Review

Extraction Methods of Oils and Phytochemicals from Seeds and Their Environmental and Economic Impacts

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Abstract: Over recent years, the food industry has striven to reduce waste, mostly because of rising awareness of the detrimental environmental impacts of food waste. While the edible oils market (mostly represented by soybean oil) is forecasted to reach 632 million tons by 2022, there is increasing interest to produce non-soybean, plant-based oils including, but not limited to, coconut, flaxseed and hemp seed. Expeller pressing and organic solvent extractions are common methods for oil extraction in the food industry. However, these two methods come with some concerns, such as lower yields for expeller pressing and environmental concerns for organic solvents. Meanwhile, supercritical CO_2 and enzyme-assisted extractions are recognized as green alternatives, but their practicality and economic feasibility are questioned. Finding the right balance between oil extraction and phytochemical yields and environmental and economic impacts is challenging. This review explores the advantages and disadvantages of various extraction methods from an economic, environmental and practical standpoint. The novelty of this work is how it emphasizes the valorization of seed by-products, as well as the discussion on life cycle, environmental and techno-economic analyses of oil extraction methods.

Keywords: seeds; supercritical CO_2 extraction; solvent extraction; expeller pressing; enzyme-assisted aqueous extraction; techno-economic analysis; life cycle assessment

1. Introduction

The sustainability and valorization of by-products have become an important focus of the food industry over the past few years. According to the Food and Agriculture Organization (FAO) of the United Nations, every year, approximately 1.3 billion tons, equivalent to 30% of total food production, is wasted globally. This volume of food waste is worth USD 750 million. Several initiatives have been implemented to combat food waste. In 2013, the United States Department of Agriculture (USDA) partnered with the United States Environmental Protection Agency (US EPA) to formally set a goal to reduce the country's food waste by 50% by 2030 [1,2]. Additionally, the EPA identified a food waste hierarchy that prioritizes feeding hungry people, feeding animals, industrial use, composting, then incineration or landfilling (in order of decreasing preference) (Figure 1) [3]. The Food Recovery Act of 2017 instituted various guidelines encouraging farms, grocery stores, restaurants and institutions to donate excess food, set up composting and anaerobic digestion programs and reduce overall food waste [4]. In California, the legislation "Senate Bill 1383" requires businesses to recover at least 20% of disposed edible food and divert it for human consumption by 2025 [5].

Among the various types of food waste generated, roots, tubers and fruits and vegetables are the most notable ones, representing 45% of the total waste. In addition, a whopping 20% of oilseeds, which come from crops such as sunflowers grown specifically to produce edible oil, are lost during agricultural production and postharvest handling

and storage [6,7]. This is a tremendous amount, considering that global oilseed production was forecasted to reach 632 million tons during 2021–2022, and is expected to be worth USD 162.5 billion by 2025 [8,9]. Furthermore, processors are aiming to reduce all forms of seed-related waste by applying various strategies including but not limited to valorizing by-products by extracting residual phytochemicals or oil for the food, cosmetic, or pharmaceutical industries. For example, tomato seeds, recovered during the processing of tomato-based products such as paste and ketchup, could be a source of edible oil. Meanwhile, in recent years consumer preference has grown for foods that promote health benefits, are environmentally friendly and offer a pleasant taste and aroma. As a result, the market for specialty oils (which refer to non-commodity oils with functional properties that are not further refined, bleached, or deodorized) has considerably increased [10]. Seeds indeed often contain desired unsaturated fatty acids and phytochemical components, which exhibit antioxidant and anti-cancer effects [11]. Among the specialty oils, coconut and olive oils (the latter of which is not from an oilseed) have become popular, with production reaching 3.67 million tons and 3.1 million tons, respectively, in 2020 [12]. Other less popular specialty oils include sesame, flaxseed and hempseed oils [13]. It should be noted that identifying what crops are grown specifically for their oilseeds (as opposed to crops that have seeds but are also utilized for other purposes) can sometimes be confusing. Thus, a summary of the categories of all the matrices discussed in this paper is included for the purpose of clarity for the readers (Table 1).
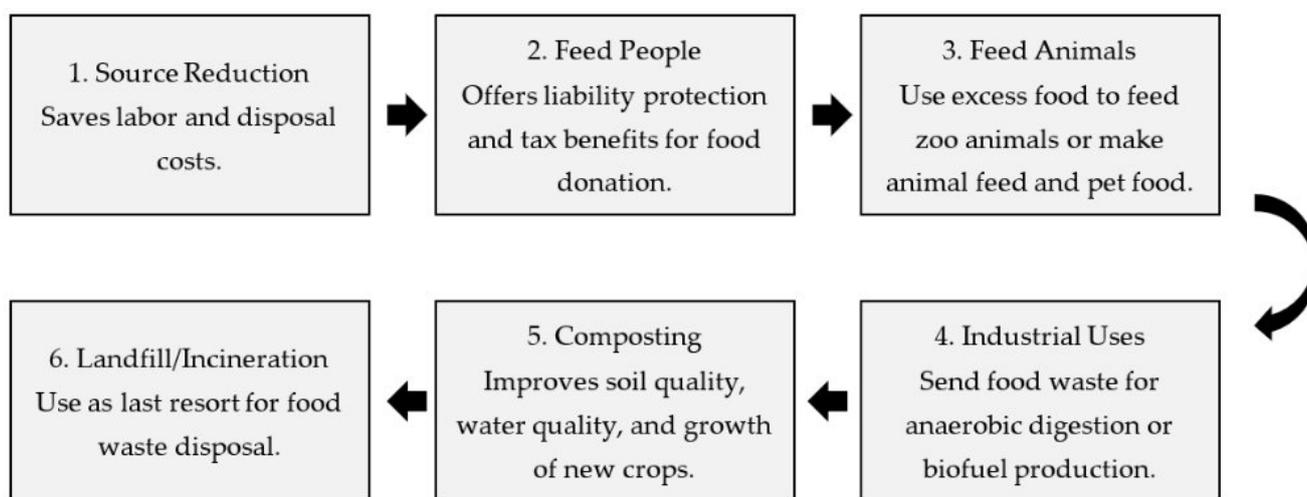

Figure 1. Priorities of the food recovery hierarchy, from most desirable (1) to least desirable (6). Adapted from [3].

Table 1. Types of extracted seed matrices in research studies covered in this literature review.

| Oilseed	Other Seed Type
Canola/Rapeseed	Almond
Linseed (also known as flaxseed)	Coriander
Jatropha curcas	Hemp
Soybean	Favela
Sunflower	Passionfruit
Camelina	Peach
Castor	*Elaeagnus mollis*
Mustard	Moringa
Peanut	Grape
	Forsythia suspense

Recently, the food industry has prioritized balancing the economic and environmental aspects of edible oil production. This shift has been driven mainly by the consumers who have been more conscientious about sustainable food production and its three pillars:

people, planet and profit. Among the oil extraction methods being considered, expeller pressing and solvent extractions are most commonly used at an industrial scale [14]. However, both methods have some major pitfalls to overcome: a lower oil yield with expeller pressing compared to solvent extraction can make the process economically disadvantageous, and the use of organic solvents brings environmental concerns. With the increasing focus on the environmental impact of unit operations used during processing and the development of green chemistry, more studies have focused on improving the extraction methods so that less energy is required and less chemical pollutants are released by these processes [15]. Supercritical CO_2 (SCO_2) and enzyme-assisted extractions are alternatives to solvent extraction and expeller pressing, which are considered traditional oil extraction methods.

This review includes studies on oil extractions of seeds that were published between 2010 until the present day, with the exception of a few studies that are older. The purpose of this review is to explore the advantages and disadvantages of oil extraction methods of seeds from the lens of sustainability and food waste reduction, as well as life cycle, environmental impact and techno-economic analyses.

2. Mechanical Pressing

Historically, oil has been pressed out of seeds by indigenous communities for centuries, and the mechanical pressing of soybeans dates back to the 1940s [14]. There are two broad categories of equipment for oil extraction: expeller press and extruder (Figure 2). Expeller pressing is often limited to small scale, on-farm seed grinding operations. For example, canola, sunflower, flax and safflower oils are extracted via expeller pressing in the mid-west and northeastern United States. Due to its low cost, expeller pressing is also often used in developing countries, such as rural India, for linseed oil extraction [14,16].
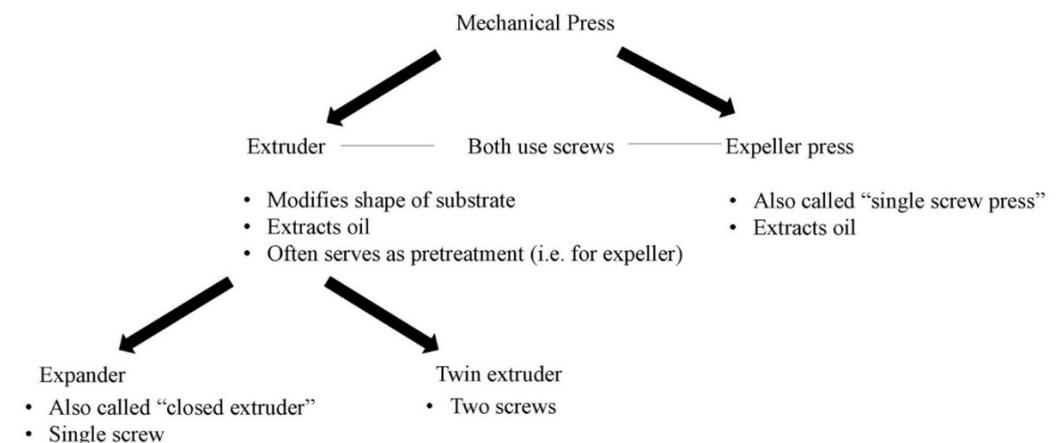
Figure 2. Major types of mechanical pressing.

An expeller press has a screw that rotates in a perforated barrel. The discharge area is partially obstructed, exerting pressure onto seeds to extract oil. Expeller pressing is considered an easy method for oil extraction because it only requires mechanical power and does not need organic solvents [17]. The extraction temperature can be kept under 50 °C to perform cold pressing, which can help preserve nutritional compounds of the oil [18]. However, one disadvantage of this method can be its lower oil recovery. If spacing is too small within the perforated barrel, or if high compaction of seeds results from pressing, it can jam the operating screw and leave 5 to 20% of the total oil in the residual cake [17,19]. Thus, there has been interest in making expeller pressing more efficient and, therefore, more economically viable.

Several parameters need to be considered to improve oil extraction yield and quality, and one such example is screw rotation. When using a pilot expeller press designed for cold pressing, increasing rotation from 1.2 to 18 rpm increased press capacity from 2.2 kg

seed/h to 29.4 seed/h, while decreasing canola oil yields from 91 to 84% [20]. Additionally, the number of presses was shown to affect the oil yield and the quality of linseed oil. Increasing the number of presses of an expeller press from one to two increased linseed oil yields from 19 to 32%, while adding a third press did not significantly affect the oil yield. Implementing a double press also led to the highest total phenol (27 mg GAE/100 g, which was a 170% increase from a single press) and total flavonoid content (7 mg rutin eq/100 eq, which was a 40% increase from a single press). Applying more than two presses started to degrade these compounds due to the high pressure and temperature [16]. Another approach to increase the oil yield was to blend oilseeds to improve the consistency of the matrix, which enhanced the permeability and oil recovery. For example, an oil recovery of 94.7% was obtained with *Jatropha* seeds blended with soybean, and decreased to 88.4 and 75.4% when blended with maize and rapeseed, respectively [21].

Another way to improve oil extraction is to perform extrusion of the seeds (Figure 2). This process, which also relies on screw configuration, is used to modify the shape and properties in applications such as expanded snacks (such as cheerios) or obtain liquid extracts from plant material. The end of the screw allows for seeds to be extruded through a perforated plate and discharges oil [17,22,23]. Extrusion has been used as pretreatment prior to expeller pressing of soybean oil, extracting over 70% of oil compared to single-step expelling, which yielded 60% [24]. This process has also been used for simultaneous treatment with fatty acid methyl ester as a solvent, extracting 98% of oil from sunflower seeds [25].

Single-screw extrusion (expander) is mostly employed at a large-scale for the pressing of oil from seeds, but twin screw systems are used in laboratory and pilot studies [18,23]. The advantage of a twin extruder is that it allows for a thermomechanical treatment of seeds and avoids further pre-treatment steps (such as dehulling, flaking, cooking) often necessary to obtain high oil yields from single-screw operations [17,22,23]. A twin extruder set to 50 rpm and a flow rate of 2.27 kg/h can extract up to 50% of coriander oil without any pretreatment [26]. Fifty percent of oil was also obtained from sunflower seeds with parameters set to 80 °C, 60 rpm and a 24 kg/h flow rate [27]. It would be worthwhile to directly compare the oil yields obtained using single versus twin screw extrusion as a pre- or co-treatment for expeller pressing. There is still more work to be conducted regarding correlating research results from lab-scale expeller pressing of various seeds and scaling up to industrial presses [17].

3. Solvent Extraction

Hexane (or *n*-hexane, which is its isomerized form) is the most commonly used organic solvent in the oilseed extraction industry due to its efficiency in oil recovery, inexpensive costs, recyclability, non-polar nature, low heat of vaporization and low boiling point (63–67 °C) [28,29]. Hexane extraction is especially utilized to produce soybean oil, which is the most consumed vegetable oil in the U.S. [30]. However, hexane is explosive, making it unsafe for workers in food-processing plants. In addition, it is both a neurological toxin and a hazardous air pollutant and can cause environmental pollution [31]. Although it is feasible to minimize these concerns with proper precautions, the production of certain foods, such as all organic foods, is restricted from hexane use. There is indeed evidence that hexane residue up to 21 ppm can be found in soy ingredients and in the 1 ppm range in vegetable oils [32,33]. For soy foods, the Food and Drug Administration (FDA) has not set maximum hexane residue limits, but the European Union (EU) prohibits hexane residue levels greater than 10 ppm. The EU has also set other hexane residue limits that vary depending on the food product [34].

There are many examples of the use of co-solvents during solvent extractions [35,36]; however, in this review we are only covering studies that discuss single solvent extractions. Alternatives to hexane such as ethanol (a natural, non-toxic solvent allowed in organic food production) have been investigated [37]. As ethanol is more polar than hexane, it has the capability to extract more polar compounds such as polyphenols, pigments and soluble

sugars. The benefit of using ethanol vs. *n*-hexane was demonstrated during the extraction of sunflower collets (ground oilcake or expanded material), with a 32% vs. 23% yield of extracted material (oil and other compounds), respectively [38]. With sunflower collets, ethanol extraction led to a 38% greater extractability of tocopherols and phospholipids compared to *n*-hexane [38]. With castor seeds, no significant difference was found in the oil yield between hexane and ethanol, but the extract obtained with ethanol had significantly higher level of sterols than in the hexane extract [39].

Oil extraction yields can be improved using other organic solvents besides ethanol. Isopropanol extracted 49 wt.% oil from favela seeds, which was significantly higher than 47% using *n*-hexane [40]. The extraction method itself can have an important impact on the choice of the organic solvent leading to higher oil extraction yield. When ultrasound, shaker and Soxhlet methods utilizing hexane, acetone, ethanol and isopropanol were compared for the extraction of passion fruit oil, the highest oil yield (26%) was obtained using hexane during Soxhlet extraction. Acetone was the most effective solvent for ultrasound extraction (24% vs. 17% when using hexane) [15]. Ethyl acetate has characteristics that could be beneficial, as it is less flammable and hazardous and 33% cheaper compared to *n*-hexane. Similar oil extraction yields were obtained during the extraction of canola seeds with hexane (21–36%) and ethyl acetate (25 to 40%), while for camelina seeds, it ranged from 9–16% for both solvents [41]. Thus, the literature provides evidence that alternative organic solvents could replace the use of hexane for a similar oil extraction yield.

4. Supercritical CO_2 Extraction

There has been a rise of SCO_2 technology over the past few decades, with over 150 supercritical fluid extraction plants located around the world in 2014, mostly in North America and Europe [42]. SCO_2 is used to de-caffeinate coffee and tea and extract oils, antioxidants, natural food colorings, aromas and flavors from various food matrices [43]. For oil extraction in particular, it has been applied to a wide variety of seeds such as apricot, canola, soybean, sunflower, grape, acorn and walnut seeds [44]. During SCO_2 extraction, pressurized CO_2 solvent is mixed with solid raw material (often ground to reduce the particle size), which allows for the extraction of the compounds of interest. A pressurized CO_2 solvent begins to form at its critical point of 31 °C and 7.38 MPa, where the gas and liquid phases come together to form a homogeneous fluid phase beyond the supercritical fluid region. The advantages of SCO_2 extraction over conventional solvent extraction methods include higher diffusivity, lower viscosity and surface tension and faster extraction times [43]. Additionally, using CO_2 has environmental benefits such as being nonflammable and recyclable. It allows for improved product quality by leaving no residues and maintaining high purity of extracted materials. For these reasons, it is often considered a "greener" extraction method compared to solvent extraction [45].

However, there are several pitfalls to using SCO_2. The non-polarity of CO_2 limits extraction capabilities of polar phytochemicals, such as phenols [46,47]. This extraction method is also expensive because it relies on equipment that handles high pressure, which increases investment and maintenance costs [48]. Additionally, there is a lack and need for continuous systems for increasing large-scale production capacity. For these reasons, widespread adoption of this extraction method by the food industry has been lagging [43,49]. While having benefits that other technologies do not have, the economical competitivity of SCO_2 is a major pitfall for its development [42].

The selection of the most favorable SCO_2 extraction parameters for pressure, temperature, solvent flow rate, size of materials and moisture content are dependent on the type of seed and molecules of interest. For hemp seed oil, increasing the pressure reduced the extraction time (4.5 h at 30 MPa vs. 3.5 h at 40 MPa), while increasing the temperature from 40 to 60 °C did not significantly impact the extraction yield [50]. Oil extraction of peach seeds was improved by decreasing the particle size and increasing the temperature, flow rate, pressure and extraction time. Applying SCO_2 for 3 h at conditions of 40 °C, 20 MPa

and 7 ml/min to 0.3 mm ground peach seeds led to a 35% oil yield. This was within the range reported for peach seeds extracted using solvents [51,52].

Sometimes the benefit of SCO_2 over solvents is observed in oil quality rather than yield. When extracting samara oil from different cultivars of *Elaeugnus mollis* Diels seeds using SCO_2, the oil yields ranged from 25–38%, which were significantly lower than with hexane (47–52%). However, the use of SCO_2 led to a higher quality oil due to the greater extraction of unsaturated fatty acids, such as linoleic acid, which promotes brain function [53]. Although the oil yield from Moringa seeds from petroleum ether extraction surpassed that of SCO_2 extractions, there was no significant difference in fatty acids, tocopherols and sterols between the two methods [54]. The SCO_2 extraction of different grape seeds successfully led to 3.4–4.8 mg/kg extraction of lycopene, a carotenoid that serves as an antioxidant and precursor to vitamin A. This represented an approximately 20% increase when compared to hexane [55,56].

However, the low polarity of CO_2 can cause difficulty in the extraction of polar lipids, such as phospholipids and phenols, and could be a major drawback for this technology. This can be overcome by combining polar co-solvents with SCO_2, which improves solubility of the solute during extraction via dipole–dipole and hydrogen bond interactions [57,58]. SCO_2 extraction of camelina seeds using ethanol as a co-solvent improved the extraction of phospholipids and phenols, and thus increased total lipid yields (34% vs. 23% for pure SCO_2 extraction) [59]. The highest total phenol content from grape seeds was achieved through a sequential SCO_2 extraction, in which non-polar components were removed from grape seeds first, and then 15% mol ethanol was added to recover phenols from defatted grape seeds. Thus ethanol-assisted SCO_2 extraction may provide oils with better health benefits by extracting higher yields of specific compounds [60].

5. Aqueous Extraction Processing

The main benefit of aqueous extractions (AEP) for seeds is that water can be used as a more environmentally friendly solvent compared to organic solvents such as hexane. With solvent extractions, the oil from the seed substrate is dissolved into the solvent phase. The oil is then recovered by the evaporation of the organic solvent. With AEP, oil is typically partitioned into the following fractions: solid residue, protein-rich skim, lipid-rich cream and free oil (Figure 3). Therefore, additional steps are necessary to release free oil, such as demulsification from the cream. However, these steps could add significant costs to oil recovery; therefore, the most ideal extraction would be one that extracts the most free oil. Hence, extraction yield is not always the best indicator of recovered free oil.

Figure 3. Image of partitioning in aqueous extraction slurry after centrifugation.

Regardless of the matrix, AEP usually has lower yields than the ones obtained with organic solvents; however, some research studies have shown competitive recovery yields up to 96% [61,62]. Pre-treatments are commonly applied prior to aqueous extractions, and all have the same goal of breaking down/softening the seed matrix to increase oil recovery. For example, roasting seeds can improve yields because applying heat to the substrate can rupture cell walls and allow for better oil release [63]. Thus, using the optimized roasting temperature and time of wild almonds led to an oil extraction yield of 35% (w/w) [61]. Flaking and extrusion prior to aqueous extraction can also promote increased cell disruption, allowing for better water penetration and release of entrapped compounds. For the aqueous extraction of soybeans, oil extraction yields improved significantly when using extruded full fat soybean flakes (68%) compared to non-treated soybean flakes (60%) [64]. Some pretreatments were shown to specifically improve free oil recovery. Flaxseed kernels pretreated with 0.3 M citric acid and dried at 70 °C for 1 h prior to aqueous extraction led to the development of a thinner cream layer and increased the free oil yields from 19 to 83%. This significant increase in free oil recovery was related to the ability of the acid treatment to affect protein properties, which led to the coalescence of oil bodies and size reduction in protein bodies [65]. Furthermore, different instruments can be used to perform aqueous oil extraction. The use of a twin-screw extruder for the aqueous extraction of sunflower seeds led to 35% higher oil yield than when processed in a blender [66].

Enzyme-assisted Aqueous Extraction (EAEP)

Enzymes are frequently used in all realms of food processing and their addition to aqueous oil extraction offers many advantages. Oil is difficult to release from the cotyledon, which is protected by cell wall structures made up of cellulose, hemicellulose, lignin and pectin [28]. Thus, seeds can be treated with substrate-specific enzymes such as carbohydrases (i.e., cellulase, hemicellulase and pectinase) to degrade the cell wall and facilitate oil release. Protease is utilized for hydrolyzing proteins in the cell membrane, which increases the extraction efficiency of seeds [67,68]. Enzyme treatment is environmentally friendly, occurs at mild temperatures and does not produce solvent residues [28,67,68]. Life cycle analyses (LCA) on enzyme usage in food, feed and pharmaceutical industries have demonstrated that enzymatic processes lead to less impact on global warming, acidification, eutrophication, ozone formation and energy consumption [69]. Enzymes can be expensive, but costs could be compensated by the increase in extraction yield or enzyme recycling [67,70].

As in any process, optimizing parameters is important to obtain good extraction yields. While the optimal pH of enzymes depends on many parameters including the type of enzymes (for example, proteases vs. carbohydrases), it is also crucial to set the pH far from the isoelectric pH (pI) of seed proteins. At their pI, proteins are insoluble, which can hinder oil extractions [28,71–73]. Temperature is another important parameter to consider when using enzymes, with the ideal range for enzymatic hydrolysis typically between 45–55 °C. If temperatures are too high, enzymes can become inactive and, thus, reduce their hydrolysis capabilities. However, temperatures that are too low can slow the reaction rates of enzymes and the extraction rate of oils [28,71,74,75].

The benefit of EAEP has been shown in comparison to AEP of seeds. For the oil extraction of Moringa seeds, individual addition of proteases and carbohydrases led to oil yields ranging from 17–23% compared to 8% for the control. Protease led to highest oil recovery due to its role in solubilizing proteins in the seed substrate [76]. Adding 0.85% alkaline protease to an almond cake slurry extracted for 1 h at pH 9 and 50 °C led to a significantly higher oil extraction (50%) compared to the non-enzymatic control extraction (42%) [77]. However, some studies show that enzyme addition does not improve oil yields [78]. For example, EAEP vs. AEP of almond cake extracted using the same enzymes and parameters mentioned above did not lead to significantly different oil extraction yields (26 and 29%, respectively). However, the change in scale may have contributed to the

different outcomes; the first study was conducted at lab scale (50 g), while the second study was at pilot scale (750 g) [79].

Another approach is to use a cocktail of enzymes, added simultaneously, during the extraction. A cocktail of cellulase, pectinase and hemicellulase was used to extract oil from yellow mustard flour through a 3-h enzyme-assisted aqueous oil extraction set to pH 4.5–5.0 and 40–42 °C. Yields of 76% of oil and 75% of protein were reported, which were significantly higher compared to aqueous extraction leading to yields of 56% of oil and 61% of protein [73]. The oil extraction of *Forsythia suspense* seeds was improved using a cocktail of cellulase, pectinase and proteinase (17 vs. 7% for AEP, respectively). This improvement was attributed to more components within the seed cell walls being degraded [80].

Sometimes enzyme addition is more helpful during the demulsification step to release free oil from the cream layer. Due to the composition of the cream layer, proteases and phospholipases are often considered [81]. The mechanisms involved during enzymatic demulsification include hydrolysis of the proteins in the emulsion, leading to larger oil droplet coalescence and free oil recovery [71,73]. Enzymatic demulsification of cream using 0.5% alkaline protease after both AEP and EAEP of almond cake significantly improved the free oil yield (60–63%) compared to the control (up to 39%) [78]. Cream from peanut seed extraction was also destabilized using alkaline protease, achieving a 65% free oil yield. This was a steep increase compared to the cream from the control, which had less than a 5% free oil yield [82]. Additionally, enzymes can be used to increase protein recovery from the skim layer. Protease-based EAEP of almond flour set to pH 9 and then adjusted to pH 5 (the pI of almond proteins) led to the production of significantly more soluble peptides compared to AEP (45 vs. 23%, respectively) [79]. These examples highlight the potential for enzymes to be used on the various fractions of EAEP for multiple food applications.

6. Life Cycle and Environmental Impact Analyses

Each oil extraction method has its own advantages and disadvantages in terms of environmental, economic and practical aspects. Therefore, the best method depends on the matrix and specific desired outcomes. Life cycle analyses (LCA) is one way in which environmental impacts can be assessed for the lifetime of any given food product, from cradle-to-grave or even cradle-to-cradle. This tool has become more popular in the food sector in the last decade, which is evident by the increasing number of publishing frequency of LCA studies regarding food topics [83,84]. LCA, which is independent of time and location variables, is often contrasted to Environmental Impact Analysis (EIA). The latter is a tool that also considers the environmental impact of food products, but unlike LCA, it also covers social impacts, such as time-related or local geographic factors [85,86].

LCA studies on edible oils frequently cover oilseed crop cultivation, oil extraction and transportation within their system boundaries [87]. Yet, there is limited information on the environmental impacts between extraction methods. An LCA study on mustard seed oil demonstrated that extraction via pressing had significantly lower environmental impacts than a combination of pressing and solvent use. The latter method showed an 8–9% increase for several impact categories, such as human toxicity and particular matter potential. The impact based on photochemical oxidant formation potential increased by 15% due to hexane emissions [88]. When comparing the use of hexane vs. ethanol during the soybean oil extraction process, the net present value (the economic metric representing cash flow) was 10.2% higher for hexane extraction; however, the global warming potential for ethanol extraction was lower by 10,600 tons of CO_{2eq} per year [89].

Additionally, EIA has been performed to compare mass flows, energy consumption and global warming potential between hexane, expeller and EAEP methods for soybean oil processing (Table 2). As with mustard seeds, it was demonstrated that the use of hexane to extract soybean oil had the highest environmental impact. Additionally, hexane displayed a higher thermal risk and impacts on acute, chronic and eco-toxicity; however, hexane extraction was the lowest regarding air pollutant and greenhouse gas (GHG) emissions. The expelling process had the lowest environmental impact because it uses the

least amount of chemical additives. However, its downside was generating the highest GHG (about 11 times more CO_2 and CH_4 emitted from 1 kg of soybean oil production compared to hexane extraction) and the highest criteria pollutant emissions due to the energy used during pressing. EAEP was concluded to be an ideal alternative candidate because it has lower environmental impacts compared to hexane extraction, and released less GHG and pollutants compared to expelling [90]. Although EAEP was again shown to lower environmental impacts in another study on soybean oil extraction, it had the highest CO_2 and GHG emissions compared to pressing and hexane, which was explained by the intensive electricity consumption used during the pretreatment (cleaning, drying, cracking, flaking and tempering) of the soybean substrate to maximize the oil yield. As a consequence, it was concluded that expelling, and not EAEP, was the cleanest oil extraction method [91].

Table 2. Comparison of published techno-economic analysis and environmental impact analysis studies on soybean oil extraction methods (adapted from [24,70,90,92,93]).

Extraction Method	Oil Yields	Profitable Capacity of Annual Oil Production	Revenue Sources	Environmental Impact Analysis
EAEP [1]	Over 80%	>17 million kg	24% from oil >70% from insoluble fibers	Similar environmental impacts to expelling Lower greenhouse gas and criteria pollutants emissions
Extruder-expelling	72%	13 million kg	23% from oil 77% from meal	Lowest environmental impacts Highest greenhouse gas and criteria pollutants emissions
Hexane	Over 99%	87 million kg	39% from oil >60% from meal and hulls	Highest environmental impact Most energy efficient Lowest greenhouse gas and criteria pollutants emissions

[1] Enzyme-assisted aqueous extraction processing.

7. Techno-Economic Analysis (TEA)

Economic feasibility is the main driver in the decision process on which extraction method to apply at an industrial scale; however, environmental impacts are increasingly being considered. Techno-economic analysis (TEA) allows the breakdown of profits and costs for any type of industrial process, and the analysis has been applied to oil extraction. A wide variety of parameters need to be considered when performing TEA, including, but not limited to, the scale of the extraction processes, type of substrate and extraction plant location [24]. Despite some variabilities in the outcomes of studies focusing on oil extraction methods, the valorization of co-products is of paramount importance for making profit and offsetting the costs for advanced extraction technology in processing plants [24,70,92]. When possible and economically viable, these co-products are widely utilized as animal feed and non-food applications instead of being discarded as food waste [24,92].

A good example illustrating this point is what occurs in the soybean oil industry (Table 2). During expeller pressing, the solid residue made of fiber and protein often has residual oil, which adds value to this co-product. When TEA was applied to a two-step extruder–expelling of soybean oil extraction, it was found that soybean meal was the driving force in profits, contributing 75% of total revenues [24]. Similarly, the importance of soybean co-products on the techno-economic value of EAEP extraction was demonstrated. Although EAEP led to an extraction yield that can compete with organic solvent extraction, the enzyme and facility costs for extraction and demulsification equipment were high. Soybean oil profits only accounted for 27% of total revenues, but co-product utilization in soybean/corn-based ethanol production made up 74% of total revenues. Other money saving practices may include recycling the enzymes and reusing the skim as a water source [70].

As with soybean oil extraction, the economic feasibility of alternative green extraction methods for other seeds were demonstrated to be dependent on their co-products. The values of the co-products (rapeseed meal and molasses) compensated for the higher crushing costs resulting from ethanol extraction compared to the hexane extraction of rapeseed oil [37]. The economics involved in the industrial scale of SCO_2 oil extraction of 3000 ton/yr of grape marc were calculated. Selling the dried skins and exhausted seed powder by-products for cattle feed garnered extra revenue of about 60 EUR/ton (USD 78/ton). The 2100 and 2700 tons/year of dried skins and exhausted seed powder produced, respectively, helped meet the breakeven point of 5.9 EUR/kg (USD 8/kg) [94]. In conclusion, the extraction yield and cost were not the sole indicators of the economic viability of an oil extraction process. Co-products were an important piece of the puzzle.

TEA is a powerful tool for evaluating facility scale-up and subsequent economics of oil extraction processes. For example, a TEA model on soybean oil hexane extraction identified that a plant capacity of 34.6 million kg of annual soybean oil production was needed for the process to financially breakeven [92]. For the EAEP of soybean oil to be profitable, annual oil production could not fall below 8.5 million kg [70]. SCO_2 extraction using two extractors in series increased production efficiency of grapeseed oil from 83–86% compared to one with only a larger single extractor. Food waste was also reduced by utilizing grape stalks and skin by-products as thermal energy during SCO_2 extraction. The grapeseed oil market value was reported to be as high as 30 EUR/kg (USD 39/kg). When making the assumption that SCO_2 extracted oil will have similar quality and thus comparable market value, it was demonstrated the oil has market potential [94]. Another simulation modeled the economics of vegetable oil extraction in a SCO_2 industrial plant, investigating how adjusting the extraction time and the particle diameter of the substrate can alter costs. Maintaining a 2.3-h SCO_2 extraction time reduced the production cost to USD 9.4/kg oil. Increasing the particle size from 0.5 to 4 mm can decrease the extraction time from 5 to 3.6 h [42].

TEA is, therefore, an integral part of determining whether an oil extraction method is feasible at a commercial scale. Therefore, processors must consider substrate preparation and extraction flow processes to make large-scale, green oil extraction more economical [40]. However, it is important to note that there are limitations to studying industrial plant economics using a simulation approach. Models typically assume laboratory scale conditions, which set ideal parameters for substrates that are less feasible at commercial scale. Therefore, scale-up predictions must be validated, and more research is needed to refine the accuracy of cost estimates [42]. Further investigation and collaboration with industrial adopters of SCO_2 technology is required to better understand these large-scale oil extraction projects.

While TEA is crucial for identifying economic feasibility, more studies are now integrating an environmental component to it. A techno-economic study comparing subcritical water, SCO_2 and solvent extractions of bioactive compounds from grape marc emphasized the energy-intensive and costly aspect of SCO_2 extraction. SCO_2 extractions had the highest cost of manufacturing (USD 88/kg product) and the lowest net present value (-USD 920,000). SCO_2 extraction also had the highest environmental impact due to energy use (11.8 kg CO_2-eq/kg product), which countered the common perception that SCO_2 technology is more environmentally friendly [47]. However, comparative studies are lacking in the scientific literature, and future development of the edible oil industry would benefit from more techno-economic analyses between various extraction methods.

8. Conclusions

The food industry has increasingly promoted a circular, green economy by prioritizing sustainability and a reduction in food waste. One way to reduce waste is through the development of functional by-products. Specialty seeds have been a target for conversion to edible oils for human consumption. Several factors such as profitability and environmental sustainability should be addressed when determining which of the many existing extraction

methods to implement. Ethanol and SCO$_2$ extractions are considered viable alternatives to using hexane. Additionally, the use of enzymes during the aqueous extraction of seeds allows for a process with less environmental risks compared to traditional hexane extraction. The implementation of economically feasible, greener extraction practices in an industry setting requires the valorization of co-products and optimization of extraction parameters. With increasing interest by consumers for sustainable food products, the specialty oil industry would benefit from improved extraction methods supported by both techno-economic studies and environmental impact and life cycle analyses.

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References

1. United States 2030 Food Loss and Waste Reduction Goal. Available online: https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal (accessed on 23 September 2021).
2. Food Wastage: Key Facts and Figures. Available online: http://www.fao.org/news/story/en/item/196402/icode/ (accessed on 23 September 2021).
3. Food Recovery Hierarchy. Available online: https://www.epa.gov/sustainable-management-food/food-recovery-hierarchy (accessed on 23 September 2021).
4. Food Recovery Act. Available online: https://policyfinder.refed.org/federal-policy/food-recovery-act (accessed on 23 September 2021).
5. Short-Lived Climate Pollutants (SLCP): Organic Waste Methane Emissions Reductions. Available online: https://www.calrecycle.ca.gov/climate/slcp (accessed on 15 June 2021).
6. Food Loss and Food Waste. Available online: http://www.fao.org/3/i4807e/i4807e.pdf (accessed on 28 April 2020).
7. Gustavsson, J.; Cederberg, C.; Sonesson, U.; Emanuelsson, A. *The Methodology of the FAO Study: "Global Food Losses and Food Waste-Extent, Causes and Prevention"*; FAO: Sweden, 2013. Available online: http://www.diva-portal.org/smash/get/diva2:944159/FULLTEXT01.pdf (accessed on 18 July 2021).
8. Oilseeds: World Market and Trade. Available online: https://downloads.usda.library.cornell.edu/usda-esmis/files/tx31qh68h/8g84nh663/3r075q71r/oilseeds.pdf (accessed on 25 September 2021).
9. Edible Oil & Fats Market Worth $162.51 Billion by 2025 | CAGR 7.6%. Available online: https://www.grandviewresearch.com/press-release/global-edible-oil-fats-market (accessed on 15 June 2021).
10. Turrini, F.; Zunin, P.; Boggia, R. Potentialities of rapid analytical strategies for the identification of the botanical species of several specialty or gourmet oils. *Foods* **2021**, *10*, 183. [CrossRef]
11. Gulcin, İ. Antioxidants and antioxidant methods: An updated overview. *Arch. Toxicol.* **2020**, *94*, 651–715. [CrossRef] [PubMed]
12. Global Vegetable Oil Consumption, 2019/20. Available online: https://www.statista.com/statistics/263937/vegetable-oils-global-consumption/ (accessed on 16 June 2021).
13. Gourmet and Specialty Oils. Available online: https://extension.okstate.edu/fact-sheets/gourmet-and-specialty-oils.html (accessed on 16 June 2021).
14. Cheng, M.H.; Dien, B.S.; Singh, V. Economics of plant oil recovery: A review. *Biocatal. Agric. Biotechnol.* **2019**, *18*, 101056. [CrossRef]
15. De Oliveira, R.C.; Davantel De Barros, S.T.; Gimenes, M.L. The extraction of passion fruit oil with green solvents. *J. Food Eng.* **2013**, *117*, 458–463. [CrossRef]
16. Kasote, D.M.; Badhe, Y.S.; Hegde, M.V. Effect of mechanical press oil extraction processing on quality of linseed oil. *Ind. Crops Prod.* **2013**, *42*, 10–13. [CrossRef]
17. Savoire, R.; Lanoisellé, J.L.; Vorobiev, E. Mechanical continuous oil expression from oilseeds: A review. *Food Bioprocess Technol.* **2013**, *6*, 1–16. [CrossRef]
18. Oilseed Fact Sheet: Oilseed Presses. Available online: https://www.uvm.edu/sites/default/files/media/Oilseed_Presses.pdf (accessed on 23 September 2021).

19. Expanding and Expelling. Available online: https://lipidlibrary.aocs.org/edible-oil-processing/expanding-and-expelling (accessed on 21 August 2021).
20. Bogaert, L.; Mathieu, H.; Mhemdi, H.; Vorobiev, E. Characterization of oilseeds mechanical expression in an instrumented pilot screw press. *Ind. Crops Prod.* **2018**, *121*, 106–113. [CrossRef]
21. Romuli, S.; Karaj, S.; Latif, S.; Müller, J. Performance of mechanical co-extraction of *Jatropha curcas* L. kernels with rapeseed, maize or soybean with regard to oil recovery, press capacity and product quality. *Ind. Crops Prod.* **2017**, *104*, 81–90. [CrossRef]
22. Uitterhaegen, E.; Evon, P. Twin-screw extrusion technology for vegetable oil extraction: A review. *J. Food Eng.* **2017**, *212*, 190–200. [CrossRef]
23. Vandenbossche, V.; Candy, L.; Evon, P.; Rouilly, A.; Pontalier, P.Y. Extrusion. In *Green Food Processing Techniques: Preservation, Transformation, and Extraction*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 289–314.
24. Cheng, M.H.; Rosentrater, K.A. Techno-economic analysis of extruding-expelling of soybeans to produce oil and meal. *Agriculture* **2019**, *9*, 87. [CrossRef]
25. Amalia Kartika, I.; Pontalier, P.Y.; Rigal, L. Twin-screw extruder for oil processing of sunflower seeds: Thermo-mechanical pressing and solvent extraction in a single step. *Ind. Crops Prod.* **2010**, *32*, 297–304. [CrossRef]
26. Sriti, J.; Msaada, K.; Talou, T.; Faye, M.; Kartika, I.A.; Marzouk, B. Extraction of coriander oil by twin-screw extruder: Screw configuration and operating conditions effect. *Ind. Crops Prod.* **2012**, *40*, 355–360. [CrossRef]
27. Kartika, I.A.; Pontalier, P.Y.; Rigal, L. Oil extraction of oleic sunflower seeds by twin screw extruder: Influence of screw configuration and operating conditions. *Ind. Crops Prod.* **2005**, *22*, 207–222. [CrossRef]
28. Kumar, S.P.J.; Prasad, S.R.; Banerjee, R.; Agarwal, D.K.; Kulkarni, K.S.; Ramesh, K.V. Green solvents and technologies for oil extraction from oilseeds. *Chem. Cent. J.* **2017**, *11*, 1–7. [CrossRef]
29. Li, Y.; Fine, F.; Fabiano-Tixier, A.S.; Abert-Vian, M.; Carre, P.; Pages, X.; Chemat, F. Evaluation of alternative solvents for improvement of oil extraction from rapeseeds. *Comptes Rendus Chim.* **2014**, *17*, 242–251. [CrossRef]
30. Soystats. Available online: https://soygrowers.com/wp-content/uploads/2019/10/Soy-Stats-2019_FNL-Web.pdf (accessed on 22 September 2021).
31. Hexane. Available online: https://www.epa.gov/sites/production/files/2016-09/documents/hexane.pdf (accessed on 21 June 2021).
32. Toxic Chemicals: Banned in Organics But Common in "Natural" Food Production. Available online: https://www.cornucopia.org/hexane-guides/nvo_hexane_report.pdf (accessed on 23 September 2021).
33. Yousefi, M.; Yousefi, M.; Hosseini, H. Evaluation of hexane content in edible vegetable oils consumed in Iran. *J. Exp. Clin. Toxicol.* **2017**, *1*, 27–30. [CrossRef]
34. Directive 2009/32/EC of the European Parliament and of the Council of 23 April 2009 on the Approximation of the Laws of the Member States on Extraction Solvents Used in the Production of Foodstuffs and Food Ingredients. Available online: https://webarchive.nationalarchives.gov.uk/eu-exit/https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02009L0032-20161109 (accessed on 23 September 2021).
35. Dagostin, J.L.A.; Carpiné, D.; Corazza, M.L. Extraction of soybean oil using ethanol and mixtures with alkyl esters (biodiesel) as co-solvent: Kinetics and thermodynamics. *Ind. Crops Prod.* **2015**, *74*, 69–75. [CrossRef]
36. Jin, C.; Zhang, X.; Geng, Z.; Pang, X.; Wang, X.; Ji, J.; Wang, G.; Liu, H. Effects of various co-solvents on the solubility between blends of soybean oil with either methanol or ethanol. *Fuel* **2019**, *244*, 461–471. [CrossRef]
37. Carré, P.; Citeau, M.; Dauguet, S. Hot ethanol extraction: Economic feasibility of a new and green process. *OCL* **2018**, *25*, 1–7. [CrossRef]
38. Baümler, E.R.; Carrín, M.E.; Carelli, A.A. Extraction of sunflower oil using ethanol as solvent. *J. Food Eng.* **2016**, *178*, 190–197. [CrossRef]
39. Sbihi, H.M.; Nehdi, I.A.; Mokbli, S.; Romdhani-Younes, M.; Al-Resayes, S.I. Hexane and ethanol extracted seed oils and leaf essential compositions from two castor plant (*Ricinus communis* L.) varieties. *Ind. Crops Prod.* **2018**, *122*, 174–181. [CrossRef]
40. Santos, K.A.; da Silva, E.A.; da Silva, C. Ultrasound-assisted extraction of favela (*Cnidoscolus quercifolius*) seed oil using ethanol as a solvent. *J. Food Process. Preserv.* **2021**, *46*, e15497.
41. Lohani, U.C.; Fallahi, P.; Muthukumarappan, K. Comparison of ethyl acetate with hexane for oil extraction from various oilseeds. *J. Am. Oil Chem. Soc.* **2015**, *92*, 743–754. [CrossRef]
42. Del Valle, J.M. Extraction of natural compounds using supercritical CO_2: Going from the laboratory to the industrial application. *J. Supercrit. Fluids* **2015**, *96*, 180–199. [CrossRef]
43. Ye, X.; Xue, S.J.; Shi, J. Green separation technology in food processing: Supercritical-CO_2 fluid extraction. In *Advances in Food Processing Technology*; Jia, J., Liu, D., Ma, H., Eds.; Springer: Singapore, 2019; pp. 73–99.
44. Sánchez-Vicente, Y.; Cabañas, A.; Renuncio, J.A.R.; Pando, C. Supercritical fluid extraction of peach (*Prunus persica*) seed oil using carbon dioxide and ethanol. *J. Supercrit. Fluids* **2009**, *49*, 167–173. [CrossRef]
45. Smigic, N.; Djekic, I.; Tomic, N.; Udovicki, B.; Rajkovic, A. The potential of foods treated with supercritical carbon dioxide (SCO2) as novel foods. *Br. Food J.* **2019**, *121*, 815–834. [CrossRef]
46. Mushtaq, M.; Sultana, B.; Anwar, F.; Adnan, A.; Rizvi, S.S.H. Enzyme-assisted supercritical fluid extraction of phenolic antioxidants from pomegranate peel. *J. Supercrit. Fluids* **2015**, *104*, 122–131. [CrossRef]
47. Todd, R.; Baroutian, S. A techno-economic comparison of subcritical water, supercritical CO_2 and organic solvent extraction of bioactives from grape marc. *J. Clean. Prod.* **2017**, *158*, 349–358. [CrossRef]

48. Carvalho, P.I.N.; Osorio-Tobón, J.F.; Rostagno, M.A.; Petenate, A.J.; Meireles, M.A.A. Techno-economic evaluation of the extraction of turmeric (*Curcuma longa* L.) oil and ar-turmerone using supercritical carbon dioxide. *J. Supercrit. Fluids* **2015**, *105*, 44–54. [CrossRef]

49. İncedayi, B.; Suna, S.; Çopur, Ö.U. Use of supercritical CO_2 in food industry. *Bulg. Chem. Commun.* **2014**, *46*, 126–130.

50. Aladić, K.; Jarni, K.; Barbir, T.; Vidović, S.; Vladić, J.; Bilić, M.; Jokić, S. Supercritical CO_2 extraction of hemp (*Cannabis sativa* L.) seed oil. *Ind. Crops Prod.* **2015**, *76*, 472–478. [CrossRef]

51. Ekinci, M.S.; Gürü, M. Extraction of oil and β-sitosterol from peach (*Prunus persica*) seeds using supercritical carbon dioxide. *J. Supercrit. Fluids* **2014**, *92*, 319–323. [CrossRef]

52. Wu, H.; Shi, J.; Xue, S.; Kakuda, Y.; Wang, D.; Jiang, Y.; Ye, X.; Li, Y.; Subramanian, J. Essential oil extracted from peach (*Prunus persica*) kernel and its physicochemical and antioxidant properties. *LWT-Food Sci. Technol.* **2011**, *44*, 2032–2039. [CrossRef]

53. Mu, J.; Wu, G.; Chen, Z.; Brennan, C.S.; Tran, K.; Dilrukshi, H.N.N.; Shi, C.; Zhen, H.; Hui, X. Identification of the fatty acids profiles in supercritical CO_2 fluid and soxhlet extraction of samara oil from different cultivars of *Elaeagnus mollis* Diels seeds. *J. Food Compos. Anal.* **2021**, *101*, 1–9. [CrossRef]

54. Ruttarattanamongkol, K.; Siebenhandl-Ehn, S.; Schreiner, M.; Petrasch, A.M. Pilot-scale supercritical carbon dioxide extraction, physico-chemical properties and profile characterization of *Moringa oleifera* seed oil in comparison with conventional extraction methods. *Ind. Crops Prod.* **2014**, *58*, 68–77. [CrossRef]

55. Caseiro, M.; Ascenso, A.; Costa, A.; Creagh-Flynn, J.; Johnson, M.; Simões, S. Lycopene in human health. *LWT* **2020**, *127*, 109323. [CrossRef]

56. Mohamed, H.B.; Duba, K.S.; Fiori, L.; Abdelgawed, H.; Tlili, I.; Tounekti, T.; Zrig, A. Bioactive compounds and antioxidant activities of different grape (*Vitis vinifera* L.) seed oils extracted by supercritical CO_2 and organic solvent. *LWT* **2016**, *74*, 557–562. [CrossRef]

57. Güçlü-Üstündağ, Ö.; Temelli, F. Solubility behavior of ternary systems of lipids, cosolvents and supercritical carbon dioxide and processing aspects. *J. Supercrit. Fluids* **2005**, *36*, 1–15. [CrossRef]

58. Asep, E.K.; Jinap, S.; Jahurul, M.H.A.; Zaidul, I.S.M.; Singh, H. Effects of polar cosolvents on cocoa butter extraction using supercritical carbon dioxide. *Innov. Food Sci. Emerg. Technol.* **2013**, *20*, 152–160. [CrossRef]

59. Belayneh, H.D.; Wehling, R.L.; Reddy, A.K.; Cahoon, E.B.; Ciftci, O.N. Ethanol-modified supercritical carbon dioxide extraction of the bioactive lipid components of *Camelina sativa* seed. *J. Am. Oil Chem. Soc.* **2017**, *94*, 855–865. [CrossRef]

60. Da Porto, C.; Natolino, A. Supercritical fluid extraction of polyphenols from grape seed (*Vitis vinifera*): Study on process variables and kinetics. *J. Supercrit. Fluids* **2017**, *130*, 239–245. [CrossRef]

61. Moghadas, H.C.; Rezaei, K. Laboratory-scale optimization of roasting conditions followed by aqueous extraction of oil from wild almond. *J. Am. Oil Chem. Soc.* **2017**, *94*, 867–876. [CrossRef]

62. Fu, S.; Wu, W. Optimization of conditions for producing high-quality oil and de-oiled meal from almond seeds by water. *J. Food Process. Preserv.* **2019**, *43*, e14050. [CrossRef]

63. Akinoso, R.; Raji, A.O. Optimization of oil extraction from locust bean using response surface methodology. *Eur. J. Lipid Sci. Technol.* **2011**, *113*, 245–252. [CrossRef]

64. Jung, S.; Mahfuz, A.A. Low temperature dry extrusion and high-pressure processing prior to enzyme-assisted aqueous extraction of full fat soybean flakes. *Food Chem.* **2009**, *114*, 947–954. [CrossRef]

65. Zhang, W.; Peng, H.; Sun, H.; Hua, X.; Zhao, W.; Yang, R. Effect of acidic moisture-conditioning as pretreatment for aqueous extraction of flaxseed oil with lower water consumption. *Food Bioprod. Process.* **2020**, *121*, 20–28. [CrossRef]

66. Evon, P.; Vandenbossche, V.; Pontalier, P.Y.; Rigal, L. Direct extraction of oil from sunflower seeds by twin-screw extruder according to an aqueous extraction process: Feasibility study and influence of operating conditions. *Ind. Crops Prod.* **2007**, *26*, 351–359. [CrossRef]

67. Liu, J.J.; Gasmalla, M.A.A.; Li, P.; Yang, R. Enzyme-assisted extraction processing from oilseeds: Principle, processing and application. *Innov. Food Sci. Emerg. Technol.* **2016**, *35*, 184–193. [CrossRef]

68. Valladares-Diestra, K.; de Souza Vandenberghe, L.P.; Soccol, C.R. Oilseed enzymatic pretreatment for efficient oil recovery in biodiesel production industry: A review. *Bioenergy Res.* **2020**, *13*, 1016–1030. [CrossRef]

69. Jegannathan, K.R.; Nielsen, P.H. Environmental assessment of enzyme use in industrial production—A literature review. *J. Clean. Prod.* **2013**, *42*, 228–240. [CrossRef]

70. Cheng, M.H.; Rosentrater, K.A.; Sekhon, J.; Wang, T.; Jung, S.; Johnson, L.A. Economic feasibility of soybean oil production by enzyme-assisted aqueous extraction processing. *Food Bioprocess Technol.* **2019**, *12*, 539–550. [CrossRef]

71. Yusoff, M.; Gordon, M.H.; Niranjan, K. Aqueous enzyme assisted oil extraction from oilseeds and emulsion de-emulsifying methods: A review. *Trends Food Sci. Technol.* **2015**, *41*, 60–82. [CrossRef]

72. Mwaurah, P.W.; Kumar, S.; Kumar, N.; Kumar, A.; Panghal, A.A.; Kumar, V.; Mukesh, S.; Garg, K. Novel oil extraction technologies: Process conditions, quality parameters, and optimization. *Compr. Rev. Food Sci. Food Saf.* **2019**, *19*, 3–20. [CrossRef]

73. Tabtabaei, S.; Diosady, L.L. Aqueous and enzymatic extraction processes for the production of food-grade proteins and industrial oil from dehulled yellow mustard flour. *Food Res. Int.* **2013**, *52*, 547–556. [CrossRef]

74. Zúñiga, M.E.; Soto, C.; Mora, A.; Chamy, R.; Lema, J.M. Enzymic pre-treatment of *Guevina avellana* mol oil extraction by pressing. *Process Biochem.* **2003**, *39*, 51–57. [CrossRef]

75. Rui, H.; Zhang, L.; Li, Z.; Pan, Y. Extraction and characteristics of seed kernel oil from white pitaya. *J. Food Eng.* **2009**, *93*, 482–486. [CrossRef]
76. Latif, S.; Anwar, F.; Hussain, A.I.; Shahid, M. Aqueous enzymatic process for oil and protein extraction from *Moringa oleifera* seed. *Eur. J. Lipid Sci. Technol.* **2011**, *113*, 1012–1018. [CrossRef]
77. Souza, T.S.P.; Dias, F.F.G.; Koblitz, M.G.B.; Juliana, J.M.L.N. Aqueous and enzymatic extraction of oil and protein from almond cake: A comparative study. *Processes* **2019**, *7*, 472. [CrossRef]
78. De Almeida, N.M.; Dias, F.F.G.; Rodrigues, M.I.; de Moura Bell, J.M.L.N. Effects of processing conditions on the simultaneous extraction and distribution of oil and protein from almond flour. *Processes.* **2019**, *7*, 844. [CrossRef]
79. de Souza, T.S.P.; Dias, F.F.G.; Koblitz, M.G.B.; de Moura Bell, J.M.L.N. Effects of enzymatic extraction of oil and protein from almond cake on the physicochemical and functional properties of protein extracts. *Food Bioprod. Process.* **2020**, *122*, 280–290. [CrossRef]
80. Gai, Q.Y.; Jiao, J.; Wei, F.Y.; Luo, M.; Wang, W.; Zu, Y.G.; Fu, Y.J. Enzyme-assisted aqueous extraction of oil from *Forsythia suspense* seed and its physicochemical property and antioxidant activity. *Ind. Crops Prod.* **2013**, *51*, 274–278. [CrossRef]
81. Yao, L.; Jung, S. 31P NMR Phospholipid profiling of soybean emulsion recovered from aqueous extraction. *J. Agric. Food Chem.* **2010**, *58*, 4866–4872. [CrossRef]
82. Zhang, S.B.; Liu, X.J.; Lu, Q.Y.; Wang, Z.W.; Zhao, X. Enzymatic demulsification of the oil-rich emulsion obtained by aqueous extraction of peanut seeds. *J. Am. Oil Chem. Soc.* **2013**, *90*, 1261–1270. [CrossRef]
83. Vidergar, P.; Perc, M.; Lukman, R.K. A survey of the life cycle assessment of food supply chains. *J. Clean. Prod.* **2021**, *286*, 125506. [CrossRef]
84. Muralikrishna, I.V.; Manickam, V. Life cycle assessment. *Environ. Manage* **2017**, 57–75.
85. Jeswani, H.K.; Azapagic, A.; Schepelmann, P.; Ritthoff, M. Options for broadening and deepening the LCA approaches. *J. Clean. Prod.* **2010**, *18*, 120–127. [CrossRef]
86. Morero, B.; Rodriguez, M.B.; Campanella, E.A. Environmental impact assessment as a complement of life cycle assessment. Case study: Upgrading of biogas. *Bioresour. Technol.* **2015**, *190*, 402–407. [CrossRef]
87. Khatri, P.; Jain, S. Environmental life cycle assessment of edible oils: A review of current knowledge and future research challenges. *J. Clean. Prod.* **2017**, *152*, 63–76. [CrossRef]
88. Khatri, P.; Jain, S.; Pandey, S. A cradle-to-gate assessment of environmental impacts for production of mustard oil using life cycle assessment approach. *J. Clean. Prod.* **2017**, *166*, 988–997. [CrossRef]
89. Potrich, E.; Miyoshi, S.C.; Machado, P.F.S.; Furlan, F.F.; Ribeiro, M.P.A.; Tardioli, P.W.; Giordano, R.L.C.; Cruz, A.J.G.; Giordano, R.C. Replacing hexane by ethanol for soybean oil extraction: Modeling, simulation, and techno-economic-environmental analysis. *J. Clean. Prod.* **2020**, *244*, 118660. [CrossRef]
90. Cheng, M.H.; Sekhon, J.J.K.; Rosentrater, K.A.; Wang, T.; Jung, S.; Johnson, L.A. Environmental impact assessment of soybean oil production: Extruding-expelling process, hexane extraction and aqueous extraction. *Food Bioprod. Process.* **2018**, *108*, 58–68. [CrossRef]
91. Cheng, M.H.; Zhang, W.; Rosentrater, K.; Sekhon, J.; Wang, T.; Jung, S.; Johnson, L. Environmental impact analysis of soybean oil production from expelling, hexane extraction and enzyme assisted aqueous extraction. In Proceedings of the 2016 ASABE Annual International Meeting, Orlando, FL, USA, 17–20 July 2016; p. 484.
92. Cheng, M.H.; Rosentrater, K.A. Economic feasibility analysis of soybean oil production by hexane extraction. *Ind. Crops Prod.* **2017**, *108*, 775–785. [CrossRef]
93. Cheng, M.H.; Rosentrater, K.A. Profitability analysis of soybean oil processes. *Bioengineering* **2017**, *4*, 83. [CrossRef]
94. Fiori, L. Supercritical extraction of grape seed oil at industrial-scale: Plant and process design, modeling, economic feasibility. *Chem. Eng. Process. Process Intensif.* **2010**, *49*, 866–872. [CrossRef]