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Sustainable Palm Oil Extraction and Trends in the Use of Green Technologies: State-of-the-Art and Future Directions

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ABSTRACT

Palm oil, which is extracted from the mesocarp of the fruit of the *Elaeis guineensis* Jacq. palm tree, is the most widely produced vegetable oil in the world. The extraction of this substance typically utilizes the conventional pressing method, a technique that is advantageous due to its low operating cost and simplified process. However, a significant drawback pertains to the substantial amount of oil retained within the fibers, amounting to approximately 1% of the total oil produced. Consequently, the fiber may contain approximately 5 to 6% of residual oil. A plethora of studies have demonstrated the efficacy of methodologies such as supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), subcritical water extraction (SBW), and aqueous enzyme extraction (WEE). In addition, techniques including ultrasound-assisted extraction (UAE), microwave-assisted extraction (WAE), and deep eutectic solvent (DES) have been shown to be effective. This review critically examines the underlying principles, performance, and sustainability implications of these emerging extraction technologies. The review highlights the potential of these technologies to enhance oil recovery, reduce environmental impacts, and improve process efficiency when compared to conventional extraction methods. This study systematically analyzes current advances and existing limitations to identify key research gaps related to process scalability and tech-economic feasibility. In addition, the review delineates prospective research trajectories that are oriented toward process optimization, hybrid extraction methodologies, life cycle assessment, and industrial-scale implementation. These research trajectories are intended to contribute to the advancement of palm oil extraction methodologies that are more efficient and sustainable.

1 | Introduction

Crude palm oil (CPO) is a globally traded agricultural commodity, with its prices primarily determined by supply and demand dynamics in the international markets. In many developing countries, crude palm oil plays a crucial role in supporting rural livelihoods and smallholder (Sibhatu 2023).

Until the beginning of the 15th century, the production and consumption of palm oil were only concentrated in Africa, but, due to its properties and its high profitability on the market, some European companies expanded their plantation fields using enslaved labor (Sibhatu 2023). This change has led to significant growth in palm oil production, which is currently increasing by 38.7% year on year, reaching a total of 179.6 million tons per year. This confirms the projected value of 88 billion dollars by 2022 (Afrizal et al. 2024). Nowadays, palm oil is considered a commodity and an agricultural product that is produced on a global scale, with prices determined by international market supply and demand (Sibhatu 2023). Its consumption has increased fivefold since 1990, and it is estimated that by 2050, consumption could reach 240 million tons due to various factors,

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such as low production costs, simple extraction, a high yield compared to other types of vegetable oil, and high productivity (Hoe et al. 2020).

This product, also known as palm oil, is extracted from the mesocarp of the *Elaeis guineensis* Jacq. fruit and is the most widely produced vegetable oil in the world (Edo et al. 2022). Two types of oil are extracted from the fruit: crude palm oil (CPO) from the mesocarp and palm kernel oil (PKO) from the kernel. Palm kernel oil (PKO) is also very important in the global oil market (Sibhatu 2023).

The oil is usually extracted by pressing, after which the pulp is separated from the fibrous material, also known as pressed fiber. Approximately 5% to 6% residual oil is still contained in the fruit pulp after pressing, made up of various compounds of high nutritional value, such as carotenoids, tocotrienols, tocopherols, phytosterols, and phenolic compounds. These can be extracted using suitable technology (Dal Prá et al. 2016).

Palm oil is one of the agricultural products that has undergone rapid expansion in countries with a tropical climate, such as Malaysia, Indonesia, Thailand, Colombia, as well as African countries, including Nigeria and Cameroon, among others. Its use makes up around 35% of all vegetable oils used around the world and it is number one in global production. More than 85% of the world's palm oil production is supplied by Malaysia, Indonesia and Thailand (Absalome et al. 2020).

Crude palm oil is rich in carotenoids, tocopherols, tocotrienols, and other bioactive compounds. Around 51% of the total fatty acids in this product are saturated, with palmitic acid being the main constituent. The remaining 49% is made up of unsaturated fatty acids, including oleic and linoleic acid, making it a balanced blend of different fatty acids. Due to its fractions, it is characterized as a semi-solid oil at room temperature, which gives it oxidative resistance, and its technological function guarantees the quality of foods made using this oil as a raw material (Edo et al. 2022).

Due to its physical, chemical and nutritional characteristics, this oil has become an alternative that is increasingly being used in food production, as well as in the industrial production of chemical compounds and fuels. It can be used in its raw form (crude oil) in cooking or undergo industrial refining for use in a variety of other foods, as well as in the pharmaceutical and cosmetics industries. It can also be used in confectionery products, margarine production, ice cream, and many other applications (Edo et al. 2022).

Demand for palm oil is expected to increase even more, especially in countries with high population growth rates such as China, India and Pakistan, due to its versatility, including its use as a biofuel alternative in the near future (Sibhatu 2023). However, palm oil production has been associated with several negative consequences, such as biodiversity loss and pollution resulting from excessive use of fertilizers and pesticides, waste produced by mills, waterway pollution, tropical forest destruction and increased greenhouse gasses (Abazue et al. 2019).

On the other hand, the palm oil industry plays a very important role in the global economy, contributing significantly to increasing the availability of vegetable oils for human consumption or industrial use (Olivares-Tenorio et al. 2024). Various economic benefits are provided by it, such as the creation of jobs, increased family income, and an improved quality of life for communities. The palm oil chain has generated millions of direct and indirect jobs, from planting the palm trees to harvesting the bunches, transportation, processing, research and development, logistics and marketing (Hassan et al. 2024).

Palm oil production has been associated with environmental issues such as deforestation and biodiversity loss, pollution from agrochemicals used in palm cultivation and oil production waste. Oil palm cultivation has also been blamed for social problems such as land conflicts, human exploitation, child labor and human rights violations (Tabe-Ojong 2024).

The palm oil industry produces toxic organic compounds that can cause eutrophication, acidification and pollution to terrestrial and aquatic ecosystems, so it is important to adopt more sustainable processes focused on environmental, economic and social aspects (Abogunrin-Olafisoye et al. 2024). Nevertheless, the palm oil industry has had a positive impact on the quality of life of rural communities living near the plantations, as it has created income and employment opportunities (Kahar et al. 2022). The production of palm oil has become a major focus for many countries due to its role as a food, energy source and commodity. However, there is growing awareness of the need to protect the environment and combat climate change. In response, some of the countries that produce palm oil have made various efforts to adopt sustainable practices (Chew et al. 2021).

Consequently, this literature review addresses the sustainable aspects of palm oil extraction, utilizing emerging methods and novel technologies for obtaining products with high nutritional value and superior waste management for the production of by-products such as biofuels and biogas for energy generation, among others. This topic is extremely important from environmental, economic and social perspectives, as it presents sustainable solutions for extracting palm oil that can mitigate the industry's impact on climate change and generate greater profitability through the sale of various bioproducts resulting from waste transformation, thereby fostering the circular bioeconomy. This can be considered an important contribution to achieving the United Nations Sustainable Development Goals (SDGs).

2 | Conventional Methods of Palm Oil Extraction

The conventional method of extracting palm oil (see Figure 1) involves subjecting the fruit to intense heat in water, followed by crushing it in a hydraulic press either a single or twin-screw model to obtain the pulp. The conventional method of extracting palm oil (see Figure 1) involves subjecting the fruit to intense heat in water, followed by crushing it in a hydraulic press either a single or twin-screw model to obtain the pulp. The pulp is then mixed with water and cooked for around 3 h, yielding a blend of palm oil and water that is characterized by its heterogeneous

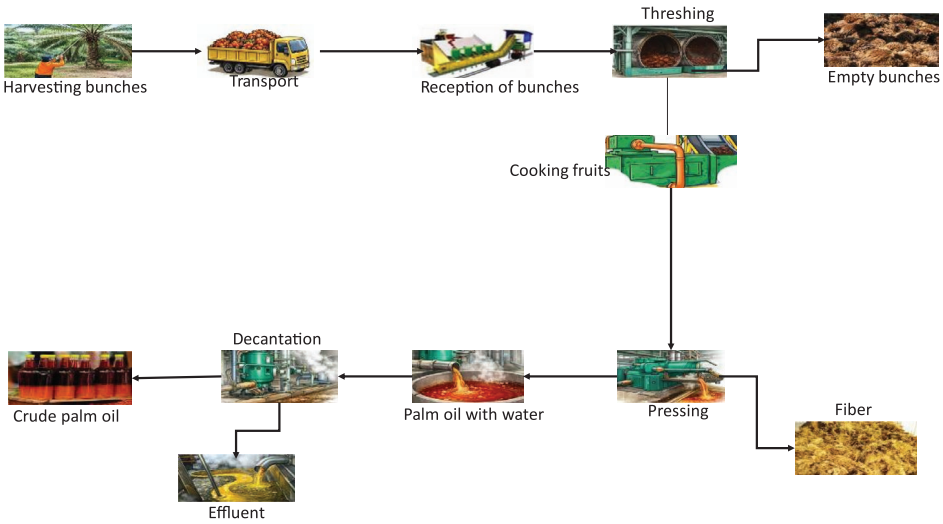


FIGURE 1 | Flowchart of conventional palm oil production.

nature, with two distinct phases. The palm oil is the supernatant of this mixture and is separated from the water by decantation or due to differences in density (Wondi et al. 2024). Crude palm oil is then subjected to the physical refining process. This process removes odorous compounds. It includes the stages of bleaching and deodorizing. Or it includes steam deacidification. This is done under low pressure (2 mmHg). The temperature ranges from 240°C–260°C. Low-boiling compounds are distilled from the neutral oil. Gas or steam is used to do this. Residues such as free fatty acids, soaps, peroxides, phosphatides and gums are eliminated (Sampaio et al. 2017). Refining enhances the quality of oil by improving its color, taste, smell and oxidative stability. This is achieved by eliminating free fatty acids, which have a boiling point of 100°C. The high temperatures used during the refining process range from 240°C–260°C for a duration of 1 to 2 h. The main advantages of refining include reducing moisture and impurities, such as aldehydes, ketones and pigments, and preventing oil hydrolysis and the formation of trans fatty acids. The main disadvantages of this stage are the potential formation of trans fatty acids, the destruction of pigments that give the oil its color and the elimination of bioactive compounds such as vitamin E, carotenoids, tocopherols and tocotrienols, since these compounds cannot withstand temperatures above 100°C for more than 1 h (Chew et al. 2022).

Palm oil mills vary considerably in terms of production capacity, depending on the operating system. Typically, small-scale mills process between 1 and 5 tons of fresh fruit bunches (FFB) per hour, while medium-scale facilities operate at a rate of 10–30 tons of FFB per hour (Ruml et al. 2022). Large mills in Malaysia and Indonesia can process between 45 and 90 t of FFB per hour (Tan et al. 2024). These differences in scale significantly impact the feasibility of integrating emerging extraction technologies, as palm oil processing is designed as a high-throughput continuous operation (Anyaoha and Zhang 2021).

The conventional method of extracting palm oil has several advantages. It has low operating costs, a simple process, and batch extraction using hydraulic presses or continuous extraction using screw presses. These processes require low energy consumption and do not use organic solvents. The yield ranges from 75%–90% (Mba et al. 2015).

The oil palm is considered economically viable due to its low production costs, simple planting process, high productivity, and high profitability (Abubakar et al. 2023). The problem with this process is that the fruit is cooked at a high temperature. We know that lipid oxidation, which is the name for the rancid flavor that can develop in food, is caused by light, temperature, and the presence of oxygen. Conventional palm oil production and extraction processes are associated with high greenhouse gas (GHG) emissions throughout their life cycle. Recent data indicate that, from 2023 to 2024, the palm oil industry is expected to emit approximately 111,780 t of CO_2 equivalent per year. These emissions reflect the high carbon intensity of the conventional production system and highlight the importance of mitigation strategies based on the adoption of more efficient extraction technologies (Nur Usmani et al. 2025).

A further disadvantage of extraction by pressing is the significant production losses, which can amount to in excess of 1% of the total volume of palm oil produced (Wondi et al. 2024). After pressing, the pulp is separated from the fibrous material. Residual oil and other high-value nutritional compounds, such as carotenoids, tocotrienols, tocopherols, phytosterols, and phenolic compounds, are found in the pressed fiber. These can be extracted using suitable technology (Dal Prá et al. 2016).

3 | Technological Innovation in Palm Oil Production

Conventional extraction processes are related to environmental impacts, including significant carbon emissions (150 to 300 kg of CO_2 equivalent per kg of extract), high costs associated with the disposal of hazardous chemical solvents (estimated at around $20 billion per year globally) and the generation of large volumes of liquid effluents requiring rigorous treatment (Nair et al. 2026).

Economic, regulatory, and environmental pressures have driven the adoption of more sustainable extraction technologies (Nair et al. 2026).

In response to growing environmental and sustainability concerns, a range of emerging green extraction technologies have been investigated to improve oil recovery efficiency, reduce solvent use, and preserve bioactive compounds. These technologies include supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), subcritical water extraction (SBW), water-enzymatic extraction (WEE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and deep eutectic solvent (DES) extraction (Fomo et al. 2020).

Consequently, scientific research has been undertaken to devise innovative extraction methodologies, with the objective of surmounting numerous production impediments, including yield, sustainability, and quality, whilst concomitantly fostering innovation in the production of vegetable oils, not least palm oil. These new extraction processes are called innovative because they offer an alternative to traditional methods (Gao et al. 2024).

Currently, few palm oil industries use innovative processes, such as new extraction methods. New technologies are used on a small scale for some stages of the processing, mainly to improve production. Most proposals for new extraction methods are implemented on a smaller scale, primarily to recover antioxidant and bioactive compounds present in the residues. These compounds are of significant commercial and nutritional importance and can be applied to improve animal and human health (Li and Cai 2021).

Studies into new extraction processes for palm oil and its residue-based active compounds are emerging as an alternative to conventional methods, particularly in academic research. These new proposals for extracting vegetable oils are based on the principles of green chemistry. Defined by IUPAC (the International Union of Pure and Applied Chemistry) as the invention, development and application of chemical products and processes to reduce or eliminate the use and generation of hazardous substances, green chemistry is also known as sustainable chemistry. The aim of green chemistry is to minimize environmental impact and increase the safety of chemical processes and products since hazardous substances cause harm to the environment, people, and animals. Scientific literature has identified extraction methods employing green technology as the most common emerging approach for recovering compounds of high nutritional value from palm oil residues. Studies have examined supercritical fluid extraction (SFE), subcritical water extraction (SCWE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), deep eutectic solvents (DES) and enzyme-assisted extraction in aqueous solution (Ma et al. 2025).

3.1 | Extraction With Supercritical Fluid (SFE)

Researchers have used the supercritical fluid extraction (SFE) method to quantify and identify bioactive molecules with antioxidant potential. This is a sustainable alternative for the valorization of palm waste by-products and considered environmentally friendly extraction method, using supercritical carbon dioxide (sc-CO_2) as a solvent. First, the palm oil is pretreated by drying and grinding the palm pulp to increase its surface area in contact with the fluid (Akanda et al. 2012). It has been demonstrated in previous studies the strict control of moisture content at this stage is essential to prevent adverse effects on solute solubility and mass transfer. Subsequently, carbon dioxide is pressurized and heated beyond its critical point, enabling it to penetrate the vegetable matrix within the extraction vessel. The extraction process takes place at temperatures ranging from 50°C–80°C. The pressure is 300 bar. This process lasts for 2 h. Once the process is complete, the residual oil is collected and the CO_2 is sent either to the chamber or recycled (Sundrasegaran and Mah 2020). Using waste from palm oil production to obtain active compounds reduces waste production and makes it easier to reuse the solvent (Chew et al. 2022). CO_2 is the most widely used solvent in supercritical extraction due to its high diffusivity and density, as well as its low viscosity. It is not flammable, so there is no risk of explosion. The process does not leave any solvent residues in the product, and due to its inertness, it does not leave any residues either (Puah et al. 2011). Other solvents, such as propane, n-butane and R134a, have also been used successfully. Propane extraction has emerged as a promising technology because it is possible to obtain a higher extraction yield in a shorter amount of time than with supercritical CO_2 (Dal Prá et al. 2016). Supercritical CO_2 has unique properties that fluids acquire in this state, which differ from those in normal conditions (i.e., as a gas or liquid). When a fluid passes its critical point (31.1°C and 73.8 bar), it enters a supercritical state. In this state, there is no distinction between liquid and gas. The fluid's density resembles that of a liquid, making it a good solvent. It also maintains high diffusivity and low viscosity, allowing better penetration into solids. This enables the extraction of soluble components. The fluid's thermodynamic properties are highly sensitive to variations in temperature and pressure. This contributes to the efficiency and selectivity of the process (Paz De Melo E Silva et al. 2023).

The main advantages of supercritical CO_2 extraction lie in the fact that it is a quick procedure (Zahid et al. 2024). The supercritical fluid penetrates the material quickly, dissolving the oil efficiently and facilitating its transport out of the matrix. This process favors the production of oils with high nutritional value, such as the recovery of carotenoids. This is due to the low temperatures used for thermosensitive compounds, the easy separation of the product from the solvent, the use of low temperatures during the process to protect thermolabile compounds, and the low operating costs due to the cheapness of the solvent and the fact that it can be recovered in a gaseous state at the end of the process, thus avoiding its emission into the atmosphere (Vicentini-Polette et al. 2024).

Supercritical carbon dioxide (sc-CO_2) extraction is a low-temperature process that can preserve heat sensitive biocompounds. However, extraction with supercritical fluids has some disadvantages, such as the difficulty of processing solid materials continuously and the high cost of capital investment, which impacts the return on investment. The high investment cost is due to the expense of the equipment required for high-pressure

systems, which necessitate thick tank walls and pipework (Chew et al. 2022).

Research on supercritical CO_2 extraction (SFE-CO_2) of oilseeds at industrial scale, using extraction units with capacities of up to 2000 L, indicates that capital investment represents a significant portion of total costs. Specifically, capital costs account for approximately 35%–40% and 28%–32% of total production costs for CO_2 flow rates of 6000 and 3000 kg per hour, respectively. Under these conditions, the lowest reported production cost was 7.8 USD per kilogram of oil, achieved in a system comprising four extraction vessels operating at 6000 kg per hour (Belwal et al. 2020). These findings demonstrate that SFE-CO_2 has been successfully implemented at industrial scale over the past four decades, particularly in applications such as the decaffeination of coffee and tea, as well as the extraction of hops and other botanical products.

More recently, studies have highlighted the potential of SFE for the extraction of virgin palm oil and its derivatives. For example, Hassan et al. (2024) reported a maximum oil recovery of 28.68% from oil palm mesocarp fiber at 31 MPa and 340 K, producing oil with a high carotenoid content (approximately 982 $\mu g\,g^{-1}$) and low free fatty acid levels. In parallel, Akolgo et al. (2023) reported that energy consumption varies according to the extraction scale, with values of 122.5, 112.9, and 82.4 $kJ\,kg^{-1}$ for manual, semi-mechanized, and large-scale mechanized systems, respectively, and associated greenhouse gas emissions of 0.6 metric tons of CO_2 equivalent per metric ton of crude palm oil (CPO).

At the pilot scale, Belwal et al. (2020) reported an energy consumption of 36,720 kJ per kilogram of oil for SFE, with no direct greenhouse gas emissions observed. Despite this environmental advantage, the high energy demand, combined with the substantial capital investment required for specialized equipment, remains a major barrier to wider industrial adoption. Consequently, the viability of SFE depends on achieving an appropriate balance between its elevated energy requirements and its long-term benefits, including improved product quality and enhanced recovery of high-value compounds (Rizkiyah et al. 2025).

Another pilot-scale study conducted in Finland demonstrated the application of closed-loop supercritical fluid extraction using carbon dioxide (CO_2) as the solvent. In this process, nearly all of the CO_2 was recycled (approximately 99%), resulting in minimal solvent losses. The economic evaluation indicated that the industrial application of the process may be viable, considering an internal rate of return of 40%, a payback period of 2.5 years, and an estimated net present value of 20 million euros over 20 years (Khalati et al. 2023).

Overall, these findings indicate that SFE is capable of producing high-quality oil enriched with bioactive compounds. However, several technical and operational challenges continue to limit its large-scale adoption in the palm oil sector. A key constraint is the high moisture content of palm mesocarp (typically 40%–50%), which reduces the solubility of lipids in supercritical CO_2 and necessitates extensive pre-drying of the biomass prior to extraction. This additional step is energy-intensive and may promote degradation of carotenoids and other heat-sensitive compounds.

3.2 | Pressurized Liquid Extraction (PLE) and Subcritical Water Extraction (SBW)

Pressurized liquid extraction (PLE) is based on the application of high temperatures and high pressure to the solvent solid sample system, with the aim of increasing the solubility of compounds, improving mass transfer and, consequently, optimizing the efficiency, low solvent consumption and speed of the extraction process (Chatzimitakos et al. 2024), (Zahid et al. 2024).

The combination of these parameters promotes diffusion, reduces viscosity, and lowers the surface tension of the solvent, thereby optimizing the speed and efficiency of the extraction process. Solvent selection is a determining factor for the process's effectiveness; its polarity must be compatible with the characteristics of the target compound to promote its release from the matrix and its solubilization, while minimizing the co-extraction of undesirable compounds (Višnjevec et al. 2024).

The use of co-solvents such as ethanol or ethyl lactate in subcritical water systems significantly enhances extraction performance by modifying solvent polarity and improving mass transfer (Bermejo et al. 2016). Ethanol water mixtures increase solute solubility and enable two-step mass transfer mechanisms, while ethyl lactate has been shown to provide higher extraction efficiency and mass transfer coefficients (Del Valle et al. 2019). The addition of organic modifiers such as ethanol reduces the dielectric constant of water, enhancing the solubility of less polar compounds. Acidified ethanol further improves extraction by promoting cell wall disruption and hydrolysis of bound compounds, facilitating solute release (Žagar et al. 2026).

Additionally, PLE (pressurized liquid extraction) operates under conditions close to the critical point of the solvents, which can increase its extraction capacity. It is a method used for the extraction of bioactive compounds from natural matrices, including plants, with potential applications in the food industry. Due to its operational characteristics, PLE has been associated with the production of extracts with various industrial applications (Chatzimitakos et al. 2024).

The process is continuous: the solvent is pumped through a sample in an extractor cell, and extraction takes place in a constant flow at a stable temperature and pressure. At the end, the extract is collected (Zahid et al. 2024).

In the intermittent process, the extractor cell is loaded with the sample and the solvent, which remain in contact for a predetermined time. After extraction, the system is depressurized, and the extract is collected. This process can be repeated in cycles (Vicentini-Polette et al. 2024).

The process's independent variables are as follows: pressurized liquid extraction (PLE) with ethanol as the solvent is considered an efficient technique because it reduces extraction time, temperature influences the solvent's viscosity to facilitate its penetration and diffusion without degrading the

solute, and the solvent is kept at high pressure under specific temperature conditions (i.e., in the vapor state at atmospheric pressure), allowing solvent savings in an intermittent process (Vicentini-Polette et al. 2024). From an operational perspective, the solvation power of the supercritical fluid is controlled by a number of variables, including pressure and temperature. These variables have a significant impact on other factors, such as density, viscosity and hydrophobicity, which in turn can affect the selectivity of the compounds in the extraction fluid (Hoe et al. 2020).

Various bioactive compounds can be extracted from different plant matrices using pressurized liquid extraction (PLE), an alternative method that stands out for its short processing time (< 30 min), the use of an inert atmosphere under high pressure (< 20 MPa) and controlled temperatures (25°C–200°C), as well as its reduced solvent consumption. This technique is applicable in various sectors, including the pharmaceutical and food industries (Fomo et al. 2020).

For instance, the pressurized liquid extraction (PLE) method is used to obtain crude vegetable oil, such as soybean oil and sunflower oil, employing solvents like ethanol and hexane under pressurized conditions (Paz De Melo E Silva et al. 2023).

Subcritical water extraction (SWE), also referred to as hot pressurized or superheated water extraction, has emerged as a promising alternative to conventional solvent-based techniques (Capaldi et al. 2024). This method employs water as a solvent under pressurized conditions at temperatures above its boiling point, typically between 100°C and 347°C and pressures ranging from 10–60 bar, allowing it to remain in the liquid state (Višnjevec et al. 2024).

Under subcritical conditions, the physicochemical properties of water are significantly altered. As temperature increases, the dielectric constant decreases, leading to a reduction in polarity, while the diffusion coefficient increases and both viscosity and surface tension decrease. These changes are primarily associated with the weakening of intermolecular hydrogen bonds (Višnjevec et al. 2024).

Consequently, extraction selectivity can be tuned by temperature: polar compounds are more efficiently extracted at lower temperatures, whereas moderately polar and nonpolar compounds exhibit higher yields at elevated temperatures. In this context, subcritical water can exhibit solvent properties comparable to organic solvents such as methanol and ethanol, while maintaining the advantage of being environmentally sustainable (Capaldi et al. 2024).

In addition to its role as an extraction medium, SWE has demonstrated effectiveness as a pretreatment strategy, particularly for recalcitrant biomass such as lignocellulosic materials. The process promotes structural disruption of the matrix, enhancing the solubility and accessibility of target compounds (Chew et al. 2024).

Overall, SWE offers several advantages, including reduced reliance on organic solvents, shorter extraction times, and improved operational safety. These attributes highlight its potential as a viable and sustainable alternative for applications in the food industry and other sectors (Roobab et al. 2025).

3.3 | Water Enzymatic Extraction (Wee)

Enzyme-assisted extraction is a technique that uses enzymes as biocatalysts in an aqueous medium, operating under moderate temperature conditions and over relatively short periods of time, taking advantage of the high substrate specificity of these enzymes (Díaz-Reinoso et al. 2023).

Aqueous enzymatic extraction (AEE), also referred to as water enzymatic extraction (WEE), is grounded in the principles of green chemistry and green engineering and has emerged as a sustainable alternative to conventional extraction methods (Gao et al. 2024). This approach employs water as the extraction medium and enzymes as biocatalysts, contributing to reduced environmental impact, shorter processing times, and improved extraction yields.

The efficiency of AEE depends primarily on the selection of suitable enzymes, used either individually or in combination. Common enzymes in assisted extraction include carbohydrases such as cellulases, hemicellulases, β-glycosidases, and xylanases, as well as proteases and pectinases. These enzymes act on the plant cell wall, which is composed of cellulose, hemicellulose, pectin, and proteins and whose complex structure limits access to intracellular compounds. By hydrolyzing these structural components, enzymatic treatment facilitates the release of oil and other target compounds (Chew et al. 2024).

However, the extraction process often leads to the formation of crude oil emulsions. The formation of these emulsions depends primarily on three factors: contact between oil and water, the presence of surfactants, and the availability of energy. Emulsification generally requires a significant input of mechanical energy to disperse the liquids into fine droplets within the continuous phase, in addition to the presence of surfactants or emulsifiers (Pérez-Gálvez et al. 2024). Under these conditions, emulsifiers play a fundamental role by reducing interfacial tension and forming an electrical or steric barrier around the droplets, preventing their coalescence. Although this stabilizes crude oil emulsions, it can reduce overall oil yield (Gao 2025).

The final separation step involves centrifuging the mixture into distinct phases: oil, emulsion, protein hydrolysate, and other residues. This process is combined with technologies such as enzymatic demulsification and isoelectric sedimentation, with the aim of promoting the separation and recovery of oils and proteins more efficiently (Jiang et al. 2025).

Demulsification therefore becomes a critical step in the process. It consists of separating an emulsion into its constituent phases, dispersed and continuous, such as water and oil, and is essential in sectors including the petroleum industry, the food industry, and water treatment. Demulsification is achieved through physical or chemical methods, including the use of demulsifiers, heating, and ultrasound (Shao et al. 2025). However, current demulsification technologies present several limitations, such as high costs, elevated energy consumption, environmental

impacts, and potential safety risks. Among the promising alternatives, the use of fatty acids stands out, as it can reduce operating costs while increasing the demulsification rate (Shao et al. 2025).

In the case of oil palm mesocarp, mechanical pretreatment is typically applied prior to enzymatic hydrolysis. Separating the mesocarp from the seed and subsequently crushing it increases the contact surface area between enzymes and substrate, thereby enhancing process efficiency (Chew et al. 2024). Particle size reduction through grinding or crushing also promotes cell wall disruption and reduces diffusion limitations, further improving extraction performance. The choice between dry and wet grinding depends on the physicochemical properties and moisture content of the raw material (Mwaurah et al. 2020).

In oil palm mesocarp specifically, whose fibers consist mainly of cellulose (37.59%) and hemicellulose (4.68%), the application of cellulases, hemicellulases, and pectinases promotes hydrolysis of these polymers, facilitating matrix disintegration and oil release (Abd Rashid et al. 2023). In general, enzyme selection depends on the composition of the raw material, the type of enzyme, and the characteristics of the enzyme preparation (Mwaurah et al. 2020).

The enzymatic hydrolysis step is generally conducted under mild conditions, at temperatures ranging from 30°C–50°C, using water or buffer solutions as the extraction medium. Key process parameters include enzyme concentration, hydrolysis time, temperature, and pH, all of which must be optimized to maximize extraction efficiency (Li and Cai 2021). Following hydrolysis, centrifugation is used to separate and remove the enzymes from the extract. The pH plays a particularly critical role, as enzyme activity is highly dependent on the reaction environment: carbohydrases typically exhibit optimal performance under acidic conditions, whereas proteases are more active in neutral to alkaline media (Díaz-Reinoso et al. 2023).

Extraction yield is strongly influenced by pH alignment with the enzyme's optimum. Conditions near the isoelectric point of proteins can reduce process efficiency due to decreased protein solubility, which hinders the release of lipid fractions associated with these macromolecules (Mwaurah et al. 2020). The use of enzyme mixtures has been shown to enhance extraction efficiency compared to single-enzyme systems, owing to synergistic interactions and the ability to operate effectively over a broader pH range. Higher oil yields have been reported in systems employing enzyme combinations at pH 4.5 (Abd Rashid et al. 2023).

Complementary techniques have also been investigated to intensify the extraction process. The application of microwave energy, for instance, can promote cell wall disruption, assist in raw material sterilization, and contribute to the reduction of residual solvents (Zamanhuri et al. 2021).

Overall, AEE offers several advantages, including reduced reliance on organic solvents, lower environmental impact, and the preservation of bioactive compounds such as antioxidants, carotenoids, and polyphenols. These characteristics contribute to improved oil quality and highlight the potential of this method for industrial applications (Chew et al. 2022; Gao et al. 2024). Reported increases in oil and bioactive compound yields range from 25%–45% depending on process conditions and raw material characteristics (Nair et al. 2026).

However, certain limitations remain. The high cost of enzymes and specialized reactors, combined with limited industrial adoption, restricts wider implementation. In conventional palm oil processing, which relies on high-temperature extraction, enzyme inactivation represents an additional challenge. The use of immobilized enzymes has been proposed as a strategy to enhance enzyme stability and reusability, thereby improving process feasibility (Gligor et al. 2019). Furthermore, the efficiency of demulsification in complex systems remains limited, and the structural and functional roles of proteins present in the emulsion and solid phases have been less explored compared to those in the aqueous phase.

With continued technological advances, AEE has the potential to establish itself as a viable technology for industrial-scale expansion, with a reduced carbon footprint and economic viability, offering a robust foundation for the sustainable use of oils and proteins in the food, pharmaceutical, and bio-based industries (Jiang et al. 2025).

3.4 | Ultrasound Assisted Extraction (UAE)

Ultrasound-assisted extraction (UAE) is based on acoustic cavitation, generated by the emission of ultrasonic wave pulses on the microsecond scale, with the aim of promoting the separation and extraction of target compounds. These high-energy pulses induce the rapid formation of cavitation bubbles, which collapse violently, generating localized conditions of high pressure and temperature (Kazemi et al. 2022). As a result, cell walls are disrupted, enhancing mass transfer and facilitating contact between the solvent and intracellular content, thereby promoting the dissolution of the desired compounds (Lefebvre et al. 2021).

The intensity of cavitation is strongly influenced by the oscillation frequency of ultrasonic waves. Low-frequency ultrasound, typically in the range of 20–100 kHz, is widely employed due to its effectiveness in promoting cell disruption and improving mass transfer (Bhadange et al. 2024; Fomo et al. 2020; Rani et al. 2021). In addition to cavitation, acoustic shearing enhances solvent agitation, promoting deeper penetration into the material and further improving extraction efficiency. Ultrasonic waves are generated through the conversion of electrical energy into high-frequency mechanical vibrations, a process carried out by piezoelectric or magnetostrictive transducers, which transform the electric field into acoustic energy propagated through the medium (Xu et al. 2025).

The effectiveness of this technology depends on several operational parameters, including solvent type and concentration, extraction time, ultrasound frequency, and temperature. In addition, solvent physicochemical properties such as surface tension, vapor pressure, and viscosity play a critical role, as they influence both wave propagation and cavitation intensity (Rani et al. 2021). Although extraction yield generally increases with ultrasound power, excessive energy input may compromise

compound stability and reduce overall process efficiency (Lefebvre et al. 2021).

UAE enhances the diffusion and release of target compounds through combined mechanical effects, significantly reducing extraction time. This technique has been successfully applied to the extraction of various vegetable oils, including rapeseed oil and oils derived from fruits and seeds, with reported yields ranging from 8%–83% under optimized conditions (Wongyai et al. 2025). In palm oil processing, fibers obtained from mechanical pressing at approximately 85°C can be subjected to ultrasonic treatment. These fibers are placed in contact with transducer plates and exposed to sonication for 30–45 min, improving particle separation and oil recovery (Chew et al. 2022).

Among its main advantages, UAE operates at relatively low temperatures, which helps preserve bioactive compounds and minimizes thermal degradation. It is also recognized for reducing extraction time and for its potential integration with conventional extraction techniques, thereby improving overall process efficiency and the recovery of valuable biocompounds. However, its main limitation lies in the high cost of equipment and operation, which may restrict its broader industrial adoption (Hoe et al. 2020).

3.5 | Deep Eutectic Solvent Extraction (Des)

Deep eutectic solvents (DES) represent a class of green solvents formed by combining hydrogen bond donors (HBD) and hydrogen bond acceptors (HBA) in specific molar ratios, resulting in a liquid system with a melting point significantly lower than that of the individual components. These systems have attracted considerable attention due to their low toxicity, biodegradability, and tunable physicochemical properties.

DES have been extensively investigated for the extraction of bioactive compounds, including phenolics and carotenoids, from plant matrices, often achieving performance comparable to or exceeding that of conventional solvents. These findings reinforce the growing interest in DES, particularly in view of their potential to reduce operational risks for workers, consumers, and the environment.

Deep eutectic solvents (DES) have emerged as alternative systems for the extraction of natural compounds, due to characteristics such as ease of preparation, low cost, reduced environmental impact, and high versatility (Shu et al. 2025). In general, these solvents are formed by combining a hydrogen-bond acceptor, often choline-based compounds, and a donor, such as organic acids or sugars. Their physicochemical properties, including low volatility, adjustable polarity, and high solubilization capacity, contribute to greater efficiency in the extraction of compounds of interest.

The development and selection of deep eutectic solvents can be aided by computational tools, such as simulations based on the COSMO model, which allow for the prediction of solubility and the evaluation of the potential of different solvent systems for extraction and separation. Although minor discrepancies may occur between simulated and experimental results, this approach has proven useful in optimizing formulations and guiding practical applications (Ma et al. 2025).

The combination of deep eutectic solvents with intensification techniques, such as ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE), has been extensively investigated with the aim of increasing extraction yield, reducing energy and solvent consumption, shortening processing time, and improving selectivity. These strategies are aligned with the principles of green chemistry and have demonstrated potential in the valorization of palm oil industry waste, enabling the efficient recovery of bioactive compounds (Bhadange et al. 2024), (Shu et al. 2025).

The deep eutectic solvent (DES) extraction method can be applied to the recovery of bioactive compounds from palm oil processing waste and can also be integrated with various sustainable extraction technologies to increase process yield (Chew et al. 2024).

In particular, microwave-assisted pretreatment using deep eutectic solvents has been associated with increased efficiency in biomass degradation, favoring the removal and recovery of lower-molecular-weight lignin. Furthermore, this method contributes to greater monosaccharide stability and lower energy consumption compared to conventional heating. Studies indicate that lignin extraction under these conditions can be performed in approximately 30 min, achieving yields close to 96%, with significant reductions in reaction time (about 87%) and energy consumption (approximately 93.5%) (Ma et al. 2025).

Complementarily, the combination of deep eutectic solvents with ultrasound has been associated with reduced extraction time and increased process efficiency and is considered a promising approach for more sustainable extraction methods. This technological integration has been applied to the recovery of bioactive compounds from palm oil processing residues, including carotenoids and vitamin E, using biomass-derived solvents (Shu et al. 2025).

In this context, the present study proposes to investigate the properties of lignin obtained from empty oil palm fruit bunches through pretreatment with deep eutectic solvents. Despite recent advances, gaps still persist in the literature regarding a comprehensive understanding of the mechanisms and parameters governing lignin extraction from biomass, highlighting the need for further studies (Bhadange et al. 2024).

3.6 | Microwave-Assisted Extraction (Mae)

Microwave-assisted extraction (MAE) has been extensively studied with the aim of increasing processing efficiency, reducing energy consumption, and preserving the nutritional integrity of palm oil (Wongyai et al. 2025). In this context, microwave-assisted extraction (MAE) stands out for its speed and operational simplicity and is considered a promising alternative to conventional methods (Wongyai et al. 2025).

Microwave-assisted extraction (MAE) is based on the selective heating of dielectric materials, typically at a frequency of

2.45 GHz, promoting rapid and volumetric heating within the matrix. This mechanism leads to the vaporization of intracellular moisture, an increase in internal pressure, and, consequently, the rupture of cell walls, facilitating the release of compounds and increasing extraction efficiency. As a result, the process can be carried out in intervals of 5 to 30 min, with energy efficiency estimated to be 30% to 50% higher than that of conventional methods (Nair et al. 2026).

From an operational and environmental standpoint, microwave-assisted extraction (MAE) offers significant advantages, including lower energy and solvent consumption, reduced processing time, and the use of smaller equipment. These characteristics contribute to increased yield and reinforce the technique's alignment with more sustainable approaches (Wongyai et al. 2025; Rani et al. 2021).

In addition to its direct application in extraction, microwave-assisted extraction (MAE) can be employed as a pretreatment step, since the radiation is applied directly to the raw material. This use has been associated with increased oil extraction yield in various crops, such as rapeseed, palm, soybean, rice bran, and cottonseed. In particular, application prior to cold pressing can improve the yield, oxidative stability, micronutrient content, and sensory properties of the oil (Rani et al. 2021). Complementarily, the combination of microwave pretreatment with solvent extraction in palm fruits has shown satisfactory results in terms of productivity and final product quality (Law et al. 2019).

The use of microwaves has also been explored in stages such as sterilization, with an energy consumption of approximately 0.38 kWh per kilogram of processed material (Shah et al. 2023). When combined with steam, this approach can promote greater thermal uniformity, reduce drying time, increase the oil extraction rate, and improve the quality of the final product. Additionally, it can contribute to the valorization of fruits with high free fatty acid (FFA) content, reducing losses and increasing the oil extraction rate (OER) (Shah et al. 2023).

Despite its advantages, microwave-assisted extraction (MAE) has limitations that must be considered. Heating conditions may promote oxidation or thermal degradation of sensitive compounds, in addition to being less efficient in extracting nonpolar or volatile compounds. The solid residue generated may also require additional processing steps, such as centrifugation and filtration. Furthermore, due to its thermal nature, the technique may not be suitable for oils rich in polyunsaturated fatty acids, which are more susceptible to degradation (Low et al. 2024).

Although it offers high potential and relative operational simplicity, the application of microwave-assisted extraction (MAE) is still predominantly limited to the laboratory scale. Thus, its feasibility at an industrial scale requires further investigation, especially in continuous processing systems, to evaluate its performance under real-world conditions (Low et al. 2024; Shah et al. 2023). According to the literature, the new extraction methods appear to be the most suitable for conventional processes due to their many advantages, including higher yields, preservation of thermolabile compounds, the use of sustainable solvents, and shorter reaction times during extraction (Zahid et al. 2024).

Recovering valuable compounds from waste contributes to sustainable development, as these bioactives have a high potential for use in the food, pharmaceutical, and cosmetics industries (Chew et al. 2022). These compounds can also be used to formulate new products thanks to their high antioxidant content, including vitamins E and C, and carotenoids. Antioxidants are important for fighting free radicals and reducing oxidative stress, which occurs when the body's ability to neutralize free radicals is exceeded by their production. This can lead to various metabolic diseases (Gonzalez-Diaz et al. 2021).

In addition to the various sustainable methods, it is important to mention the large amount of waste produced during palm oil processing. This waste can be used as a raw material in different processes (Abdullah et al. 2024).

The extraction of palm oil results in around 13 million tonnes of vegetable waste being generated every year, and more than 118.4 million tonnes of effluent are produced by industries in Malaysia (Siddiqui et al. 2024).

These residues can be used to formulate new compounds thanks to their high concentrations of carotenoids that protect membranes against the impact of free radicals, as well as tocopherols, tocotrienols, coenzyme Q, and antioxidants (Gonzalez-Diaz et al. 2021).

Recovering these compounds through waste reuse has made the process more sustainable by taking environmental issues into account. Once recovered, these bioactive compounds can be used in food, pharmaceutical, and cosmetic products (Chew et al. 2024).

The valorization of waste provides several environmental and social benefits, such as the creation of sustainable jobs and improved family income. Various studies have been carried out to evaluate these advantages (Abogunrin-Olafisoye et al. 2024).

Integrating sustainable methods can innovate the industry by focusing on minimizing environmental impact, reducing energy consumption, and recovering waste. It can also diversify the business portfolio to increase economic revenue. From a social point of view, it can eradicate poverty, provide decent work and economic growth, promote industry and innovation, encourage responsible consumption and production, and take climate action. At the same time, it can align with SDGs 1, 8, 9, 12, and 13 (Roobab et al. 2025).

Therefore, despite the emergence of various extraction techniques, the palm oil industry still faces many difficulties when it comes to implementing these techniques. These difficulties include high investment costs for new production structures and skilled labor, as well as the need for industrial production scale (Hoe et al. 2020).

Critical parameters such as extraction time, solvent type, and temperature are important for maximizing process efficiency

and minimizing environmental impact compared to conventional techniques (Roobab et al. 2025).

3.7 | Hybrid Technologies

Despite the specific advantages of individual extraction techniques, recent research has highlighted the use of hybrid approaches that combine complementary methods to maximize process efficiency (Mishra et al. 2025).

Recently, there has been a growing body of research on the development of hybrid extraction methods, involving various combinations of emerging technologies, such as ultrasound-assisted extraction (UAE), pressurized liquid extraction (PLE), microwave-assisted extraction (MAE), and supercritical fluid extraction (SFE), among others (Capaldi et al. 2024). The primary objective of using these technologies is to improve the efficiency and precision of extraction processes, with the potential to complement or replace traditional methods (Soni et al. 2025). However, their applications on an industrial scale remain limited due to their low levels of technological maturity (Capaldi et al. 2024).

The integration of different extraction technologies aims to optimize the process as a whole, overcoming the limitations inherent in each individual method. Combining two or more techniques into a single system allows for the incorporation of their specific advantages, reducing the need for multiple sequential steps and, consequently, the physical space, processing time, and energy demand compared to serial configurations (Capaldi et al. 2024).

3.7.1 | Ultrasound-Assisted Extraction Combined With Pressurized Liquid Extraction (UAE–PLE)

Ultrasound-assisted extraction (UAE) has the potential to increase process efficiency, reduce solvent consumption, and shorten extraction time. In turn, pressurized liquid extraction (PLE) enhances diffusion rates and the solubility of target compounds, enabling faster and more efficient extraction.

These techniques are combined in a sequential manner. First, the sample is prepared by grinding or homogenizing the matrix to increase the contact area. Next, ultrasonic pretreatment is applied, in which the sample is subjected to ultrasonic waves in the presence of a suitable solvent, promoting the rupture of cell walls and the initial release of the compounds (Panda and Gorantla 2025).

Subsequently, the sample is transferred to the pressurized liquid extraction system, where the process occurs under high temperature and pressure conditions, intensifying the extraction. Finally, the resulting extract may undergo additional purification or concentration steps, depending on the process requirements (Soni et al. 2025). In general, the combined application of these technologies results in greater extraction efficiency compared to the isolated use of each technique (Soni et al. 2025).

3.7.2 | Supercritical Fluid Extraction Combined With Ultrasound (SFE–UAE)

Ultrasound-assisted supercritical fluid extraction (UASFE) utilizes ultrasonic waves to enhance mass transfer during supercritical fluid extraction. This promotes increased solubilization of compounds and disruption of cellular structures, facilitating compound release.

The synergistic interaction between these techniques generally results in higher yields and extraction rates compared to their isolated application. For instance, combining ultrasound with supercritical CO_2 in rice bran oil extraction increased the extraction rate from 9.94% to 12.65% under optimized conditions (160 W, 40 min), due to improved mass transfer at the solid-liquid interface (Soni et al. 2025).

3.7.3 | Microwave-Assisted Extraction Combined With Enzyme-Assisted Extraction (MAE–EAE)

Microwave-assisted extraction combined with aqueous enzymatic extraction (MAEA) has been applied to recover various bioactive compounds. This method relies on enzymes that degrade cell walls, facilitating lipid diffusion and compound release (Capaldi et al. 2024).

Enzyme-assisted extraction (EAE) presents limitations such as high enzyme cost, scaling challenges, and limited hydrolysis efficiency, which may reduce extraction yields. The integration with microwave irradiation helps mitigate these limitations by enhancing matrix disruption and intensifying the process (Acharya et al. 2026).

In palm oil applications, enzyme selection depends on fiber composition and optimal pH conditions. The combined approach generally results in higher yields compared to individual techniques (Abd Rashid et al. 2023; Olivares-Tenorio et al. 2024).

3.7.4 | Supercritical Fluid Extraction Combined With Enzyme Assisted Extraction (EAS–SFE)

The combination of supercritical CO_2 extraction with enzymatic treatment and polar co-solvents is considered a promising approach for improving extraction efficiency. Enzymes modify the matrix by breaking down complex structures, increasing compound accessibility, while co-solvents enhance solubilization. Following enzymatic treatment, the supercritical fluid penetrates the material due to its high diffusivity and liquid-like solvation capacity, enhancing extraction. This synergy improves mass transfer and reduces resistance (Acharya et al. 2026).

Supercritical fluids exhibit intermediate properties between liquids and gasses, enabling efficient diffusion and solubilization. Operational parameters such as pressure and temperature can be adjusted to control fluid density and solvation capacity, optimizing extraction efficiency (Patil et al. 2021). Additionally, the recovery and reuse of CO_2 and enzymes

contribute to improved sustainability and reduced operational costs (Patil et al. 2021).

Furthermore, several studies report the occurrence of synergistic effects, evidenced by increased productivity and extraction selectivity. However, the implementation of hybrid systems requires an appropriate balance between the technologies involved, since unwanted interactions can compromise process performance. Furthermore, the integration of multiple technologies entails higher initial investment and, in some cases, greater energy consumption, which requires high operational efficiency to offset the associated costs (Capaldi et al. 2024).

4 | Discussion

In this section, we discuss the main oil extraction technologies, including supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), subcritical water extraction (SBW), water-enzyme extraction (WEE), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and deep eutectic solvent (DES) systems, highlighting their respective advantages, limitations, and potential for industrial application.

A comparative analysis of extraction methods used in the palm oil industry reveals a landscape characterized by tradeoffs between operational robustness, extraction efficiency, product quality, and environmental performance. Mechanical pressing remains the dominant technology, primarily due to its high continuous processing capacity, scalability to industrial levels, and relative operational simplicity. Extraction yields generally exceed 85%–90%, depending on process conditions and fruit quality (Panjapornpon et al. 2024). However, this method has significant limitations, including residual oil losses in fibrous streams, significant generation of lignocellulosic waste, and partial degradation of heat-sensitive compounds, such as carotenoids and tocopherols, during thermal stages such as sterilization.

From an environmental perspective, reliance on steam-based systems represents one of the main critical issues in the conventional process. Although lignocellulosic residues are frequently used as fuel in boilers, contributing to on-site energy generation (Sundrasegaran and Mah 2020), the high energy consumption and associated emissions make this stage one of the main contributors to the process's global warming potential (Sari et al. 2023). This impact is exacerbated by the complementary use of fossil fuels, such as diesel, in power generation systems, establishing this stage as one of the main contributors to greenhouse gas emissions in the palm oil industry, with estimated values of approximately 2.16×10^7 kg of CO_2 equivalent per kilogram of oil produced per year (Sari et al. 2023).

Furthermore, the continuous operation of industrial units, with typical capacities ranging from 30–60 t of fruit bunches per hour, imposes significant constraints on the incorporation of emerging technologies (Gonzalez-Diaz et al. 2021).

Among the technologies reviewed, SFE shows strong potential for producing high-quality oil enriched with carotenoids and other bioactive compounds. However, its high capital cost, batch operation mode, and sensitivity to feed moisture limit its applicability for bulk palm oil production. In contrast, alternative methods, such as pressurized liquid extraction (PLE) and enzymatic extraction, are still predominantly in the laboratory or pilot stages (TRL 3–6), limited by batch operation, high investment costs, and scaling challenges.

Supercritical fluid extraction using CO_2 is notable for its high selectivity and the favorable properties of the solvent, such as low toxicity and easy separation (Nozari and Kander 2025). However, its application in the palm oil industry is limited. Factors such as the high moisture content of the mesocarp (40%–50%), which reduces lipid solubility and requires preliminary drying steps, increase energy consumption and operating costs (Rizkiyah et al. 2025). Additionally, batch operation and the high investment in high-pressure equipment limit its economic viability, making it more suitable for the recovery of high-value-added compounds, such as carotenoids and phytosterols, than for large-scale oil production (Sundrasegaran and Mah 2020; Panda and Gorantla 2025).

Similarly, pressurized liquid extraction (PLE) and subcritical water extraction (SBW/SWE) are based on modifying the properties of the solvent under elevated temperature and pressure conditions, thereby increasing extraction efficiency (Cao et al. 2025). In the case of subcritical water, the reduction in the dielectric constant allows for the solubilization of moderately non-polar compounds, expanding its potential as a green technique (Višnjevec et al. 2024). The use of co-solvents in subcritical water extraction (SBW) significantly influences extraction efficiency by modifying solvent polarity, solubility, and mass transfer characteristics. The addition of organic modifiers such as ethanol reduces the dielectric constant of water, enhancing the solubility of less polar compounds. Acidified ethanol further improves extraction by promoting cell wall disruption and hydrolysis of bound compounds, facilitating solute release (Žagar et al. 2026). Green solvents such as ethyl lactate have also gained attention due to their tunable polarity and biodegradability, enabling efficient extraction of both polar and moderately non-polar compounds. Moreover, co-solvents can reduce interfacial tension and improve wettability of the matrix, thereby enhancing mass transfer rates. However, their use introduces additional process complexity, including solvent recovery requirements and potential impacts on selectivity and downstream purification.

Mass transfer limitations in subcritical water extraction are strongly influenced by particle size, solvent-to-feed ratio, flow rate, and residence time. Smaller particle sizes enhance extraction by reducing internal diffusion resistance and increasing surface area, while flow rate affects external mass transfer and residence time. In many cases, extraction is controlled by intraparticle diffusion, with temperature influencing diffusion coefficients and solubility (Díaz-Reinoso et al. 2023).

Nevertheless, high temperatures can induce undesirable reactions, such as triglyceride hydrolysis and the degradation of sensitive compounds, in addition to increasing the process's energy requirements. PLE and SBW offer improved solvent efficiency but require high temperatures and pressures, which increase energy consumption and may lead to thermal degradation of sensitive compounds. Furthermore, the limited capacity of available equipment restricts its application on a large industrial scale.

Enzymatic extraction in aqueous medium (WEE) offers advantages associated with mild operating conditions (40°C–55°C), which favor the preservation of heat-sensitive compounds and reduce energy consumption (Onyegirim et al. 2025). However, the formation of stable emulsions during enzymatic hydrolysis hinders phase separation, requiring additional steps such as centrifugation or pH adjustment, which increase the complexity and costs of the process (Višnjevec et al. 2024). Furthermore, the cost of enzymes, their limited stability, and prolonged reaction times pose additional challenges to their industrial application. Strategies such as enzyme immobilization and process integration have been proposed to improve their feasibility.

One of the main economic obstacles to aqueous enzymatic extraction is the high cost of enzymes, which can account for 30% to 60% of total processing costs, while the reuse of enzymes is limited due to loss of activity and dilution. The process also requires several operational steps, such as centrifugation to break the emulsion, increasing energy consumption and operational complexity (Jiang et al. 2025).

Enzyme inactivation has significant technical and economic implications in enzyme-assisted extraction (WEE). Enzymes are generally inactivated after hydrolysis and remain in the aqueous phase; however, their recovery and reuse are limited due to dilution and loss of activity (Gao 2025). As a result, enzymes are typically treated as single-use consumables, significantly increasing operating costs. From a technical-economic perspective, enzyme costs constitute one of the main obstacles to industrial application, potentially accounting for a large portion of operating expenses (OPEX). In addition, water consumption is high, typically requiring large solid-to-liquid ratios, which increases costs related to energy supply, transportation, and wastewater treatment. The formation of stable oil-in-water emulsions requires high-speed centrifugation, making the subsequent separation one of the most energy-intensive steps in the process, and this further increases operating costs (Jiang et al. 2025). In summary, the cost per kilogram of oil extracted via WEE is typically higher than in conventional solvent extraction, unless significant improvements are made, such as enzyme reuse, reduced water usage, improved energy efficiency, and greater valorization of byproducts.

Process intensification techniques, such as ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE), have also been investigated. UAE improves mass transfer through the phenomenon of cavitation, reducing extraction time and allowing for combination with other techniques (Thilakarathna et al. 2023; Wongyai et al. 2025). UAE shows promise as process intensification techniques, but challenges related to scalability and reactor design remain unresolved. However, it has limitations related to high energy consumption, equipment costs, and scaling difficulties, especially due to the non-uniform distribution of acoustic waves in large volumes (Díaz-Reinoso et al. 2023; Bhadange et al. 2024).

Similarly, microwave-assisted extraction (MAE) promotes rapid dielectric heating, facilitating cell rupture and the release of intracellular compounds (Onyegirim et al. 2025). Although it offers advantages such as reduced processing time and improved energy efficiency, its large-scale application is limited by the difficulty of ensuring uniform heating in large-volume systems, which can lead to the degradation of sensitive compounds.

Finally, deep eutectic solvents (DES) are an emerging class of green solvents as a promising alternative in the context of green chemistry, due to their versatility and potential application in biorefinery systems, but their application to palm oil extraction is still at an early stage of development.

However, their application in palm oil extraction is still in its early stages, limited by high viscosity, difficulties in solvent recovery, and relatively high costs (Novia et al. 2026; Riaño 2025). Furthermore, the need to optimize formulations and operating conditions, often dependent on computational approaches, highlights the still exploratory nature of this technology. Despite this, promising results have been observed in related applications, such as the extraction of lignin from lignocellulosic residues (Yaakob et al. 2024).

In general, although emerging technologies offer significant advantages in terms of selectivity, product quality, and the potential for reducing environmental impacts, their industrial application remains limited by technical, economic, and operational challenges. The predominance of mechanical pressing therefore reflects its suitability for the demands of large-scale continuous processing. In this context, future advances are likely to focus on the integration of technologies and the development of hybrid approaches, aiming to reconcile industrial efficiency with environmental sustainability.

To support the evaluation and comparison of these technologies, Technology Readiness Levels (TRLs) provide a standardized framework for assessing technical maturity. This scale ranges from 1–9, where levels 1–3 correspond to laboratory-scale development, 4–6 to pilot-scale validation, and 7–9 to industrial or commercial deployment (Tables 1 and 2). Despite ongoing advances, significant gaps persist between technologies developed at the research level and their effective implementation at industrial scale, highlighting a critical barrier to innovation in the palm oil sector (Belwal et al. 2020).

The analysis demonstrates that mechanical pressing remains the only fully industrially viable technology (TRL 9) due to its high throughput, continuous operation, and low production cost. In contrast, emerging green extraction technologies are predominantly at laboratory to pilot scale (TRL 3–6) and face significant barriers to industrial implementation.

5 | Conclusion

Currently, emerging technologies have not demonstrated the ability to directly replace conventional mechanical extraction at an industrial scale, corroborating the hypothesis that full substitution remains technically unfeasible based on the available evidence. In this context, hybrid approaches that integrate emerging technologies into conventional processes represent a

TABLE 1 | A comparative analysis of the investment levels, operating costs, adaptability, and technological maturity of each emerging technology.

Extraction method	CAPEX	OPEX	Scalability	TRLs	Key	References
Conventional extraction	Medium	Low	High	9 (a mature technology used in industry)	Economically viable option for large-scale palm oil production, primarily due to its high throughput and relatively low operating costs	(Gonzalez-Diaz et al. 2021)
Supercritical fluid extraction	High capital	High operating costs	High	8–9 mature technology	High investments in equipment's and maintenance and high energy consumption	(Višnjevec et al. 2024) (Belwal et al. 2020) (Rizkiyah et al. 2025)
Pressurized liquid extraction	High investment	high operating costs	Low	5–7	High instrumentation expenditures	(Belwal et al. 2020)
Subcritical water extraction	High investment	igh	Low	4–7	High temperature and pressure	(Bhadange et al. 2024)
Enzymatic water extraction	High	High	Medium	3–6	High cost of the enzyme/high costs associated with enzyme recovery and high energy demand	(Masoodi et al. 2022) (Višnjevec et al. 2024)
Ultrassonic assisted extraction	Low/Medium	High	Low/medium	3	Low operational cost in long run	(Chemat et al. 2020) (Soni et al. 2025)
Microwave assisted extraction	Medium			2–3	High operating costs	(Chemat et al. 2020)
Deep eutetic solven	Low	Medium	Medium	2–4	High energy consumption and difficulties in solvent recovery	(Novia et al. 2026)

TABLE 2 | Summarizes the main extraction methods, highlighting their industrial applications in the palm oil industry and other sectors, as well as their efficiency levels and respective limitations.

Extraction method	Industry	Limitation	Eficiency	Tipe of aplication	References
Conventional extraction	Palm oil	Residual oil in fibers	85% efficiency, high residual oil	Industrial aplication	(Chew et al. 2024)
Supercritical fluid extraction	Palm oil fruits and pressed fiber mesocarp	Needs specifics equipment's and experience	High yield	Pilot/industrial (refining)	(Panda and Gorantla 2025) (Onyegirim et al. 2025)
Pressurized liquid extraction	Food, pharmaceuticals and nutraceutical industry	High initial investment	Medium	Medium/industrial scale	(Chatzimitakos et al. 2024)
Subcritical water extraction	Nutraceutical Biocompounds	High Investments	High	Medium/industrial	(Olivares-Tenorio et al. 2024)
Enzymatic water extraction	Palm oil kernel		High yield, purity		
Ultrassonic assisted extraction	Food industry, nutraceutical and palm oil pressed fibers	High initial cost	Medium	Pilot and medium scale	(Chew et al. 2024) (Mishra et al. 2025)
Microwave assisted extraction	Nutraceutical, food industry, cosmetics and palm kernel mill	High initial investment	Medium	Pilot	(Soni et al. 2025)
Deep eutetic solven	Waste kernel mill/ farmaceutical industry	Requires special equipment or procedures	High	Pilot	(Novia et al. 2026; Riaño 2025)

promising pathway for advancing sustainability in the palm oil industry. These approaches have shown potential to increase oil recovery (with reported gains of 5%–10%), reduce operational losses, and enable the valorization of high-value compounds from residual streams. Additionally, the optimization of operational parameters, including the reduction of extraction time (from 60 to 90 min to less than 45 min), combined with process intensification strategies, contributes to lowering energy consumption (on the order of 20%–30%) while simultaneously improving yields. These findings indicate that incremental improvements, when systematically integrated, can lead to significant gains in overall process efficiency and performance. However, important limitations persist, particularly the predominance of data derived from laboratory- or pilot-scale studies and the high initial costs associated with implementing hybrid systems. These factors highlight the need for comprehensive techno-economic analyses and life cycle assessments (LCA) to enable robust comparisons with conventional processes under representative industrial conditions. Future research should prioritize validation at pilot and pre-industrial scales, as well as explore artificial intelligence driven approaches for process optimization and dynamic control, aiming to support the development of more efficient, scalable, and environmentally sustainable extraction systems.

Author Contributions

Constantino Lucas Queta conceived and designed the study, conducted the research, and drafted the initial version of the manuscript. Alessandra Lopes de Oliveira performed data analysis and critically revised the first version of the manuscript. Aline Silva Mello Cesar contributed to data analysis and critically revised the final version of the manuscript. All authors contributed to the development of the study and approved the final version of the manuscript.

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Ethics Statement

This study did not involve human participants or animals. Therefore, ethical approval was not required in accordance with applicable institutional and international guidelines.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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