperature: 60 °C Pressure: 20 MPa Time: 1.34 h	21.6%	[67]
	Temperature: 60 °C Pressure: 35 MPa Time: 2.5 h Raw-material moisture: 7.8% Flow rate: 30 g/min	15.7%	[33]
Oenocarpus distichus Mart. pulp	Temperature: 50 °C Pressure: 35 MPa Time: 3 h	45.2%	[12]
	Temperature: 60 °C Pressure: 27 MPa Time: 3 h	46%	
Cyphomandra betacea (Cav.) Sendtn. seeds	Temperature: 51 °C Pressure: 38 MPa Time: 2.5 h S/F: 22.5 Raw-material moisture: 4.5% Particle size: 0.69 mm	17.4%	[71]

Table 4. *Cont.*

Raw-Material	Extraction Conditions	Yield	
Oenocarpus bacaba pulp	Temperature: 60 °C Pressure: 42 MPa Time: 3 h Raw-material moisture: 4.2%	60.4%	[77]
Plukenetia volubilis L. seeds	Temperature: 60 °C Pressure: 50 MPa Time: 3 h Raw-material moisture: 2.4% Particle size: 1.5–2 mm	23.5%	[65]
	Temperature: 60 °C Pressure: 45 MPa Time: 4.5 h Raw-material moisture: 3.3% Particle size: 1.64 mm	26.8% **	
Lycopersicon esculentum L. seeds	Temperature: 60 °C Pressure: 35 MPa Time: 2 h Particle size: 1 mm	7.8%	[78]
Virola surinamensis seeds	Temperature: 80 °C Pressure: 35 MPa Time: 3 h Raw-material moisture: 2.5% Particle size: 0.24 mm	64.4%	[23]
Acrocomia aculeata kernel	Temperature: 40 °C Pressure: 22 MPa Time: 3.3 h Raw-material moisture: 3.3% Particle size: 0.481 mm	41.6%	[17]
Pterodon spp. fruits	Temperature: 50 °C Pressure: 20 MPa Time: 4.5 h Raw-material moisture: 2.3% Solvent flow rate: 12 g CO_2/min	31.1%	[55]
Pentaclethra macroloba seeds	Particle size: 0.57 mm Temperature: 40 °C Pressure: 30 MPa Solvent flow rate: 0.7 kg CO_2/h Particle size: 1.19 mm	42.05%	[56]
	Temperature: 40 °C Pressure: 30 MPa Time: 120 min Solvent flow rate: 4 mL/min Particle size: 1.19 mm	23.3%	[79]
Solanum lycopersicum seeds	Temperature: 60.2 °C Pressure: 40 MPa Solvent flow rate: 64.6 g/min Particle size: 1.00 mm	16.9%	[80]
Psidium guava seeds	Temperature: 50 °C Pressure: 45 MPa Time: 60 min Raw-material moisture: 8% Co-solvent: ethanol at 3 mL/min	10.45%	[81]

Table 4. *Cont.*

Raw-Material	Extraction Conditions	Yield	
Maximiliana maripa pulp	Temperature: 52 °C Pressure: 35.7 MPa Time: 150 min Solvent flow rate: 30 g CO_2/min Raw-material moisture: 8.05% Average particle diameter: 0.490 mm Pure CO_2	8.6%	[82]
	Temperature: 60 °C Pressure: 20 MPa Time: 170 min Solvent flow rate: 2 cm^3/min Raw-material moisture: 11.7% Mean particle diameter: 1.6×10^{-3} m CO_2 + Ethanol	3.6%	[42]
	Temperature: 60 °C Pressure: 20 MPa Time: 60 min Raw-material moisture: 11.7% Average particle diameter: 1.6×10^{-3} m	20.4%	
Pterocaulon lorentzii leaves and inflorescences	Temperature: 40 °C Gradual pressure increments: 9 to 30 MPa Time: 100 (leaves) and 110 min (inflorescences) Solvent flow rate: 1 kg/h Raw-material moisture: 5.27 (inflorescences) and 2.08% (leaves) Average thickness of fibers: 0.061 (inflorescences) and 0.148 mm (leaves)	109.05 (leaves) and 610.03 mg coumarins/g of extract (inflorescences)	[83]
Lippia graveolens HBK leaves.	Temperature: 45 °C Pressure: 35 MPa Time: 300 min Solvent flow rate: 30 g CO_2/min	4.1%	[84]
Capsicum annuum L. fruits	Temperature: 65 °C Pressure: 35.78 MPa Time: 90 min Particle size: 0.78 mm Raw-material moisture: 4–6% Solvent flow rate: 3 L/min	4.91%	[75]
Genipa americana L. fruits	Temperature: 60 °C Pressure: 30 MPa Mean particle diameter: 0.23 mm Raw-material moisture: 5.1% Solvent flow rate: 2.5 g CO_2/min	4.6%	[85]
Bactris gasipaes epicarp	Temperature: 40 °C Pressure: 40 MPa Time: 210 min Raw-material moisture: 7.1%	12.12%	[40]
Geoffroea decorticans almond	Temperature: 60 °C Pressure: 40 MPa Time: 120 min Raw-material moisture: 4.93% Solvent flow rate: 3.62 g CO_2/min	47%	[57]

Table 4. *Cont.*

Raw-Material	Extraction Conditions	Yield	
Dipteryx alata Vogel seeds	CO_2 + water Temperature: 60 °C Pressure: 20 MPa Time: 240 min Raw-material moisture: 2.30 g/100 g Mean particle diameter: <0.85 mm Solvent flow rate: 3 mL/min	21.67 g/100 g	[21]
	CO_2 + Alcohol Temperature: 50 °C Pressure: 30 MPa Time: 240 min Raw-material moisture: 2.30 g/100 g Mean particle diameter: <0.85 mm Solvent flow rate: 3 mL/min	31.06 g/100 g	
	CO_2 + Alcohol:water Temperature: 60 °C Pressure: 20 MPa Time: 240 min Raw-material moisture: 2.30 g/100 g Mean particle diameter: <0.85 mm Solvent flow rate: 3 mL/min	21.67 g/100 g	
Capsicum annuum industrial waste	CO_2 Temperature: 45 °C Pressure: 35 MPa Time: 185 min Average particle diameter: 1.8 mm	22 g/100 g	[25]
	CO_2 Temperature: 60 °C Pressure: 20 MPa Mean particle diameter: 0.48 mm Solvent flow rate: 3 g CO_2/min	9.60%	[86]
	CO_2 + Ethanol Temperature: 40 °C Pressure: 25 MPa Mean particle diameter: 0.48 mm Solvent flow rate: 3 g CO_2/min Ratio ethanol/sample: 0.5 mL/g	10.08%	
Mauritiella armata Mart. pulp	Temperature: 40 °C Pressure: 30 MPa Time: 61 min Mean particle diameter: 2.107 mm Solvent flow rate: 17 g/min	41.57 g/100 g	[43]
Cyperus esculentus L. nut	Temperature: 40 °C Pressure: 28 MPa Time: 90 min	28.56 g/100 g	[87]
Rubus glaucus seeds	Temperature: 60 °C Pressure: 35 MPa Time: 150 min Raw-material moisture: 7.60% Solvent flow rate: 30 g/min	14.5%	[33]
Annona squamosa seeds	Temperature: 45 °C Pressure: 25 MPa Time: 60 min Solvent flow rate: 2.5 mL/min Raw-material moisture: 6.21% Average particle size: 427 nm	0.29 g/g	[88]

Table 4. *Cont.*

Raw-Material	Extraction Conditions	Yield	
Annona muricata L. seeds	Temperature: 40 °C Pressure: 30 MPa Time: 210 min Solvent flow rate: 0.7 kg/min Raw-material moisture: 4.98% Mean particle size: 0.53 mm	16.4%	[89]
Pachira aquatica Aubl. seeds	Temperature: 60 °C Pressure: 30 MPa Time: 120 min Solvent flow rate: 1.21 kg/h Raw-material moisture: 3.25% Average particle size: 1.19 mm	51.78%	[90]
Bertholletia excelsa cake (by-products)	Temperature: 60 °C Pressure: 40 MPa Time: 180 min Solvent flow rate: 40 g/min Raw-material moisture: 0.25% Particle size: <1 mm	59.2%	[13]
Renealmia petasites Gagnep. seeds	Temperature: 40 °C Pressure: 35 MPa Time: 40 min Solvent flow rate: 1.06×10^{-4} kg CO_2/s	4.15%	[19]
Gliricidia sepium seeds	Temperature: 60 °C Pressure: 30 MPa Time: 90 min Solvent flow rate: 2.5 mL/min	11.79%	[91]
Oenocarpus mapora H. Karst fruit	Temperature: 60 °C Pressure: 35 MPa	7.45%	[20]
	Temperature: 43.5 °C Pressure: 27.07 MPa Time: 120 min Solvent flow rate: 39 g/min Raw-material moisture: 6% Particle size: 350–500 µm	30.4 g/100 g	[22]
Mauritia flexuosa L.f. pulp	Temperature: 42 °C Pressure: 20 MPa Time: 60 min Solvent flow rate: 42 g CO_2/min	44.85%	[11]
Carica papaya seeds	Temperature: 65 °C Pressure: 25 MPa Time: 240 min Solvent flow rate: 15 g CO_2/min Particle size: 0.26 mm Co-solvent flow rate: 10% of CO_2 flow rate	36.67%	[92]
Pterodon emarginatus Vogel seeds	Temperature: 40 °C Pressure: 30 MPa Time: 65 min Solvent flow rate:4.5 g CO_2/min Average particle size: 0.87 mm	40 g/100 g	[59]
Dipteryx lacunifera Ducke cake	Temperature: 40 °C Pressure: 20 MPa Time: 240 min Solvent flow rate: 1.0 kg/h Raw-material moisture: 4.50 g/100 g	15.52%	[60]

Table 4. *Cont.*

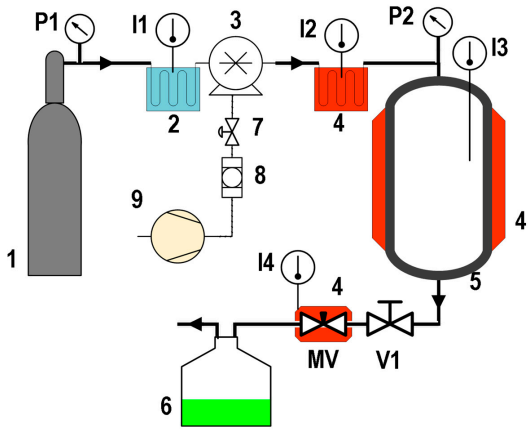
Raw-Material	Extraction Conditions	Yield	
Astrocaryum vulgare pulp	Temperature: 60 °C Pressure: 30 MPa Time: 180 min Solvent flow rate: 8.85 × 10^{-5} kg/s Average particle size: 1 mm Raw-material moisture: 5%	36.75%	[44]
Caryocar brasiliense Cambess almonds	Temperature: 45 °C Pressure: 25 MPa Time: 110 min Solvent flow rate: 5.0 g/min Average particle size: 3.5 g/min	27.6%	[61]
Hyptis suaveolens (L.) Poit seeds	Temperature: 80 °C Pressure: 45 MPa Time: 193 min Solvent flow rate: 0.88 kg/h Raw-material moisture: 8.94% Particle size: > 75 µm	62.36%	[93]
Passiflora ligularis Juss. (seeds)	Temperature: 40 °C Pressure: 40 MPa Time: 60 min Solvent flow rate: 3.62 g/min Raw-material moisture: 1.57% Mean particle diameter: 0.60 mm	24.97%	[73]
Astrocaryum aculeatum almonds	Temperature: 50 °C Pressure: 25 MPa Solvent flow rate: 1.8 × 10^{-4} kg/s Raw-material moisture: 3.7% Particle size: 1.19 mm	34.41 g/ 100 g	[72]

** Pilot scale.

5.2. SFE Equipment

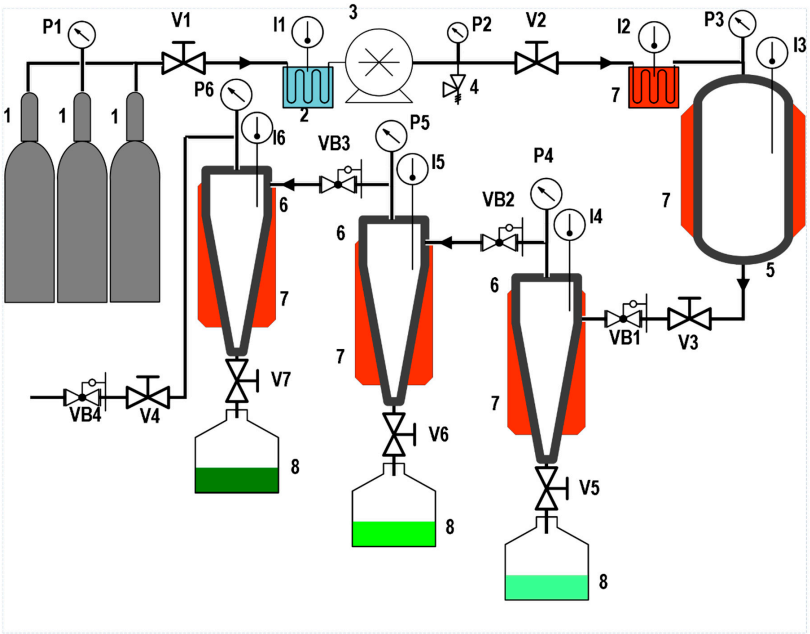
Figures 1–3 illustrate representative diagrams of laboratory, pilot, and industrial-scale SFE equipment. Usually, laboratory-scale SFE equipment is used for studies to determine the dynamic extraction behavior and to determine thermodynamic conditions of extraction of bioactive components from raw materials. The scale-up of the SFE process involves some modifications in the configuration of the SFE equipment, mainly due to the volume of CO_2 consumption; in laboratory scale equipment, the extract is collected at the end of the extraction line immediately after depressurization during dynamic extraction. This is different in pilot plant (Figure 2) and industrial scale (Figure 3) equipment, requiring separation vessels located after the extraction vessel in order to progressively reduce the solvent pressure to a pressure that allows its reuse through a recirculation system; in pilot scale equipment, the recirculation system may or may not be included (Figure 2). In the literature consulted, studies are described that used pilot plant and industrial-scale SFE equipment for the extraction of oils/fats from Amazonian raw materials. In the extraction of oil from *P. edulis* seeds, a pilot scale equipment with a 0.5 L vessel, incorporated with two 0.5 L separation vessels, was used to obtain 15.7% of oil rich in linoleic acid [33]. A different configuration of pilot SFE equipment was used in the extraction of oil from *O. mapora* pulp; the equipment consisted of a 1 L capacity vessel [22]. In the extraction of oleoresins from *L. graveolens*, equipment consisting of an extraction vessel, a separator and a CO_2 recirculation system was used; according to the results of the study, this technology proved to be efficient [84]. Another pilot SFE equipment configuration was used for the

recovery of oil from *B. excelsa* cake from beverage production; the equipment consisted of a 273 mL vessel with two 0.5 L separators [13]. A semi-industrial unit with a 4.2 L extraction vessel was used for the extraction of oil from tomato waste [66]. In another work, a unit with a 12 L extraction vessel and two 6 L separators was used to obtain omega-3-rich *P. volubilis* oil [65].



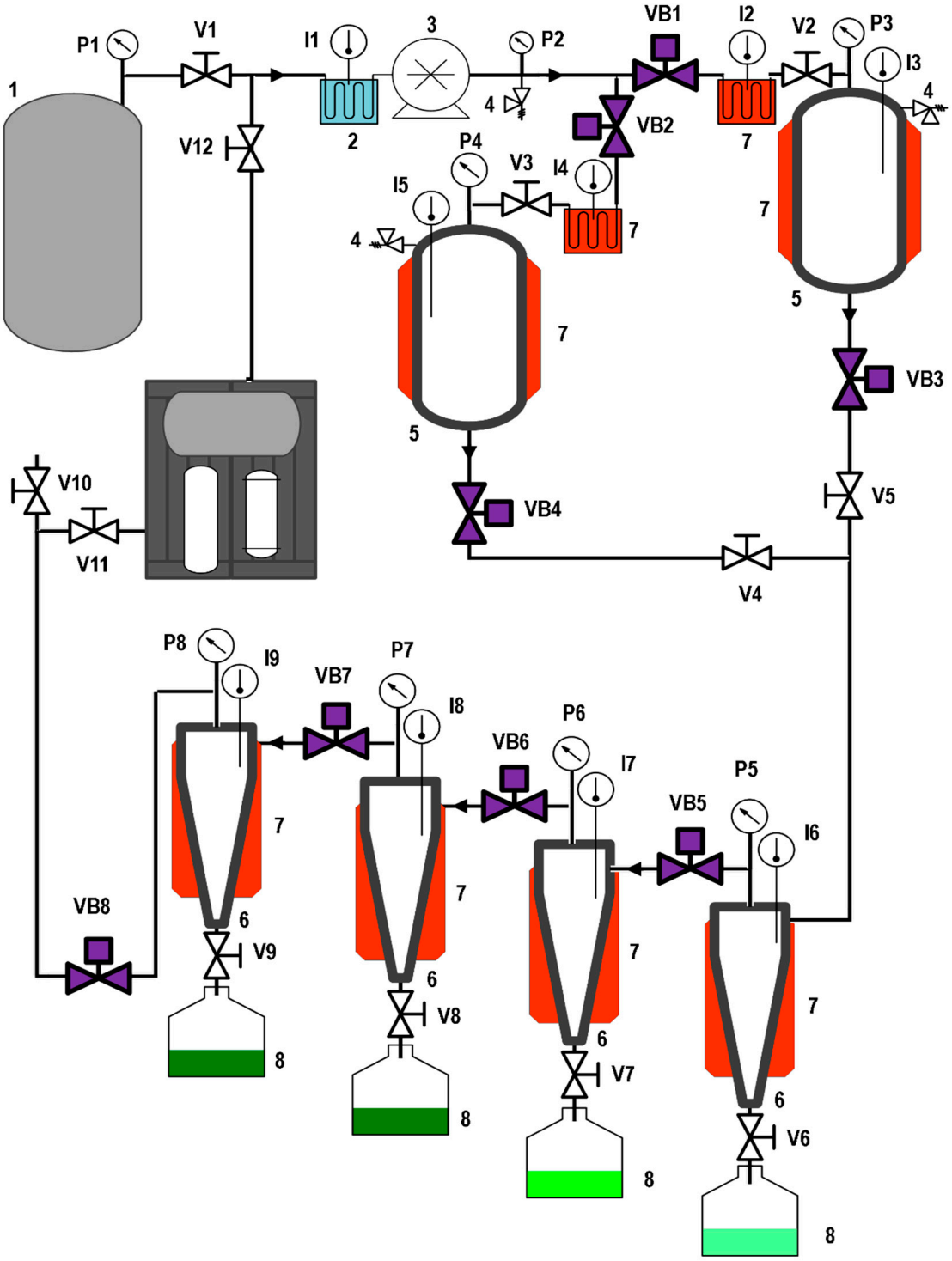
1	CO_2 reservoir	6	Extract collecting vessel
2	Cooling bath	I1 - I2 - I3 - I4	Temperature indicator
3	Pump	P1 - P2	Pressure gauge
4	Heating system	V1	Blocking valve
5	Extraction vessel	VM	Micrometering valve
7	Air Pressure Regulator	8 — 9	Air filter and Compressor

Figure 1. Laboratory SFE equipment.



1	CO_2 reservoir	7	Heating system
2	Cooling	8	Extract collecting vessel
3	Pump system	I(1, 2, 3, 4, 5, 6)	Temperature indicator
4	Safety valve	P(1, 2, 3, 4, 5, 6)	Pressure gauge
5	Extraction vessel	V(1 - 7)	Blocking valve
6	Separator	VB (1, 2, 3, 4)	Back pressure valve

Figure 2. Pilot SFE equipment.



1	CO_2 reservoir	7	Heating system
2	Cooling	8	Extract collecting vessel
3	Pump system	9	CO_2 recycling system
4	Safety valve	I(1 - 9)	Temperature indicator
5	Extraction vessel	P(1 - 8)	Pressure gauge
6	Separator	V(1 - 12)	Blocking valve
VB (1 - 8) Back pressure valve (Automated systems)			

Figure 3. Industrial SFE equipment.

6. Fatty Acids from AOFs

Table 5 shows the main fatty acids found in oils and fats extracted from some Amazonian raw materials using SFE. Note that some of these species are not exclusive to the Amazon region and may be found elsewhere. Recent research was conducted using pulp, seeds, fruits, leaves, and by-products (cakes) from the oil and fat industry. Some oils extracted via supercritical fluids from seeds, such as *P. edulis* [67] and *C. betacea* [71], are notable for their high content of polyunsaturated fatty acids, particularly linoleic and linolenic acids. On the other hand, oils from other raw materials presented a high content of monounsaturated fatty acids, with oleic acid standing out, which was observed in oils from the pulp of *E. oleracea* [94], *O. distichus* [12], *O. bacaba* [77], and seeds of *M. oleifera* [95], among others. Several studies have shown the importance of unsaturated fatty acids in human nutrition [96,97]. Unsaturated fatty acids, linoleic (18:2n6) and α-linolenic (18:3n3), are essential fatty acids since the human body cannot synthesize and must be obtained from dietary sources; these are precursors of the long-chain polyunsaturated fatty acids (PUFAs) of the omega-6 and omega-3 family [98,99]. PUFAs are necessary to maintain cell membranes, brain functions, and the transmission of nerve impulses under normal conditions, among other functions [99,100]. Other lipid extracts obtained by supercritical fluids presented a high content of saturated fatty acids, such as the one obtained from seeds of *V. surinamensis* [23] and pulp of *O. distichus* [12]. An interesting cis-11-Eicosenoic acid (C20:1) content was observed in extracts obtained from *M. oleifera* leaves, this fatty acid having antimicrobial properties against antibiotic-resistant *Staphylococcus aureus* [95]. The oil from the seeds of *V. surinamensis* also showed antimicrobial activity against *S. aureus* [23]. The variability of the composition and potential bioactive properties of the fatty acids of AOFs obtained by SFE reveals an opportunity for the development of functional products and the need for further research efforts for new applications.

Table 5. Main fatty acids of AOFs that are obtained by SFE-CO_2 from some Amazonian species.

Raw Material	Fatty Acids *	Content (%)	
P. edulis seeds	Linoleic C18:2	70.9	[67]
	Oleic C18:1n9	16.6	
	Palmitic C16:0	9.4	
E. oleracea pulp	Oleic C18:1n9	52.73	[94]
	Palmitic C16:0	23.47	
	Linoleic C18:2n6	15.54	
	Palmitoleic C16:1	5.49	
V. surinamensis seeds	Myristic C14:0	71.66	[23]
	Lauric C12:0	23.48	
	Palmitic C16:0	1.86	
	Pentadecanoic C15:0	1.44	
	Decanoic C10:0	1.03	
O. distichus pulp	Oleic C18:1n9	66.22	[12]
	Palmitic C16:0	17.62	
	Linoleic C18:2n6	12.10	
	Stearic C18:0	2.39	
O. bacaba pulp	Oleic C18:1n9	60.52	[77]
	Palmitic C16:0	22.05	
	Linoleic C18:2n-6	13.37	
	Stearic C18:0	2.68	

Table 5. *Cont.*

Raw Material	Fatty Acids *	Content (%)	
M. oleifera leaf	cis-11-Eicosenoic C20:1	54.44	[95]
	Palmitic C16:0	23.65	
	Linoleic C18:2n6	6.84	
	Oleic C18:1n9	5.92	
	Stearic C18:0	3.93	
	cis-5,8,11,14,17-Eicosapentaenoic C20:5n-3	1.99	
	Myristic C14:0	1.13	
M. oleifera seed	Oleic C18:1n9	74.50	[95]
	Palmitic C16:0	7.92	
	Stearic C18:0	7.10	
	Arachidic C20:0	4.28	
	Linolenic C18:3n3	2.50	
	Palmitoleic C16:1	1.49	
C. betacea seeds	Linoleic C18:2n6	66.67	[71]
	Oleic C18:1n9	17.94	
	Palmitic C16:0	10.41	
	Stearic C18:0	2.84	
	α-Linolenic C18:3	1.92	

* Only fatty acids with content ≥ 1% reported in the literature are shown.

7. Fat-Soluble Bioactive from AOFs

AOFs are notable for their rich content of bioactive secondary metabolites (Table 6). Table 6 shows some minority compounds present in oil obtained by the SFE process from species occurring in the Amazon region; tocopherols, triterpenes, and phytosterols were identified. Tocopherols were identified in the seed oil of *P. edulis* [67], *A. aculeata* [17], and *C. betacea* [71], with *P. edulis* oil standing out for its γ-tocopherol content [67]. Tocopherols are characterized by being a natural form of vitamin E, with anti-inflammatory action and antioxidant properties [101]. The squalene triterpene was identified in the species *P. edulis* [74] and *C. betacea* [71]. Squalene is biosynthetic precursor for phytosterol and cholesterol [102]. This compound is naturally found in oils such as olive, palm, wheat germ, amaranth, and rice bran oil; however, shark liver oil remains the richest source [102]. Squalene has antioxidant properties, acts on skin hydration, has a preventive effect on breast cancer, is antitumor and cardioprotective, and decreases serum cholesterol levels [103]. Phytosterols were identified in the species *P. edulis* [67,74], *A. aculeata* [17], and *C. betacea* [71], with β-sitosterol having the highest concentration present in *P. edulis* seed oil [67]. Phytosterols are compounds found in Amazonian oils and fats (Table 6). Phytosterol supplementation can contribute to the treatment of hypercholesterolemia in children and adolescents [104]. The bioactive components of AOFs tend to be lost during refining in industrialization [105]; in that context, it is important to develop adequate extraction and transformation processes to develop quality products with functional properties and commercial value [106]. In this section, we focus on the compounds reported in Table 6, but in the literature consulted, other minority components are reported in oils and fats from Amazonian raw materials obtained by SFE.

Table 6. Bioactive compounds identified in oils and fats extracted by SFE.

Raw-Material	Compounds Type	Compounds	Content (mg/100g)	
P. edulis seed	Tocopherol	α-tocopherol	2.5	[67]
		γ-tocopherol	11.3	
		δ-tocopherol	3.9	
	Phytosterol	Campesterol	38.7	
		Estigmasterol	98.6	
		β-sitosterol	157.5	
		Δ5 avenasterol	18.5	
		Δ7 stigmasterol	7.1	
		Δ7 avenasterol	9.4	
		Methylene cycloartenol	8.9	
		Citrostadienol	9.6	
A. aculeata seed	Tocopherol	α-tocopherol	1.33	[17]
		γ-tocopherol	1.81	
		δ-tocopherol	5.08	
P. edulis seed	Terpene	Squalene	11.13 **	[74]
	Phytosterol	Campesterol	0.78 **	
		Estigmasterol	2.43 **	
		β-sitosterol	2.58 **	
A. aculeata seed	Phytosterol	Lanosterol	0.58 **	[17]
		Campesterol	1.71	
		β-sitosterol	22.99	
C. betacea seed	Terpene	Squalene	6.82 ¥	[71]
	Tocopherol	γ-tocopherol	2.10 ¥	
	Phytosterol	Dihydrolanosterol	0.64 ¥	
		β-sitosterol	3.01 ¥	
		Cycloartenol	2.40 ¥	

** mg/mL and ¥ mg/g.

8. Potential Uses and Perspectives of Amazonian Lipids Obtained by SFE

Recent studies on AOFs highlight their considerable potential for health benefits and broad industrial applications, including in the food, pharmaceutical, and cosmetic sectors [7,106]. The thermophysical, chemical, and nutritional properties of fats/oils obtained from Amazonian species, such as *T. grandiflorum*, *A. murumuru*, *A. vulgare*, *V. surinamensis*, *C. guianensis*, *P. macroloba*, *O. bacaba*, *B. excelsa*, and *O. bataua*, are interesting for the development of food products [6,107,108]. Recent research cited in this review shows that the application of supercritical fluids using carbon dioxide as an extraction solvent has proven to be a good eco-friendly alternative to produce Amazonian lipids of high biological value. Although these scientific studies show the advantages of the SFE process compared to conventional techniques, there are still limited scientific studies on the application of AOFs obtained by SFE for product development. But due to their composition of lipid and lipid-soluble compounds, Amazonian oils extracted by supercritical fluids present diverse properties, such as antioxidant capacity [19,20,43,56,81,87,90], capacity to inhibit neurodegenerative enzymes [19], oxidative stability [87], nutraceutical [22,44,81], antibacterial [84], and allelopathic activity [94], which would allow them to be used as ingredients or additives in a wide range of products of interest to the food, pharmaceutical, cosmetic, and other industries. On the other hand, an interesting alternative that requires further research is the use of AOFs for their enrichment with liposoluble components, with the objective of developing functional products. For example, rice oil can be used as a cosolvent for extracting lycopene from papaya by SFE [109], and other applications can be made with

conventional oils and fats. Recent research shows a promising horizon for the development of products with raw materials rich in lipids of Amazonian origin for markets specialized in natural products. From a technological perspective, the implementation of an AOFs industry would face the challenge of scaling up the SFE process. Table 4 in Section 5 shows the parameters of the SFE process at non-commercial scales. Process times can be observed in some cases to be considerably long, mainly due to the high content of the lipid fraction in the raw material, making the SFE process considerably extended. In this regard, some innovations have been reported in the literature, such as SFEAP [110], GAME [111], and simultaneous extraction with cold pressing and supercritical fluids [26]. Although these innovations are promising, scaling up to a commercial level is still pending. On the other hand, the complexity of the composition of bioactive molecules in the lipid fraction of Amazonian raw materials could become a challenge for the manufacture of products with specific functional properties. The prospects for industrialization of AOFs obtained by SFE are interesting but challenging for the scientific and industrial community; some aspects that need to be addressed are the supply and preparation of raw materials due to the variability of their physical, chemical, and perishability characteristics of each Amazonian species. On the other hand, it is necessary to address the development of technological packages that allow the processing of AOFs to maintain the functional properties from the raw material to the manufactured product.

9. Conclusions

The Amazon region has favorable soil and climatic conditions for the development of a great diversity of plant species that produce fruits, seeds, pulps, and other parts of the plant, which have a lipid composition and fat-soluble compounds that are promising for various sectors of modern industry. The diversity of Amazonian raw materials represents a challenge for SFE processing due to their physical–mechanical and compositional characteristics, requiring the development of procedures for their conditioning, which involve moisture conditioning, particle size reduction, and shelling of fruits and seeds, among others. The composition of AOFs represents an opportunity for the natural products industry due to their content of polyunsaturated fatty acids and liposoluble secondary metabolites that confer diverse bioactive properties reported in the current scientific literature. The SFE processing of AOFs has been explored at laboratory and pilot scales, requiring commercial scale studies and/or studies on the feasibility and economic viability; in that sense, there may be some limitations due to the seasonality of these raw materials and production areas. The production of AOFs using supercritical fluid technologies is advancing; its potential for various applications in pharmaceuticals, functional foods, and cosmetics is supported due to its composition of bioactive phytochemicals, which makes it stand out from conventional oils and fats. In this context, further efforts in research, development, and innovation are needed for the industrialization of AOFs.

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