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*Review*

# Impact of Use of Ultrasound-Assisted Extraction on the Quality of Brazil Nut Oil (*Bertholletia excelsa* HBK)

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**Abstract**

The quality of materials extracted from plant sources, such as oilseeds, is significantly affected by the extraction techniques employed. Thermo-photosensitive bioactive compounds are especially susceptible, often resulting in a loss of functional properties during conventional processing. In this context, studies involving unconventional or "innovative" extraction methods have emerged as a strategic approach to preserve the quality of the extracted material (whether by-product or biomass) by aligning with the core principles of green chemistry and the expansion of sustainable production chains. This approach promotes both raw material integrity and the protection of human and environmental health. These efforts contribute to a virtuous cycle of technological innovation and environmentally sound practices. This review focuses on how ultrasound-assisted extraction affects the quality of plant-derived materials, particularly Brazil nut oil. The article compiles data published over the last five years (2020–2025), following the PRISMA methodology. Recent studies highlight the synergistic potential of ultrasound as a green technology for isolating Brazil nut oil, offering enhanced nutritional and functional properties. This aligns with the growing demand for healthier food products obtained through sustainable industrial processes and presents opportunities for diverse applications across several industry sectors.

**Keywords:** ultrasound; extraction; Brazil nut oil; green technologies; bioactive compounds

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## 1. Introduction

The Brazil nut oil market was valued at USD 4 million in 2023 and is projected to reach USD 7.8 million by 2030, with an estimated annual growth rate of 6.8% during the 2024–2030 period [1]. These figures reinforce the need for research into more efficient and economically viable methods for the extraction, application, and consumption of this oil. Brazil nut oil is widely recognized for its high nutritional and technofunctional potential. It serves as a key ingredient in numerous products within the food, pharmaceutical, cosmetic, and dermocosmetic industries, owing to its rich composition of polyunsaturated fatty acids, vitamins, and antioxidants [2–4].

In this context, extraction technologies that minimize structural damage to the lipid matrix have gained prominence. These innovative approaches aim to align with the core

pillars of green chemistry—human health, raw material integrity, and environmental sustainability—by promoting practices that reduce waste, limit environmental degradation, and ensure more efficient use of energy and solvents [5,6].

The shift from conventional extraction methods to cleaner technologies, often involving the use of so-called green solvents, has been reported as a promising strategy to enhance extraction efficiency and material quality while minimizing harm to humans and nature [7]. Cleaner techniques include the use of enzymes, salt-assisted processes, microwaves, supercritical fluids, and ultrasound-assisted extraction [8–11]. Green solvents are chemicals that minimize environmental impact and toxicity when compared to traditional solvents. They are obtained from renewable sources, such as plants or biomass, and can be biodegradable, reducing pollution and promoting sustainability [8,11,12].

Among these techniques, an ultrasound-assisted extraction (UAE) using green solvent has demonstrated particular advantages, as shown in laboratory-scale research. It reduces the degradation of thermo- and photosensitive bioactive compounds and enables a faster, less complex, and cost-effective process compared to traditional methods such as Soxhlet extraction, mechanical pressing, and microwave or enzymatic approaches [7,9,13,14]. UAE aligns closely with the principles of green chemistry by safeguarding raw material quality and supporting environmental and human health. It also represents an entry point for broader technological innovation and sustainable industrial practice.

Recent research has intensified efforts to compare conventional and green extraction technologies, often revisiting well-established raw materials such as Brazil nuts [7,9,13–15]. Within this landscape, UAE emerges as a scientifically rigorous and promising approach, with considerable potential for application across various industrial sectors.

Bhargavaa et al. (2021) [16] highlight that in the food industry, ultrasound can be applied for supplementing the unit operations or in the processing of the food product by either direct exposure or using an instrument such as a sonotrode or ultrasonic water bath. Specifically, in basic unit operations of the food industry, it is applied in the following: filtration—liquid food products; freezing and crystallization—transfer milk products; fruits and vegetables and meat; thawing—frozen products; brining/pickling—cheese, meat, fish, etc.; drying—dehydrated food products; foaming—protein; degassing/deaeration—carbonic beverages, aqueous solutions; cooking—meat products, vegetables; emulsification—emulsions, e.g., mayonnaise; cutting—soft products; sterilization/pasteurization—milk, juice; rehydration—vegetables, grains, etc.; and extraction—food and plant material.

Different reviews have been conducted on the applications of ultrasound technology in the extraction, preservation, storage, and processing of food [16–21]. However, a specific review covering the application of ultrasound-assisted extraction of Brazil nut oil has not been presented. So, this review paper summarizes this type of extraction. The research is justified because the Brazil nut is one of the most important oleaginous seeds from the Amazon region. Its nutritional richness is internationally acknowledged. Therefore, it has been extensively researched by different industrial segments and attracted heavy investment aimed at isolating its major nutritional and functional products. One of the major industrial interests is in its lipid portion focusing on investigating more profitable and economical isolation and/or extraction. The review is based on a systematic approach and meta-analytical perspective, focusing on studies published between 2020 and 2025. Particular attention is given to sustainability considerations and alignment with green chemistry principles.

## 2. Materials and Methods

This study is a systematic review conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [22]. Literature searches were performed using the following databases: PubMed, Web of Science, Elsevier's, Science Direct, Willey Online Library Scielo, Taylor & Francis, ACS—American Chemical Society, Google Scholar.

The review followed a protocol based on the POT strategy (Population, Outcome, and Type of study), considered appropriate for the scope of this research. The review covered studies published between 2020 and 2025.

The review focused on ultrasound-assisted extraction technologies, specifically identifying studies that described their applications and assessed the quality of the extracted lipid material. The POT protocol was applied to structure, summarize, and analyze the selected studies, according to the following criteria:

P—Population: Studies involving lipid extraction from Brazil nuts. Excluded were studies focusing on other oilseeds, in vitro experiments, case reports, descriptive studies, opinion pieces, editorials, letters to the editor, theses, dissertations, conference proceedings, books, and book chapters.

O—Outcome: Studies that investigated recent technologies for extracting lipids from Brazil nuts, with or without the use of green solvents—particularly ultrasound—and that reported general characteristics, extraction yield, and the nutritional–functional composition of the resulting oil.

T—Type of study: Original scientific articles addressing the extraction of oil or lipid fractions from Brazil nuts—the lipid fraction can refer to different types of lipids present in the oil, such as fatty acids (saturated or unsaturated) and other lipid substances—indexed in the Web of Science, Science Direct, Willey Online Library Scielo, Taylor & Francis, Elsevier's, ACS—American Chemical Society, and Google Scholar.

All three authors independently conducted systematic searches using a combination of Medical Subject Headings (MeSH) and free-text terms. The initial search terms included the following: "ultrasound-assisted isolation of Brazil nut oil", "green extraction of Brazil nut oil", "lipid extraction optimization", "lipid profile quality", "extraction with clean technologies", "Brazil nut (*Bertholletia excelsa* HBK) and lipid fraction", "green oil extraction", "Amazonian oilseeds", and "lipid portion of Brazil nuts". Boolean operators AND and OR were used to refine the search, following the syntax rules of each database. The resulting studies were screened manually for duplicates and assessed for eligibility.

## 3. Results

The database search initially retrieved 114 records (K represents the number of articles found on each base). After the removal of 85 duplicates, 29 articles remained. Following title and abstract screening, 19 studies that did not address ultrasound-assisted extraction or the quality of Brazil nut oil were excluded, leaving 10 articles for full-text review. In total, 10 studies were included in the final analysis of this review (Figure 1).

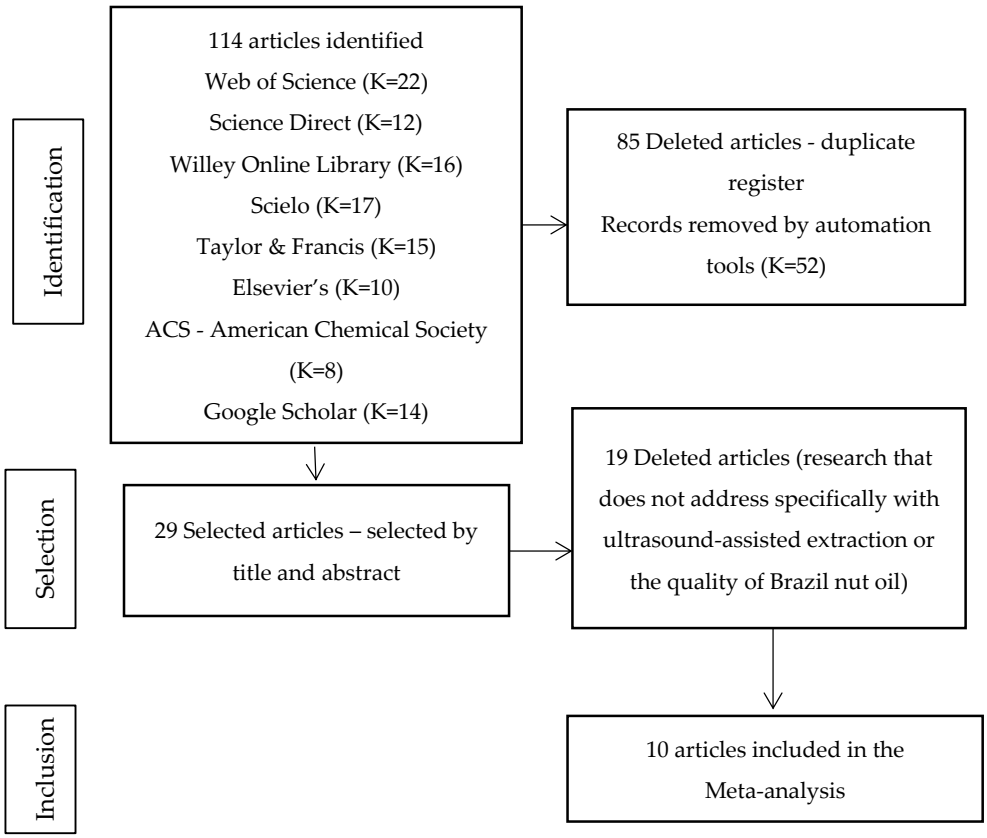



**Figure 1.** Flowchart of paper selection.

The discussion and synthesis of the research findings were organized and discussed following a brief introductory comparison with conventional extraction techniques.

### *3.1. Brazil Nut: General Aspects*

The Brazil nut tree (*Bertholletia excelsa* H.B.K.) is one of the most prominent oilseed species native to the Amazon region and is considered one of its greatest natural resources. According to data from the Plant Extraction and Forestry Production System (PEVS-2023) of the Brazilian Institute of Geography and Statistics (IBGE), Brazil nut production averages approximately 25,000 tons per year [23]. This production volume highlights its economic significance in Brazil's trade balance, with substantial domestic and international demand for whole nuts, both shelled and unshelled [2].

Brazil nut kernels are recognized for their exceptional nutritional and functional composition, with a lipid content ranging from 60% to 70%. This lipid-rich matrix contains a wide array of bioactive compounds, including selenium, $\alpha$- and $\gamma$-tocopherols, phenolic compounds, folate, magnesium, calcium, proteins, and both monounsaturated (MUFA) and polyunsaturated fatty acids (PUFAs) [4,24].

Brazil nut oil has been incorporated into several industrial sectors, including food, pharmaceuticals, and dermocosmetics, due to its valuable physicochemical and bioactive properties [2,3]. Given the consistent quality of kernels sourced from a specific geographic region, there is a recognized need for more detailed studies on Brazil nuts (*Bertholletia excelsa* H.B.K.), particularly regarding their lipid composition and potential for industrial use [15]. As product diversification continues, Brazil nut oil has become increasingly available in the retail market under various commercial brands.

### *3.2. Traditional Extraction Methods Versus Ultrasound-Assisted*

Until recently, oil extraction from oilseeds was primarily carried out using conventional methods such as solvent extraction, steam distillation, or mechanical pressing. These solvent-based techniques typically require the use of large quantities of toxic and environmentally harmful organic solvents, leading to significant waste generation [2,7,9]. Moreover, these methods demand long processing times and consume large amounts of energy. Additional purification steps are also required to eliminate solvent residues and ensure that the final product is safe for consumption. Critically, prolonged exposure to such processing conditions can degrade lipophilic bioactive compounds and unsaturated fatty acids present in the oil, ultimately compromising its quality [25].

As a result, the limitations in yield and material quality imposed by traditional separation methods have driven the search for more sustainable and efficient extraction techniques. These new approaches apply the principles of green chemistry—reducing energy consumption, replacing harmful organic solvents with greener alternatives, and improving both yield and oil quality [7,25–27] (Figure 2).

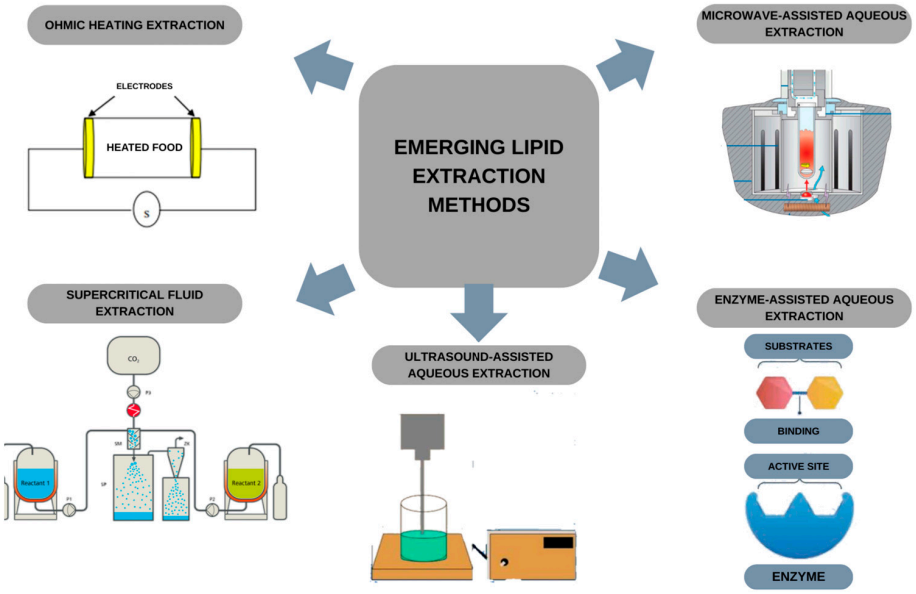



**Figure 2.** Emerging lipid extraction methods.

Oils derived from plant sources are widely utilized in the pharmaceutical, food, biofuel, and dermocosmetic industries [28,29]. Extraction methods can be classified into traditional extraction methodologies and emerging extraction technologies, with technoeconomic and environmental advantages and disadvantages [25,30] (Table 1).

**Table 1.** Advantages and disadvantages of different extraction methods.

| Traditional Extraction Methodologies | Advantages | Disadvantages | Fonte |
|---|---|---|---|
| Maceration | Simple extraction technique; extraction of thermolabile chemicals, low-temperature extraction | Long period of time Lower yield, not economical, the solvent of choice generates waste Waste solvent can be an environmental pollutant | Bisht et al. (2025) [31] Senapati and Behera (2023) [32] |

**Table 1.** *Cont.*

| Traditional Extraction Methodologies | Advantages | Disadvantages | Fonte |
|---|---|---|---|
| Mechanical pressing | Simple extraction technique, low cost, does not need organic solvents, the extraction temperature can be 50 °C to perform cold pressing, preserving nutritional compounds of the oil, reduces environmental impact, making it ecofriendly extraction technique that supports sustainable food systems | Lower oil recovery; limitation in equipment construction Low extraction capacity exposure of the sample to oxidative agents | Lavenburg et al. (2021) [33] Gaikwad et al. (2025) [34] |
| Soxhlet | Low cost; simple operation; high extraction rate | Long extraction time, large reagent and energy consumption (high extraction temperatures) low efficiency and generation of large amounts of environmentally polluting waste | Zhou et al. (2022) [35] Irianto et al. (2025) [36] Bisht et al. (2025) [31] |
| Folch | Fast, easy to handle large number of samples, the complete process is gentle | Toxic reagents are used, which are harmful to human health and the environment, generation of large amounts of environmentally polluting waste | Zhou et al. (2022) [35] Irianto et al. (2025) [36]. |
| Bligh–Dyer | Lipid extraction and separation can be achieved at the same time, simple extraction technique; extraction of thermolabile chemicals, low-temperature extraction | Extractive reagents are toxic and have few substitutes. The cost is high, generation of large amounts of environmentally polluting waste | Zhou et al. (2022) [35] Irianto et al. (2025) [36] |

**Table 1.** *Cont.*

| Traditional Extraction Methodologies | Advantages | Disadvantages | Fonte |
|---|---|---|---|
| Super-/subcritical fluids/pressurized lipids extraction | High extraction efficiency, less use of toxic reagents and easy separation of lipids; protect bioactive compounds, reduce energy consumption and pollution, functions quicker than conventional techniques, increasing efficiency, and operates at lower temperatures, avoiding thermal degradation of heat-sensitive chemicals | It has selectivity to lipids of different polarity and the equipment is more expensive, not economically viable, requires considered technical knowledge high maintenance cost | Zhou et al. (2022) [35] Irianto et al. (2025) [36] Hu et al. (2023) [37] |
| Pulsed electric fields | The operation is simple and pollution-free, processing large number of samples, eliminating harsh chemicals, heavy solvents, and extreme mechanical effects on cells. By using plain water as a solvent, PEF reduces environmental impact, making it an ecofriendly extraction technique that supports sustainable food systems | It is necessary to control the proper electric field strength. Electric fields are too high and may adversely affect the extraction. Requires considered technical knowledge, high maintenance cost | Ramaswamy et al. (2024) [38] Bisht et al. (2025) [31] |
| Ultrasound-assisted extraction | Simple extraction technique: extraction of thermolabile chemicals, low-temperature extraction, by using plain water as a solvent reduces environmental impact, making it an ecofriendly extraction technique that supports sustainable food systems | Ultrasonic equipment is relatively expensive and sensitive, at least in larger operations, building large-scale equipment for industries that evenly distribute waves is a challenge. Powerful ultrasound may also break fragile compounds, so significant control over parameters is necessary. It is also noisy | Zhou et al. (2022) [35] Irianto et al. (2025) [36] Bisht et al. (2025) [31] Simayi et al. (2023) [39] |

**Table 1.** *Cont.*

| Traditional Extraction Methodologies | Advantages | Disadvantages | Fonte |
|---|---|---|---|
| Microwave-assisted extraction | The temperature in the process is low, and the energy required is less. High extraction rate can be achieved in a short time, faster extraction times, less solvent consumption, greater extraction rates, and cheaper costs | This extraction process is affected by temperature, time, ethanol concentration, and solvent-to-sample ratio. Penetration depth, uneven heating in complex matrices, and the risk of overheating thermolabile compounds can affect extraction efficiency. The cost of specialized equipment is higher than traditional methods, and the need for electromagnetic shielding presents safety concerns | Zhou et al. (2022) [35] Irianto et al. (2025) [36] Bisht et al. (2025) [31] Tapia-Quiros et al. (2023) [40] |
| Enzyme-assisted extraction | Selective to substrate, pretreatment can be completed at room temperature and pressure to reduce energy consumption, sustainable and environmentally friendly extraction method with commercial potential, integrated with green technologies, as it requires less energy than conventional extraction techniques | The price of enzyme preparation is high, it is necessary to optimize the conditions to obtain the highest extraction rate, incomplete hydrolysis of plant cell walls, and scalability issues for industrial applications | Zhou et al. (2022) [35] Irianto et al. (2025) [36] Bisht et al. (2025) [31] |

The comparative analysis bases of technoeconomic feasibility (Table 1) highlight relevant aspects for defining the choice of the decision-making process regarding which extraction method to apply on a laboratory and industrial scale. One of the most important is the generation of environmental impacts, but there is a wide variety of parameters to be considered: from the choice of raw material, type of substrate, types of equipment, techniques, and quality yields, combined with the valorization of by-products or biomass, which should be taken as a basis for the cost analysis of advanced extraction technologies in processing plants [41].

The emerging extraction methods individually for their "mixtures" are considered within a tripod: technically, economically, and environmentally better than traditional methods, which categorize them as "green" methodologies because they are more ecologically suitable, with advantages such as reduced use of solvents and consequent minimal

generation of waste that is harmful to the environment, more suitable for thermosensitive compounds, greater preservation of functionality, greater extraction yield in certain compounds, and quality of residual biomass, among others [16,25].

However, these methods also have disadvantages such as difficulty in scaling to the industrial sector, longer extraction times, more expensive equipment and operation costs, complex extraction conditions, need for greater specialization of operators, and more specific suitability for certain raw materials, among others [24,25,36,38].

Solvent extraction, a method widely used in the industrial production of vegetable oils, predominantly relies on n-hexane due to its high efficiency. However, this solvent presents significant challenges, including toxicity and high flammability, which increase the risks associated with the extraction environment. Furthermore, the high temperatures required during certain processing stages can compromise oil quality. These effects may include elevated acidity, alterations in protein composition, and, consequently, a reduction in the nutritional and economic value of the final product [37–39].

Solvent extraction comprises various techniques with differing levels of efficiency and cost. Soxhlet extraction, a conventional method widely employed in research, is based on the principle of solid–liquid extraction. This technique enables continuous solvent circulation and is effective for isolating compounds of interest. However, due to its labor-intensive and time-consuming nature, it is often replaced by faster and more scalable methods in industrial settings [41].

On the other hand, supercritical fluid extraction—typically using $CO_2$ as a non-flammable solvent—offers significant advantages in terms of selectivity and the quality of the extracted product. This method is particularly suitable for high-value-added oils, as it enables the efficient extraction of bioactive compounds without altering their structural properties. However, the extremely high pressures required to maintain oil solubility (approximately 400 bar) make supercritical extraction a costly technique, which limits its applicability on an industrial scale [11]. Therefore, despite its potential, supercritical extraction faces challenges related to installation and operational costs, making it less economically viable than more conventional methods such as Soxhlet extraction.

Mechanical pressing is another widely adopted method in the food industry, whereby oil is extracted from the solid matrix through compression in continuous presses, typically equipped with a helical screw. This process effectively reduces residual oil content to approximately 5%. In addition to being a well-established and low-cost technique, mechanical pressing better preserves the natural characteristics of the oil when compared to methods involving high temperatures or chemical solvents [31,41–44].

Over the years, continuous expeller pressing has gradually replaced traditional mechanical pressing, offering several advantages over organic solvent extraction. This technique is effective for extracting oils from various oilseeds and generally provides good yield. However, despite its efficiency, the process typically leaves between 4% and 8% of residual lipids in the press cake, which limits the complete recovery of oil present in the seeds [40,41,44,45].

In recent years, increasing attention has been given to emerging solvent-free oil extraction technologies. These alternatives aim not only to improve extraction yields but also to provide economic benefits, reduce environmental impacts, and ensure the quality of the final product. The development of clean technologies has become a growing trend, seeking to meet global demands for more sustainable industrial practices while also promoting consumer well-being [40,44,46].

Currently, new extraction techniques such as aqueous extraction—using water as a solvent—are under active investigation. This process begins with the mechanical disruption

of oilseed cell walls through grinding and pressing, which facilitates the release of lipid globules and enables a more sustainable oil recovery process [47].

Enzymatic extraction presents another sustainable alternative to traditional methods. Because it operates at low temperatures, this approach minimizes the degradation of heat-sensitive compounds, thereby preserving oil quality. Furthermore, the absence of chemical solvents significantly reduces the environmental impact by eliminating the generation of toxic waste. This method has proven effective in sectors such as food, pharmaceuticals, and animal feed, offering additional benefits such as lower greenhouse gas emissions and alignment with environmentally friendly production standards. These features are consistent with the growing demand for cleaner technologies that mitigate contributions to global warming [48–50].

Microwave-assisted extraction and salt-assisted extraction are emerging methods that enhance the recovery of oils and bioactive compounds. The microwave technique converts electromagnetic energy into heat, accelerating the extraction process without disrupting the molecular structures of the sample matrix, thereby improving efficiency. Salt addition, in turn, helps prevent emulsion formation, facilitating oil separation. Both methods have proven effective in releasing bioactive compounds—such as flavonoids and polysaccharides—that are of particular relevance to the food and pharmaceutical industries [44,46,51].

The combination of techniques such as microwaves, ultrasound, and salt addition has been employed to optimize the efficiency of enzymatic aqueous extraction. Ultrasound, for instance, utilizes frequencies above 20 kHz to generate sound waves that disrupt the cellular matrix, facilitating the release of target compounds such as oils. This results in improved solvent penetration and shorter processing times. Additionally, the method demonstrates high selectivity and is classified as a green technology due to its low energy consumption and reduced environmental impact. These integrated approaches are increasingly valued for their efficiency and sustainability [44,51–53].

In parallel, the replacement of harmful organic solvents (many of which are derived from petrochemical industry by-products) has become an environmental imperative. These traditional solvents often compromise the quality of raw materials and pose serious ecological risks. In contrast, ultrasound-assisted extraction using solvents derived from renewable organic sources has been shown to reduce the environmental impact and yield products of higher quality [54].

For these reasons, over the past two decades, numerous technologies have been investigated and developed in pursuit of greener extraction approaches. Among them, innovative and environmentally friendly alternatives such as ultrasound-assisted extraction (UAE) have been studied under various operational conditions to enhance the recovery of seed-derived compounds. These studies have focused on key quality parameters, including the physicochemical, nutritional, and sensory attributes of the final products [54]. Within this context, UAE emerges as a promising technology, either as a stand-alone method or in combination with other techniques, capable of achieving sustainability goals closely aligned with the principles of green chemistry.

UAE operates using acoustic energy at frequencies above 20 kHz (beyond the audible range for humans), which generates cavitation within the extraction medium. This phenomenon involves the formation, growth, and collapse of microbubbles, releasing localized energy that disrupts the cellular matrix. As a result, the membrane structures are ruptured, facilitating solvent penetration and the subsequent release and separation of lipids and other target compounds. There are two main types of equipment used for UAE: the ultrasonic bath and the probe-type (or benchtop) sonicator [40,54,55].

In addition to the operating parameters, solvent selection plays a critical role in these processes. Ideal solvents should exhibit high solubilization capacity and chemical stability, while also being cost-effective and operationally compatible. This contrasts with traditional solvents such as n-hexane—a non-renewable, toxic compound widely used for lipophilic material extraction—which often leaves harmful residues in the final product despite its high extraction efficiency [19]. Therefore, it is essential to continue investigating optimal lipid extraction methods that reduce energy consumption and processing time, improve yields, and minimize the environmental drawbacks associated with conventional oil and biocompound extraction technologies [10,56].

### *3.3. Ultrasound-Assisted Extraction (UAE)*

In the context of applied research on the extraction of fats and oils, ultrasound technology has been employed to recover oils from oilseeds and other promising crops. It has been shown to improve extraction yield, depending on the solvent used, and to facilitate the recovery of phytochemicals [14,27]. UAE offers several advantages over conventional extraction methods. It requires relatively simple equipment, is easy to implement, and is both environmentally friendly and economically viable. It also consumes less solvent, requires lower energy input, and demonstrates high extraction efficiency [9,27].

One of the key advantages of UAE is its mild operating conditions, which help preserve minor lipophilic compounds such as phytochemicals, thereby enhancing the nutritional and functional value of the oil [14,27]. These gentle conditions also contribute to greater oxidative stability and product quality. Moreover, UAE can be used either on its own or in combination with other technologies (such as microwave-assisted, enzymatic, or supercritical fluid extraction) either as a core method or as a pretreatment step [9,14,27,57]

The principle behind ultrasound-assisted extraction is based on acoustic cavitation and oscillation, which occur when ultrasonic waves are applied using a probe or bath operating at frequencies of 20 kHz and 40 kHz, respectively (Figure 3). These waves generate microscopic vibrations in the medium that form voids or bubbles, transferring energy to the solid particles suspended in the solvent [9,14,27]. As cavitation bubbles grow near the surface of solid structures, their collapse at high amplitude causes cell walls to rupture, accelerating the release of target compounds into the solvent phase. Cavitation has consistently demonstrated superior performance compared to conventional extraction techniques [27].

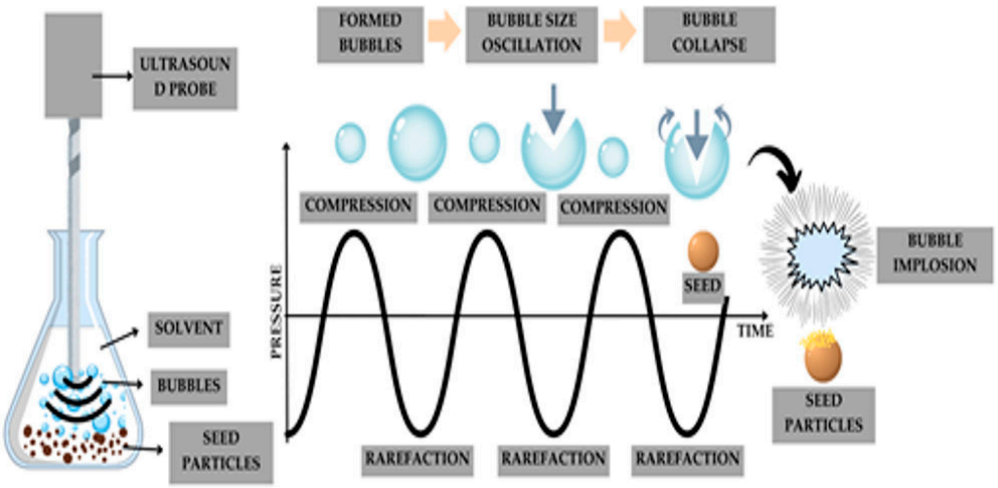



**Figure 3.** Ultrasonic cavitation.

This method, which combines pressurized solvents with ultrasonic energy, represents an innovative and sustainable approach that minimizes the use of chemical solvents and enhances the environmental sustainability of oilseed processing. The illustration demonstrates the ultrasound-assisted extraction mechanism, with emphasis on acoustic cavitation as a key enabler of efficient and ecofriendly extraction.

On the left side of the figure, a container holds seed particles suspended in solvent and is exposed to the action of an ultrasonic probe (US Probe), which emits high-frequency sound waves into the liquid. These waves induce the formation of microbubbles whose dynamic behavior is depicted throughout the diagram. At the center, a graph shows the pressure oscillations within the liquid, highlighting alternating compression and rarefaction cycles. During rarefaction, bubbles expand; during compression, they shrink. This cyclic process leads to periodic size fluctuations until the bubbles reach a critical size and collapse violently.

On the right side of the image, the consequences of bubble implosion are illustrated. The collapse of bubbles releases intense localized energy, disrupting seed tissues and enhancing the release of oils and bioactive compounds. Depending on the specific processing conditions, this method can significantly improve extraction efficiency while reducing environmental impact.

Ultrasound applications can be categorized into two main groups:

1. High-power (low-frequency) ultrasound, operating in the range of 16–100 kHz with intensities between 10 and 1000 W/cm$^2$, and;
2. Low-power (high-frequency) ultrasound, operating between 100 kHz and 1 MHz with intensities below 1 W/cm$^2$ [58].

High-power ultrasound is primarily used to induce changes in the physicochemical properties of membranes, accelerate sample preparation, facilitate liquid–liquid extraction, and support processes such as emulsification and homogenization. In contrast, low-power ultrasound is typically applied in the analysis of the physicochemical properties of food products, where precise, non-destructive measurements are required.

Among the various ultrasound systems available, the two most commonly used in extraction processes are the ultrasonic bath and the ultrasonic probe, as illustrated in Figure 4. The ultrasonic bath typically operates at frequencies close to 40 kHz and allows for temperature control. The most advanced models include an internal agitator and circulating water to enhance energy distribution, providing an indirect action on the sample. Some models may operate at slightly lower frequencies, around 25 kHz.

The ultrasonic probe (also known as a benchtop sonicator), on the other hand, generates more intense acoustic waves in direct contact with the sample. Operating at approximately 20 kHz, this system does not allow for temperature control but is more effective at breaking down the cell walls of raw materials due to its concentrated energy delivery [58].

Ultrasound-assisted extraction (UAE) has been widely applied to isolate various compounds, including bioactives, phenolics, and flavonoids, among others. It is considered a highly accessible technique due to its relatively low implementation and operational costs. UAE also presents environmental advantages, as it typically requires only small volumes of solvent and is often compatible with sustainable solvents such as water and ethanol. Its mechanism enhances the diffusion of the solvent across membrane structures, improving overall efficiency. Moreover, the technique is characterized by a rapid processing cycle, which helps minimize energy use, temperature exposure, and the degradation of target compounds [59].

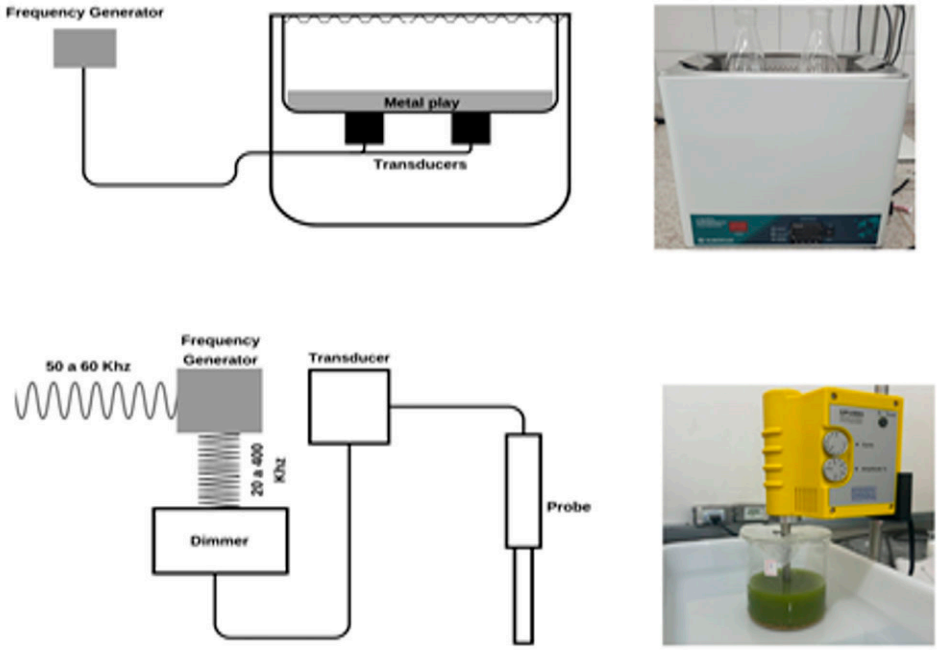



**Figure 4.** Ultrasonic bath and probe-type sonicator.

One of the most notable benefits of ultrasound-assisted extraction is its increased efficiency, largely attributed to acoustic cavitation and associated mechanical effects. Cavitation facilitates the breakdown of cell walls, thereby enhancing solvent penetration into the lipid matrix. Additionally, ultrasound promotes solvent agitation, which increases the surface contact area between solvent and solid material, further improving mass transfer into the sample. These combined effects contribute to shorter extraction times, lower solvent and energy consumption, and reduced thermal damage to the material—ultimately preserving some bioactive compounds [25,44].

## 4. Discussion

Abrantes et al. (2024) [60] investigated Brazil nut oil extraction methods, highlighting mechanical pressing as an alternative to conventional techniques. The results showed that oil obtained through cold pressing exhibited a higher concentration of total phenolic compounds (TPCs), saturated fatty acids, and gallic acid derivatives, as well as elevated antioxidant activity. In contrast, oils extracted using pressurized solvents presented a superior fatty acid profile, with greater concentrations of linoleic acid and polyunsaturated fatty acids (PUFAs), along with higher levels of phytosterols such as β-sitosterol. The use of pressurized n-propane yielded a higher extraction efficiency (13.7%) and a distinct phenolic profile, while the use of solvent mixtures increased the content of squalene and specific phenolic compounds (such as ellagic acid derivatives and myricetin 3-O-rhamnoside) albeit with a lower yield.

Although the study by Abrantes et al. (2024) [60] demonstrated higher yields and elevated levels of linoleic acid, β-sitosterol, and squalene in ultrasound-assisted extraction with pressurized fluids, this can be attributed to the greater efficiency and selectivity of the technique. Solvents such as n-propane, commonly used in subcritical and supercritical extractions, have a higher capacity for extracting bioactive compounds compared to conventional methods like cold pressing. This is due to the lower polarity of n-propane relative to hexane, which enhances its ability to solubilize lipids and lipid-soluble compounds, such as phytosterols and unsaturated fatty acids, while preserving the lipid profile of the sample [61].

It is important to note that the substances extracted in these processes are not conventional oils in the strict sense, but rather lipid fractions, which include a mixture of lipids with varying polarities and properties. Traditionally, the term "oil" refers to a mixture primarily composed of triglycerides. In contrast, lipid fractions may contain fatty acids, phytosterols, and other bioactive compounds, which do not constitute the complete oil matrix. Therefore, the term "fraction" more accurately describes these enriched extracts [61].

Carvalho et al. (2022) [30], in a comparison of different organic solvents used for Brazil nut oil extraction, demonstrated that isopropyl alcohol yielded better results than ethanol, with yields of 54.6% and 31.7%, respectively. These findings indicate that different extraction methods result in significant variations in both the chemical composition and functional properties of the oil, reinforcing the need to align extraction techniques with the intended final product.

Thilakarathna et al. (2023) [27] pointed out that, despite its promising performance, the large-scale industrial application of ultrasound remains limited due to the high capital investment required for installing high-power/amplitude equipment. In addition, the lack of technical expertise poses a significant challenge for small and medium-sized oil producers. While numerous laboratory-scale studies have demonstrated the potential of UAE, few have been translated to pilot- or industrial-scale operations. Nevertheless, ultrasound-assisted techniques outperform conventional methods in several respects. For instance, green solvents can replace organic solvents in Soxhlet extraction systems, although this may result in lower yields. Moreover, the study also reported that conventional methods tend to produce oils with higher levels of impurities and require longer processing times and energy input, which can lead to reduced pigment retention and alterations in oil color parameters.

The use of UAE for extracting both lipophilic and hydrophilic bioactive compounds from oilseeds has the potential to enhance recovery by employing different solvent systems [31]. This is particularly relevant given that hexane, the most commonly used solvent, targets lipophilic substances. Replacing hexane in food-grade applications not only reduces environmental risks but also enables the development of healthier and safer products. This review presented the influence of key variables on extraction yields from different oilseeds. However, as optimal UAE conditions are highly dependent on matrix composition, further research is needed to determine the ideal parameters for each type of seed or extraction objective. To date, limited exploration has been carried out on the use of alternative methods compared to conventional extraction techniques for such compounds.

In industrial contexts, n-hexane remains the dominant solvent used for vegetable oil extraction. However, its flammability presents a safety risk, and it is estimated that 2 L of solvent is lost for every metric ton of grain processed—contributing to harmful gas emissions and environmental pollution in surrounding areas [30]. Therefore, when evaluating oil yield and composition, it is essential to consider the type of solvent used. Even when adopting green methods with alcohol-based solvents, an important caveat remains as follows: although the literature generally agrees that over 90% of the extractable matter constitutes oil, the polarity of the solvent significantly influences the composition of the lipid fractions obtained, differing substantially from the profiles generated by hexane. To mitigate such environmental and health risks, further investigation into alternative, greener solvents is warranted (Table 2).

**Table 2.** Summary of selected articles.

| Author | Title | Results | Conclusion |
| --- | --- | --- | --- |
| Abrantes et al. (2024) [60] | Brazil Nut Semi-Defatted Flour Oil: Impact of Extraction Using Pressurized Solvents on Lipid Profile, Bioactive Compounds Composition, and Oxidative Stability | Pressurized n-propane extraction yielded 13.7–13.8% oil, while the $CO_2$/n-propane mix yielded 2.2%. Squalene reached up to 1007 mg/100 g (4.5× higher than Brazil Nut Kernel Oil—BNKO), β-sitosterol ranged from 40–41 mg/100 g, and linoleic acid from 42.0–42.3%. Cold-pressed oil (BNKO) had higher phenolics (8.23 mg GAE/100 g) and antioxidant activity (DPPH: 366 µmol/100 g) compared to pressurized oils (~5.2–5.8 mg and ~198 µmol, respectively). Oxidative stability was highest (12 h) in Oil Extracted with Pressurized Fluid—OPF[p1], OPF[p2], and OPF[m], and lowest (6.5 h) in OPF[p3]. | Compared oils extracted from Brazil nut flour defatted by cold pressing and by pressurized solvents. The pressurized method outperformed traditional pressing in recovering bioactive compounds and improving lipid profile. |
| Thilakarathna et al. (2022) [27] | A Review on Application of Ultrasound and Ultrasound-Assisted Technology for Seed Oil Extraction | UAE achieved oil yields ranging from 8% to 83%. Kapok seed oil showed 92.29% recovery in 10 min (vs. 5.7 h for SE, 8 h for SXE). Ultrasound-Assisted Enzymatic Extraction (UAEE) increased pomegranate seed oil yield by 18.4% and reduced time by 91.7%. UASE increased passion fruit seed oil yield from 12.3% to 20.6%. Ultrasound Assisted Microwave Extraction (UAME) extracted 85.23% tiger nut oil, and Allanblackia seed oil reached 64.15% yield with 92.16% efficiency. | Comparative review of traditional and innovative extraction methods (ultrasound, enzymatic, supercritical, microwave), evaluating yield, cost–benefit, lipid profile, and oil stability. |
| Chalapud & Carrín (2023) [26] | Ultrasound-Assisted Extraction of Oilseeds—Sustainability Processes to Obtain Traditional and Non-Traditional Food Ingredients: A Review | The article highlights that ultrasound-assisted extraction (UAE) improves oil and bioactive compound yields from oilseeds, using less time, energy, and solvent compared to traditional methods. UAE also enhances the quality of extracts and facilitates the use of green solvents. It supports sustainable food ingredient production but still faces challenges in scalability, economic evaluation, and process modeling. | Use of UAE with milder solvents in food production supports environmentally friendly practices and the development of healthier and safer products. |

**Table 2.** *Cont.*

| Author | Title | Results | Conclusion |
| --- | --- | --- | --- |
| Vasquez-Rojas et al. (2023) [11] | Extraction and Analytical Characterization of Phenolic Compounds from Brazil Nut (Bertholletia excelsa) | Adding 7.5 phr of Epoxidized Brazil Nut Oil (EBNO) to Poly(lactic acid) (PLA) increased elongation at break by 70.9% and crystallinity by over 400%, while tensile strength and Young's modulus dropped by 40.9% and 11%, respectively. The glass transition temperature (Tg) decreased by up to 3.7 °C. Thermal degradation onset (T5%) was reduced by 14 °C. Biodegradability remained unaffected, with 90% disintegration in 27 days. | Compared different extraction methods and solvents with UAE; evaluated yield, quality, and antioxidant activity indices. |
| Perez-Nakai et al. (2023) [3] | Novel Epoxidized Brazil Nut Oil as a Promising Plasticizing Agent for PLA | Epoxidized Brazil nut oil (EBNO) increased the elongation at break of PLA by 70.9% with 7.5 phr added, while reducing tensile strength and Young's modulus by 40.9% and 11%, respectively. EBNO also increased PLA crystallinity from 5.3% to 27.1%, lowered the glass transition temperature by up to 3.7 °C, and did not impair biodegradability—achieving 90% disintegration within 27 days under composting conditions. | Demonstrated the potential of epoxidized Brazil nut oil, extracted via UAE, as a bioplasticizer for PLA, increasing resistance and durability. |
| Carvalho et al. (2022) [30] | Brazil Nut Oil: Extraction Methods and Industrial Applications | The review study compared the efficiency of extracting oil from Brazil nuts using different solvents, with hexane having the highest yield with 69% oil, followed by petroleum ether with 66%, ethyl alcohol with 31.7% and isopropyl alcohol with 54.6%. Brazil nut oil using UAE indicates parameters compatible with current legislation in Brazil. | Found isopropyl alcohol to deliver better extraction yield than ethanol (54.6% vs. 31.7%) in Brazil nut oil extraction. |
| Oliveira et al. (2025) [14] | Ultrasound-Assisted Extraction and Characterization of Brazil Nut Oil (Bertholletia excelsa) | The acidity index found for Brazil nut oil was $0.45 \pm 0.09$, while the saponification index was $522.89 \pm 9.00$, and the refractive index was $1.7107 \pm 0.001$. The fatty acid composition consisted of 36–45% oleic acid and 33–38% linoleic acid. | UAE proved to be a practical, fast, and cost-effective method, maintaining oil quality and suitability for both food and cosmetics applications. |

**Table 2.** *Cont.*

| Author | Title | Results | Conclusion |
| --- | --- | --- | --- |
| Freitas et al. (2024) [7] | Green Extraction Technologies: A Path to the Amazon Bioeconomy Development | Highlights EAU with promising results in yield, extract quality, and environmental aspects. Cites a study on the optimization of the extraction of antioxidant phenolic compounds from Brazil nut cake, obtained under the following conditions: ethanol–water (40:60; v/v); 2.5 min of homogenization; and 1 h of extraction at 60 °C. Also discusses a study by authors who identified high yields of oil extraction from the Brazil nut beverage by-product, by supercritical fluid with carbon dioxide (SC–CO2) under conditions of 400 bar and 60 °C. | Optimization of UAE parameters (frequency, power, time) enables extraction of key compounds with yields comparable to classical methods, but in less time. |
| Khalid et al. (2023) [9] | Recent Advances in the Implementation of Ultrasound Technology for the Extraction of Essential Oils from Terrestrial Plant Materials: A Comprehensive Review | Studies with UAE demonstrate a yield of up to 71% for essential oil extraction, higher than that found with the conventional Soxhlet method, which obtained 54%. Another study conducted with carrot seed essential oil obtained a 33% increase in oil yield using the UAE technique. UAE demonstrates greater efficiency, high selectivity, durability, scalability, and cost-effectiveness. | UAE was shown to be efficient, selective, durable, scalable, and cost-effective; compatible with integration into hybrid techniques. |
| Gomes et al. (2020) [62] | Development and Sun Protection Factor of Emulsified Formulation Containing Brazil Nut Oil | Emulsion formulations using Brazil nut oil were incorporated into the Octyl-methoxycinnamate UV filter at a concentration of 1%. The potential antioxidant activity test showed EC50 values of 7.41 $mgmL^{-1}$ and 5.73 $mgmL^{-1}$ for the chosen emulsions. The base formulation developed with Brazil nut oil showed adequate characteristics for incorporation of a sunscreen. | Developed and tested emulsified formulations containing Brazil nut oil extracted via ultrasound-assisted hexane method for sun protection factor (SPF) efficacy. |

Several physicochemical parameters are used to assess the quality and suitability of Brazil nut oil for industrial and nutritional applications. Among the most relevant are the acidity, ash content, density, iodine value, peroxide value, refractive index, saponification value, and moisture content.

According to Resolution RDC No. 481 of the Brazilian National Health Surveillance Agency (ANVISA, 2021) [63], which regulates vegetable oils, fats, and creams, cold-pressed and unrefined oils must exhibit an acidity value no higher than 4 mg KOH/g and a peroxide value of up to 15 meq/kg [30].

Peroxide and acidity levels are closely associated with the sensory acceptability of edible oils, thus affecting not only food safety but also consumer satisfaction [64]. Given its high

concentration of linoleic acid, Brazil nut oil is particularly susceptible to oxidative reactions, which may lead to the development of off-flavors and diminished consumer approval.

Ash determination reflects the presence of inorganic residues in the oil. This involves subjecting the sample to incineration at temperatures above 500 °C, with the remaining mass being considered the ash content [30]. Moisture determination is equally important, as excess water content contributes to hydrolytic oxidation. In such cases, the enzymatic action of lipases can lead to the breakdown of triacylglycerols, resulting in hydrolytic rancidity and the production of free fatty acids [65,66].

The use of emerging technologies such as ultrasound-assisted extraction (UAE) can significantly improve the quality of Brazil nut oil. UAE has been shown to reduce both acidity and peroxide levels to below the limits established by Brazilian legislation [7,14,63], indicating superior quality and reduced oxidative degradation.

Moreover, UAE has proven effective in preserving some bioactive compounds such as total tocopherols and phenolic compounds—natural antioxidants that help prevent lipid oxidation and improve the oil's oxidative stability [15]. This also supports the maintenance of desirable sensory characteristics by preventing the formation of volatile compounds responsible for off-odors and flavors.

Another advantage of UAE is its operational efficiency. The process significantly shortens the extraction time, reduces solvent consumption, and is recognized as a green and sustainable technology. These features are particularly relevant in the current food and cosmetics industries, which increasingly prioritize environmentally friendly and energy-efficient production methods [15].

In summary, ultrasound-assisted extraction represents a promising alternative to conventional techniques for obtaining Brazil nut oil. It promotes substantial improvements in oil quality and functionality while aligning with global trends toward more sustainable, efficient, and consumer-safe processing methods. UAE shows strong potential for application across the food, cosmetic, and pharmaceutical industries.

## 5. Conclusions

This review demonstrates that, within the time frame analyzed, ultrasound-assisted extraction (UAE) is a promising and sustainable technique for extracting vegetable oils, including Brazil nut oil (*Bertholletia excelsa* H.B.K.). However, few studies are found with optimized parameters with statistical analysis tools and comparative technical, economic, and environmental comparison data between traditional extraction methods in relation to emerging ones.

In the research presented on cutting time, EAU stands out for its efficiency in extracting oils, bioactive compounds, and antioxidant potential, given the action of the characteristics of the cavitation process at reduced temperatures, inferring reduced impact on matrices and thermosensitive compounds, reducing the extraction time, with lower solvent consumption, reducing the environmental impact, especially when compared to conventional methods, such as mechanical pressing or the use of toxic organic solvents.

UAE not only enhances oil yield but also preserves the nutritional quality and functional properties of the final product, including essential fatty acids and bioactive compounds. Moreover, it enables the use of green solvents, thereby promoting safer consumer products and compliance with current environmental standards.

The studies presented were largely focused on laboratory-scale or pilot studies, but for the application of UEA in oil extraction, such as that of Brazil nut oil, on an industrial scale, it will first be necessary to adhere to the discourse of green chemistry and to realize that UEA is an advanced technology that can surpass existing methods in the industry; for example, organic solvents can be replaced by green solvents, with increased yield in

oil extraction. In order to have investments in the installation of high-power/amplitude units, despite the foreseeable increase in processing steps, there is a need to serve a growing audience of consumers who increasingly take food labeling into account, in the search for healthier foods.

Despite its advantages, the industrial-scale application of UAE still faces challenges, including high initial investment costs and a lack of standardized operational parameters for different raw materials. There is a clear need for further studies focused on process optimization, particularly for Brazil nut oil extraction. These studies should aim to develop efficient protocols that take into account critical variables such as the extraction time, temperature, solvent type, and ultrasound settings. Combining laboratory-scale experiments with industrial scaling based on the tripod of technology, economy, and environmental sustainability.

Therefore, continued research in this field is essential to solidify UAE as a viable technology for industrial adoption—both from economic and environmental standpoints—contributing to the sustainable use of Amazonian biodiversity and to the diversification of products derived from Brazil nuts.

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