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Green extraction technologies for coconut oil-based biodiesel production in the Philippines: A critical review

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ABSTRACT

Philippine biodiesel production relies almost entirely on coconut oil (CNO) as feedstock for coconut methyl ester (CME), a dependence increasingly strained by supply volatility. Recent efforts to raise blending mandates further were suspended after adverse weather sharply reduced coconut output and drove up CNO prices. Expanding CME supply therefore requires new feedstocks or better recovery from the existing one. Oil palm diversification remains constrained by heavy import dependence, leaving CNO recovery the more immediate lever. This review critically evaluates four green extraction technologies — microwave-assisted, ultrasound-assisted, enzyme-assisted, and supercritical fluid extraction (SFE) — against conventional milling and against one another, then ranks each technology's Philippine readiness through an Analytic Hierarchy Process weighing evidence maturity, feasibility, oil quality, efficiency, and environmental criteria. SFE emerges as the clear front-runner, backed by the most direct coconut-specific evidence among the four and compositional advantages unmatched elsewhere, including pressure-tunable lauric acid enrichment exceeding 50% and consistently low peroxide values; the ranking holds under alternative weightings. Its principal barrier is economic rather than technical: high-pressure equipment demands capital investment ill-suited to a smallholder-dominated, low-unit-value commodity feedstock. Pairing SFE with in situ transesterification to consolidate extraction and conversion could offer a route to offset this cost, alongside pilot-scale validation on Philippine copra. Doing so could position CNO recovery as a durable lever for meeting the Philippines' stalled biodiesel blending targets.

Keywords: supercritical fluid extraction; microwave-assisted extraction; ultrasound-assisted extraction; enzyme-assisted extraction; in situ transesterification; coconut methyl ester.

INTRODUCTION

Declining fossil fuel reserves and the environmental costs of their continued use have intensified global efforts to develop renewable and more sustainable energy sources. In the Philippines, these concerns led to the enactment of Republic Act No. 9367, or the Biofuels Act of 2006, which promotes the development and use of domestically produced biofuels to reduce dependence on imported petroleum, mitigate harmful and greenhouse gas emissions, and generate economic opportunities (Republic of the Philippines, 2007). Philippine biodiesel is produced as coconut methyl ester (CME), with coconut oil (CNO) serving as its established domestic feedstock. Earlier plans to raise the blend to 5% (B5) by 2015 and 10% (B10) by 2020 were not implemented, owing to limited infrastructure investment, inconsistent feedstock availability, and volatile petroleum and CNO prices (Acda, 2022; Alonzo, 2016); the blending requirement consequently remained at B2 for roughly 17 years.

A significant policy shift occurred in October 2024, when the nationwide biodiesel requirement rose from B2 to B3, with further increases to B4

and B5 scheduled for October 2025 and 2026 (Department of Energy Philippines, 2024). This progression, however, has since encountered renewed supply and price pressures: international CNO prices rose sharply while coconut production was hit by El Niño and successive typhoons, with output reported to have declined by approximately 20% (USDA Foreign Agricultural Service, 2025). In response, the National Biofuels Board suspended the B4 and B5 increases in mid-2025 (Department of Energy Philippines, 2024; Miguel & Calderon, 2026). Expanding CME utilization, then, depends less on conversion capacity or blending mandates than on a reliable, economically viable feedstock supply.

High feedstock cost and limited feedstock diversity remain major challenges for the Philippine biodiesel sector. Oil palm has been identified as a promising supplementary feedstock (Landoy et al., 2022; Ritchie, 2021), though heavy reliance on imports limits its near-term contribution (USDA Foreign Agricultural Service, 2025). Feedstock diversification therefore appears insufficient on its own; improving the recovery of the country's existing coconut resource offers a complementary pathway. Conventional CNO production depends heavily on copra milling — drying, mechanical expression, and, where applicable, solvent extraction (Pestaño & Jose, 2016) — and while these technologies are mature, opportunities remain to improve oil recovery, resource utilization, and environmental performance (Oseni et al., 2017).

Microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), and supercritical fluid extraction (SFE) have emerged as alternative or complementary oil-recovery approaches for seeds and nuts. These four rely on fundamentally different mechanisms and have been investigated across a wide range of oil-bearing matrices (Ferreira et al., 2022; Ibrahim & Onwualu, 2005; Yusuf, 2018). Performance varies considerably with matrix and intended product, so no single technology is universally superior. Industrial applicability depends as much on energy demand and scalability as on yield (Alazaiza et al., 2026; Shahbaz et al., 2025), a consideration weighing heavily when the target lipid is a high-volume intermediate like biodiesel feedstock rather than a specialty product. Pulsed electric field processing is a related technology, but it functions chiefly as a pretreatment intensifying conventional pressing or solvent extraction rather than as a standalone method (Ferraz & Silva, 2025), and is excluded from this review's scope. Figure 1 summarizes how constraints in coconut feedstock supply and CNO production motivate evaluating these four technologies for biodiesel-oriented lipid recovery.

Several reviews have examined these technologies for extracting vegetable oils from seeds and nuts (Ferreira et al., 2022; Ibrahim & Onwualu, 2005; Yusuf, 2018). Their comparative suitability for recovering CNO specifically as a biodiesel feedstock, however, remains insufficiently examined. A technology optimized for premium edible oils does not necessarily deliver the throughput or downstream compatibility that biodiesel-oriented recovery requires.

This review addresses that gap by evaluating MAE, UAE, EAE, and SFE against conventional copra milling and against one another, across extraction efficiency, oil quality, feasibility, environmental performance, and the maturity of evidence specific to CNO. These criteria are then weighed and synthesized through the Analytic Hierarchy Process, lending the resulting technology-readiness ranking a level of analytical rigor uncommon in qualitative technology comparisons. Building on this assessment, we then consider what adopting the most promising technology would require in the Philippine context, including its potential integration with in situ transesterification to streamline downstream CME conversion.

THE PHILIPPINE CNO INDUSTRY: RELEVANCE TO BIODIESEL SUPPLY

Understanding the potential contribution of emerging extraction technologies to Philippine biodiesel production requires first establishing the industry and process context in which any new technology would operate. The following subsections trace this context from the coconut sector's scale and policy environment, through agricultural and postharvest constraints, to the conventional extraction process CNO currently undergoes.

Current industry landscape

The coconut industry remains an important component of Philippine agriculture and rural livelihoods. In 2023, approximately 3.7 million ha were planted with coconut, accounting for about 27% of the country's agricultural land

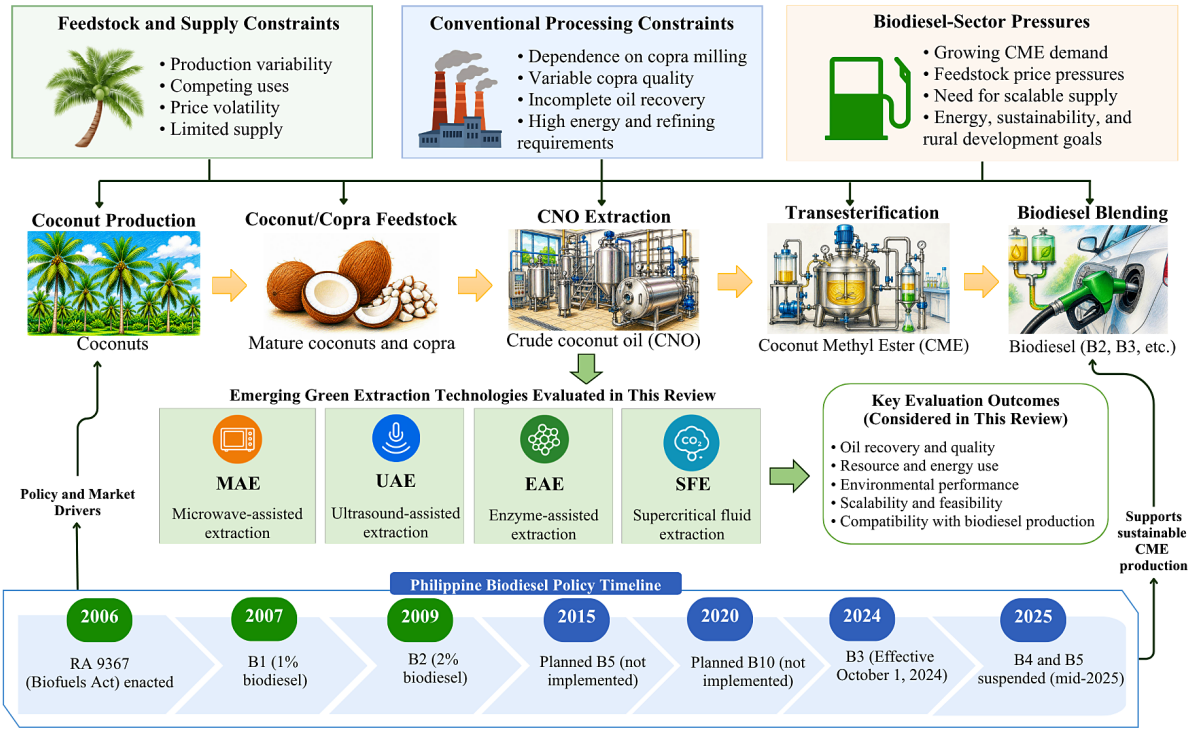

Figure 1. Conceptual framework linking CNO extraction with biodiesel production in the Philippines. Feedstock constraints, limitations of conventional processing, and biodiesel-sector pressures motivate evaluating MAE, UAE, EAE, and SFE for CNO recovery. The policy timeline shows the drivers behind rising CME demand, while technologies are assessed for oil recovery, quality, resource and energy needs, environmental performance, scalability, and downstream compatibility

and comprising approximately 345 million fruit-bearing trees (Philippine Coconut Authority, 2023a). Production is dominated by smallholder farms, supporting more than 2.5 million farming households (Aguilar et al., 2022). This dispersed structure gives the industry considerable socioeconomic importance but also contributes to persistent challenges in productivity, feedstock aggregation, and processing access.

CNO remains the country's principal commodity oil, recovered through two routes. Virgin coconut oil (VCO) comes from fresh mature kernel through processes that avoid conventional copra refining, while most industrial CNO is produced from dried kernel, or copra (Aytaç, 2022; Marina et al., 2009). Copra-derived CNO may be sold crude or refined into refined, bleached, and deodorized (RBD) CNO for food, oleochemical, and fuel applications (Hossain et al., 2012; Kappally et al., 2015; Lima & Block, 2019). For biodiesel, this distinction matters less for VCO's premium attributes than for the availability and processing requirements of the lipid stream feeding transesterification.

The processing sector is supported by substantial infrastructure: 63 active oil mills with a combined annual crushing capacity of approximately 4.54 million metric tons (MMT) of copra, and 45 refineries with roughly 1.52 MMT of annual capacity (Aguilar et al., 2022). Milling is concentrated in Southern Luzon and Mindanao, while refining sits closer to export centers in Luzon. In 2024, CNO production reached approximately 1.85 MMT, of which about 1.48 MMT was exported as crude or refined oil (USDA Foreign Agricultural Service, 2025). This scale of export illustrates a core feature of the domestic feedstock problem: CME production competes for CNO within a market strongly integrated into international trade.

In 2022, CNO exports alone reached approximately 0.998 MMT, valued at USD 1.74 billion, with the United States, the Netherlands, and Malaysia as principal destinations (Philippine Coconut Authority, 2022). This export orientation generates real economic value, but it also means domestic biodiesel producers compete within a feedstock market shaped by global demand and price.

Extraction technologies must therefore be evaluated not only on their ability to recover oil, but on whether they could realistically expand the CNO supply available for domestic CME production.

CNO as feedstock for Philippine biodiesel production

The Biofuels Act mandates the incorporation of domestically produced biofuels into petroleum fuels sold in the Philippines (Republic of the Philippines, 2007). The minimum bioethanol blend in gasoline was set at 5%; biodiesel blending in diesel began at 1% and was later raised to 2% (B2). The Philippine Department of Energy (DOE) leads implementation, with the National Biofuels Board monitoring compliance and recommending program measures. Fiscal incentives accompany the mandate, including tax exemptions for local biofuels and their feedstocks.

The staged B3–B5 mandate introduced in Section 1 is formalized under DOE Department Circular No. DC2024-05-0014. Each one-percentage-point increase in the mandatory CME blend requires approximately 100–120 million L, or 88,000–105,000 metric tons, of additional CME — corresponding to roughly 900 million coconuts (Department of Energy Philippines, 2024; Miguel & Calderon, 2026). Even the B3 mandate alone represents a substantial claim on domestic coconut supply, before accounting for existing food, oleochemical, and export demand.

Diversifying the feedstock base has consequently drawn attention as a potential solution. Landoy et al. (2022) evaluated candidate biodiesel feedstocks for the Philippines – including coconut, oil palm, soybean, jatropha, used cooking oil, and microalgae – and identified oil palm as the most promising supplement, owing to its productivity and lower carbon footprint. The productivity gap is substantial: global average yields reach approximately 3.06 metric tons ha^{-1} for palm, versus 0.29 for coconut (Ritchie, 2021). The government has pursued initiatives to expand domestic oil-palm production accordingly, reflected in the Philippine Palm Oil Industry Roadmap 2024–2033 (Philippine Coconut Authority, 2023b).

This promise is nevertheless tempered by import dependence. Approximately 1.0 million metric tons — 82.6% of the Philippine palm oil supply — was imported in 2024. Of the 1.11 million metric tons consumed, only 13.2% went to industrial applications, including biodiesel (USDA Foreign Agricultural Service, 2025). This limits palm oil's near-term capacity to substitute for CNO at scale, reinforcing why CNO remains the feedstock most directly tied to Philippine CME viability. Feedstock diversification and CNO-recovery improvements are best understood as complementary strategies, not competing ones.

Policy and industry modernization

Institutional development of the coconut sector is led by the Philippine Coconut Authority (PCA) under the Department of Agriculture. The Philippine Coconut Industry 2021–2040 Roadmap identifies productivity improvement, product diversification, and modernization of postharvest and processing systems as key directions (Aguilar et al., 2022). These objectives carry weight because much of Philippine coconut production originates from smallholder farms, while processing remains concentrated in established facilities.

This environment was reinforced by Republic Act No. 11524, the Coconut Farmers and Industry Trust Fund Act, which directs coconut levy assets toward farmer and industry programs (Republic of the Philippines, 2021). Such programs create a policy context in which green extraction technologies may eventually be evaluated, but their existence is not evidence that these technologies are already technically or economically suitable for Philippine CNO production. Adopting a new technology specifically for CME production would need to demonstrate advantages within a value chain that also serves food, export, and oleochemical markets — not merely higher laboratory-scale performance. Any proposed process must be weighed against existing copra collection systems, established milling capacity, and the comparatively low unit value of a bulk biodiesel feedstock relative to specialty coconut products.

Production and postharvest constraints

The Philippine coconut industry faces constraints affecting both the quantity and quality of feedstock reaching processors. Average productivity has remained at approximately 40–45 nuts per tree annually, well below yields attainable from improved planting materials (Aguilar et al., 2022). Senile palms, slow replanting, and fragmented smallholdings all contribute to this gap. For biodiesel, these limitations translate directly

into constraints on the volume and consistency of lipid available for conversion to CME.

Postharvest handling adds further variability. Copra production requires substantial drying of fresh kernel before storage and extraction. Sun drying is inexpensive but slow and weather-exposed; direct-fire drying is faster but can introduce smoke contamination; hot-air or kiln systems offer more control at higher cost (Pestaño & Jose, 2016). Poor drying can compromise copra quality and burden subsequent processing.

Feedstock quality cannot be separated from extraction performance. A process that performs well on uniform laboratory material may respond differently to industrial copra varying in moisture and contamination (Ibrahim & Onwualu, 2005). The value of MAE, UAE, EAE, or SFE in the Philippine context will therefore depend partly on how well each tolerates these characteristics — one of the criteria considered later in the comparative analysis. The coconut value chain also generates several co-products (Varghese et al., 2024), so modernizing CNO extraction should aim to maximize oil recovery without compromising residual-solid value or raising energy and waste-management demands, a consideration that matters most where extraction economics cannot rely on specialty-oil pricing.

Conventional CNO production via copra milling

Copra milling remains the principal route for CNO production and is supported by established collection networks, mills, and export channels. Approximately 80% of Philippine coconut production has historically been converted into copra (Aguilar et al., 2022). Fresh kernel moisture is high; Thanaraj et al. (2007) reported a reduction from approximately 50% to 8% through kiln drying, while Pestaño and Jose (2016) reported well-dried copra at approximately 7% moisture, declining further to 4–5% during storage. Conventional CNO production can be divided into copra pretreatment, oil extraction, and post-extraction processing.

Copra pretreatment

Copra enters processing as large, irregular pieces rather than the small, uniform particles typical of many oilseeds. It therefore requires size reduction before efficient mechanical expression. Conventional preparation involves sequential comminution and flaking, reducing dried copra to particles roughly 10 mm and then to flakes approximately 1 mm thick (Varghese et al., 2024). These figures are approximate processing ranges rather than fixed specifications. After size reduction, copra is thermally conditioned to adjust temperature and moisture before pressing. Particle size, moisture, temperature, and pressure together strongly influence the efficiency and quality of mechanically expressed oils (Ibrahim & Onwualu, 2005). This sequence of drying, comminution, flaking, and conditioning represents a significant share of the material and energy demands of conventional CNO recovery, and provides a useful baseline for evaluating emerging technologies.

CNO extraction

Mechanical expression is the principal means of recovering oil from prepared copra. Conditioned material is pressed in screw-type expellers, where progressive compression separates oil from the solid matrix. This is attractive industrially because it runs continuously and needs no organic solvent (Varghese et al., 2024). However, efficiency depends strongly on particle size, moisture, temperature, and pressure (Ibrahim & Onwualu, 2005; Yusuf, 2018), and expression is inherently incomplete, leaving oil in the press cake.

Processors can therefore combine pressing with solvent extraction of the residual cake, typically using hexane for its affinity for nonpolar lipids and ease of recovery. This improves total recovery but adds solvent handling, separation, and recycling steps, along with occupational and environmental considerations largely absent from mechanical expression alone (Ferreira et al., 2022; Ibrahim & Onwualu, 2005). Greater oil recovery therefore does not automatically mean better overall process performance. Reduced solvent dependence is frequently cited as an advantage of emerging technologies, but such claims must be judged against the entire process – energy demand, extraction time, equipment requirements, and residual-biomass utilization – not solvent use alone.

Post-extraction processing and biodiesel feedstock requirements

Oil leaving extraction contains entrained solids, moisture, free fatty acids (FFA), and other non-triglyceride constituents. Crude CNO is typically clarified before further handling; where higher purity is

needed, it undergoes refining (Gupta, 2017). Refining generally comprises degumming, neutralization, bleaching, and deodorization, together producing RBD CNO suitable for food, oleochemical, and other applications (Lima & Block, 2019; Varghese et al., 2024). Figure 2 summarizes this pathway, from copra preparation through extraction, clarification, and refining, together with the subsequent conversion of CNO to CME.

For biodiesel, processing requirements differ from those governing premium edible oil. The central question is whether the recovered lipid supports efficient transesterification and CME compliance with fuel-quality specifications. High FFA and water content can interfere with alkali-catalyzed transesterification by promoting soap formation, raising catalyst consumption, and reducing ester recovery (Leung et al., 2010; Ma & Hanna, 1999). An extraction technology's suitability for biodiesel therefore cannot be judged on yield alone; lipid quality also determines how much additional drying or neutralization is needed before conversion.

This relationship provides an additional criterion for comparing emerging technologies with conventional milling. An alternative process could improve the CNO-to-CME chain by increasing recovery or reducing pretreatment needs, but such gains must be weighed against added capital, energy, or complexity (Alazaiza et al., 2026; Shahbaz et al., 2025). The technologies examined in the following sections are therefore evaluated both for their ability to recover CNO and for their implications for downstream CME production.

EMERGING GREEN EXTRACTION TECHNOLOGIES FOR SEED AND NUT OILS

The limitations of conventional oil recovery have driven the development of extraction technologies that intensify mass transfer while reducing processing time, solvent use, or thermal exposure (Ferreira et al., 2022). MAE, UAE, EAE, and SFE each employ a fundamentally different mechanism to improve the release or recovery of intracellular lipids.

Each technology's operating principles, process variables, and experimental evidence for

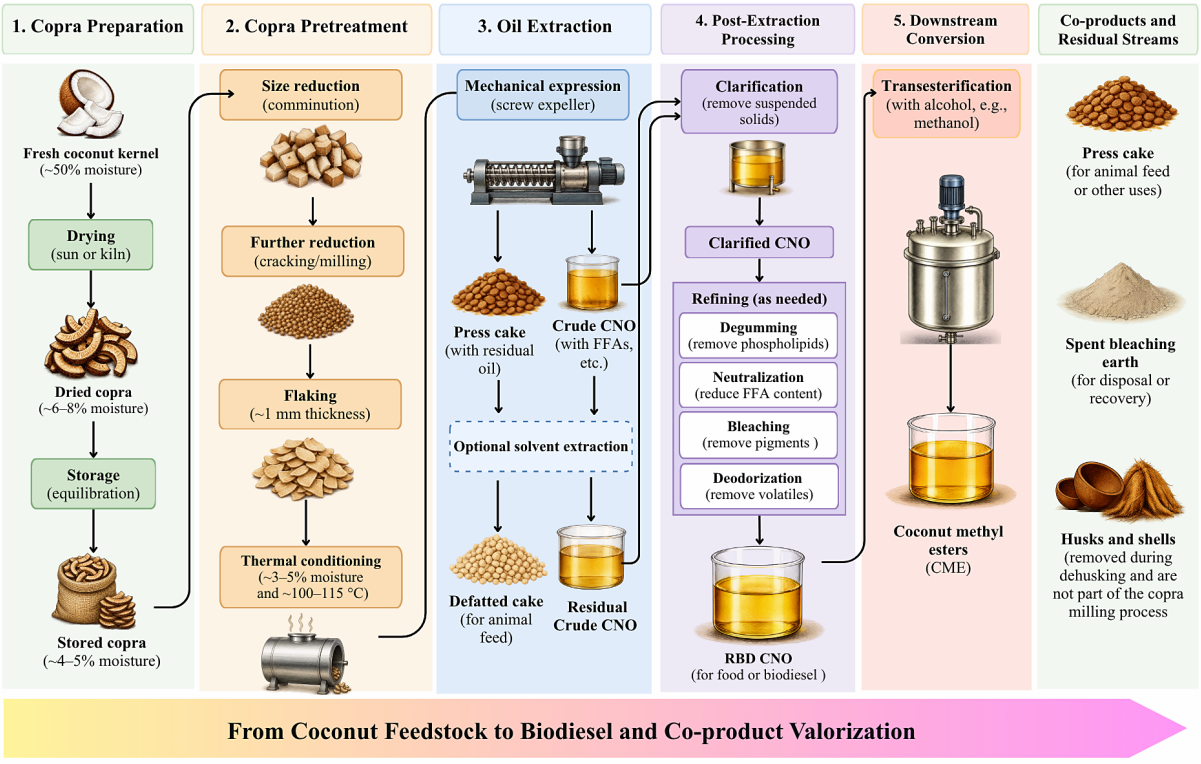

Figure 2. Process flow for conventional CNO production via copra milling in the Philippines, from preparation and drying through mechanical expression, optional solvent extraction, clarification, and refining to CME-ready CNO. Major co-products and residual streams are also indicated.

seed and nut oil recovery are examined in turn below. These considerations carry particular weight for biodiesel-oriented CNO production, where extraction must support a high-volume lipid feedstock that meets the quality thresholds transesterification requires (Leung et al., 2010; Ma & Hanna, 1999), rather than maximize bioactive compound concentration.

Microwave-assisted extraction

MAE uses electromagnetic radiation, generally 300 MHz to 300 GHz, to heat the extraction system rapidly. Unlike conventional heating, which transfers thermal energy progressively from the surface inward, microwave energy interacts directly with susceptible molecules through dipole rotation and ionic conduction, converting electromagnetic energy into heat within the medium (Ferreira et al., 2022; Lopez-Avila & Luque de Castro, 2014). This rapid internal heating raises the temperature and pressure of intracellular moisture, disrupting cellular structures and releasing lipids into the extraction medium.

MAE's effectiveness depends on both feedstock and operating conditions, including power, irradiation time, temperature, moisture, particle size, solvent-to-solid ratio, and the medium's dielectric properties (Ferreira et al., 2022). Nonpolar solvents like hexane absorb microwave energy poorly, but since oils are themselves nonpolar and dissolve poorly in polar media, the practical remedy is not a polar solvent alone but a nonpolar-polar solvent mixture, which improves microwave coupling while preserving lipid solubility; moisture already present in the matrix can also serve as an absorber (Lopez-Avila & Luque de Castro, 2014). The extraction medium must therefore be chosen for microwave interaction as well as lipid solubility.

MAE systems generally comprise a magnetron, waveguide, extraction chamber, and control systems (Lopez-Avila & Luque de Castro, 2014). As shown in Figure 3, prepared biomass is contacted with an extraction medium within the chamber, where irradiation drives heating and mass transfer, before the extract is separated from residual solids and solvent recovered where applicable. Closed-vessel configurations permit operation above the solvent's boiling point; Figure 3 depicts one representative arrangement rather than a universal one.

MAE may serve as a direct extraction technique or as a pretreatment before mechanical or solvent extraction (Lopez-Avila & Luque de Castro, 2014). For feedstocks already thermally conditioned before pressing, microwave treatment can function as an intensified conditioning step rather than a stand-alone process. This pretreatment has been studied across rapeseed, hazelnut, avocado, olive, soybean, sunflower, rice bran, and sesame (Azadmard-Damirchi et al., 2011). Hazelnut treated at 400 W for 240 s reached 45.3% oil yield (Uquiche et al., 2008); soybean pretreated before hexane extraction reached up to 10% at 620 W for 30 s (Gabe & Silva, 2022); and avocado treated with microwaves before hexane extraction reached 97% yield, versus 54% for hexane alone (Ortiz Moreno et al., 2003).

Direct MAE has also been investigated, primarily for oil yield. Hu et al. (2018) achieved 24.1% yield in tiger nut oil at 420 W and 75 °C for 55 min — about 6.5 times faster than conventional extraction, despite the lower yield. A continuous pilot-scale system recovered over 93% of total oil from soybean and rice bran (Terigar et al., 2011), while an aqueous salt-aided method achieved 32.08% yield from peanut, below the 43% from Soxhlet-hexane but avoiding organic solvents entirely (Shalmashi, 2023). Yield under direct MAE therefore varies with matrix and configuration, and cannot be assessed apart from time and solvent requirements.

Microwave treatment can also affect oil composition: MAE-extracted tiger nut oil showed lower acid and peroxide values alongside higher phenolics, tocopherols, and phytosterols than conventionally extracted oil (Hu et al., 2018). Such effects matter less for biodiesel, where preserving the triglyceride fraction and controlling FFA and moisture matters more than nutraceutical recovery (Ferreira et al., 2022).

Excessive power or treatment time can cause localized overheating and degrade thermally sensitive constituents (Lopez-Avila & Luque de Castro, 2014), and performance is sensitive to matrix moisture and dielectric properties, requiring feedstock-specific optimization (Ferreira et al., 2022). At larger scale, microwave penetration, field distribution, and uniform heating of heterogeneous matrices become challenging. Shorter laboratory extraction times alone cannot establish lower industrial energy use, since throughput and capital requirements must be weighed alongside yield (Alazaiza et al., 2026; Shahbaz et al., 2025).

For CNO recovery, MAE has recently been evaluated directly, with results depending on

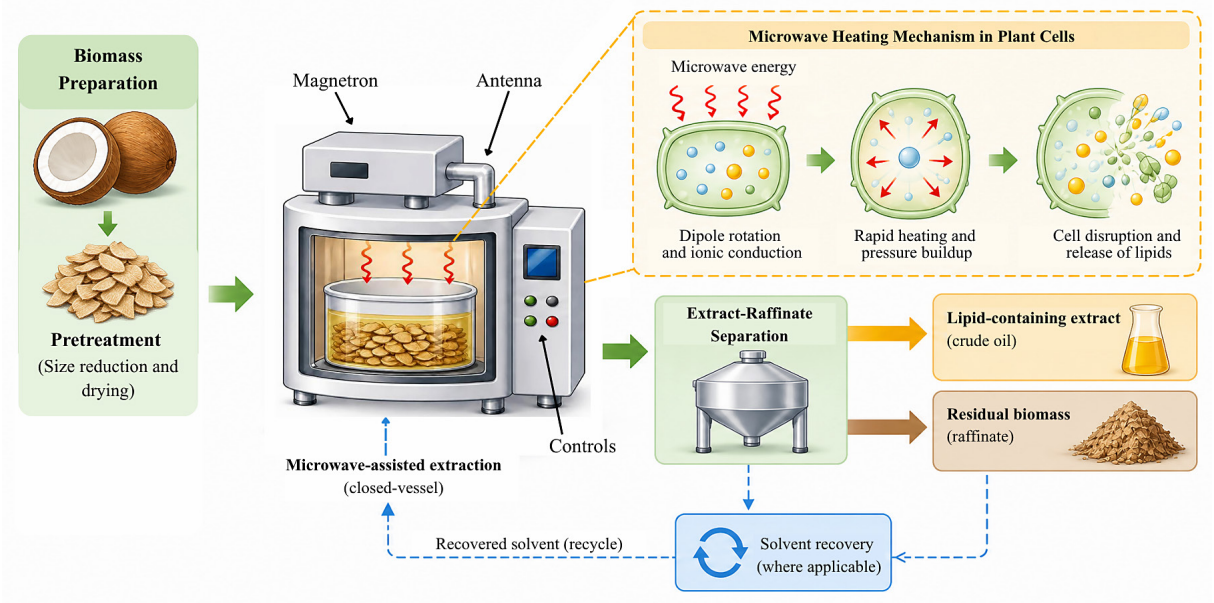

Figure 3. Schematic representation of an MAE system for seed and nut oil recovery. Biomass is prepared, then irradiated within the extraction chamber, where microwave energy drives dipole rotation and ionic conduction, raising intracellular temperature and pressure to disrupt cell structures and release lipids into the extraction medium. The mixture then undergoes extract-raffinate separation, with recovered solvent recycled to the extraction stage.

processing route. In wet systems, Martínez-Padilla et al. (2022) reported that microwave treatment (1 min, 4.31 kW/kg) of coconut milk raised oil yield by approximately 20% over an untreated control, recovering up to 81% of pulp oil in the milk fraction. Negi et al. (2024) found that microwave pretreatment (450 W, 2 min) of coconut cream before centrifugation and freeze–thaw raised VCO yield to 91.53%, versus 86.28% for untreated cream, attributing the gain to volumetric heating that ruptures cell walls and denatures the lipoprotein membrane around oil bodies.

Results are more mixed for dried copra. Hakimi et al. (2019) compared direct MAE against Soxhlet and ultrasound-assisted extraction on copra residue using hexane, the standard solvent in copra processing. MAE gave the lowest yield of the three (62.97% at 15 min, versus 75.8% for ultrasound and 81.39% for Soxhlet at their respective optimal times), attributed to hexane's low dielectric constant limiting microwave coupling. It nonetheless gave the lowest FFA content (0.37% versus 0.5% and 0.67%), a quality advantage relevant to biodiesel conversion since lower FFA reduces saponification risk during transesterification; fatty acid composition did not differ meaningfully across methods. Similarly, Maria et al. (2026) found that microwave preheating before mechanical pressing did not significantly improve yield over conventional oven drying, though it reduced residual moisture and FFA and extended predicted shelf life.

This contrast suggests MAE's benefit for CNO depends on whether the kernel is processed wet or dry: aqueous treatment shows a clearer yield advantage, while microwave processing of dried copra, whether as pretreatment or direct extraction, appears to improve quality more than recovery. Notably, Hakimi et al.'s (2019) hexane-based system may itself have constrained MAE's yield, given hexane's poor microwave coupling noted earlier; whether a polar solvent or solvent mixture would close this gap on industrial-scale Philippine copra remains untested. Evaluation under such conditions, rather than fresh milk or small-batch hybrid coconut, is still needed to confirm whether MAE offers a meaningful commercial advantage.

Ultrasound-assisted extraction

UAE employs high-frequency sound waves to intensify the release of intracellular compounds from plant matrices. Its principal mechanism is acoustic cavitation: alternating compression and rarefaction cycles form, grow, and collapse microscopic bubbles, generating localized shear forces, microjets, and turbulence that disrupt plant tissue and expose intracellular oil to the extraction

medium (Chemat et al., 2017; Shen et al., 2023). This improves solvent penetration, contact area, and diffusion pathways for lipid transfer.

Ultrasound can serve as the principal extraction technique or as a pretreatment intensifying solvent, aqueous, enzymatic, or mechanical recovery. Li et al. (2004) showed ultrasound enhanced soybean oil extraction with hexane via increased mass transfer and cellular disruption. UAE has since been extended to flaxseed, pomegranate, papaya, raspberry, Brazil nut, macadamia, hazelnut, and moringa, among other matrices (Samaram et al., 2013; Schons et al., 2017; Shah Buddin et al., 2018; Teng et al., 2016; Tian et al., 2013; Wong et al., 2019; Zhang et al., 2008; Zhu et al., 2012).

Effectiveness depends on ultrasonic frequency, power, amplitude, time, temperature, particle size, solid-to-liquid ratio, and solvent type, as well as the medium's viscosity, surface tension, and vapor pressure (Chemat et al., 2017; Shen et al., 2023). Greater intensity strengthens cavitation up to a point, beyond which yield gains taper; conditions must therefore be optimized per matrix-solvent system rather than by power or temperature alone.

UAE may use ultrasonic baths, where energy transmits indirectly through the vessel, or probe systems, which deliver energy directly into the mixture at greater local intensity (Chemat et al., 2017; Shen et al., 2023). As shown in Figure 4, biomass is dispersed in a solvent and sonicated under temperature control before the liquid phase is separated from residual solids — one representative probe-based configuration among several possible arrangements.

Enhancement varies considerably by matrix and system. Zhang et al. (2008) shortened flaxseed extraction substantially relative to conventional processing; Tian et al. (2013) achieved high pomegranate seed oil recovery under mild conditions; and Samaram et al. (2013) reduced papaya seed oil extraction from hours to approximately 30 min while maintaining comparable fatty acid composition. These results support UAE's core advantage: accelerated mass transfer without prolonged conventional heating.

UAE can also intensify aqueous or enzymatic extraction, since cavitation-induced damage improves solvent or enzyme access. Liu et al. (2019) combined enzymatic treatment with ultrasonication for *Sapindus mukorossi* oil, while Shah et al. (2005) did so for *Jatropha curcas* — illustrating UAE's role as an intensification step rather than a standalone technology, a distinction relevant again in the next subsection (EAE).

Beyond yield, ultrasound can alter oil composition. Samaram et al. (2013) found

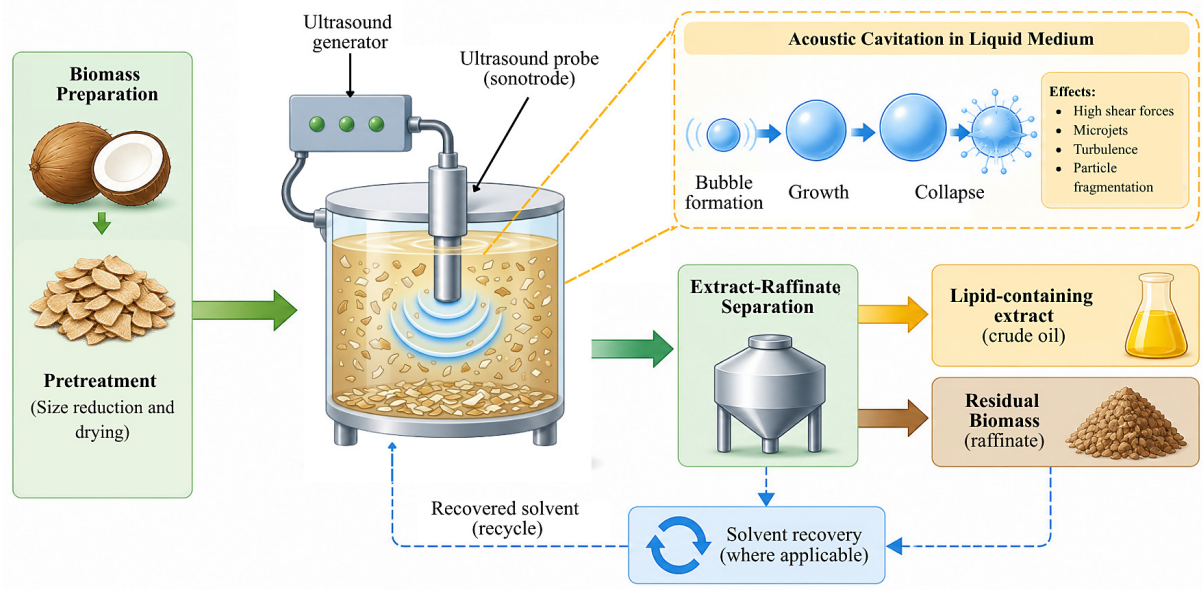

Figure 4. Schematic representation of a probe-based UAE system for seed and nut oil recovery
Biomass is prepared, then sonicated via an ultrasound probe within the extraction vessel,
where acoustic cavitation drives bubble formation, growth, and collapse, generating shear forces, microjets,
turbulence, and particle fragmentation that disrupt plant tissue and release oil into the medium.
The mixture then undergoes extract-raffinate separation, with recovered solvent recycled to the extraction stage.

UAE-extracted papaya oil retained fatty acid composition comparable to solvent-extracted oil despite a significantly altered triacylglycerol profile, with lower triolein. Since the ester profile after transesterification depends primarily on fatty acid composition rather than triacylglycerol arrangement, this suggests UAE need not compromise CME quality even where triacylglycerol shifts occur; such shifts more likely affect the oil's own crystallization behavior. UAE's moderate bulk temperature can also reduce thermal exposure relative to heated extraction (Hernández-Santos et al., 2016; Tian et al., 2013), though quality preservation cannot be assumed from low bulk temperature alone.

Cavitation nonetheless creates energetic localized conditions — transient high temperature and pressure that can accelerate oxidation of susceptible compounds despite moderate average temperatures (Chemat et al., 2017; Shen et al., 2023). Probe systems add practical concerns, including sonotrode erosion under prolonged high-intensity operation. Power and time must therefore be optimized for recovery, quality, and equipment durability alike.

UAE's environmental advantage depends on how it is integrated into the full process (Alazaiza et al., 2026; Shahbaz et al., 2025): retaining hexane still requires solvent handling and recovery, while aqueous or enzyme-assisted configurations avoid petroleum solvents but add separation steps. Green credentials should therefore rest on solvent use, energy input, and waste generation, not on ultrasound itself.

Scale-up is a major challenge: acoustic intensity decreases with distance from the source, and larger reactors risk nonuniform cavitation, requiring attention to transducer placement, geometry, and flow (Cauduro et al., 2025; Chemat et al., 2017). Laboratory and pilot-scale systems demonstrate technical feasibility but not yet economic competitiveness at high throughput.

For CNO recovery, cavitation may intensify residual-oil recovery or serve as pretreatment before pressing, and direct evidence now exists. Martínez-Padilla et al. (2022) found ultrasound treatment (2.5 min, 6.85 W/cm²) of coconut milk improved oil extraction by 10–16% and protein recovery by up to 86%, alongside a 77.6% increase in recovered phenolics. Che-U-Bong et al. (2025) instead pretreated coconut residue — the solid by-product of milk or copra processing — with ultrasound (180 W, 45 min) before extracting the oil in ethanol at 60 °C, chosen as a food-safe alternative to hexane. This yielded 23.3% oil with FFA and peroxide values (0.9% and 0.25 meq/kg oil) below thresholds recommended for crude CNO.

SEM confirmed the mechanism: pretreated residue showed cracked, porous surfaces consistent with cavitation-induced cell disruption, versus a compact surface untreated. The pretreated oil also showed lower markers of secondary lipid oxidation alongside higher phenolic content and radical-scavenging activity than oil from untreated residue (Che-U-Bong et al., 2025) — evidence that ultrasound pretreatment need not compromise, and may even improve, the oxidative stability relevant to CME storage. This makes residual coconut solids a plausible secondary CNO stream for the biodiesel value chain, though ethanol recovery adds a solvent-handling step absent from direct kernel milling — one instance of the broader liquid-biomass contact that solvent- or water-assisted UAE requires beyond dry copra milling. As with the microwave findings in the previous subsection, this evidence comes largely from fresh coconut milk or residue processing rather than industrial copra; copra-specific studies remain needed to confirm whether the same gains hold for the Philippine dry-milling route.

Enzyme-assisted extraction

EAE relies on hydrolytic enzymes to weaken structural components of plant tissue that restrict access to intracellular oil. Cellulases and hemicellulases hydrolyze structural polysaccharides, pectinases disrupt pectin-rich intercellular regions, and proteases degrade proteins stabilizing lipid bodies (Nadar et al., 2018; Vovk et al., 2023). The resulting loss of cellular integrity improves lipid accessibility and facilitates oil recovery.

Effectiveness depends on the feedstock's biochemical composition and hydrolysis conditions, including enzyme type and concentration, pH, temperature, time, particle size, solid-to-liquid ratio, and agitation (Nadar et al., 2018; Streimikyte et al., 2022; Vovk et al., 2023). Because enzymes have characteristic pH and temperature optima, conditions must sustain activity while limiting processing time and oil deterioration; enzyme cocktails suit heterogeneous matrices by targeting distinct structural barriers, though effectiveness remains feedstock-dependent.

EAE may be applied as an aqueous process, a pretreatment before mechanical or solvent

extraction, or part of a hybrid system. In aqueous EAE, comminuted biomass is dispersed in water and treated with enzymes under controlled pH and temperature (Ferreira et al., 2022). As shown in Figure 5, hydrolysis weakens the matrix and releases oil, which is then separated from the aqueous and solid fractions — though part may remain in cream or emulsified phases rather than as free oil. Figure 5 depicts one simplified configuration rather than a universal one.

Aqueous EAE has been applied across several seeds: Jiang et al. (2010) recovered both oil and protein hydrolysates from peanut; Mat Yusoff et al. (2016) extracted *Moringa oleifera* oil; and Latif et al. (2008) recovered oil and protein from canola. This capacity for simultaneous fractionation distinguishes EAE from methods focused solely on lipid recovery.

EAE also functions as a pretreatment before conventional pressing. Passos et al. (2009) enhanced grape seed oil recovery with a cell-wall-degrading cocktail; Concha et al. (2004) pretreated rose-hip seed; and Candan and Arslan (2021) found pretreatment improved apricot kernel recovery but not flaxseed — showing that successful hydrolysis does not guarantee improved recovery, since feedstock architecture governs the outcome.

EAE has further been combined with ultrasonication (Liu et al., 2019, for *Sapindus mukorossi*; Shah et al., 2005, for *Jatropha curcas*) and with microwave-ultrasound treatment for tiger nut (Hu et al., 2020), and can precede solvent extraction, as shown for soybean (Domínguez et al., 1995). Such combinations illustrate EAE's versatility as an intensification step, though solvent-retaining systems still carry solvent handling and recovery burdens.

Mild hydrolysis temperatures can benefit oil quality: Kaseke et al. (2021) examined enzymatic pretreatment's effect on pomegranate seed oil, and favorable phenolic and tocopherol retention has been reported broadly for enzyme-assisted systems (Ferreira et al., 2022). These benefits matter less for biodiesel, where minimizing FFA, moisture, and protein or phospholipid carryover matters more than preserving bioactive constituents.

A major limitation arises after oil release: proteins, phospholipids, and other surface-active components can stabilize oil-in-water emulsions, leaving oil in cream phases rather than as separable free oil (Shao et al., 2025). Centrifugation, pH adjustment, or demulsification may be needed, so EAE performance should distinguish total oil released from oil actually recovered.

The aqueous environment adds water-handling burdens — mixing, heating, and wastewater treatment scale with liquid-to-solid ratio, while long hydrolysis times constrain throughput. Enzyme cost and the need to maintain pH and temperature further affect economics (Nadar et al., 2018; Plyduang et al., 2026). Comparing enzyme sources for coconut specifically, Eshtiaghi and Nakthong (2021) found that a crude bromelain-rich extract prepared from pineapple achieved a

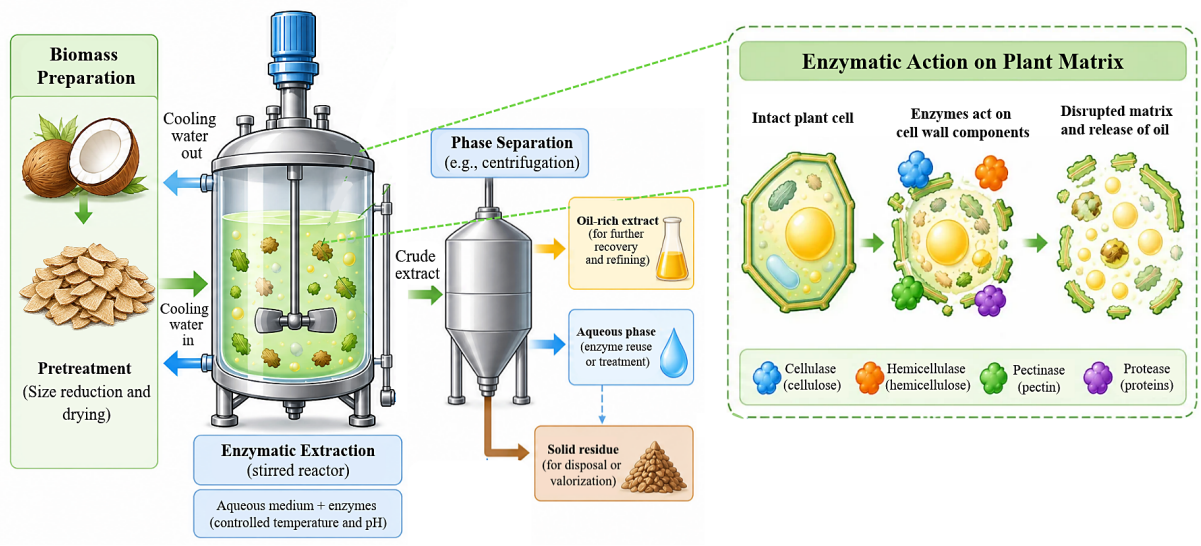

Figure 5. Schematic representation of an aqueous EAE system for seed and nut oil recovery
Biomass is treated with various hydrolyzing enzymes in a stirred, temperature- and pH-controlled reactor, degrading cell-wall and lipid-body components to release oil. The mixture then undergoes phase separation into oil-rich extract, aqueous phase, and solid residue, with enzymes optionally recovered for reuse.

20.5% oil yield from coconut meat rasp under optimized conditions (1% w/w, pH 6.5, 60 °C, 6 h), closely approaching yields obtained with a commercial technical enzyme blend under its own optimum conditions. This suggests plant-derived crude extracts could offset some of the enzyme-cost burden noted above, provided supply and activity remain consistent at industrial scale.

These considerations grow more consequential at scale generally, where uniform distribution and phase separation must also be maintained. EAE's environmental advantage therefore depends on whether reduced solvent use and co-product recovery offset enzyme, water, and separation costs (Nadar et al., 2018; Plyduang et al., 2026).

For CNO recovery, compatibility with the existing process route is a key concern. Copra is highly dried, whereas aqueous EAE requires water for hydrolysis and separation — reintroducing water to material that has already undergone energy-intensive drying (Nadar et al., 2018; Vovk et al., 2023). EAE may therefore suit fresh coconut kernel or other wet-processing routes better than conventional copra milling, potentially coupling CNO recovery with protein- and carbohydrate-rich fraction valorization.

Direct evidence for CNO now exists as well. Maria et al. (2026) applied lipase (Lipozyme TL IM) and ultrasound to microwave-preheated coconut pulp and achieved yields up to 74.26% — substantially higher than the 62.8% obtained by mechanical pressing alone — but at a cost to quality across their broader experimental range, where FFA reached as high as 16.95% and moisture up to 1.3% at the most extreme conditions tested. Their numerically optimized condition, balancing yield against quality, instead predicted 72.3% yield alongside 5.51% FFA, only marginally above the ~5% threshold at which base-catalyzed transesterification risks saponification (Ramos et al., 2009), indicating the practically relevant operating point sits close to, rather than far past, the CME-relevant quality threshold.

Any benefit from avoiding drying would still need to be weighed against enzyme consumption, hydrolysis time, water handling, and recovered-oil quality; a wet route also departs further from established Philippine infrastructure (Aguilar et al., 2022) than using EAE merely as pretreatment. Direct studies on coconut matrices are needed to compare recovery, water and enzyme demand, energy consumption, and transesterification performance. EAE currently appears most promising for integrated wet-processing or biorefinery applications (Jiang et al., 2010; Latif et al., 2008; Mat Yusoff et al., 2016), but its advantages for high-throughput biodiesel-oriented CNO production remain undemonstrated.

Supercritical fluid extraction

SFE uses a fluid held above its critical temperature and pressure, combining liquid-like density with gas-like diffusivity and low viscosity, letting it penetrate porous plant matrices while retaining solvent capacity (Ferreira et al., 2022; Reverchon & De Marco, 2006). This gives it a mechanism distinct from MAE, UAE, and EAE, which enhance yield by disrupting the cell wall via microwave-induced pressure, cavitation, or enzymatic hydrolysis. SFE's action is staged instead: at low to moderate extraction, it selectively degrades pectic polysaccharides and hemicelluloses, loosening the pectin-hemicellulose network and raising wall porosity without breaking it, so lipids diffuse out through the intact structure (Femenia et al., 2001). Only at higher recovery does the wall undergo major disruption, including cellulose loss, after which oil release resembles that of mechanically or chemically ruptured cells — a staged mechanism demonstrated in almond SC-CO_2 extraction but not yet investigated for CNO.

CO_2 remains the most widely used fluid for lipid extraction: its critical point is mild (31.1 °C, 7.38 MPa), and it is nonflammable, low in toxicity, and readily separated from the extract by depressurization, with low polarity giving it strong affinity for triglycerides (Ferreira et al., 2022; Sahena et al., 2009). A typical SFE system built around it comprises a CO_2 supply, pump, heat exchanger, high-pressure extraction vessel, and separator (Figure 6): biomass contacts pressurized CO_2, dissolved lipids transport to the separator, where reduced pressure or temperature precipitates the oil, and CO_2 is recompressed and recycled — a pressure-controlled separation that avoids the evaporation-intensive recovery step conventional solvent extraction requires.

Extraction behavior within this system is governed principally by pressure and temperature, which together set fluid density, solute vapor pressure, and solvent power (Reverchon & De Marco, 2006; Sahena et al., 2009). Pressure generally raises density and solubility, though the effect weakens at higher levels, while temperature has competing effects, lowering density but raising vapor

pressure. Other parameters include CO_2 flow rate, particle size, feed moisture, and polar co-solvents such as ethanol, which aid recovery of polar constituents but complicate downstream separation (Ferreira et al., 2022; Shahbaz et al., 2025).

This tunability has enabled application to numerous seeds and nuts: Ferreira et al. (2022) compiled studies on pecan, walnut, Brazil nut, almond, hazelnut, macadamia, and sapucaia, with performance varying by matrix and conditions. Salvador et al. (2016) obtained a maximum pecan oil yield of 58.4% at 30 MPa and 40 °C, below Soxhlet yields but with comparable fatty acid composition, illustrating that SFE need not exceed gravimetric yield to offer value, given its selectivity, quality, and freedom from residual solvent.

SFE has similarly been applied to sunflower, rice bran, soybean, apple seed, and moringa, among other matrices (Belo et al., 2019; Ferrentino et al., 2020; Rai et al., 2016; Sookwong & Mahatheeranont, 2017). In apple seed oil, higher pressure raised both oil yield and tocopherol content, but higher temperature had the opposite effect on tocopherol recovery (Montañés et al., 2018). Even extreme pressure-temperature combinations produced only marginal yield gains — evidence that pushing pressure and temperature together does not straightforwardly improve outcomes.

Oil quality is a principal SFE advantage: moderate temperatures and limited oxygen exposure reduce deterioration, and depressurization leaves little CO_2 residue. Ferreira et al. (2022) found SFE-extracted nut oils generally retained fatty acid profiles comparable to conventional extraction, though tocopherol and phenolic content varied by matrix — benefits that matter more for premium oils than for biodiesel feedstock, where triglyceride recovery and control of moisture, FFA, and residual solvent take priority over nutraceutical concentration.

These quality benefits, however, should not obscure SFE's economic and environmental trade-offs. SFE should not be considered environmentally advantageous simply because CO_2 replaces hexane: compression requires substantial energy, and its footprint depends on electricity demand, recycling efficiency, and throughput. The principal barriers are therefore high-pressure operation and economics: vessels, pumps, and separators must withstand substantial pressure, raising equipment cost and safety requirements above atmospheric extraction, and batch loading can constrain throughput. SFE is technically established industrially, but viability depends strongly on scale, feedstock value, and yield (Perrut, 2000; Temelli, 2009) — considerations that weigh more heavily for bulk biodiesel feedstock, given its narrower margin for absorbing high-pressure costs.

Unlike most alternative approaches reviewed here, SFE has been investigated directly and extensively for coconut oil. Punvichai et al. (2026) evaluated temperature (35–100 °C), pressure (74–450 bar), and time (30–90 min) for SC-CO_2 extraction of Thai copra, finding lower temperature with higher pressure and longer time favored yield: at 35 °C, 450 bar, and 90 min, oil yield reached 42.32% — 2.3 times higher than screw pressing and 94.4% of hexane extraction. Peroxide values under these conditions (1.26 meq O_2/kg oil) were lower than for screw pressing (1.46) and hexane extraction (1.57), consistent with SC-CO_2's low-oxygen environment limiting oxidative degradation.

The same study found SC-CO_2 selective for lauric acid (C12:0), CNO's dominant fatty acid: content rose from ~47% in screw-pressed or hexane-extracted oil to a maximum of 52.02% at 35 °C, 150 bar, and 90 min, before declining above 250 bar as higher CO_2 density co-extracted longer-chain lipids and unsaponifiable matter. Since ester chain length affects CME properties such as cetane number and cold-flow behavior, this pressure-tunable enrichment offers a route to adjust CME composition without blending or post-extraction fractionation.

Independently, a Chinese patent (State Intellectual Property Office of the P.R.C., CN101524099A, 2009) describes a comparable process — SC-CO_2 extraction of dried, ground coconut kernel with ethanol as entrainer, followed by pressure-reduction separation — reporting VCO recovery of 85–90% at 25–40 MPa, 35–45 °C, and 1–3 h. Though not peer-reviewed, this independently filed process broadly corroborates SC-CO_2's viability for coconut lipid recovery.

SFE also offers a feature relevant to biodiesel: potential integration with reaction. Supercritical systems have been investigated for simultaneous or sequential extraction and transesterification with *Jatropha curcas*, soybean, rapeseed, palm, and canola (Kondo et al., 2002; Lee et al., 2014; Lim & Lee, 2013; Rezaei & Temelli, 2001), potentially reducing separation steps — relevant since CNO is evaluated here as a CME feedstock rather than an edible oil. Integrated coconut

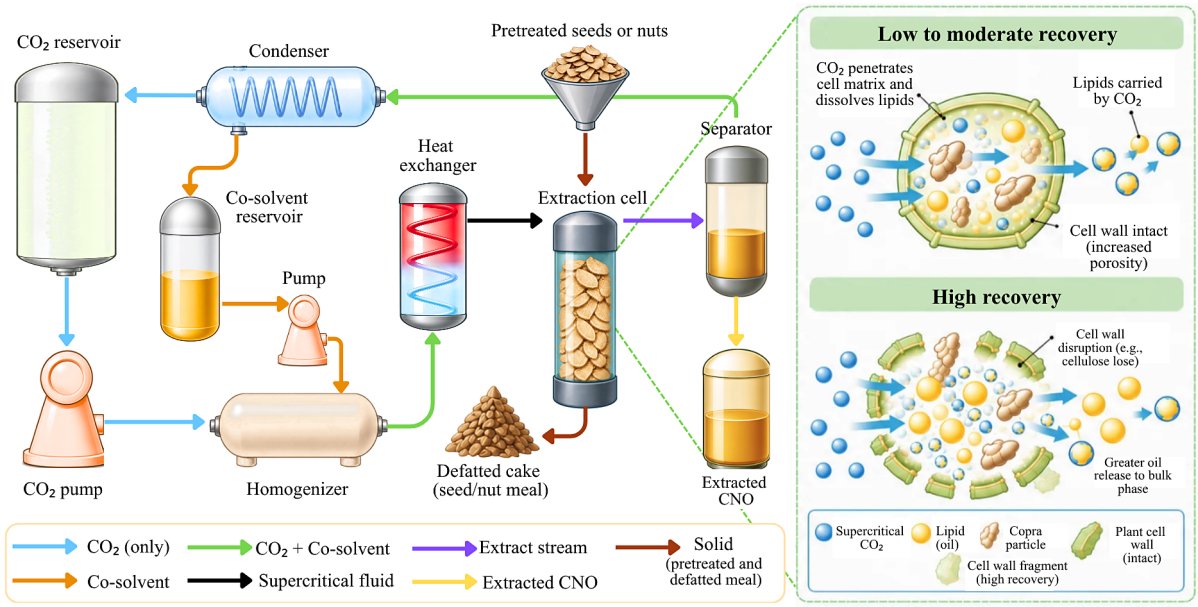

Figure 6. Schematic of an SFE system for coconut oil recovery from copra. Supercritical CO_2, optionally combined with a co-solvent, passes through extraction cells before separators recover the oil and the CO_2 is recycled. The inset shows the staged cell-level mechanism: at low to moderate recovery, CO_2 dissolves lipids that diffuse out through an intact, increasingly porous cell wall; at high recovery, the wall itself disrupts, releasing oil more freely into the bulk phase.

SFE-transesterification remains unstudied, and the gains reported by Punvichai et al. (2026) are not yet confirmed at throughput scales relevant to commodity biodiesel production.

SFE therefore warrants closer examination for Philippine CNO than simple extrapolation from other matrices. Its affinity for triglycerides, mild temperatures, tunable solvent power, freedom from solvent residues (Reverchon & De Marco, 2006; Sahena et al., 2009), and coconut-specific yield and selectivity gains (Punvichai et al., 2026), are notable strengths. Its staged extraction mechanism adds a further advantage: because bulk cellular material stays largely contained until the wall itself fails, oil recovered before that threshold likely carries less co-extracted debris than mechanically or solvent-ruptured oil, a potential purity benefit for downstream CME refining that has not yet been tested for CNO.

These strengths are counterbalanced by high capital requirements, compression energy, and throughput constraints that weigh especially heavily for a commodity biodiesel feedstock (Perrut, 2000; Temelli, 2009). Whether the advantages offset these costs under Philippine copra-processing conditions is examined comparatively in the next section, before the following section turns to SFE's specific application in Philippine CNO and CME production.

TECHNOLOGY ASSESSMENT FOR PHILIPPINE CNO-CME ADOPTION

Comparative synthesis across MAE, UAE, EAE, and SFE

On extraction efficiency, no technology shows a consistent advantage across matrices, and the reported percentages aren't directly comparable, since studies differ in what "% yield" represents: Punvichai et al. (2026) report oil mass as a percentage of total dry biomass, while Hakimi et al. (2019) report it as a percentage of total recoverable oil content, so a larger number can simply reflect a different definition rather than better performance. On dried copra residue, Hakimi et al.'s (2019) comparison against Soxhlet extraction found MAE gave the lowest yield of the three methods tested, UAE intermediate. Maria et al.'s (2026) microwave preheating before mechanical pressing similarly produced no significant yield gain, while their enzyme-ultrasound treatment of microwave-preheated pulp achieved the largest quantified improvement among all direct CNO comparisons, 74.26% against a 62.8% baseline, though on fresh pulp rather than dried copra. Punvichai et al.'s (2026) SFE yield of 42.32% from dried Thai copra was 2.3 times higher than screw pressing and approached hexane extraction. Read

together, EAE and SFE show the clearest gains over their own baselines, while MAE shows no advantage, or a disadvantage, on the dry-copra route specifically, though these comparisons hold only within each study, not against each other's absolute figures.

Oil quality is more consistently favorable than yield, with one partial exception. Maria et al.'s (2026) numerically optimized EAE condition, balancing yield against quality, predicted 72.3% yield alongside 5.51% FFA, only marginally above the ~5% threshold at which base-catalyzed transesterification risks saponification (Ramos et al., 2009); higher-yield conditions within their broader experimental range pushed FFA considerably higher, but the practically optimized operating point sits close to, rather than far past, the CME-relevant threshold. MAE and UAE both improved FFA and, in UAE's case, peroxide values relative to their respective baselines (Che-U-Bong et al., 2025; Hakimi et al., 2019). SFE produced the lowest peroxide values of any technology examined and offers a compositional lever, tunable lauric acid enrichment, unavailable to the other three (Punvichai et al., 2026).

Feasibility is where the technologies diverge most, and where Philippine infrastructure specifically matters. MAE and EAE share a structural mismatch with dried copra, though for different reasons: MAE's mechanism partly depends on matrix moisture as a microwave absorber, depleted in copra dried to 4–5% moisture (Lopez-Avila & Luque de Castro, 2014), while EAE's hydrolysis requires reintroducing water to material already put through energy-intensive drying (Nadar et al., 2018). UAE's constraint is physical rather than compositional, acoustic intensity attenuates with distance from the source, and remains unresolved beyond pilot scale (Cauduro et al., 2025; Chemat et al., 2017). SFE's barrier is capital intensity: high-pressure equipment raises cost and safety requirements well above atmospheric alternatives (Perrut, 2000; Temelli, 2009), a burden that weighs heavily against a low-unit-value commodity feedstock.

Table 1. Cross-technology comparison of MAE, UAE, EAE, and SFE for CNO recovery

Criterion	MAE	UAE	EAE	SFE
Evidence maturity for CNO	Tested on wet and dry routes (coconut milk/cream, copra) (Martínez-Padilla et al., 2022; Negi et al., 2024; Hakimi et al., 2019; Maria et al., 2026)	Tested on coconut milk and residue, wet/residue routes only (Martínez-Padilla et al., 2022; Che-U-Bong et al., 2025)	Tested on fresh coconut pulp; no dry-copra evidence (Eshtiaghi & Nakthong, 2021; Maria et al., 2026)	Most direct and comprehensive: dedicated Thai copra study (Punvichai et al., 2026)
Extraction efficiency	Underperformed UAE and Soxhlet extraction on copra residue; no gain from preheating before pressing (Hakimi et al., 2019; Maria et al., 2026)	Moderate improvement on copra residue; below solvent baseline (Hakimi et al., 2019; Martínez-Padilla et al., 2022)	Largest quantified gain, but on fresh pulp (Maria et al., 2026)	2.3× higher compared to screw pressing; approaches hexane yield (Punvichai et al., 2026)
Oil quality	Improved FFA relative to comparators (Hakimi et al., 2019; Maria et al., 2026)	Improved FFA and peroxide values (Che-U-Bong et al., 2025)	FFA marginally exceeds biodiesel-relevant threshold at optimized yield; considerably higher at extreme conditions (Maria et al., 2026)	Lowest peroxide values; tunable lauric acid enrichment (Punvichai et al., 2026)
Feasibility/ scalability	Moisture-dependence mismatched with dried copra (Lopez-Avila & Luque de Castro, 2014; Hakimi et al., 2019)	Acoustic attenuation unresolved beyond pilot scale (Chemat et al., 2017; Cauduro et al., 2025)	Requires reintroducing water to dried copra (Nadar et al., 2018; Vovk et al., 2023)	High capital and pressure-equipment costs (Temelli, 2009; Perrut, 2000)
Environmental performance	Solvent-handling burden due to polar-nonpolar solvent mixture requirements; additional separation steps (Alazaiza et al., 2026; Shahbaz et al., 2025)	Ethanol/aqueous variants reduce solvent use, additional separation steps (Alazaiza et al., 2026; Che-U-Bong et al., 2025)	Solvent-free, but adds wastewater treatment demand; additional separation steps (Nadar et al., 2018; Plyduang et al., 2026)	No solvent residue; compression-energy intensive (Sahena et al., 2009; Shahbaz et al., 2025)

Note: FFA = free fatty acid. CME-relevant FFA threshold follows Ramos et al. (2009).

Environmental performance depends on process integration rather than the technology itself. Hexane-based MAE and UAE both carry solvent handling and recovery burdens, though the available remedy differs: UAE's mechanism does not depend on solvent polarity, so a full switch to ethanol is feasible and reduces petroleum solvent use, while MAE requires a nonpolar solvent to retain lipid solubility, so its practical mitigation is a nonpolar-polar solvent mixture rather than a full substitution, still leaving a separation burden (Alazaiza et al., 2026). EAE's aqueous route avoids organic solvents but scales its own wastewater demand with liquid-to-solid ratio (Nadar et al., 2018; Plyduang et al., 2026). SFE avoids solvent residue and permits CO_2 recycling, but its compression energy means it cannot be assumed environmentally superior by default (Sahena et al., 2009; Shahbaz et al., 2025). Table 1 summarizes this cross-technology comparison.

Multicriteria evaluation of technology readiness

Because the evidence above spans different feedstock forms, scales, and reported metrics, this evaluation applies the Analytic Hierarchy Process (AHP) to organize readiness for Philippine adoption systematically rather than relying on an unweighted narrative comparison. AHP derives priority weights from pairwise comparisons of the evaluation criteria, following Saaty (2008), and applies these weights to score the four technologies against the readiness objective established above.

Table 2 presents the pairwise comparison matrix for the five criteria, constructed on Saaty's 9-point scale and reflecting the priority ordering discussed above: evidence maturity for CNO first, followed by feasibility, oil quality, extraction efficiency, and environmental performance. The resulting weights yielded a consistency ratio of CR = 0.022, well within the acceptability threshold of 0.10 (Saaty, 2008), confirming the pairwise judgments are internally coherent. Each technology was then scored from 1 to 5 per criterion, and composite priorities were obtained in Table 3 by combining these scores with the derived weights.

SFE ranks first, followed by MAE, UAE, and EAE. To test whether this ranking depends on the priority given to evidence maturity, a sensitivity analysis was performed (Saaty, 2008) by permuting the pairwise matrix to make feasibility, rather than evidence maturity, the dominant criterion, while holding all other pairwise relationships fixed; this permutation preserves the original consistency ratio exactly (CR = 0.022), avoiding an internally inconsistent comparison. The ranking order was unchanged under this alternative weighting (SFE > MAE > UAE > EAE in both scenarios; Supplementary Material S1, Table S6), indicating that SFE's readiness advantage and EAE's comparative disadvantage are not artifacts of how heavily evidence maturity is weighted relative to feasibility.

This evaluation should be read as a transparent synthesis of the evidence in the previous section, not as a validated decision-support output. Weights were derived through the authors' own pairwise judgments rather than an independent stakeholder panel, and scores reflect literature synthesis rather than measurements collected under standardized conditions. Full derivation steps, including the geometric-mean weight calculations and consistency verification, are provided in Supplementary Material S1. A formal industry-facing assessment would benefit from stakeholder-elicited weights and pilot-scale trials on Philippine copra specifically, a gap this review returns to in its concluding recommendations.

IMPLEMENTATION PATHWAYS FOR PHILIPPINE CNO-CME ADOPTION

Implementation requirements for supercritical fluid extraction

Two gaps stand out. First, the evidence base, though the most direct and comprehensive of the four technologies, rests on Thai rather than Philippine copra (Punvichai et al., 2026). The two are not identical: Punvichai et al.'s material was dried to 8% moisture or below, while Philippine copra typically reaches 4–5% under variable postharvest handling (Pestaño & Jose, 2016). Both fall within a similarly low moisture range, however, well short of a compositional divide that would undermine the comparison. Even so, Philippine copra itself has not been evaluated under supercritical conditions. Second, SFE's feasibility barrier is capital intensity rather than compositional mismatch: high-pressure vessels, pumps, and separators require investment and safety infrastructure well beyond conventional screw-press expellers (Perrut, 2000; Temelli, 2009).

Table 2. Pairwise comparison matrix for evaluation criteria (Saaty 9-point scale)

Criterion	Evidence maturity	Feasibility	Oil quality	Efficiency	Environmental
Evidence maturity	1	3	4	5	6
Feasibility	1/3	1	2	3	4
Oil quality	1/4	1/2	1	2	3
Efficiency	1/5	1/3	1/2	1	2
Environmental	1/6	1/4	1/3	1/2	1

Note: Derived weights: evidence maturity = 48.7%, feasibility = 22.8%, oil quality = 14.2%, efficiency = 8.7%, environmental performance = 5.6%. Consistency index CI = 0.025; consistency ratio CR = 0.022 (Saaty, 2008).

Table 3. Technology scores and composite readiness rankings

Criterion (weight)	MAE	UAE	EAE	SFE
Evidence maturity (48.7%)	4	3	3	5
Feasibility (22.8%)	2	2	2	2
Oil quality (14.2%)	4	4	3	5
Efficiency (8.7%)	3	4	4	4
Environmental performance (5.6%)	3	3	3	4
Composite score	3.40	3.00	2.86	4.17
Rank	2	3	4	1

Note: Composite score = Σ (criterion score × weight). Full derivation is provided in Supplementary Material S1.

This capital intensity interacts unfavorably with the smallholder-dominated, geographically dispersed supply structure and concentrated milling capacity established earlier (Aguilar et al., 2022). A high-pressure facility would likely need centralized, large-volume operation to offset its cost, implying copra aggregation beyond current mill catchment areas — a logistics burden not captured in laboratory-scale yield or quality figures.

SFE's compositional advantage may partly offset this barrier: its pressure-tunable lauric acid enrichment (Punvichai et al., 2026), unavailable to MAE, UAE, or EAE, allows part of the extracted oil to be positioned toward higher-value lauric-rich applications alongside bulk CME feedstock, rather than committing the entire output to a single low-margin product. The fiscal incentives accompanying the Biofuels Act mandate (Republic of the Philippines, 2007), noted earlier, could also partially offset capital costs, though whether they suffice to justify high-pressure investment for a commodity feedstock remains untested and would require dedicated techno-economic analysis beyond this review's scope.

Pilot-scale validation using Philippine copra, rather than continued extrapolation from other studies, is therefore the most direct next step toward establishing whether SFE's readiness advantage translates into a viable Philippine investment case.

Integration with in situ transesterification

Beyond its standalone performance, SFE's compatibility with in situ transesterification (ISTE) further strengthens its case for Philippine adoption. In ISTE, oil extraction and transesterification — the reaction of triglycerides with a short-chain alcohol, typically methanol, in the presence of a catalyst, to yield fatty acid methyl esters (FAME) and glycerol — are combined into a single operation rather than performed sequentially (Leung et al., 2010; Ma & Hanna, 1999), reducing solvent and energy use and removing refining steps that would otherwise sit between extraction and conversion (Samuel et al., 2012). Paired with SC-CO_2 extraction specifically, the low-moisture, high-purity oil SFE produces can improve reaction efficiency relative to feedstocks carrying more water or non-triglyceride material into the reactor (Go et al., 2016; Lim & Lee, 2013). Figure 7 illustrates one possible configuration, combining supercritical CO_2 extraction with ISTE in a single processing train.

ISTE integration with SFE has already been demonstrated for other oil-rich biomass, as noted previously, though not yet for coconut, and this precedent extends across a wider body of work spanning both configurations noted above — indicating that reactive extraction under supercritical conditions is broadly transferable rather than specific to one oil matrix. On the SC-CO_2 side, Kondo et al. (2002) coupled continuous SC-CO_2 extraction of canola oil with an inline, lipase-catalyzed ethanolysis reactor at 24–35 MPa, showing extraction and reaction can run as connected

stages within a single supercritical train rather than as separate unit operations.

Catchpole et al. (2012) showed the same principle for reaction under CO_2 more broadly, esterifying fish and borage seed oil directly under supercritical CO_2 while using extraction pressure itself to strip reaction products and concentrate polyunsaturated fatty acids in one vessel. Microalgal feedstocks have been processed analogously, including ethanol-impregnated *Nannochloropsis oculata* extracted and converted under supercritical CO_2, as reviewed in Ideris et al. (2022).

On the alternative, CO_2-free track, supercritical alcohol itself serves as both solvent and reagent. Lim & Lee (2013) optimized this configuration for *Jatropha curcas* seeds, reaching a 99.67% FAME yield at 300 °C and 9.5 MPa with supercritical methanol alone, without catalyst or co-solvent; Ishak et al. (2017) achieved a comparable 97.9% yield on the same feedstock at 280 °C and 12 MPa. The same approach has converted microalgal biomass, including supercritical ethanol conversion of *Nannochloropsis salina* and supercritical methanol conversion of *Spirulina platensis* at a 99.32% FAME yield, as reviewed in Ideris et al. (2022). Together, the two tracks span oilseed and microalgal feedstocks, CO_2-mediated and CO_2-free configurations, and enzymatic and non-catalytic mechanisms — strengthening the case that comparable integration is achievable for coconut despite the absence of direct precedent.

Evidence specific to coconut, while not yet paired with supercritical CO_2, is more encouraging than that gap alone might suggest. Khang et al. (2014) achieved a 96.7% biodiesel yield directly from copra in a single step, using a methanol-tetrahydrofuran co-solvent mixture at 60 °C and a 60:1 methanol-to-oil molar ratio, with tetrahydrofuran improving oil-methanol miscibility and reaction rate relative to methanol alone. Their copra carried an FFA content of 6.9%, above the saponification-risk threshold established earlier (Ramos et al., 2009), which is why they used sulfuric acid rather than a base catalyst — an acid-catalyzed route that tolerates high-FFA feedstock without triggering soap formation.

This dependence on acid catalysis to manage feedstock FFA underscores why extraction method matters upstream of the reaction itself: a technology that reliably delivers low-FFA oil reduces the need for such catalyst workarounds, simplifying catalyst selection and potentially widening the operating window for ISTE. SFE's own tendency toward lower FFA and peroxide values relative to conventional extraction (Punvichai et al., 2026) suggests it may be well suited to this role, feeding ISTE with oil already

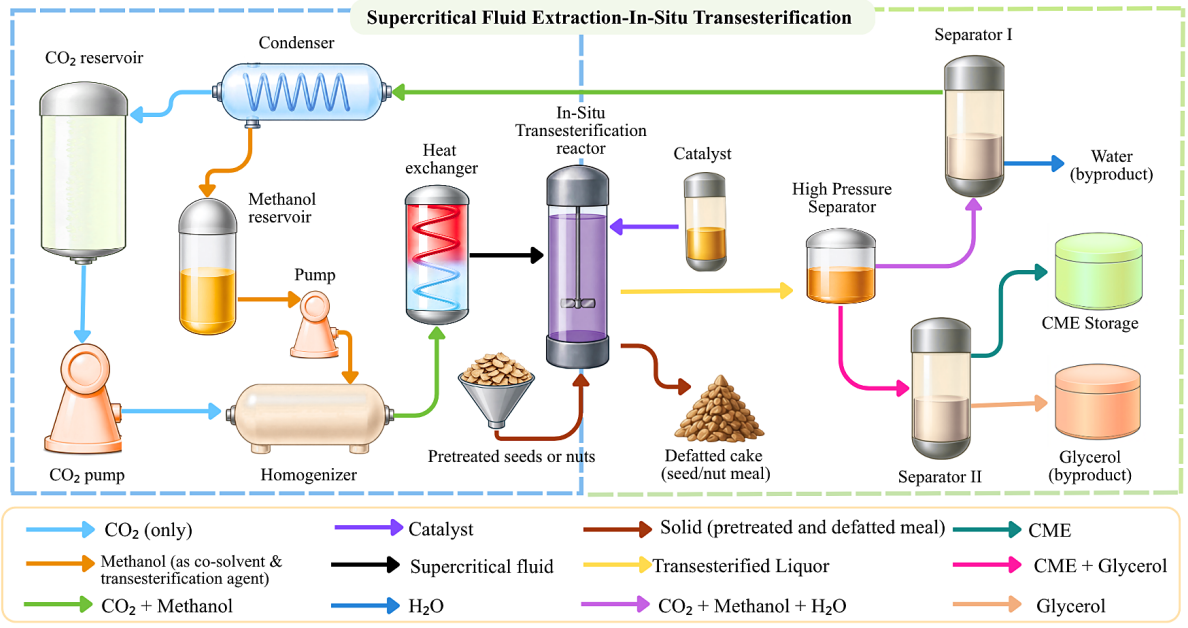

Figure 7. Conceptual schematic of an integrated SFE-ISTE system. Feedstock is contacted with supercritical CO_2 and a methanol-catalyst stream in a shared vessel, where lipids are simultaneously solubilized and converted to FAME, then separated into FAME, glycerol, and residual solids, with CO_2 recompressed and recycled.

closer to a quality threshold that supports simpler, base-catalyzed conversion.

Separately, Sulaiman et al. (2014) applied ISTE to solid coconut waste — the residual solids remaining after coconut milk extraction — achieving yields up to 97% using n-hexane as co-solvent under optimized conditions. Since neither this study nor Khang et al. (2014) used CO_2 as the extraction medium, they show that coconut-derived feedstocks respond well to ISTE in principle, without confirming how that response would change once supercritical CO_2 replaces the co-solvents used here.

This leaves SFE-ISTE integration for coconut specifically as an unstudied combination. Given SFE's compositional advantages for CNO — pressure-tunable lauric acid enrichment and low peroxide values (Punvichai et al., 2026) — pairing supercritical extraction with ISTE could compound these benefits: eliminating the separate oil-recovery step SFE would otherwise require, while retaining the low-moisture, high-purity extract that favors efficient transesterification. Such integration could also partially offset the capital burden discussed above by consolidating extraction and conversion — two otherwise separately capitalized steps — into a single unit operation. This reduces equipment footprint per unit of CME relative to running SFE and conventional transesterification in sequence.

For the Philippine coconut sector, SFE-ISTE integration raises the possibility of co-locating oil extraction and biodiesel conversion within decentralized facilities positioned closer to smallholder collection points (Aguilar et al., 2022), rather than aggregating and transporting copra to separate extraction and conversion sites. Such facilities could also process coconut residue (Che-U-Bong et al., 2025) and other byproducts already generated by existing VCO and desiccated coconut operations (Pestaño & Jose, 2016), aligning with circular-economy principles by recovering value from streams that would otherwise be discarded, while producing both edible-grade oil fractions and CME from a shared footprint. Whether this integration is economically viable at Philippine scale, however, remains untested, and would require pilot demonstration alongside the copra-specific SFE validation already identified as a priority.

Taken together, SFE's path to Philippine adoption rests on two complementary developments: pilot-scale validation using Philippine copra to close the evidence gap left by Thai data (Punvichai et al., 2026), and ISTE integration to offset capital intensity by consolidating extraction and conversion into a single process. Neither has yet been demonstrated at the feedstock and scale this review identifies as most relevant, leaving both as priorities for the research agenda this paper's concluding section returns to.

CONCLUSIONS

This review evaluated MAE, UAE, EAE, and SFE against conventional copra milling and against one another as pathways for improving CNO recovery for Philippine CME production. Weighed together through the AHP-based synthesis in the previous section, SFE emerged as the highest-ranked technology (composite score 4.17, ahead of MAE, UAE, and EAE), a result that held even when feasibility rather than evidence maturity was treated as the dominant criterion. Its readiness reflects the most direct coconut-specific evidence base of the four technologies and compositional advantages unavailable elsewhere — tunable lauric acid enrichment and low peroxide values — though, as established previously, capital intensity rather than any compositional mismatch with dried copra remains its binding constraint on Philippine adoption.

Building on the gaps identified throughout this review, four priorities stand. First, pilot-scale SFE trials on industrial Philippine copra are needed to confirm whether the yield, quality, and lauric acid enrichment demonstrated on Thai material hold under Philippine postharvest conditions. Second, the techno-economic question left open earlier — whether Biofuels Act fiscal incentives justify SFE's capital costs for a commodity feedstock — merits dedicated analysis this review's scope did not permit. Third, SFE-ISTE integration merits coconut-specific study, since the precedent established for other oilseed and microalgal feedstocks has not yet been tested on coconut. Fourth, the AHP-based ranking would benefit from weights elicited directly from Philippine processors, regulators, and equipment suppliers, rather than the authors' own judgments alone.

Extraction improvements alone cannot resolve the sector's feedstock constraints; oil palm diversification remains a necessary complement. Within the coconut value chain, though, SFE paired with in situ transesterification offers the most technically substantiated outlook for expanding

domestic CME supply without abandoning the country's existing copra-based infrastructure. Nor is this case intrinsic to coconut: SFE's affinity for triglycerides and its demonstrated integration with in situ transesterification extend to oil palm, Jatropha, and other oil-rich biomass the Philippines may develop as feedstock supply grows. Coconut is where the evidence is strongest today, but the underlying principle — evaluating extraction and conversion together, not extraction alone — will matter for whichever feedstock the country turns to next.

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