

SUSTAINABLE INNOVATIONS IN PALM OIL EXTRACTION: A COMPREHENSIVE OVERVIEW OF GREEN TECHNOLOGIES

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ABSTRACT

This review critically examines recent advancements in green extraction methods for palm oil production, emphasising their potential to improve sustainability, extraction efficiency and product quality. Innovative green technologies, including supercritical carbon dioxide (SCCO₂) extraction, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE) and deep eutectic solvents (DES), provide eco-friendly alternatives that maintain or even enhance oil yield and quality. Notably, SCCO₂ extraction produces high-purity oils rich in bioactive compounds, while UAE and MAE demonstrate significant energy efficiency and superior preservation of nutrients. DES, an emerging solvent, enhances extraction processes with a lower environmental impact. Comparative analysis reveals that these methods not only reduce environmental risks but also improve product safety and quality. The review concludes by highlighting the need for further optimisation of these techniques, positioning them as essential for the future of sustainable and responsible palm oil production.

Keywords: eco-friendly, green extraction, palm oil.

Received: 9 September 2024; **Accepted:** 14 March 2025; **Published online:** 5 June 2025.

INTRODUCTION

Palm oil is one of the most widely produced and consumed vegetable oils globally, playing a crucial role in the food, cosmetic, and biofuel industries (Anggoro et al., 2024; Mah et al., 2024; Yusof et al., 2023). Its extensive use and economic significance, particularly in countries like Malaysia and Indonesia, have made palm oil a vital agricultural commodity (Khairuddin et al., 2021; Shaari et al., 2021; Zainal Abidin et al., 2024). However, the traditional methods of extracting palm oil, such as

mechanical pressing and solvent extraction, have become less favorable due to their inefficiency in recovering valuable bioactive compounds and their inability to meet increasing demands for high-quality oil (Irianto et al., 2024; Nikolova et al., 2024). These conventional techniques often result in lower extraction yields and are unable to preserve the nutritional and functional properties of sensitive compounds, which limits the potential for producing value-added products (Ayoib et al., 2020; Phan-Tai & Brunner, 2023; Promraksa et al., 2020; Zain et al., 2020).

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As global awareness of sustainability and environmental responsibility grows, there is increasing pressure on the palm oil industry to adopt more sustainable practices. This has led to the development and adoption of green extraction technologies that aim to reduce the environmental impact of palm oil production while maintaining or even enhancing the efficiency and quality of the extraction process (Chan et al., 2018; Iftikhar et al., 2017; Mulia et al., 2018; Valasques et al., 2018). Green extraction methods such as supercritical carbon dioxide (SCCO₂) extraction, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE) and deep eutectic solvents (DES) are at the forefront of this shift, offering innovative solutions that align with global sustainability goals.

Green extraction methods such as MAE, UAE and SCCO₂ offer promising alternatives to conventional extraction processes by minimising environmental impacts and enhancing extraction efficiency (Irianto et al., 2024; Rizkiyah et al., 2023). MAE operates by utilising microwave energy to rapidly heat both the solvent and sample, leading to faster extraction and better preservation of heat-sensitive compounds (Alvi et al., 2022; Siddique et al., 2022). It is particularly noted for its energy efficiency, as the process allows for precise control of temperature and extraction time. Similarly, the UAE uses ultrasonic waves to create cavitation, which improves mass transfer and cell disruption, making it highly effective at extracting bioactive compounds while preserving their integrity due to the mild conditions (Liu et al., 2022; Yusoff et al., 2022). Both MAE and UAE are recognised for reducing solvent use and energy consumption, contributing to more sustainable extraction practices in industries such as palm oil production (Rani et al., 2021).

SCCO₂ extraction, on the other hand, operates by using carbon dioxide (CO₂) in its supercritical state, where it exhibits both gas-like diffusivity and liquid-like solvation power (Ahangari et al., 2021; Arumugham et al., 2021). This method is particularly valuable for producing high-purity oils without the need for toxic organic solvents. SCCO₂ has been extensively utilised in palm oil extraction, offering a cleaner and more selective method that produces high-quality oils while minimising environmental impact. Additionally, emerging solvents like DES are offering biodegradable and non-toxic alternatives, further enhancing the sustainability of extraction methods (Guía-García et al., 2022; Saravanakumar et al., 2023). DES, composed of renewable organic salts and hydrogen bond donors, represents a new frontier in green extraction technologies, offering efficiency and environmental benefits in line with sustainable development goals. Together, these

green extraction methods hold great potential for transforming industrial extraction practices, making them more environmentally friendly and resource-efficient (Chew et al., 2024).

This review aims to provide a comprehensive analysis of these green extraction methods, comparing their efficiency, yield and impact on the quality of palm oil against conventional methods. By examining the advantages and challenges associated with each technology, this review seeks to highlight the potential of green extraction methods to revolutionise the palm oil industry, making it more sustainable and aligned with global environmental standards. As the industry continues to evolve, the adoption of these green technologies is not only a response to environmental concerns but also a strategic move towards producing higher quality, safer and more sustainable palm oil products.

MAE FOR PALM OIL EXTRACTION

MAE has garnered attention as a green and efficient technology for palm oil extraction, providing significant advantages in terms of energy savings, extraction efficiency and preservation of bioactive compounds (Kamaruddin et al., 2023; Li et al., 2023). In comparison to traditional methods, MAE utilises microwave energy to heat the extraction solvent and sample simultaneously, leading to rapid temperature increases that break down cell structures and enhance mass transfer as shown in *Figure 1*. By applying controlled microwave radiation, MAE can optimise the extraction of palm oil and its bioactive components, such as antioxidants and fatty acids, with reduced energy consumption and environmental impact (Kostas et al., 2017; Mandal et al., 2007; Tambun et al., 2021). This review examines key studies on MAE for palm oil extraction, focusing on how different process parameters (solvent selection, temperature, time and microwave power) affect extraction yield and product quality (Chemat et al., 2020).

One of the critical parameters in MAE is the selection of solvents, which plays a crucial role in determining extraction efficiency and the quality of the extracted compounds. Several studies have demonstrated the use of DES as a green alternative to conventional organic solvents. For instance, Han and Hadi (2024), and Ng and Nu'man (2021) employed DES composed of choline chloride and amino acid (ChCl-AA) with 30% water to extract ferulic acid, an antioxidant, from palm oil by-products. At an extraction temperature of 60°C and times ranging from 6–15 min, these studies achieved significant yields of ferulic acid with high radical scavenging activity. The use of DES not only enhances the sustainability of the extraction process

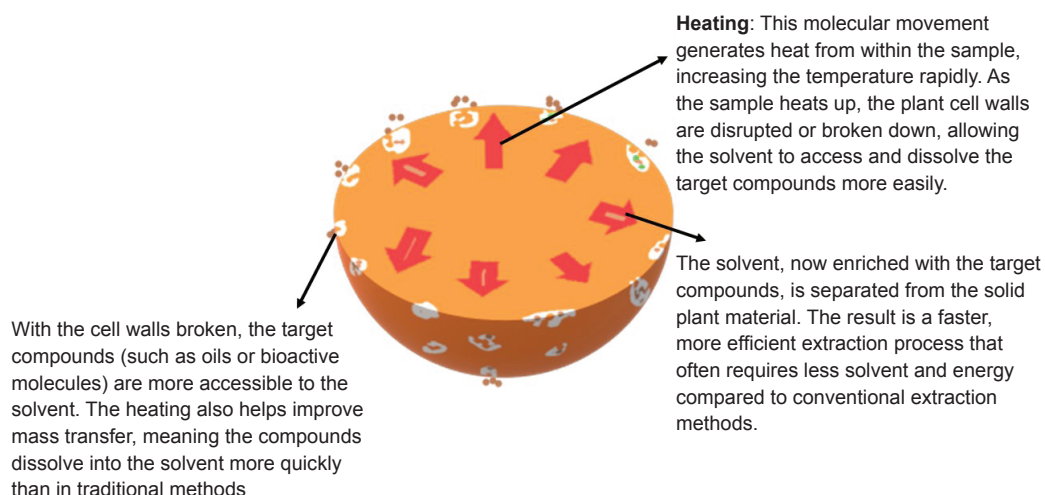


Figure 1. Mechanism of microwave-assisted extraction (MAE) for palm oil recovery.

but also allows for selective extraction of bioactive compounds, providing added value beyond palm oil production.

Temperature is another crucial factor in MAE, as it affects both the extraction kinetics and the stability of bioactive compounds. Nuchdang et al. (2022) studied the extraction of palm oil using isopropanol as a solvent at 150°C, resulting in an oil yield of 11.70%. While higher temperatures can accelerate extraction rates, they can also lead to the degradation of sensitive compounds. Therefore, it is important to balance the temperature to optimise yield without compromising the quality of the extracted oil. Zamanhuri et al. (2021, 2022) explored the use of microwave extraction at different power levels (100 and 300 W) and extraction times (30 min), resulting in a 64.00% crude palm oil (CPO) yield and high palmitic acid content. These studies highlight the need to carefully optimise microwave power and temperature to achieve maximum extraction efficiency while preserving the integrity of bioactive compounds.

Extraction time is also a significant parameter in MAE. Shorter extraction times can enhance energy efficiency and reduce operational costs, making the process more sustainable. For example, Phatthiya et al. (2024) combined microwave-assisted pyrolysis with SCCO_2 extraction to achieve an oil yield of 63.09%–67.72% within a relatively short time. This process produced oils enriched with valuable fatty acids, such as dodecanoic and octadecanoic acids, demonstrating that integrating MAE with other extraction technologies can further improve yields and product quality. Similarly, Rashid et al. (2023) applied a microwave-assisted enzyme aqueous (MAEA) extraction method with a 4 hr incubation period, achieving a 39.48% oil yield along with high squalene content. This extended extraction time allowed the enzymes

to break down the cell walls more effectively, enhancing the recovery of both oil and bioactive compounds.

The power of the microwave itself is a critical parameter, as it directly influences the rate of heating and the efficiency of cell disruption. Higher microwave power increases the energy delivered to the sample, accelerating the extraction process. However, excessive power can cause localised overheating, potentially leading to the degradation of sensitive compounds. For instance, Kanjanapongkul (2021) found that combining ohmic heating with microwave pretreatment resulted in a 47% CPO yield with lower free fatty acid (FFA) content and reduced energy consumption. This combination of technologies highlights the potential of using lower microwave power in conjunction with other thermal methods to balance efficiency and product quality. Additionally, Ong et al. (2021) demonstrated that microwave pretreatment improved the yield of palm oil from oil palm decanter cake (OPDC) when followed by Soxhlet extraction, showing that careful adjustment of microwave power can significantly enhance extraction outcomes.

The process parameters in MAE (solvent selection, temperature, time and microwave power) are critical in determining the success of palm oil extraction. By optimising these parameters, MAE can enhance oil yields, improve the recovery of bioactive compounds, and minimise energy consumption, making it a highly sustainable extraction method. The reviewed studies show that integrating MAE with other green technologies, such as enzyme-assisted extraction or SCCO_2 extraction, can further improve the efficiency and sustainability of the process. As the demand for greener extraction methods grows, MAE is well-positioned to play a key role in the future of palm oil extraction, offering an environmentally-friendly

alternative to traditional extraction methods while maintaining high-quality outputs.

Table 1 provides comprehensive summary of recent studies on MAE techniques applied to palm oil recovery, highlighting the diversity of extraction conditions, yields and outcomes. The reviewed research spans from enzymatic-assisted MAE and DES applications to advanced integrations with ohmic heating and SCCO₂ processes. The yield of palm oil and bioactive compounds varies widely depending on extraction parameters such as temperature, solvent type and microwave intensity. Notably, several studies demonstrated improved oil yield and quality, as well as enhanced recovery of valuable compounds like ferulic acid and squalene. In addition, various outcomes such as energy efficiency, antioxidant activity and compositional enrichment were reported, underscoring the

potential of MAE as a green and scalable technology for palm oil processing.

UAE FOR PALM OIL EXTRACTION

UAE has emerged as an effective and environmentally friendly method for extracting valuable compounds from palm oil and its by-products. The studies summarised in *Table 2* demonstrate the versatility and effectiveness of UAE in enhancing extraction yields, reducing processing times and improving the quality of extracted products. This technique relies on ultrasonic waves to create cavitation bubbles in the extraction medium, which collapse and generate localised high temperatures and pressures as shown in *Figure 2*.

TABLE 1. OVERVIEW OF STUDIES ON MAE FOR PALM OIL EXTRACTION, DETAILING EXTRACTION CONDITIONS, YIELDS AND OUTCOMES

Authors	Extraction condition	Yield	Outcome
Han and Hadi (2024)	Deep eutectic solvent (ChCl-AA with 30% water) and microwave at 60°C for 6 min	Not specified for oil; 40.3 mg/g ferulic acid	Ferulic acid from unsterilised fruitlets showed higher radical scavenging activity; sterilisation did not significantly affect ferulic acid content.
Phatthiya et al. (2024)	High-intensity microwave-assisted pyrolysis, followed by SCCO ₂ extraction	63.09%–67.72% for SCCO ₂ -oil extract	SCCO ₂ oil enriched with acids such as dodecanoic, n-hexadecanoic, and octadecanoic acids; the production cost of bio-phenol was estimated.
Bauwens and Purcaro (2024)	Microwave-assisted saponification for MOAH analysis	Not specified	Reduced variability in MOAH quantification; improved internal standard partitioning, significant reduction in uncertainty.
Rashid et al. (2023)	MAEA extraction (2% mixed enzyme, pH 8, 4 hr incubation)	39.48% oil yield, 961.77 mg/100 g squalene	MAEA significantly increased oil yield and squalene content; suitable for producing squalene-rich virgin palm oil.
Nuchdang et al. (2022)	MAE with isopropanol at 150°C	11.70% oil yield	MAE comparable to Soxhlet extraction; moderate energy consumption; yielded aromatic and phenolic compounds.
Zamanhuri et al. (2022)	Microwave extraction (300 W, 30 min, 80 g mesocarp loading)	Not specified	Second-order kinetic model represented extraction; effective in reducing POME production and increasing extraction efficiency.
Kanjanapongkul (2021)	Ohmic and microwave heating pretreatment	47% CPO yield	Combined ohmic-microwave pretreatment produced lower FFA content, higher yield, and lower energy consumption than single processes.
Ong et al. (2021)	Microwave pre-treatment followed by Soxhlet extraction	3.289 g of palm oil from OPDC	Microwave pre-treatment improved extraction yield and altered physicochemical properties; RSM helped optimise parameters.
Zamanhuri et al. (2021)	Microwave-assisted extraction at 100 W, 64% yield for CPO, 300 W for PFA distillate	64% CPO yield, high palmitic acid content in distillate	Efficient cell structure breakdown, high-quality CPO; optimal conditions identified for PFA extraction.
Ng and Nu'man (2021)	Microwave-assisted DES extraction (ChCl-AA, 30% water, 60°C, 9–15 min)	0.609–1.123 mg/g ferulic acid	Effective extraction of ferulic acid with good antioxidant properties; optimised DES composition.
Nomanbhay et al. (2018)	MAE with enzymatic hydrolysis	Not specified	Enhanced phenolic compound extraction yield; significant time reduction compared to conventional methods.

Note: MOAH - mineral oil aromatic hydrocarbons; RSM - response surface methodology; FFA - free fatty acid; PFA - palm fatty acid; POME - palm oil mill effluent; CPO - crude palm oil; MAEA - microwave-assisted enzyme aqueous; MAE - microwave-assisted extraction; DES - deep eutectic solvents; OPDC - oil palm decanter cake.

TABLE 2. OVERVIEW OF STUDIES ON UAE FOR PALM OIL EXTRACTION, HIGHLIGHTING EXTRACTION CONDITIONS, YIELDS AND OUTCOMES

Authors	Extraction condition	Yield	Outcome
Ben-Youssef et al. (2017)	Ultrasound extraction with n-hexane and 2-MeTHF	7.24%–5.97% lipid yield from date palm seeds	Ultrasound and microwave extraction significantly reduced extraction time (30 min vs. 8 hr) and increased lipid yield compared to maceration (about 6% vs. 4%).
Ngadi and Rusli (2014)	UAE is using sodium hydroxide solution	Not specified for lignin	Ultrasound extraction was more efficient than conventional heating, resulting in higher lignin yield, lower reaction temperature and shorter reaction time.
Martínez-Girón et al. (2024)	Ultrasound-assisted emulsion with sunflower oil at 480 W for 5 min	Carotenoid content: 67.61 µg/g	Stable emulsion with provitamin A activity, chemically and physically stable for 35 days; potential as a bio functional food additive.
Ordoñez-Santos et al. (2015)	UAE at 1,528 W/m ² , 35°C, 30 min	163.47 mg/100 g total carotenoids	UAE optimised using RSM; higher carotenoid yield compared to maceration; validated model showed good consistency.
Zain et al. (2020)	UAE at 25°C, 0.5 hr, 4:1 methanol-water ratio	TPC: 335.30 mg QCE/g, TFC: 60.67 mg QCE/g	Optimised extraction conditions resulted in high polyphenolic and flavonoid content with strong free radical scavenging activity.
Ordoñez-Santos et al. (2019)	UAE at 48°C, 28 min, 0.0037 g/mL solid-solvent ratio	151.50 mg/100 g carotenoids	UAE yielded 33.6% more carotenoids than maceration; optimised using RSM and validated experimentally.
Putra et al. (2022)	UAE with 70% methanol	Not specified	UAE was less effective compared to Soxhlet extraction for polyphenol and flavonoid yield; antioxidant activity measured was promising but inconclusive.
Cypriano et al. (2008)	UAE with 1:1 HCl-H ₂ O ₂ for 60 min	~100% extraction of Cu and Pb	UAE effectively extracted trace metals, showing good correlation with conventional methods; suitable for oil quality assessment.

Note: QCE - quercetin equivalents; TPC - total phenolic content; TFC - total flavonoid content; UAE - ultrasound-assisted extraction; RSM - response surface methodology; Cu - copper; Pb - leads; HCl - hydrogen acid; H₂O₂ - hydrogen peroxide.

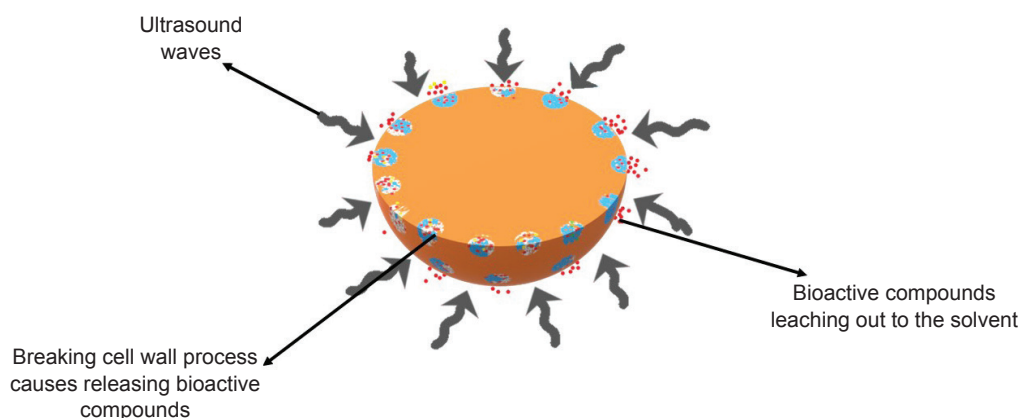


Figure 2. Mechanism of ultrasound-assisted extraction (UAE) for palm oil recovery.

These conditions break down cell walls, improving mass transfer and extraction efficiency. In comparison to traditional extraction methods, UAE offers advantages such as shorter extraction times, lower energy consumption and enhanced yields of bioactive compounds like lipids, carotenoids and polyphenols (Kumar et al., 2021; Liu et al., 2022; Wen et al., 2018). The effectiveness of UAE, however, depends heavily

on optimising key process parameters such as solvent selection, temperature, extraction time and ultrasonic power, each of which plays a crucial role in determining the yield and quality of the extracted materials (Escalapez et al., 2011).

Solvent choice is a critical factor in the UAE, influencing the extraction efficiency and the solubility of target compounds. For

instance, Ben-Youssef et al. (2017) demonstrated that using a combination of n-hexane and 2-methyltetrahydrofuran (2-MeTHF) significantly improved lipid yield from date palm seeds, achieving a higher extraction rate and faster processing times than traditional maceration. The ability to tailor solvent selection for specific applications shows the UAE's versatility in improving extraction outcomes across various matrices. Similarly, studies that focused on bioactive compounds like carotenoids have shown that solvent composition and concentration directly affect the recovery of high-value extracts, especially when combined with optimised temperatures to preserve sensitive compounds.

Temperature is another critical factor in the UAE, particularly for heat-sensitive compounds like carotenoids. Ordoñez-Santos et al. (2015, 2019) explored the optimisation of UAE conditions using Response Surface Methodology (RSM), revealing that relatively low temperatures (35°C–48°C) were sufficient to extract high yields of carotenoids from palm oil by-products, outperforming traditional extraction methods. These results highlight the UAE's ability to balance efficient extraction with the preservation of delicate bioactive compounds, ensuring high-quality outputs. Moreover, the moderate temperatures used in the UAE help to retain the nutritional and functional properties of the extracted compounds, further emphasising their potential in producing health-beneficial oils and additives.

Extraction time also plays a key role in the UAE's efficiency. Shorter extraction times not only reduce energy consumption but also make UAE a more commercially viable technique for large-scale applications. Zain et al. (2020) demonstrated the effectiveness of UAE in extracting polyphenols and flavonoids from palm oil by-products within just 30 min, achieving high levels of antioxidant activity. These results illustrate the UAE's ability to quickly and efficiently extract bioactive compounds with minimal energy input, making it an attractive option for industries aiming to reduce their carbon footprint while maintaining high-quality outputs. The reduction in processing time without compromising yield is a significant advantage of UAE over conventional extraction methods, which often require hours of operation.

Ultrasonic power is another essential parameter that directly influences the cavitation process, impacting the breakdown of plant cells and the release of compounds. Higher ultrasonic power can enhance extraction efficiency by creating more intense cavitation effects, but it must be carefully controlled to prevent degradation of sensitive compounds. Martínez-Girón et al. (2024) used high ultrasonic power (480 W) to successfully form stable

carotenoid emulsions, showing that UAE can be effectively applied not only for extraction but also for the formulation of bio functional products. This highlights the UAE's broader applications beyond extraction, such as in the development of nutraceuticals and food additives, further expanding its industrial relevance.

The UAE offers numerous advantages for palm oil extraction, including shorter processing times, lower energy consumption and higher yields of valuable bioactive compounds. The success of the UAE depends on optimising key parameters like solvent selection, temperature, extraction time and ultrasonic power, each of which influences the overall efficiency and quality of the extraction. By fine-tuning these parameters, UAE can be adapted to extract a wide range of compounds, from lipids to polyphenols, while maintaining the integrity of heat-sensitive bioactive. Given its environmental benefits and industrial scalability, the UAE represents a promising green technology for the future of palm oil extraction, offering an efficient and sustainable alternative to traditional methods.

SCCO₂ FOR PALM OIL EXTRACTION

SCCO₂ extraction has become a preferred green technology for palm oil extraction due to its efficiency and ability to operate under mild conditions, preserving the quality of the extracted oils and bioactive compounds. By using CO₂ in its supercritical state, which combines the properties of both liquids and gases, SCCO₂ can effectively dissolve and extract oils while minimising the use of harmful organic solvents as shown in *Figure 3*. This makes it a highly sustainable method, particularly for industries focused on producing high-quality palm oil rich in valuable compounds such as carotenoids, tocopherols and fatty acids. The performance of SCCO₂ extraction is greatly influenced by process parameters like solvent modifiers, temperature, pressure and particle size, all of which play a crucial role in determining extraction yields and outcomes.

One critical factor in improving SCCO₂ extraction efficiency is the use of solvent modifiers. Studies such as Barbi et al. (2020) and Krishnaiah et al. (2012) demonstrated that adding ethanol as a co-solvent significantly enhances the recovery of bioactive compounds like fatty acids and tocopherols. Ethanol, being a polar solvent, increases the solubility of certain compounds that are not easily extracted by pure SCCO₂, resulting in higher yields and improved oil quality. These findings highlight the importance of combining SCCO₂ with appropriate solvent modifiers to maximise extraction efficiency and target specific compounds that add value to palm oil products.

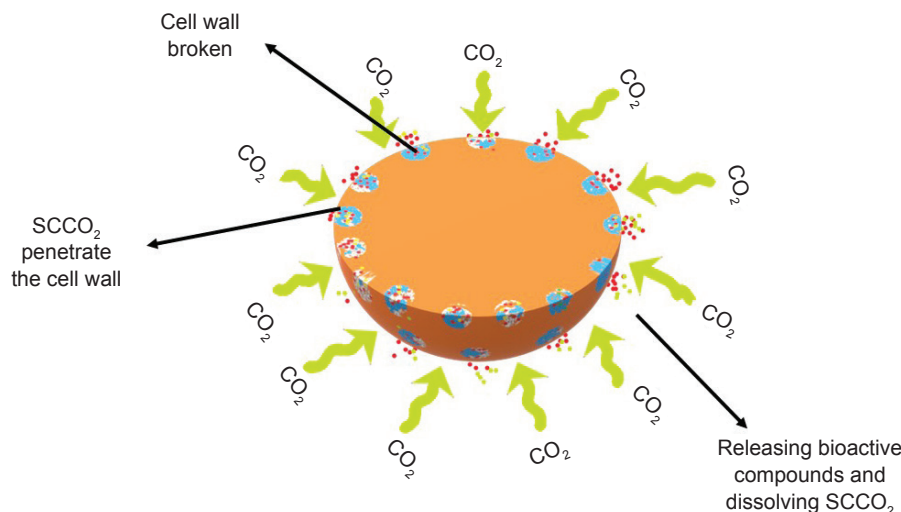


Figure 3. Mechanism of supercritical carbon dioxide (SCCO₂) for palm oil recovery.

Temperature and pressure are equally important in SCCO₂ extraction as they directly influence the solubility of oils and bioactive compounds. Studies by Norhuda and Omar (2009) and Zaidul et al. (2007) showed that higher pressures and temperatures lead to increased extraction yields and alter the composition of the extracted oils. For example, higher pressures tend to extract longer-chain fatty acids more efficiently, contributing to oil products that are richer in specific bioactive compounds. Optimising these parameters is key to improving the overall efficiency of the extraction process while ensuring that the quality of the oil is maintained or enhanced, particularly when dealing with heat-sensitive compounds like carotenoids and tocopherols.

SCCO₂ extraction is particularly valued for its ability to recover high-value compounds, such as carotenoids, tocopherols and squalene, which have significant applications in food, cosmetics and pharmaceuticals. Puah et al. (2006, 2007, 2011) demonstrated that SCCO₂ can extract palm oil components rich in carotenoids and vitamin E under mild conditions, producing high-quality oils suitable for commercial applications. Similarly, Al-Darmaki (2012) showed that a thermal gradient during extraction significantly improved the recovery of squalene, a compound with high antioxidant properties. These studies emphasised the potential of SCCO₂ for producing functional palm oil products enriched with bioactive compounds, which adds significant value to the oil beyond its basic nutritional properties.

Particle size and extraction duration also significantly impact the efficiency of SCCO₂ extraction. Rahman et al. (2012) found that smaller particle size increased oil yield, as smaller particles provide a larger surface area for mass transfer. Additionally, studies like Hossain et al. (2016) showed that adjusting the extraction time can

maximise oil recovery while preserving the nutrient quality of the oil. This is particularly important in producing de-oiled palm kernel cake (PKC), which can be used for human and animal consumption. Optimising these physical parameters ensures that SCCO₂ extraction not only improves oil yields but also maintains the integrity of both the oil and the remaining by-products, making the process more versatile and sustainable.

In conclusion, SCCO₂ extraction presents numerous advantages for palm oil extraction, particularly in its ability to enhance oil yields while preserving bioactive compounds under environmental-friendly conditions. The use of co-solvents, temperature, pressure, particle size and extraction time all play a significant role in optimising the process for specific applications, whether in food, pharmaceuticals or cosmetics. The growing body of research shows that SCCO₂ is an efficient and sustainable alternative to conventional extraction methods, with potential for further refinement through the continued exploration of solvent modifiers and the integration of alternative supercritical fluids like subcritical propane. This positions SCCO₂ extraction as a key technology in the sustainable production of palm oil and its high-value derivatives.

DES FOR PALM OIL EXTRACTION

DES have gained significant attention as a promising class of green solvents for palm oil extraction and processing due to their low toxicity, biodegradability and sustainability. Formed by mixing a hydrogen bond acceptor and a hydrogen bond donor, DES results in a eutectic mixture with a much lower melting point than its individual components, enhancing their effectiveness in various extraction processes. This section discusses recent

advancements in DES applications for extracting valuable bioactive compounds from palm oil and its by-products, demonstrating their potential for revolutionising the industry.

DES have been particularly effective in extracting bioactive compounds from palm biomass. For instance, Ng and Hadi (2022) demonstrated the ability of choline chloride-based DES to selectively extract ferulic acid, a potent antioxidant, from oil palm pressed fibre. This extraction method proved to be a more sustainable alternative to traditional solvents, which are often harmful to the environment. Further, Ng et al. (2024) highlighted the economic and environmental advantages of DES by showcasing their recyclability, allowing for repeated use without significant loss of efficiency. This ability to recycle DES makes them highly suitable for large-scale applications in the palm oil industry, where both sustainability and cost-effectiveness are critical considerations.

The integration of DES with other green technologies has further enhanced the efficiency of palm oil extraction. Zain et al. (2020) integrated choline chloride-based DES with macroporous resin to produce enriched oil palm flavonoids, which have applications in natural wound healing. This combination not only improved the yield and purity of the extracted flavonoids but also maintained their bioactivity, which is often compromised under conventional extraction conditions. Similarly, Yaakob et al. (2024) combined DES with MAE to extract lignin from oil palm empty fruit bunches (EFB). This synergistic approach significantly reduced processing time while improving extraction yields (achieved a 57.12% yield), demonstrating the potential of combining DES with other green technologies to enhance the efficiency of lignocellulosic biomass processing.

Understanding the physicochemical properties of DES is essential for optimising their use in extraction processes. Zain et al. (2021) characterised the solubility, viscosity and thermal stability of choline chloride-based DES, providing valuable insights that are crucial for achieving high extraction efficiency and selectivity. Similarly, Hadi et al. (2015) investigated the performance of DES in extracting tocopherols (vitamin E compounds) from CPO. Their findings revealed that DES could effectively extract these bioactive compounds while preserving their bioactivity, making DES suitable for producing high-quality palm oil derivatives with enhanced nutritional properties.

DES have also proven to be effective in extracting specific compounds from palm oil and its by-products. Mulia et al. (2018) demonstrated the selective extraction of palmitic acid, a widely used saturated fatty acid, using betaine-based DES. Rizki et al. (2022) further explored the use of natural DES for extracting tocotrienols and tocopherols

(vitamin E isomers) from CPO, achieving high extraction yields while maintaining the stability and functionality of these compounds. The highest vitamin E concentration and extraction efficiency were 4,439 mg/kg and 74.98%, respectively. Additionally, Manurung et al. (2020) showed that menthol-based DES could efficiently extract carotenoids, important antioxidants and pigments, from CPO, offering a sustainable method for producing carotenoid-rich palm oil products.

Beyond extraction, DES have been employed in the fractionation and pretreatment of palm oil biomass. Yong and Wu (2024) explored the fractionation of oil palm fronds using ethanol-assisted DES, focusing on enhancing enzymatic saccharification and lignin extraction. The inclusion of ethanol in the DES system significantly improved the fractionation process, resulting in higher yields of fermentable sugars and more efficient lignin recovery (Ethanol-assisted DESs able to preserve 60%–84% of β -O-4 linkages in lignin). These findings suggest that DES could play a crucial role in improving the pretreatment of palm oil biomass for various downstream applications, including biofuel production.

Table 3 presents an overview of studies employing SCCO_2 extraction for palm oil recovery, emphasising the influence of extraction conditions, yields and outcomes. These studies reflect the versatility and efficiency of SCCO_2 as a green extraction technique, with operating parameters such as temperature, pressure, co-solvent use (e.g., ethanol) and extraction duration playing critical roles in oil yield and quality. The reported oil yields vary considerably, ranging from 0.18% to 70.00%, often influenced by matrix type, particle size and the presence of high-value bioactives like tocopherols, carotenoids and squalene. Notably, several works demonstrated the ability of SCCO_2 to enhance the extraction of nutritionally important fractions and separate fatty acids selectively. Furthermore, innovations such as the use of subcritical propane, ethanol-modified SCCO_2 and thermodynamic modelling (e.g., Peng-Robinson EOS) have advanced process optimisation, improving both oil recovery and quality. Collectively, these findings underline SCCO_2 extraction as a promising and tunable method for valorising palm-based biomass into high-value oil products.

COMPARATIVE ANALYSIS OF GREEN EXTRACTION METHODS

Efficiency and Yield

In the quest for more sustainable and environmentally friendly methods of palm oil extraction, several green technologies have been developed and evaluated. This section compares

TABLE 3. OVERVIEW OF STUDIES ON SCCO₂ FOR PALM OIL EXTRACTION, HIGHLIGHTING EXTRACTION CONDITIONS, YIELDS AND OUTCOMES

Authors	Extraction condition	Yield	Outcome
Barbi et al. (2020)	SCCO ₂ (333.15 K, 20 MPa) and pressurised ethanol	3.6% (SCCO ₂), 20.4% (SCCO ₂ + EtOH), 47.8% (PLE)	PLE showed the highest recovery of oil. SCCO ₂ + EtOH increased recovery compared to pure SCCO ₂ . The oil was rich in unsaturated fatty acids and bioactive compounds, suitable for food and pharmaceuticals.
Norhuda and Omar (2009)	SCCO ₂ at 50°C–70°C and 27.6–48.3 MPa	Not specified	The overall mass transfer coefficient increased with temperature and pressure, indicating improved extraction efficiency under higher temperature and pressure.
Al-Darmaki et al. (2012)	SCCO ₂ with isothermal and temperature gradient (313–353 K, 10–20 MPa)	Squalene increased from 2%–16% in the top product	High squalene recovery (95%) and concentration achieved. The thermal gradient along the column enhanced squalene recovery.
Hossain et al. (2016)	SCCO ₂ (44.6 MPa, 60°C, 50 min)	49.2% oil yield	SCCO ₂ maintained nutrient compositions in deoiled PKC, which is suitable for human and animal consumption. Significant reduction in anti-nutrient compositions was observed.
Norulaini et al. (2004)	SCCO ₂ at 80°C and 27.6–48.3 MPa for 30–60 min	28.2%–44.75% oil yield depending on pressure	The solubility of oil increased with pressure, and fatty acid composition varied across different fractions.
Zaidul et al. (2007)	SCCO ₂ (313.2–353.2 K, 20.7–48.3 MPa)	49 g oil/100 g palm kernel at 48.3 MPa and 353.2 K	Higher pressure resulted in the extraction of longer chain fatty acids. A kinetic mass transfer model was developed to estimate CO ₂ usage for a given yield.
Puah et al. (2011)	SCCO ₂ (14–30 MPa, 40°C–80°C)	0.1751–6.60 mg/g CO ₂	Solubility of palm oil components in SCCO ₂ was influenced by acylglycerols and FFAs. Optimal solubility was at 60°C and 30 MPa.
Hong et al. (2010)	SCCO ₂ with Peng-Robinson EOS (333.2–373.2 K, 8.5–35 MPa)	Not specified	PR-EOS with Wong-Sandler mixing rule effectively predicted vapor-liquid equilibria of palm oil and SCCO ₂ .
Promraksa et al. (2020)	SCCO ₂ for palm oil and α -tocopherol extraction	Not specified	Axial dispersion played a significant role in constant extraction-rate periods. Extraction of α -tocopherol confirmed the role of axial dispersion.
Puah et al. (2006)	SCCO ₂ (14–30 MPa, 40°C)	>1,000 ppm carotenoids, 350 ppm vitamin E	SCCO ₂ produced carotenoids-rich palm olein with a lower cloud point, comparable to commercial olein.
Phan-Tai and Brunner, (2023)	Subcritical propane (50 bar, 120 min)	70% oil yield	Compressed propane effectively extracted oil enriched in carotenes and tocotrienols. Subcritical propane was a viable alternative to SCCO ₂ for simultaneous recovery of valuable compounds.
Norulaini et al. (2004)	SCCO ₂ (80°C, 27.6–48.3 MPa, 30–60 min)	37.5%–44.75% oil yield	Oil yield increased with pressure, and fatty acid composition varied across different fractions. SCCO ₂ was effective for separating lauric and oleic acids.
Krishnaiah et al. (2012)	SCCO ₂ (19.8 MPa, 51°C) with ethanol	Not specified	SCCO ₂ with ethanol effectively extracted tocopherols, tocotrienols and fatty acids. Oil quality improved with increasing ethanol content.
Rahman et al. (2012)	SCCO ₂ (27.57–41.36 MPa, 40°C–70°C) with different particle sizes	9.26 g oil/100 g sample	Smaller particle sizes increased oil yield. SCCO ₂ was effective in extracting residual oil, producing defatted PKC.

Note: PLE - pressurised liquid extraction; FFA - free fatty acid; PKC - palm kernel cake; SCCO₂ - supercritical carbon dioxide; CO₂ - carbon dioxide; EtOH - ethanol.

the efficiency and yield of various green extraction methods, such as SCCO₂ extraction, UAE, MAE and DES, based on data from recent studies.

SCCO₂ extraction has gained popularity due to its ability to operate without toxic solvents while maintaining high extraction efficiency. For example, Barbi et al. (2020) demonstrated that SCCO₂, when combined with ethanol as a co-solvent, could significantly enhance oil recovery from *Maximiliana maripa* pulp. The study reported a yield of 20.4% with SCCO₂ + ethanol, compared to only 3.6% with pure SCCO₂. This method was found to be particularly effective in extracting unsaturated fatty acids and bioactive compounds, which are valuable for food and pharmaceutical applications. Similarly, Zaidul et al. (2007) found that SCCO₂ extraction at higher pressures (48.3 MPa) resulted in a substantial yield of 49 g oil/100 g palm kernel, demonstrating the method's potential for high-yield extractions when optimised for pressure and temperature.

UAE is another method that has shown promise in enhancing the extraction yield of palm oil and its derivatives. The efficiency of UAE is primarily attributed to the cavitation effect, which enhances the penetration of solvents into plant materials, thereby increasing the extraction rate. For instance, studies like those by Othman et al. (2017) showed that UAE could achieve up to 83.0% removal of phenol from wastewater using a palm oil-based solvent, highlighting its effectiveness in both extraction yield and environmental impact. Although direct comparisons of palm oil yield using UAE are less common, its ability to enhance the extraction of valuable compounds from palm oil waste products suggests significant potential for further development.

MAE is recognised for its rapid heating and efficient energy transfer, which can lead to reduced extraction times and improved yields. Studies such as those by Han and Hadi (2024) on the MAE of ferulic acid from palm fruitlets have shown that MAE can maintain high bioactivity in the extracted compounds while achieving considerable yields. MAE's ability to efficiently break down plant cell walls enhances the extraction of oils and other valuable compounds, making it a competitive method in terms of yield and efficiency, particularly for compounds that are sensitive to conventional heating methods.

DES have emerged as a green alternative to conventional organic solvents, offering a non-toxic, biodegradable and cost-effective solution for biomass pretreatment. Studies like those by Loow et al. (2017) and Jablonský et al. (2018) have shown that DES, when combined with other methods such as UAE or SCCO₂, can significantly enhance the extraction yield of specific components like xylose and phenolic compounds from lignocellulosic

biomass. For example, Loow et al. (2017) reported a 25.0% increase in xylose recovery when using DES in conjunction with an inorganic salt, compared to using the salt alone. This highlights DES's potential in improving extraction efficiency, especially when integrated into multi-step extraction processes.

When comparing these green extraction methods, SCCO₂ stands out for its ability to achieve high yields, particularly when combined with co-solvents like ethanol. However, this method requires high-pressure equipment, which can be cost-prohibitive for some applications. UAE and MAE offer lower-cost alternatives with good efficiency, particularly for extracting heat-sensitive compounds and enhancing yields from waste materials. DES, while still emerging, shows great promise in improving the efficiency of existing extraction processes and reducing the environmental footprint. Overall, the choice of extraction method depends on the specific application, the desired compounds, and the available resources. Each method has its strengths, with SCCO₂ being ideal for high-value oil extraction, UAE and MAE offering quick and efficient alternatives for various compounds, and DES providing a versatile and green solution for enhancing extraction processes. The integration of these methods into a comprehensive extraction strategy can potentially maximise both efficiency and yield while minimising environmental impact.

Comparison of Extraction Yields with Conventional Methods

Conventional methods such as mechanical pressing and solvent extraction have traditionally dominated the palm oil extraction industry. Mechanical pressing, commonly used in small to medium-scale operations, typically achieves an oil yield of about 20.0%–25.0% (Cheng et al., 2021). While this method is cost-effective and straightforward, it is not particularly efficient, often leaving a significant amount of oil in the palm kernel or fruit pulp. On the other hand, solvent extraction using hexane could achieve higher yields, often up to 45.0%–50.0% (Ong et al., 2021). However, the use of hexane poses serious environmental and health risks due to its toxicity and flammability, along with the significant energy required for solvent recovery and the potential for solvent residues in the final product. These drawbacks make solvent extraction less desirable from a sustainability perspective.

In contrast, green extraction methods offer promising alternatives that can match or exceed the yields of conventional methods while mitigating their environmental impacts. For example, SCCO₂ extraction has demonstrated yields comparable to or higher than those of solvent extraction, particularly when co-solvents like ethanol are used. Study by

Barbi et al. (2020) showed that SCCO₂ with ethanol achieved a yield of 20.4% from *Maximiliana maripa* pulp, which, while slightly lower than conventional solvent extraction, is notable for its significantly reduced environmental impact. Zaidul et al. (2007) reported an even higher yield of 49 g oil/100 g of palm kernel using SCCO₂ under optimal pressure conditions, matching or surpassing yields from traditional solvent methods.

UAE, though less extensively studied for palm oil yield specifically, has shown effectiveness in enhancing extraction processes for other valuable compounds, suggesting its potential for high oil yields. For instance, Othman et al. (2017) demonstrated an 83.0% removal of phenol from wastewater using a palm oil-based solvent, highlighting UAE's efficiency in extracting compounds from complex matrices. Similarly, MAE is recognised for its rapid, energy-efficient process, which can yield comparable results to solvent extraction while significantly reducing processing time. Han and Hadi (2024) reported successful extraction of ferulic acid from palm fruitlets using MAE, retaining high bioactivity and suggesting that MAE could also enhance palm oil extraction yields with proper optimisation.

DES, an emerging technology, has shown great promise in improving extraction efficiency. Loow et al. (2017) observed a 25.0% increase in xylose recovery using DES combined with inorganic salts, compared to conventional methods. Although direct

comparisons with palm oil extraction are limited, these efficiency gains suggest that DES could potentially match or exceed conventional solvent extraction yields when optimised for palm oil.

In summary, while conventional methods such as solvent extraction offer high yields, their environmental and health-related drawbacks are significant. Green extraction methods, although sometimes yielding slightly lower percentages, offer substantial advantages in terms of sustainability, safety and process efficiency. SCCO₂ extraction stands out for achieving high yields comparable to solvent extraction without the need for toxic chemicals. UAE and MAE provide rapid, energy-efficient alternatives well-suited for extracting high-value compounds from palm oil and its by-products. DES shows great promise as a green solvent that could further enhance yields with minimal environmental impact. As these green technologies continue to advance and be optimised, they are poised to become the preferred methods for sustainable palm oil extraction, aligning industry practices with global sustainability goals.

Table 4 provides comparative analysis of green extraction methods employed in palm oil extraction, highlighting the efficiency, yields, benefits and limitations of each technique. The reviewed methods include SCCO₂, UAE, MAE and DES, each offering distinct advantages for enhancing extraction performance. SCCO₂ is noted for its high efficiency, especially when combined

TABLE 4. COMPARATIVE ANALYSIS OF GREEN EXTRACTION METHODS FOR PALM OIL EXTRACTION

Extraction method	Key studies	Efficiency	Yield	Advantages	Challenges
SCCO ₂	Barbi et al. (2020); Zaidul et al. (2007)	High efficiency, especially with co-solvents like ethanol. High pressure improves mass transfer and extraction rates.	3.6% yield with pure SCCO ₂ . 20.4% yield with SCCO ₂ + ethanol. 49 g oil/100 g palm kernel at high pressure.	Solvent-free, environmental-friendly. High yield for unsaturated fatty acids and bioactive compounds.	Requires high-pressure equipment, increasing cost. Optimisation is needed for specific applications.
UAE	Ali et al. (2023); Anggoro et al. (2024); Zain et al. (2020)	Cavitation effect enhances solvent penetration, improving extraction rate.	83.0% phenol removal from wastewater using palm oil-based solvent.	Low cost, efficient for waste treatment. Enhances the extraction of valuable compounds from waste products.	Limited direct studies on palm oil yield. Optimisation needed for large-scale applications.
MAE	Han and Hadi (2024); Yaakob et al. (2024)	Rapid heating and efficient energy transfer, reducing extraction time.	High bioactivity retention in extracted compounds.	Fast, energy-efficient. Suitable for heat-sensitive compounds.	Requires specialised equipment. Potential for uneven heating at larger scales.
DES	Jablonský et al. (2018); Loow et al. (2017)	Improves delignification and biomass pretreatment, especially when combined with other methods.	25.0% increase in xylose recovery with DES + inorganic salt.	Non-toxic, biodegradable and cost-effective. Enhances extraction when integrated with other methods.	Emerging technology, require further optimisation. Scalability and consistency need evaluation.

Note: SCCO₂ - supercritical carbon dioxide; UAE - ultrasound-assisted extraction; MAE - microwave-assisted extraction; DES - deep eutectic solvents

with co-solvents like ethanol, delivering high-quality oil rich in unsaturated fatty acids but requiring high-pressure systems and cost-intensive optimisation. UAE demonstrates outstanding potential in wastewater valorisation through phenol removal, promoting sustainability but suffers from limited direct studies on palm oil. MAE offers rapid, energy-efficient extraction with excellent bioactivity retention, making it ideal for heat-sensitive compounds; however, its scalability and need for precise thermal control remain challenges. DES, as an emerging and environmentally benign technique, has shown promise in improving delignification and biomass pretreatment, although it still requires optimisation and validation for consistency at scale. Overall, the table underscores the complementary roles of these methods in advancing sustainable palm oil extraction technologies.

CONCLUSION

The transition to green extraction methods in the palm oil industry marks a critical advancement towards sustainability by addressing both environmental concerns and the demand for higher-quality products. While conventional methods like mechanical pressing and solvent extraction have been reliable in terms of yield, they are becoming less favored due to their environmental and health-related drawbacks, inefficiency in preserving bioactive compounds, and substantial waste generation. In contrast, green extraction technologies not only meet but often surpass conventional techniques in terms of efficiency, yield, and product quality, while significantly minimising environmental impact.

SCCO₂ extraction has proven particularly effective in achieving high yields and maintaining the nutritional integrity of palm oil, especially when used with co-solvents like ethanol to improve extraction efficiency. Technologies like UAE and MAE offer rapid, energy-efficient processes that preserve bioactive compounds, making them ideal for high-quality palm oil derivatives. The emerging application of DES demonstrates substantial potential by improving extraction efficiency with minimal environmental harm, although more research is needed to further optimise its performance.

Despite these promising developments, challenges remain in scaling up these green technologies for widespread industrial application. Future studies should focus on refining process parameters, reducing energy consumption further, and improving the cost-effectiveness of these methods. In addition, more research is needed to assess the long-term economic viability and the potential of combining green extraction techniques

to maximise extraction yields and product quality. As these technologies continue to evolve, they are expected to become the industry standard, contributing significantly to the mitigation of environmental impacts while maintaining the high standards of palm oil products. Therefore, further exploration into the integration of these methods with circular economy models and renewable energy sources could unlock even greater potential in creating a fully sustainable palm oil production system.

ACKNOWLEDGEMENT

The authors would like to acknowledge the National Research and Innovation Agency (BRIN) and Institut Teknologi Sepuluh Nopember for supporting this work.

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