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Novel oil extraction technologies: Process conditions, quality parameters, and optimization

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Abstract

Conventional techniques of extracting oil using organic solvents pose health, safety, and environmental concerns. In modern extraction methods, green solvents such as water, ethanol, ethyl acetate, carbon dioxide, ionic liquids, and terpenes are currently gaining prominence. These green solvents present no signs of pollution and remain in liquid form over a temperature range of 0 to 140 °C. Other techniques covered in this review include microwave-assisted enzymatic extraction, ultrasound-assisted extraction, supercritical fluid technology, high pressure–assisted extraction, and pulse electric field–assisted extraction. These techniques are considered environmentally friendly because they exhibit less hazardous chemical synthesis, use renewable feedstock, and reduce the chemical load and emissions generated by organic solvents. Aqueous enzymatic extraction is a novel technique that uses enzymes as the medium for extraction of oil. Selection of the enzymes solely depends on the structure of the oilseed and the composition of the cell wall. Studies reveal an enzyme to substrate ratio of 1% to 8%, the temperature of 40 to 55 °C, and a pH of 4 to 8 to be typical for enzymatic extraction of oil from different oilseeds. Microwave-assisted extraction has proven to impart significant effects on mass transfer and offers high throughput and extraction efficiency. A microwave power of 275 to 1,000 W and a temperature range of 30 to 60 °C are noticed in the different studies. The review presents a comprehensive account of the modern extraction techniques, the parameters responsible for yield and quality, and their industrial applications. Besides, the review highlights the optimized parameters for oil extraction from different oil-bearing materials.

KEYWORDS

enzymatic aqueous extraction, microwave-assisted extraction, nonconventional extraction techniques, oil yield, pulse electric field–assisted extraction, ultrasound-assisted extraction

1 | INTRODUCTION

Market assessment indicates an increasing demand for oils, fats, and lipids across the globe. Oils and lipids are not only used in the food industries in manufacturing of edible products but are also a major component in other nonedible applications such as cosmetics, varnishes, adhesives, lubricants, soaps, synthetic resins, greases, paints, and waxes (Boulard et al., 2015). The commonly produced vegetable oils in the world are presented in Table 1. The method used for extraction of the oil is of paramount importance as it determines the quality of the final products and the possible environmental implications. Currently, both conventional and novel methods are being used either in full-scale or as pilot

TABLE 1 Global vegetable oil consumption in the year 2018/2019

Oil type	Oil production in Mton/year	Percentage of world production
Palm oil	69.57	35.01%
Palm kernel oil	7.97	4.02%
Soybean oil	57.05	28.77%
Rapeseed oil	27.83	14.08%
Sunflower oil	17.75	8.95%
Peanut oil	5.53	2.79%
Cottonseed oil	5.15	2.59%
Coconut oil	3.41	1.72%
Olive oil	3.07	1.55%
Total	198.3	100%

Source: Statista.com

projects in extracting these oils and fats. However, conventional oil extraction techniques such as mechanical expression and solvent extraction dominate the oil extraction industry (Tiwari, 2015). The need for novel techniques lies in the fact that traditional methods have different shortcomings like more energy, more time, low yield, and less environmentally friendly (Sharma et al., 2019). The physical methods of oil extraction can only recover approximately 80% of oil present in oleaginous material; hence, to recover the remaining 20%, different technology has to be applied (Puertolas, Alvarez-Sabatel, & Cruz, 2016). Solvent extraction is widely adopted owing to the simplicity and economy of the process. The commonly used solvents are hexane and *n*-hexane because they result in the highest (95%) yield (Tan et al., 2016). Particularly, *n*-hexane is preferred due to its superior attributes such as simple recovery, low latent heat of vaporization (330 kJ/kg), narrow range of boiling point (63 to 69 °C), high solubility, and its nonpolar nature. Unfortunately, the application of these organic solvents raises health, safety, and environmental concerns and, therefore, regardless of their high extraction efficiency, their usage is not only harmful and toxic but also leads to air pollution (Konopka, Roszkowska, Czaplicki, & Tanska, 2016; Kumar, Kumar, Dash, Scholz, & Banerjee, 2017). Additionally, in spite being permitted in food industries by European Commission and Food and Drug Administration (FDA), hexane is still considered and categorized as hazardous and is not preferred by some international bodies (Castejon, Luna, & Senorans, 2018).

Nevertheless, vegetable oil extraction consumes large quantities of hexane, and therefore, there is a need to explore green technologies such as aqueous enzymatic-assisted extraction and green solvents such as ionic liquids and terpenes (Sahad, Md Som, & Sulaiman, 2014). Green solvents present a huge potential to replace the commonly used *n*-hexane without compromising the quality of oil and oil recovery process. Research shows that nonconventional extraction techniques have eliminated effectively and successfully the shortcomings posed by traditional methods in extracting valuable components from plants and seed materials. The superiority of these techniques over convectional techniques lies with the improved quality of extracted products. They are time efficient and the amount of solvent consumed is less. Furthermore, they are ecofriendly, results in high yield, cost-effective, and co-products can be obtained without any deterioration in quality (Chemat et al., 2017). This paper presents a comprehensive account of the modern extraction techniques, the parameters responsible for yield and quality, and their industrial applications. It emphasizes on enzyme-assisted extraction, microwave, ultrasound pretreatment, and supercritical fluid extraction as they offer sustainable strategies and tools capable of outdoing the traditional extraction techniques. For comparison, the performance of Soxhlet extraction as a traditional extraction technique is also presented.

2 | SOLVENTS USED FOR OIL EXTRACTION

Apart from mechanical and hydraulic expression, other techniques entirely rely on solvents in which the oil is dissolved and later separated through evaporation and distillation or with de-emulsification and centrifugation. Conventional techniques use organic solvents like *n*-hexane, hexane, petroleum ether, ethyl acetate, acetone, and chloroform (Ibrahim, Omilakin, & Betiku, 2019; Okeleye & Betiku, 2019). Recent advancements have brought about green solvents such as water, ethanol, carbon dioxide (CO_2), and terpenes, which are naturally occurring. They are derived from agricultural residue among other petroleum sources (Prat et al., 2015). Castejon et al. (2018) suggests that a mixture of water, ethanol, and ethyl acetate, when optimized, can be used as a hexane-free alternative. Although some green solvents are nonpolar in nature, they have solubility properties similar to those of conventional solvents and can dissolve like molecules. Terpenes contain isoprene units and include d-limonene, p-cymene, and α-pinene, which are majorly obtained from agricultural residue. D-limonene, for instance, is extracted from citrus fruits, whereas α-pinene is from pine (Kumar et al., 2017).

Ionic liquids, also known as green "designer" solvents, on the other hand, are nonaqueous solution of salts prepared by combining organic cations and organic or inorganic anions. They present no signs of environmental pollution and remain in liquid form over a temperature range of 0 to 140 °C. Contrary to conventional organic solvents, they are noninflammable, versatile, and thermally stable and possess low vapor pressure (Chemat et al., 2019). The greatest potential of ionic liquids lies on their ability to possess two types of ions making them more versatile with regard to the design of solvents possessing certain physicochemical attributes such as specific conductivity, solubility, polarity, and hydrophobicity (Cooney, Young, & Nagle, 2009). Additionally, their polarity can be adjusted to conform to the required hydrophobicity/hydrophilicity. With regard to this property, Dharaskar (2012) noted that about 600 solvents had been employed in various processes. Ma et al. (2011) indicated that using ionic liquids under microwave-assisted technique to extract oil from Baill fruits reduced extraction time and energy requirement. The cationic and anionic nature of these liquids exhibits a significant impact that boosts extraction efficiency (Ullah, Wilfred, & Shaharun, 2017). As far as oil extraction is concerned, little has been done regarding their technical and economic viability, and in as much as they offer a promising future, more research is needed to substantiate their feasibility.

3 | OIL EXTRACTION TECHNOLOGIES

3.1 | Aqueous enzymatic extraction

Aqueous extraction is a traditional technique that uses water as a solvent to extract oil from oleaginous materials. Because water takes long to degrade the cell wall of oil-bearing material, the process is less effective and results in low yield. To counter this limitation, aqueous enzymatic extraction (AEE) uses both water and enzymes to degrade the cell wall network of the oil-bearing material, thereby allowing for the transfer of intercellular contents. AEE is a promising novel and green extraction technique because it is not only simple to carry out but also have low energy requirements (Yusoff, Gordon, Ezeh, & Niranjan, 2016). Further, the cell wall of plant materials is composed of cellulose, hemicellulose, and pectin all of which can easily be broken down by the wide range of commercially available enzymes (Table 2). Because the lipid molecules are amphipathic, only the water-soluble portion diffuses into the water, while the other components culminate into an emulsion. The oil is further de-emulsified either by the application of enzymes that dissolves it or by changing the temperature of the emulsion (Zhang, Lu, Yang, Li, & Wang, 2011). Use of enzymes permits the separation of selected components without changing their properties and this positively influences the sensory attributes of the final product in terms of taste and smell (Yusoff, Gordon, & Niranjan, 2015). AEE portrays tremendous potential as it can extract oil and proteins simultaneously owing to the insolubility of water in oil as well as segregation and recovery of desired compounds without any damage (Li et al., 2014). Further, the aqueous media facilitates the concurrent removal of phospholipids, which eliminates the degumming process on extracted oil and consequently reduces the overall production cost. The final products are highly suitable for human consumption when compared to other extraction methods and the oil obtained from enzyme-assisted extraction portrays superior quality properties. AEE is considered the most environmentally friendly process as it reduces the chemical load generated by organic solvents. Additionally, this technique can be used to extract any desired compound from plant materials. However, its success heavily lies on a good understanding of the architecture of the oilseed. Common co-products of oil extraction include non-toxic and value-added proteins and fiber (Kumar et al., 2017). Enzymatic extraction can be used alongside other extraction techniques as illustrated in Figure 1.

TABLE 2 Summary of the commonly used enzymes and their commercial names

Commercial name of the enzyme	Composition of the enzyme
Alcalase®, Alcalase 2.4 L, Flavourzyme® 1000 L, Multifect Neutral®, Papain, and Protamex	Protease
Lipomod 699 L and LysoMax™	Phospholipase A2
Celluclast 1.5 L® and Rohalase® OS	Cellulase
Pectinex®, Pectinase 1.06021, Pectinex Ultra SP, and Pectinase Multieffect FE®	Pectinase
Termamyl 120 L	α-Amylase
Bioliva	Cellulase, hemicellulase, pectinase, and other minor enzymes
Protizyme™	Three different protease enzymes with optimal pH of 3 to 4, 5 to 7, and 7 to 10
Viscozyme® and Viscozyme L	(Carbohydrases): Cellulase, hemicellulase, arabinase, xylanase, amylase, and β-glucanase
Kemzyme	Cellulase complex, hemi-cellulase complex, α-amylase, β-glucanase, protease, and xylanase
Natuzyme	Cellulase, xylanase, phytase, α-amylase, and pectinase

Source: Sigmaaldrich.com; Novozymes.com.

3.2 | Selection of appropriate enzymes

The major role of enzymes used in AEE is to degrade and break down the cell wall of the oilseed to facilitate the release of oil from the matrix. Application of enzymes either

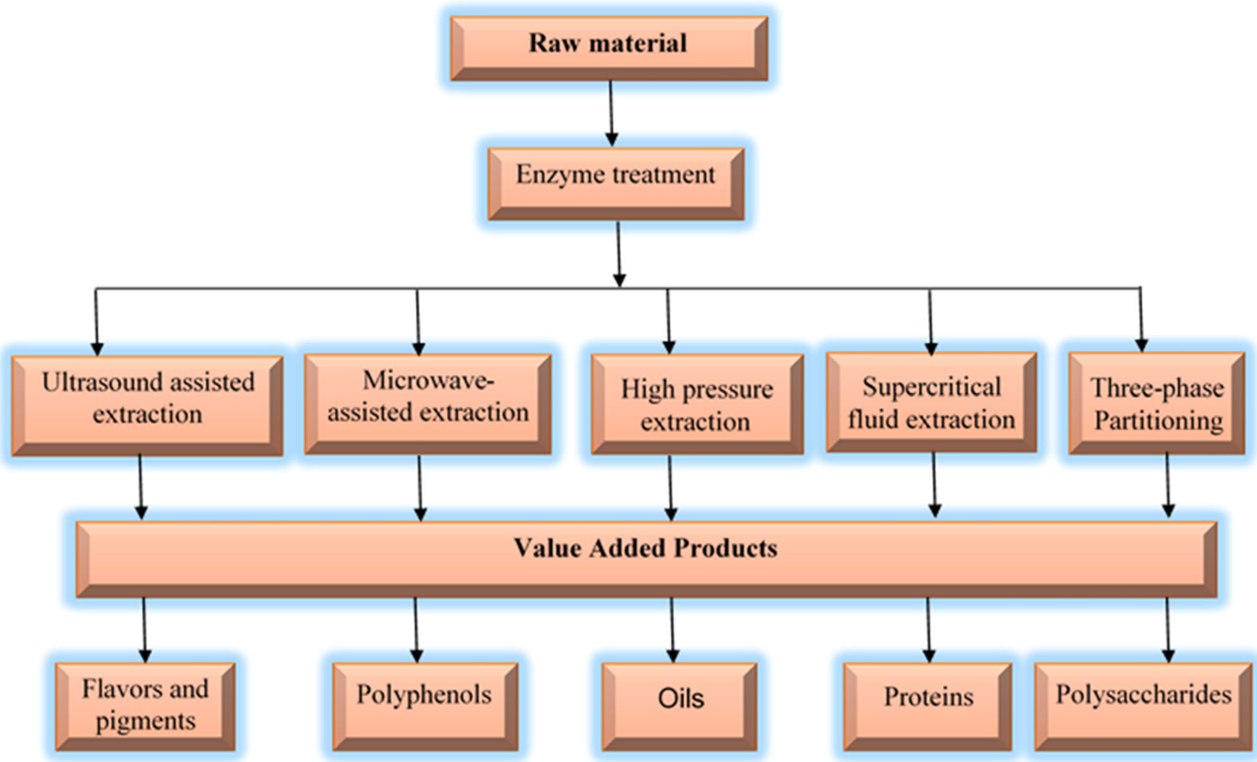

FIGURE 1 Ideal scheme of various enzyme-assisted extraction methods and the value-added products

individually or as a combination of different enzymes has a positive effect on the overall oil yield. However, selection depends on the anatomy of the oil-bearing seed, the type of enzyme in use, as well as the constituents of the enzyme (Passos, Yilmaz, Silva, & Coimbra, 2009; Zhang et al., 2011). More specifically, the location of oil within the cell and the specific component surrounding it are the critical factors that act as obstacles in extraction of oil (Yusoff et al., 2015). Commonly used cell wall degrading enzymes include cellulase, pectinase, hemicellulase, protease, and phospholipase, and selection solely depends on the structure of the oilseed as well as the composition of the cell wall. Ideally, the cotyledon in most oil-bearing seeds is composed of protein and lipid bodies of varying composition depending on species under consideration. In some oilseeds, for example, peanuts and soybeans, the lipid molecules are embedded with the protein molecules and surrounded by a cell wall containing cellulose, hemicelluloses, lignin, and pectin (Tabtabaei & Diosady, 2013; Yusoff et al., 2016). Table 2 shows the different enzymes used in oil extraction with their commercial names.

Wu, Johnson, and Jung (2009) in their experiment to extract oil from soybean flakes using AEE observed that protease treatment resulted in the highest yield (96%) among the different samples treated with cellulase, pectinase, hemicellulase, and protease. Treatment of extruded soybeans with cellulase and with a mixture of cellulase and protease resulted in no significant increase in oil yield (68%). However, treatment of the extruded soybeans with protease alone yielded 88% of oil (Jung, Maurer, & Johnson, 2009). In another study, bush mango kernel flour treated with Alcalase®, Pectinex®, and Viscozyme® resulted in 35.0%, 42.2%, and 68.0% yield of mango kernel oil (Womeni et al., 2008). Womeni et al. (2008) also noted that apart from increasing the yield, AEE simultaneously improved the quality and content of bioactive compounds (carotenoids and phenolics) in the oil. These studies elucidate that the major component in the cotyledon of the oil-bearing seed is the primary determinant of the enzyme to be employed. As far as soybeans are concerned, the protease hydrolyzes the proteins in the soybean facilitating the release of oil. In a similar study, rapeseed, whose cell wall is predominantly composed of pectin, was treated with pectinase and yielded 85.9% of oil (Lamsal, Murphy, & Johnson, 2006). Yusoff et al. (2015) indicate that from the previously conducted studies, it is not possible to conclude whether the application of enzymes individually or as a combination results in higher yields or not, but notes that a mixture of different enzymes has worked synergistically in numerous instances. Consequently, the success of this novel technology heavily relies on prior understanding of the structure of the target oilseed and judicious use of enzymes is paramount for higher yields and recovery of co-products. Other influential parameter relating to the process such as particle size, pH, temperature, and enzyme to substrate ratio should also be

TABLE 3 Enzyme-assisted extraction of oil from different oilseed and relevant parameter

Source	Enzyme used	Experimental conditions	Yield	Reference
Moringa oleifera	Neutrase 0.8 L® and Celluclast 1.5 L®	Enzyme:substrate ratio: 8 (w/w); pH 4.5; Temp: 40 °C; incubation time: 1 hr	70%	Latif, Anwar, Hussain, and Shahid, 2011
Palm fruit	Cellulase and pectinase	Enzyme:substrate ratio: 4%; pH 4.0; Temp: 50 °C; incubation time: 30 min	90–93%	Teixeira et al., 2013
Pumpkin	Rohament CL®, Colorase®, and Rohapect UF®	Enzyme:substrate ratio: 2%; pH 7.4; Temp: 54 °C; incubation time: 15.4 hr	72.64%	Konopka et al., 2016
Bush mango kernel	Viscozyme L®	Enzyme:substrate ratio: 2%; pH 3.5 to 5.5; Temp: 55 °C; incubation time: 18 hr	68%	Womeni et al., 2008
Pine kernel	Alcalase Endo-protease®	Enzyme:substrate ratio: 1.5; pH 8.4; Temp: 51 °C; incubation time: 3 hr	89.12%	Li et al., 2011
Watermelon seeds	Protex 6 L®	Enzyme dose: 2.63%; pH 7.89; Temp: 47.13 °C; incubation time: 7.8 hr	97.92%	Sui, Jiang, Li, and Liu, 2011
Peanut	Alcalase 2.4 L®	Enzyme:substrate ratio: 1 (w/w); Temp: 45 °C; incubation time: 9 hr	91.98%	Jiang et al., 2010
Yellow mustard flour	Protex 6 L®	Enzyme:substrate ratio: 3 (w/w); pH 4.5; Temp: 50 to 60 °C; incubation time: 3 hr	91%	Tabtabaei and Diosady, 2013
Bayberry kernels	Cellulase and neutral protease	Enzyme:substrate ratio: 3.17; Temp: 51.6 °C; incubation time: 4 hr	31.15%	Zhang et al., 2012

taken into consideration (De Faveri, Aliakbarian, Avogadro, Perego, & Converti, 2008; Zhang et al., 2011).

3.3 | Effect of pretreatment prior to enzymatic extraction

Recent studies indicate that pretreatment of the substrate before extraction increases oil yield. Pretreatment weakens the cellular structure that acts as the barrier to oil release and at the same time prevents the formation of an oil–water emulsion, which is somewhat cumbersome to separate upon extraction (Li et al., 2012). Potential pretreatment methods need not be enzyme based but AEE succeeds the pretreatment. The use of ultrasound as a pretreatment results in cavitation that accelerates the rate of leaching out of the components contained in the plant cells including oil (Li, Jiang, Sui, & Wang, 2011). In one of the studies, Jung and Mahfuz (2009) highlighted that the application of high pressure on the substrate results in protein aggregates that when further hydrolyzed by proteases enzymes facilitates the extraction of oil. In case of mechanical expression or solvent extraction, enzyme pretreatment prior to extraction plays a great role in loosening up the cell wall and this facilitates extraction. Accordingly, the chances of formation of oil in water emulsion are minimized (Hosni et al., 2013).

3.4 | Factors affecting aqueous enzymatic extraction

Several factors are key for optimum oil yield using green solvents in AEE. In order to devise a viable extraction process, critical factors affecting yield need to be explored and optimized. These parameters are optimized by the different researchers and are presented in Table 3.

3.4.1 | Particle size

In order to facilitate the release of oil from the cells of oil-bearing material, it is imperative to increase the surface area of contact of the material with the solvent. This, in turn, allows for faster and easier infiltration of the transfer media. Reducing the size causes a higher disruption of the cell wall and reduces the length of the diffusion path through which both enzymes and cellular components have to diffuse (Passos et al., 2009). Reduction of size is achieved through grinding or milling and the structural and chemical constituents as well as the moisture content of the oilseed determines whether dry or wet milling is to be carried out. Those oleaginous materials containing high moisture content such as coconut are ground through the wet method, whereas those with low moisture, for example, soybean and rapeseed are better milled through the dry method (Rovaris et al., 2012). From a general perspective, small-sized particles favor oil extraction from oleaginous materials; however, the skeletal and skinny component of the oilseed should be avoided because they lower the microporosity and thereby reducing the efficiency of extraction. In some cases, if the oilseed contains high oil content, the small-sized particles tend to adhere together and this affects the efficiency of oil extraction (Nyam, Tan, Lai, Long, & Man, 2009). Wu, Johnson, and Jung (2009) conducted a test on linseed and obtained a 31% increase in yield as a result of reducing the size of the particles from 400 to 100 μm.

3.4.2 | pH

Higher efficiency of oil extraction is only achieved at an optimum pH and each enzyme has its specific optimum value. If oil extraction is done at the isoelectric point of proteins, the process might be hampered because proteins tend to be insoluble at this point (Tabtabaei & Diosady, 2013). The effect occurs because, in most oilseeds, the lipids molecules are embedded with the proteins molecules. Attempts to counter variations in the pH of the enzymes while keeping the isoelectric point of the proteins within the optimum range are the main reason to use a mixture of enzymes (Yusoff et al., 2015). In one of such studies, oil yield from flaxseed was highest (73.9%) when treated with a concoction of cellulase, hemicellulase, and pectinase enzymes at a ratio of 1:1:1 and at a pH in the range of 4.5 to 5.0 than when subjected to either of the individual enzyme (Long et al., 2011). Soybean treated with a mixture of Alcalase 2.4 L® and Celluclast 1.5 L® resulted in 26.82% of oil at a pH of 4.5% and 20.63% of oil under uncontrolled pH. Similarly, when treated with Alcalase 2.4 L® and Viscozyme L®, the oil yield was 29.48% and 20.23% for a pH of 4.5 and uncontrolled pH, respectively (Rovaris et al., 2012).

3.4.3 | Incubation temperature

Temperature is one of the critical factors as far as any oil extraction technique is concerned. Besides pH, enzymes are also sensitive to temperature and are active within a narrow range of temperature (Rui, Zhang, Li, & Pan, 2009). Generally, AEE is most effective at or below 45 °C depending on the fatty acids present and the type of oilseed. Temperature above 45 °C denatures the proteins and lowers enzymatic hydrolysis, hampering the process of oil extraction (Kumar et al., 2017). Studies show that the optimum temperature for enzymatic extraction is 30 °C for olive, 34 °C for linseed, and 40 °C for peanut (Aliakbarian, Faveri, Converti, & Perego, 2008; De Faveri et al., 2008). These studies suggest that it is vital to determine the optimum temperature for a given oil-bearing seed for maximum yield.

3.4.4 | Enzyme to substrate ratio

Oil yield is directly proportional to the concentration of the enzymes in the extraction media. The higher the concentration of enzymes, the greater the interaction between the substrate and the specific enzymes that degrade the peptide bonds facilitating oil yield (Teixeira, Macedo, Macedo, da Silva, & Rodrigues, 2013). However, degradation of the extracted oil occurs beyond a certain saturation point. Negative effects of oversaturation include the development of off-flavors and bitterness in the oil (Jiang, Hua, Wang, & Xu, 2010). Little has been done so far in determining the specific amount of enzyme required for effective extraction but generally, more than 1% the weight of the substrate is needed at a minimum (Nadar, Rao, & Rathod, 2018).

3.4.5 | Water to substrate ratio

Water acts as the media for oil extraction among other functions such as facilitating diffusion and mobility of both oil and enzymes as well as enhancing hydrolytic reactions necessary for the recovery process (Li et al., 2011). The moisture content of the oleaginous material is the primary determinant of how much water is needed to avoid a very thick suspension. However, care should also be exercised not to dilute the enzyme whose concentration is key in the process (Kumar et al., 2017).

3.4.6 | Agitation

Shaking regime determines the time taken for the process to be completed as well as the separation of the resulting oil from the emulsion. Agitation disrupts the mechanical barriers and causes uniform mixing of the constituents, thereby facilitates mass transfer and reduces process time. Abdulkarim, Lai, Muhammad, Long, and Ghazali (2006) investigated the impact of agitation in recovering oil from *Moringa oleifera* and revealed that among agitation speeds of 50, 80, and 120 rpm, the latter yielded larger sized oil droplets that were easier to separate from the mixture. However, depending on the quality, quantity, and type of oilseed, agitation is bound to form a uniform and stable emulsion that becomes difficult to separate (Yusoff et al., 2015).

In a study to extract oil from palm fruit, Teixeira et al. (2013) applied a 4% enzyme dose (cellulase and pectinase) at a pH of 4.0 and a temperature of 50 °C for 30 min. The oil yield was 90% to 93%. In extracting oil from bay leaves, cellulase, hemicellulose, and xylanase enzymes were used at an enzyme to substrate ratio of 8, pH of 4.5, and 40 °C for 1 hr. A 92.5% yield was recorded (Boulila et al., 2015). In a similar study, pine kernel was treated with Alcalase Endoprotease® enzyme at a pH of 8.4 and 51 °C for 3 hr. The oil production was 89.12% at an enzyme to oilseed ratio of 1.5 (Li et al., 2011). In another study, Konopka et al. (2016) applied a 2% dose of Rohapect UF®, Rohament CL®, and Colorase® enzymes to pumpkin seeds and maintained a pH of 7.4 at 54 °C for 15.4 hr. They recorded a 72.64% oil yield. Womeni et al. (2008) used Viscozyme and Alcalase enzymes on bush mango kernel for 18 hr. The kernel to enzyme ratio was 0.19 and the enzyme concentration was 2%. The highest yield recorded was 68.0%. More details on how the process parameters affect yield are presented in Table 3.

3.5 | Challenges in aqueous enzymatic extraction

The demand for green solvents and technologies is alarming and mainly owing to the environmental, health, and energy concerns posed by the conventional techniques and organic solvents. The green solvents possess great potential to replace the commonly used hexane. However, terpenes pose scalability issues because they have a high boiling point, density, viscosity, and consequently, high heat of vaporization. The limitations can be overcome by using terpenes at low temperature and pressure (Kumar et al., 2017). Despite the huge potential and advantages of AEE (Table 7), the process is still limited due to the high cost of enzymes and the long incubation time if a pretreatment is not applied. The unavailability of the enzymes deters its commercial applicability. An additional problem is the formation of oil in water emulsion. Ideally, it is almost impossible to avoid emulsification of the recovered oil, which demands one extra step, de-emulsification (Raghavendra & Raghavarao, 2010; Yusoff et al., 2015). To recover the extracted oil from yellow mustard flour, Tabtabaei and Diosady (2013) de-emulsified the oil in water emulsion by employing different proteases and phospholipids so as to hydrolyze the target emulsifiers. Protex 6 L® and phospholipase de-emulsification treatment resulted in 91% oil yield from mustard oil–water emulsion. Unfortunately, the economics of the process are compromised with the increased cost of enzymes (Long et al., 2011). In a recent study, Yang et al. (2019) effectively de-emulsified the camellia oil by freezing the emulsion at –20 °C followed by thawing at 50 °C and sequentially centrifuging it at 1,775 × *g* for two cycles of 15 min each. After every cycle, the mixture separated into three segments: free oil as the supernatant, emulsified oil as the middle layer, and residue at the bottom. The yield was 89.37%, which closely compared with cold-pressed and solvent extracted oil at 90.85%.

4 | MICROWAVE-ASSISTED EXTRACTION

4.1 | Extraction mechanism

Microwave-assisted extraction (MAE) is a trending extraction technique considered to have high throughput and extraction efficiency when compared to other conventional methods. MAE relies on a microwave generator that delivers microwave energy to a polarizable material consisting of the solvent and the oil-bearing material. Microwave radiations interact with dipoles present in the sample matrix causing them to oscillate in response to the changing electromagnetic fields. The oscillation/rotation of the dipoles generates heat on the surface of the material and the heat is further transferred to the inside of the material by conduction. Besides the dipoles from the solvent used in the extraction process, microwave radiations interact with the water present within the cells of the oil-bearing material resulting into a quick and uniform penetration of the heat to the target tissues (Zhang, Su, & Zhang, 2018). This heat results in the formation of water vapor and electroporation effects, which disrupts the cell wall of the oilseed and enhances efficient extraction of intracellular metabolites. Microwave radiation is a noncontact source of energy; hence, it provides effective heating, minimized thermal gradient, and selective heating when needed (Table 7). Accordingly, extraction time is considerably reduced (15 to 20 min), uses less volume of solvent, accommodates both polar and nonpolar solvents, increases yield with good reproducibility, and yields superior sensory attributes, that is, color, odor, and aroma in products (Pico, 2013; Balasubramanian, Allen, Kanitkar, & Boldor, 2011).

Microwave energy has proven to impart significant effects on the rate of diverse processes in both the food and chemical industries. Particularly, dielectric heating has gained a lot of attention in extracting essential oils, antioxidants, pigments, and aromas among other natural products (Chemat, Vian, & Cravotto, 2012). As far as product quality and yield are concerned, microwave irradiation allows for direct coupling of molecules through selective absorption; thus, it results in superior products compared to conventional heating and extraction techniques (Khan & Rathod, 2018). Hu et al. (2018) optimized MAE of essential oil from tiger nut and noted that oil by MAE technique exhibited superior oxidation stability and physicochemical properties.

4.2 | Microwave-assisted enzymatic extraction

Apart from using microwave radiation as the prime extraction agent, the technique can be used alongside other extraction methods to enhance mass transfer and component recovery. Microwave-assisted enzymatic extraction (MAEE) takes advantage of enzymes, that is, high selectivity, ability to catalyze specific reactions, and keen specificity so as to boost extraction efficiency of the overall process. Conventionally, enzymatic reactions are slow and take longer time to complete (Kuo, Chen, Chen, Liu, & Shieh, 2012) One of the trending approach to accelerate these reactions is the application of microwave energy that produces synergistic effects and augments the rate at which enzymatic reactions take place (Zhang et al., 2018). Additionally, radiations from microwave delay denaturalization of the enzymes, and hence, boost their stability profile over time. Lipase enzyme showed improved stability when treated with microwave heating as compared to conventional heating (Khan & Rathod, 2018).

4.3 | Effect of temperature, power, and nature of the solvent

With regard to microwave extraction, an increase in temperature increases the frequency factor of the microwave radiation and consequently raises the rate of collision between molecules. The more the energy, the more the tendency of the molecules going to higher energy state. Similarly, increased

TABLE 4 Microwave-assisted extraction of oil from different oleaginous material

Oil source	Extraction technique	Experimental conditions	Yield	Reference
Pumpkin seeds	Microwave-assisted enzyme extraction	Enzymes used: cellulase, hemicellulase, pectinase, β-glucosidase, and neutral proteinase; microwave power: 419 W; Temp: 44 °C; pH 5; solute/solvent: 1:10; extraction time: 66 min	65%	Jiao et al., 2014
Fructus forsythia	Microwave-assisted enzyme extraction	Enzymes used: cellulase, hemicellulase, and β-glucosidase; microwave frequency: 2,450 Hz; microwave power: 1,000 W; Temp: 100 °C; extraction time: 5 min	45.30%	Jiao et al., 2012
Isatis indigotica seeds	Microwave-assisted enzyme extraction	Enzymes used: 1.82% (1:1:1) cellulose, proteinase, and pectinase; microwave power: 375 W; Temp:43 °C; extraction time: 83 min	59.27%	Gai et al., 2013
Yellow horn seed	Microwave-assisted enzyme extraction	Enzymes used: cellulase, hemicellulase, and pectinase; Solid–liquid ratio: 5 mL/g; microwave power: 500 W; Temp: 60 °C; extraction time: 30 min	60.50%	Li et al., 2012
Moringa oleifera	Microwave-assisted extraction	Liquid–solid ratio: 8:1; microwave power: 300 W; Temp: 30 °C; extraction time: 7 min (at intervals of 5 times)	94.21%	Zhong et al., 2018
Sandbox seed	Microwave-assisted extraction	Liquid–solid ratio: 40:1 (ethyl acetate); microwave power: 180 W; extraction time: 5 min	72.75%	Ibrahim et al., 2019
Sandbox seed	Microwave-assisted extraction	Liquid–solid ratio: 40:1 (*n*-hexane); microwave power: 180 W; extraction time: 5 min	56.25%	Ibrahim et al., 2019
Lavender	Microwave-ultrasound-assisted extraction	Enzyme: cellulase and hemicellulase; microwave power: 275 W; ultrasound power: 50 W; Extraction time: 52.5 min		Rashed et al., 2017

Note. Solvent used in all the studies in this table is hexane unless otherwise stated.

randomness of the particles leads to faster synthesis (Khan & Rathod, 2018). High temperature also denatures the protein compounds facilitating the recovery of components bound by these molecules. However, care should be exercised as very high temperature affects the nutritional and sensory characteristics of the final product. Effect of power is analogous to that of temperature, whereby high power leads to faster movement of molecules and reaction rates. Low power, on the other hand, extends the time needed to achieve phase transition temperature (Zhang et al., 2018). Optimum power is recommended so that extraction takes a reasonable amount of time at a reasonable cost. Optimized parameters for oil extraction from different oil-bearing materials are as presented in Table 4.

Nonpolar solvents when used in microwave extraction demonstrate a poor solvent-to-microwave synergism owing to their low dielectric constant. Further, the mechanism behind microwave heating is based on molecular or dipole rotation coupled with ionic conduction. For these reasons, polar solvents are the most preferred for microwave extraction because they have a high dielectric constant, absorb more microwave radiations (high loss factor), and they promote conductivity. Moreover, polar solvents have demonstrated superior results than the nonpolar solvents in most cases (Khan & Rathod, 2018). Ethanol has excellent microwave absorption properties, whereas the commonly used hexane is transparent to microwave radiations. In spite of this, hexane is usually used in MAEE after combining it with a small proportion (approximately 10% v/v) of water, salt, or other polar solvents, which is the typical procedure of using nonpolar solvents in MAEE (Tatke & Jaiswal, 2011). Addition of water to nonpolar solvents promotes hydrolization and also minimizes the chances of oxidation of the extract. One of the major drawbacks of MAEE in oil extraction is the oxidation of unsaturated fatty acids, particularly when volatile solvents are used. Presently, the use of green solvents such as water and enzymatic aqueous extractants is gaining popularity (Zhang et al., 2012).

Extraction time is of paramount importance as far as MAEE is concerned. Initially, it offers a positive impact by increasing the yield but eventually becomes deleterious. Beyond a specific optimum value, the yield either stabilizes or diminishes owing to thermal degradation and oxidation of the extract (Veggi, Martinez and Meireles, 2013). Apart from avoiding overheating, the time needed for MAEE is considerably reduced. In instances when prolonged microwave heating is desired, the extraction should be done in cycles. However, such an approach consumes a large amount of solvent, which adds up to the total production cost (Routray & Orsat, 2012).

TABLE 5 Ultrasound-assisted extraction of oil from different oleaginous material

Source	Extraction technique	Experimental conditions	Yield	Reference
Pomegranate seeds	Ultrasound-assisted enzyme extraction	Enzymes used: cellulase and Peclyve®; Temp: 55 °C; extraction time: 2 hr	15.80%	Goula et al., 2018
Flaxseed	Ultrasound-assisted enzyme extraction	Enzymes used: immobilized cellulase, pectinase, and hemicellulase; ultrasound frequency: 20 kHz; ultrasound power: 250 W; Temp: 45 °C; extraction time: 30 min	62.50%	Long et al., 2011
Perilla seeds	Ultrasound-assisted enzyme extraction	Enzymes used: cellulase, Viscozyme L®, Alcalase 2.4 L®, Protex 6 L®, and Protex 7 L®; ultrasound power: 250 W; Temp: 50 °C; extraction time: 30 min	50.20%	Li et al., 2014
Moringa oleifera	Ultrasound-assisted extraction	Ultrasound power: 200 W; Temp: 30 °C; extraction time: 15 min	91.35%	Zhong et al., 2018

5 | ULTRASOUND-ASSISTED EXTRACTION (ULTRASONICATION)

5.1 | Extraction mechanism

Ultrasound-assisted extraction (UAE) has gained popularity in recent years because of its ability to improve the efficacy of various processes. As a green and novel extraction technique, it is highly scalable as far as the extraction of oil and other bioactive compounds is concerned (Wen et al., 2018). Its extraction mechanism is attributed to the production of cavitation bubbles, vibration, mixing, and pulverization among other complex mechanical effects. Collectively, the processes disrupt the cell wall, increase the permeability of the cell wall, and intensifie the rate of mass transfer. Propagation of ultrasound waves at a specific critical value in liquids creates a negative pressure in the fluid and consequently results in cavitation. The negative pressure develops when compression and expansion cycles of the ultrasound waves exceed the local tensile strength of the liquid. This phenomenon yields many tiny bubbles that grow with time to a point where they induce shear forces and turbulence in the as they collapse. The effective frequency range for this technique is 20 to 50 kHz (Carcel, Garcia-Perez, Benedito, & Mulet, 2012). In practical situations, the collapsing of cavitation bubbles produces a rapid micro jet on the surface of the material, which results in peeling of the surface, breakdown of the cell wall, and erosion and exudation of cellular content (Pico, 2013). Additionally, cavitation is capable of changing the chemical processes in a system and initiating new reaction mechanisms through the formation of free radicals. In case water is used as the solvent, the dominant free radicals are the hydroxyl radicals; depending on the process, the radicals modify the components of the cells such as proteins (Arzeni et al., 2012; Wen et al., 2018). Increasing temperature and pressure generate more shear energy, turbulence, and cavitation. Cavitation, thermal, and mechanical effects are the prime cell wall degrading mechanisms during extraction and the combination of the three effects causes rupturing of the cell wall. Further, they increase the rate of chemical reactions and reduce the size of the particles. These synergistic effects account for the reduced extraction time and facilitate mass transfer without significantly damaging the extracts (Ashokkumar, 2015; Ayim, Ma, Alenyorege, Ali, & Donkor, 2018).

In an attempted to evaluate the effectiveness of UAE when used alongside AEE, Datt (2017) revealed that there is no significant variation in oil recovery from maize germ by either solvent extraction or ultrasound aqueous enzymatic extraction (UAEE), but highlighted that oil from UAEE had better quality and stability over time.

5.2 | Process factors affecting ultrasonication

The type of solvent, its concentration, temperature, time, and frequency of the ultrasound waves determine the effectiveness and efficiency of the extraction process. Table 5 presents the optimized parameters for oil extraction from different oil-bearing materials. Although the intensity of cavitation is a factor of the frequency of the ultrasound waves, the physical properties of the solvent such as viscosity, surface tension, and vapor pressure affect the transmission of the wave streams within the media and retards the extraction process in overall (Esclapez, Garcia-Perez, Mulet, & Carcel, 2011). Increase in surface tension and vapor pressure of the solvent reduces the intensity of cavitation and for this reason, water acts as the common solvent in UAE. Ethanol, methanol, and hexane comprise the other solvents in use with ethanol being preferred in the extraction of bioactive compounds because it does not pose any safety concerns.

The thermal effect produced by high extraction temperature favors solvent diffusion rates. On the other side, lower temperature enhances cavitation and consequently the yield. The temperature ought to be maintained within a suitable range so as not to compromise the extraction process (Wen et al., 2018). Similarly, the extraction time need to be optimized to determine the optimum range. Although extended time favors oil yield, it also induces undesirable

TABLE 6 Supercritical Fluid extraction of oil from different oilseeds

Source	Experimental conditions		Reference
	Temperature (°C)	Pressure (MPa)	
Canola seed	40 to 60	200 to 250	Pederssetti et al., 2011
Chia seed	40 to 80	136 to 408	Uribe, Perez, Kauil, Rubio, Alcocer, 2011
Corn germ	35 to 86	210 to 525	Rebolleda, Rubio, Beltran, Sanz, and Gonzalez-Sanjose, 2012
Grape seed	40 to 60	200 to 400	Jokic, Bijuk, Aladic, Bilic, and Molnar, 2016
Hemp seed	40 to 60	300 to 400	Aladic et al., 2015
Melon seed	40 to 80	200 to 400	Nyam, Tan, Lai, Long, and Man, 2011
Passion fruit seed	40 to 60	150 to 250	De Oliveira et al., 2013
Rape seed	40 to 60	250 to 350	Yu, Wang, Liu, Liu, and Wang, 2012
Soybean seeds	40 to 60	300 to 500	Jokic et al., 2012
Sesame seeds	40 to 60	190 to 250	Corso et al., 2010
Safflower seed	35 to 60	220 to 280	Han, Cheng, Zhang, and Bi, 2009
Peach seed	30 to 50	100 to 300	Mezzomo, Mileo, Friedrich, Martinez, and Ferreira, 2010

nutritional and sensory changes in the extracted product (Sun, Liu, Chen, Ye, & Yu, 2011).

6 | SUPERCRITICAL FLUID EXTRACTION (SCFE) TECHNOLOGY

Supercritical fluid extraction (SCFE) technology uses supercritical fluid at vapor–liquid critical point to extract oil and other plant components. The supercritical state is only achieved when the solvent is subjected to temperature and pressure beyond its critical point. At the critical point, there is no distinctive gas or liquid phase and the solvent behaves more like a gas with solvating properties of a liquid. The gas-like viscosity on the other hand results in high rates of mass transfer (Chemat et al., 2019). Commonly used solvent is carbon dioxide (CO_2) because it is inert, abundant, noninflammable, nontoxic, possess moderate critical properties (Table 6), and can easily be recovered from the reaction streams. CO_2 is a solvent generally regarded as safe and its inclusion in products is not harmful to human health. Moreover, recycling of CO_2 in this technique avoids the greenhouse effect that is detrimental to the environment (Mouahid, Crampon, Toudji, & Badens, 2013; Yen, Yang, Chen, & Chang, 2015). SCFE is gaining grounds in both the food and pharmaceutical industries. The extraction process requires less time, is highly selective, and is environmentally friendly because it does not use organic solvents (Santana, Jesus, & Larrayoz, 2012). The principal merit of this technique is that no follow-up separation steps are required to obtain the oil from the substrate mixture.

The efficacy of SCFE extraction heavily depends on the intrinsic and extrinsic factors to the process. The former includes temperature and pressure that determine the physical state of the solvent, while the latter encompasses characteristics of the sample and interaction of the oil-bearing cells with supercritical carbon dioxide (SC-CO_2). These factors pose a complex interaction and judicious experimenting is necessary to optimize the process (Sharif et al., 2014). Table 6 indicates the combination of temperature and pressure commonly used in oil extraction from different oilseeds. In spite of having a simple extraction process, application of SCFE technology is limited due to high equipment cost.

Studies show that nonpolar SC-CO_2 technology is most feasible for extraction of neutral lipids, for example, triglycerides, although phospholipids may not solubilize in the solvent (Chatterjee & Bhattacharjee, 2014). Some other studies report that increasing the pressure at constant temperature increases yield and similarly, lowering the temperature at a given pressure leads to increased solubility of solutes (Taher et al., 2014). Polar solvents such as ethanol are used as modifiers to solve the problem of low polarity of SC-CO_2 and this enhances oil production. The high cost of the technology and low polarity coupled with temperature factor hamper the application and commercialization of this extraction technique. Despite these challenge, scaling-up of the technology is easy and has gained grounds in lipid extraction (Kumar et al., 2017).

7 | PULSE ELECTRIC FIELD–ASSISTED EXTRACTION

Pulse electric field (PEF)–assisted extraction is a groundbreaking nonthermal technology that is used to improve the extraction efficiency of vegetable oil from various oilseeds. The technology involves the discharge of direct electric pulses into the oleaginous material for a short duration of time (microseconds to milliseconds) and high voltage, up to 50 kV (Bozinou, Karageorgou, Batra, Dourtoglou, & Lalas, 2019). The oil-bearing material is placed between a high voltage electrode and a grounded electrode. The electric pulses traverse through the cell membrane and generate electric fields (up to 10 kV/cm), which disintegrates the membrane molecules based on their net charge. The separation of membrane molecules results in the formation of pores and increases the permeability of the cell wall of the plant tissues. Consequently, the diffusion of solutes through the cell wall is enhanced by electroporation, and this favors the extraction of intracellular substances like oil and other components of interest. Pulse duration and pulse interval are the two fundamental factors affecting the effectiveness of PEF treatment (Poojary et al., 2017).

As an emerging physical technology, it improves mass transfer processes, and PEF pretreatment on crushed oilseeds increases oil yield and recovery of bioactive compounds. The technology allows for a reduction in malaxation temperature while preserving yield and sensory quality of the final product. Moreover, PFE is an effective de-emulsification technique because it facilitates coalescence of oil molecules contained in the oil in water emulsion. Therefore, the yield is improved through double mechanisms: electroporation from the tissues and recovery of oil from the emulsion. PEF technology is a “cold technology” as the intensities applied hardly raises the temperature of the mixture by 5 °C and this helps in maintaining the quality of food products (Zeng & Zhang, 2019).

Puertolas et al. (2016) conducted a pilot study to investigate the effect of PEF on olive seeds in a small olive oil mill and noted a high potential of PEF in industrial applications. Compared to the control, PEF technology improved the oil yield by 13.3%. Correspondingly, the oil presented an 11.5% increase in polyphenols, 9.9% phytosterols, and 15% increase in total tocopherols than the control. The study applied an electric field of 2 kV/cm and 65 J of energy. Additionally, the study noted that PEF technology recovered approximately 50% of residual oil that remains in the olive seed after mechanical extraction. In a similar study, yield increased by 54% when the olive paste was subjected to 2 kV/cm of electric fields without malaxation time and temperature. At 26 °C, the malaxated paste showed no increase in yield compared with the control, but at 15 °C, PEF treatment portrayed a 14.1% increase in oil yield (Abenoza et al., 2013). Bakhshabadi, Mirzaei, Ghodsvali, Jafari, and Ziaiifar (2018) noted an increase in oil production and a 0.96% increase in the density of oil when black cumin seeds were treated with a 3.25 kV/cm of electric field and an intensity of 30 pulses.

8 | HIGH PRESSURE–ASSISTED EXTRACTION

High pressure–assisted extraction (HPAE) is rather new and superior compared to other extraction techniques because it avoids heating of the substrate, and thus preserves the properties of the bioactive compounds and other biological activities (Alexandre et al., 2017). Depending on the intensity of the applied pressure, the process can be categorized as high pressure (above 100 MPa), medium to high-pressure process (10 to 100 MPa), and low pressure (below 10 MPa). With regard to the operating temperature, the process can also be categorized as pressurized liquid extraction (low temperature) or pressurized hot water extraction if the temperature is high (Putnik et al., 2017). The applied pressure disrupts the plant tissues, interrupts the cell wall and the cell membrane, and facilitates the transfer of the soluble matters between the solvent and the substrate. The fundamental theory behind HPAE is the phase behavior theory, which dictates that solubility of a substance is enhanced at higher pressure. Under the pressurized condition, the solvent permeates more rapidly through the cells, contacts cellular constituents, and actively dissolves the target components in a short time (Ferrentino, Asaduzzaman & Scampicchio, 2018). HPAE offers several advantages such as prevention of thermal degradation of food constituents, acts rapidly and uniformly over the substrate, retains high bioactivity by maintaining covalent bonds, requires less time, and gives a high oil yield compared to most extraction techniques (Huang, Hsu, Yang, & Wang, 2013). Table 7 summarizes the merits and shortcomings of the different novel extraction techniques. In an attempt to investigate the state of development of these technologies, Table 8 highlights some of the latest patents in oil extraction.

9 | HAZARD ASSESSMENT OF VEGETABLE OIL PROCESSING

Vegetable oil extraction is associated with certain environmental, health, and safety hazards emanating from the solvents used and residues left after the extraction process. Volatile and flammable solvents like hexane and petroleum ether used during extraction result in highly flammable vapors that are not only detrimental to the environment but also unsafe when inhaled (Landucci et al., 2011). When the extraction process is operated under high temperatures and pressure, there is a high possibility of explosion. Particularly, microwave extraction is one of the nonconventional extraction technique that operates at elevated temperatures and as a result, there is bumping of the substrate–solvent mixture. In fact, if care is not exercised, an explosion is bound to occur. The environmental, health, and safety issues are as discussed below.

9.1 | Solid waste and byproducts

Oil extraction is associated with significant quantities of solid waste and process byproducts. The waste includes kernels,

TABLE 7 Summary of the merits and shortcomings of various novel oil extraction techniques

Extraction method	Advantage	Disadvantage
Heating reflux, Soxhlet (Tan et al., 2016; Tiwari, 2015)	Low investment cost and increased yield	High temperature, a large amount of solvent required, and solvents are hazardous
Microwave-assisted extraction (Hu et al., 2018; Chemat et al., 2012)	Reduced processing time and solvent usage (economical), environmentally friendly, and improved oil yield	Applies high temperatures, centrifugation or filtration is required to separate residue from extract, most suitable for polar solvents (efficiency is reduced for nonpolar or volatile solvents)
Microwaves + ultrasonication (Ashokkumar, 2015; Carcel et al., 2012)	Reduces energy consumption, high purity, and significantly improves extractability of active compounds	Extra energy requirements and prolonged extraction time that slows down the process
Microwave + enzymatic extraction (Kuo et al., 2012; Zhang et al., 2018; Khan & Rathod, 2018)	High efficiency and specificity, improves the release of intracellular contents, and allows for simultaneous recovery of multiple components	Bumping phenomena is likely to occur, and there is excessive heating of the substrate.
Ultrasound-assisted extraction (Ayim et al., 2018; Wen et al., 2018; Pico, 2013)	Reduced extraction time and solvent requirements, low thermal damage to the final product, greater solvent penetration, and consequently high yield	Swelling of the plant material thus inferior quality of by-products, high power requirements, and difficult to scale up for commercial application
Enzyme-assisted extraction (Yang et al., 2019; Kumar et al., 2017; Yusoff et al., 2015)	Enhanced extraction of cellular material, nontoxic extraction process, rapid, and highly specific	Additional and tedious operation in wet conditions, efficiency depends on lipid composition of the oil-bearing material, and cost-intensive
Pressurized solvent extraction (Huang et al., 2013; Putnik et al., 2017)	Reduced processing time and solvent use	High investment costs, high temperature resulting in thermal degradation, and low throughput
SC–CO_2 extraction (Kumar et al., 2017; Yen et al., 2015; Chatterjee & Bhattacharjee, 2014)	Gentle treatment of heat-sensitive substances, environmentally friendly, CO_2 is inexpensive, enhanced transport properties due to relatively high diffusivity and low viscosity of SC-CO_2, offers selective extraction, and fewer process steps	High pressures, high capital and operating cost, phase equilibrium of the solvent/solute system is complex, and highly polar substances are insoluble

empty fruit bunches, barks, and leaves of fruits or trees depending on the oleaginous material under consideration. The quantity of the waste generated is directly proportional to the quantity of the raw material and the availability of systems for reprocessing the disposed off materials into value-added products for commercial purposes (Reddy, Khan, Archana, Reddy, & Hameeda, 2016). In commercial oil processing, other wastes include soap stock acids used during chemical refining; bleaching earth, metals, and pigments; catalysts used in the filters for hardening process; and mucilage from degumming and deodorizer distillate. With the application of modern processing techniques, most of the wastes can be avoided (Yusoff et al., 2015).

9.2 | Wastewater

Apart from solid waste, water used in the washing and neutralization of oil has an elevated concentration of organic matter, a high biochemical oxygen demand and chemical oxygen demand. Additionally, the water may contain a high content of suspended solids, oils and fats, organic nitrogen, and pesticide residues originating from the raw material. Subsequently, the water is discarded as waste because it is not only a threat to the health and safety of the operators but also to the environment (Panghal, Chhikara, Sindhu, & Jaglan, 2018; Rovaris et al., 2012).

9.3 | Emissions to air

Volatile organic compounds and particulate matter are the principal emissions released to the environment from oil extraction operations. Volatile emissions normally emerge from the solvents used for extraction, whereby not all of the vapor is condensed back to liquid state but instead is emitted into the atmosphere. Other attributable causes of emissions include leakages within the systems and evaporation of the solvent into the environment. Further, odors are also generated from such processes as vacuum evaporation and soap splitting. As far as particulate matter is concerned, dust emanates from the raw material during the cleaning, screening, and crushing, which are fundamental steps for substrate preparation (Konopka et al., 2016; Kumar et al., 2017).

TABLE 8 Recent patents in the extraction of lipids, oils, and fats

Patent	Title	Description/application	Applicant
US20080305531 A1	Compositions and methods for making and modifying oils	Making and modifying plant and animal oils that are low in particular fatty acid(s)	Lam, Weiner, Hitchman, Barton, and Lyon, 2015
US20120282383 A1	High-shear application in processing oils	Processing of oils using a high-shearing system and an inert or reactive gas	Hassan, Hassan, and Anthony, 2015
US20130011887 A1	Oil degumming methods	Degumming of oils and fats by removing nonhydratable phospholipids (NHPs), hydratable lipids, and lecithins from them	Dayton, Galhardo, Barton, Hitchman, Lyon, O'Donoghue, and Wall, 2015
US20140206890 A1	Vegetable oil extraction	Extracting vegetable oil by heating the light-colored material and later subjecting it to two sonication treatments, first at a frequency in the range of 0.4 to 1 MHz and another above 1 MHz	Augustin, Juliano, Mawson, Swiergon, and Knoerzer, 2016
US20070260080 A1	Light-color plant oils and related methods	Production of light-colored oils. Removal of colored bodies from plant oils using cationic ion exchange resins	Lee and Pfalzgraf, 2009
US20130323396 A1	Method of producing and refining vegetable oil	Refining of vegetable oil using polyol-containing solvents, for example, glycerol and an alkalizing agent for selective recovery of free fatty acids contained in the oil	Norn and Nielsen, 2018
US20100288621 A1	Microwave gas flow apparatus for extracting essential oils, and other pigments.	Obtaining essential oils and other pigments from plant material and medicinal herbs using microwave radiation heating	Lee, 2011
US20110263883 A1	Extraction with fractionation of oil and products from oil-bearing material	Extracting lipids of varying polarities from plant materials using membrane filters	Kale, Hu, and Sommerfeld, 2012
US20110233203 A1	Microwave integrated soxhlet	Extraction of oil and other bioactive compounds using a microwave unit configured with a soxhlet extraction unit	Visinoni and Pirola, 2014
US20130247451 A1	Processes for producing lipids	Extraction of vegetable oil and consequently the production of industrial products such as hydrocarbons from the lipids	Vanhercke, Petrie, El Tahchy, Singh, and Liu, 2014
US20120196332 A1	Enzyme method of extracting oils and proteins from vegetable matter in an aqueous medium	Extraction of oils, proteins, and fermentable sugars from oleaginous materials using enzymes at certain activity ratio	Muniglia, Girardin, Piffaut, and Ricochon, 2014
US20100012583 A1	Advanced biorefinery process	Refining of biomass by disrupting its cellular structure using a combination of high shear force, high temperature, cavitation, and enzymes to assist in the hydrolysis of the components	Stuart, 2012
US20170253829 A1	Subcritical water-assisted oil extraction and green coal production from oilseeds	Extraction of oil by swelling the oilseeds to disrupt the cell wall. It is an optimized process that removes impurities from oils, hydrolyzes proteins, and maximizes energy recovery.	Kumar and Majeranowski, 2017

10 | CONCLUSION AND FUTURE TRENDS

Currently, it is almost impossible to identify a production process in the food, chemical, pharmaceutical, or even cosmetic industry that does not rely on extraction processes. In the last two decades, researchers and scientists have devoted their work in developing alternative technologies to help extract oil and bioactive compounds from fruits and vegetables. With the currently available techniques, optimization must be done properly to improve yield as well as provide more mechanistic-oriented research. In almost all the techniques, there is solvent purification process and large amount of waste generated after extraction of oil and other bioactive compounds from the substrate. With the ever-increasing demand for oils and fats, more research is needed to eliminate this process (solvent purification) and to develop alternative value-added co-products from the waste left after extraction. Further, because most of the techniques are being applied at laboratory level or as small pilot projects, advanced research and technological improvement is needed to bring them to industrial level of application.

Recent trends in oil extraction have been centered on developing solutions that minimize the usage of harmful organic solvents and the development of green and renewable solvents to produce safer and high-quality products. There is a greater emphasis on safety, environmental, and economic aspect of the extraction methodologies in use. Extraction of essential oils from plant sources using novel extraction techniques offers a promising future. In comparison to traditional techniques, modern methods have been evaluated for efficiency and applicability with regard to the growing consumer demand for safe and high-quality products. Most of the novel techniques offer superior quality products because they are nonthermal. Further, they have proven advantageous in obtaining quality plant extracts in a shorter time, with less energy demand and with low amounts of solvents. Despite these advantages, it is necessary to combine different techniques particularly the thermal techniques to achieve sustainable processing with a guarantee of safe products. This may be an avenue toward discovering even better ways of obtaining high-quality oils, lipids, and fats. As far as green, efficient, and environmentally friendly processes are concerned, there is the need for further research in order to overcome the challenges offered by the currently available green technologies without compromising yield and quality. Conventional extraction techniques offer unique properties with the possibility of selective extraction as well as superior physicochemical properties of the extracts. Though different researchers have investigated the optimum conditions for the extraction of oil from different oilseed using the different technologies, there is a need for further improvements. With reduced ecological footprints, green solvents definitely hold the future of the oil extraction industry.

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AUTHOR CONTRIBUTIONS

Dr. Anil Panghal, Dr. Mukesh K. Garg, Dr. Vijay Kumar Singh, and Er. Peter W. Mwaurah conceptualized and drafted the outline to the manuscript. Er. Peter W. Mwaurah, Er. Sunil Kumar, and Dr. Arun K. Attkan collected the relevant research and review papers on the topic. Er. Peter W. Mwaurah, Er. Sunil Kumar, and Dr. Nitin Kumar developed the original draft manuscript. In the course of developing the review paper, comments or suggestions were discussed among all authors. All authors contributed significantly in the review and proofreading of the manuscript.

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