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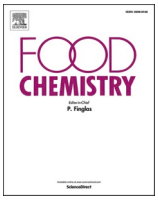

Review

Deacidification of vegetable oils: advanced technologies, mechanistic insights, and emerging strategies

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ABSTRACT

Vegetable oils often contain free fatty acids (FFAs), which compromise their quality and limit their use in food, cosmetics, and biofuels. Effective deacidification is essential for refining oils. This review examines the origins and chemistry of FFAs and key factors influencing oil acidity. It assesses traditional deacidification methods like chemical and physical refining highlighting their benefits and drawbacks. Additionally, advanced technologies like enzymatic deacidification, membrane separation, etc. are discussed for their mechanisms, efficiency, and industrial feasibility. Enzymes and electrochemical processes enable selective FFA removal with minimal solvent use, while ionic liquids and plasma techniques offer novel, environmentally sustainable pathways. Comparative analysis evaluates these strategies on effectiveness, cost, and environmental impact. This review concludes that future deacidification research is shifting toward green, eco-friendly solvents, low-waste, and digitally optimized refining strategies. Hybrid and enzyme-assisted systems represent the most promising pathways for sustainable, high-quality vegetable oil production aligned with industrial and environmental standards.

1. Introduction

Vegetable oils represent one of the most significant renewable bio-resources serving as crucial intermediates across the food, cosmetic, pharmaceutical, and renewable energy sectors. Their wide-ranging utility is attributed to their functional versatility, biodegradability, and abundant availability from diverse plant sources such as soybean, sunflower, palm, and canola (Afzal et al., 2022; Meijaard et al., 2024). These oils are indispensable in food systems as cooking media, emulsifiers, and nutritional carriers, in cosmetics as emollients and moisturizers, and in bioenergy as feedstocks for biodiesel and bio lubricants. The increasing emphasis on quality enhancement and sustainability has driven a global rise in vegetable oil consumption reflecting both industrial and consumer demand for natural, functional, and renewable products. Palm oil dominates global production among major oils, exceeding 65 million metric tons annually with Indonesia and Malaysia accounting for over 85 % of the total (Ahmad Hamidi et al., 2022). Soybean oil follows primarily produced in the United States, Brazil, and Argentina, with global production reaching approximately 255 million metric tons (Dilawari et al., 2022). In India, palm oil remains the most consumed followed by groundnut, mustard, and sunflower oils with the domestic industry supported by both indigenous oilseed production and

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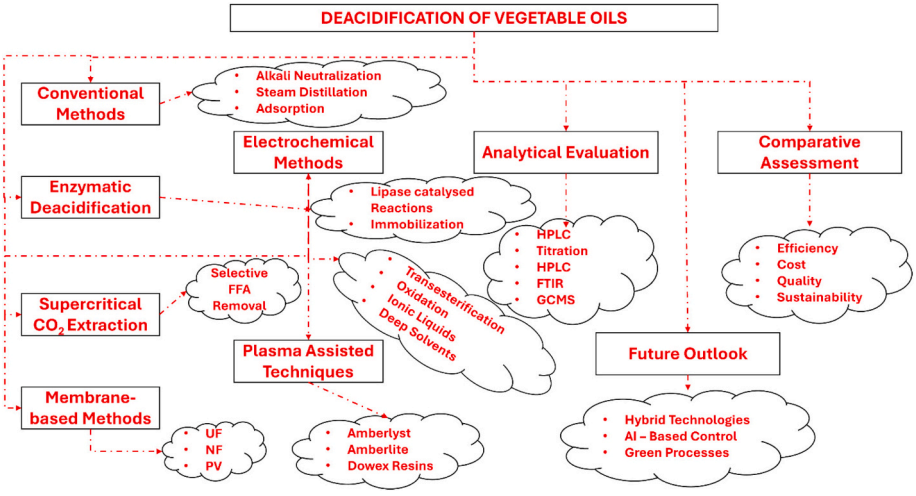


Fig. 1. Overview of deacidification of oils via methods, evaluations, comparative assessment and future outlook.

imports of palm and soybean oils (Mustafa & Iqbal, 2021). The extensive reliance on vegetable oils underscores the need for refined, high-quality products suitable for a range of end uses from edible consumption to advanced industrial formulations.

A primary determinant of vegetable oil quality is the concentration of free fatty acids (FFAs) which significantly influence oxidative stability, flavour, shelf life, and processing performance (Chen & Sun, 2023; Gharby, 2022). FFAs are produced through hydrolysis of triglycerides, a process catalysed by moisture, heat, microbial enzymes, or prolonged storage. Their accumulation is accelerated by suboptimal storage conditions, mechanical damage to oilseeds, or inefficient extraction and refining methods. Elevated FFA content contributes to rancidity, undesirable odours, and colour changes by diminishing oil quality and consumer acceptability. In edible oils, excessive FFAs reduce nutritive value and may pose potential health risks (Santos et al., 2018). In cosmetic formulations, they promote oxidative instability and texture degradation while in biodiesel production high FFA levels interfere with transesterification reactions leading to lower yield and inferior fuel properties (Di Pietro et al., 2020; Sharma, Barthwal, et al., 2022; Sharma, Sharma, et al., 2022; Lopresto et al., 2024). Hence, controlling and reducing FFA concentration is a central goal in refining to ensure product stability, safety, and market value. Deacidification is the process of removing FFAs which is a critical refining stage that enhances oil quality, stability, and economic value. Traditionally, deacidification has been performed through chemical and physical refining. Chemical neutralization is the most established technique that employs alkali reagents such as sodium hydroxide to convert FFAs into soaps which are subsequently separated from the oil phase. Although effective, this method leads to significant oil losses, produces large volumes of soap stock waste, and necessitates extensive wastewater treatment (Okpo & Edafiadhe, 2024; Gumus et al., 2023). Physical refining, which relies on steam distillation or molecular distillation at elevated temperatures offers a solvent-free alternative but may cause degradation of thermolabile bio actives such as tocopherols and phytosterols, while also consuming substantial energy (Asbbane et al., 2024; Ma et al., 2024). The environmental, economic, and operational drawbacks of these methods have prompted a search for more sustainable and efficient deacidification strategies.

The emerging approaches to deacidification have shown promise in overcoming the limitations of traditional techniques. Enzymatic deacidification which employs lipases to catalyse selective hydrolysis or esterification of FFAs under mild conditions which offers high specificity, minimal nutrient loss, and low energy requirements (Bassut et al., 2022; Baena et al., 2022; Cavalcante et al., 2024). Membrane-based separation technologies such as ultrafiltration, nanofiltration, and pervaporation exploit molecular size or polarity differences to separate FFAs without the use of solvents allowing continuous operation and reduced environmental impact (Abdorrezaee & Raisi, 2021; Huang et al., 2024; Wang et al., 2024). Adsorption techniques utilizing activated carbon, silica, or bio-based adsorbents efficiently bind FFAs, particularly in oils with complex matrices, providing cost-effective and scalable alternatives (Chung et al., 2018; KP et al., 2025). Supercritical fluid extraction, particularly using supercritical carbon dioxide (SC-CO_2), has emerged as a clean, non-toxic, and tunable method for selective FFA removal while preserving sensitive compounds (Grigaliūnaitė & Ruiz-Méndez, 2023). Similarly, novel solvent systems such as ionic liquids (ILs) and deep eutectic solvents (DESs) are gaining attention for their tunable polarity, recyclability, and compatibility with green chemistry principles (Baklouti et al., 2023; Schuh et al., 2023). Electrochemical deacidification is another innovative technique that uses controlled electrical potentials to drive FFA migration or conversion reactions without chemical reagents, aligning with sustainability goals (Abbas & Asel, 2023; Alkhadra et al., 2022). In parallel, hybrid processes combining enzymatic, membrane, or supercritical operations with ILs or DESs are being explored to maximize efficiency, minimize waste, and maintain oil integrity (Fabiane et al., 2023).

The comparative evaluations across oil types and industrial contexts remain scarce, despite this growing technological diversity. Most studies focus on individual techniques or specific applications such as edible oils or biodiesel production without integrating insights across sectors. Furthermore, the influence of deacidification on bioactive compounds such as tocopherols, phenolics, and phytosterols and their correlation with nutritional, oxidative, and sensory properties is still underexplored (Dominic & Baidurah, 2025; Kwaśnica et al., 2022; Colonia et al., 2023). The lack of interdisciplinary synthesis impedes the identification of optimal deacidification strategies that balance efficiency, quality preservation, and environmental sustainability. It is essential to systematically analyse both conventional and emerging deacidification methods to address these research gaps highlighting their operational mechanisms, advantages, and limitations. The refinement of vegetable oils must align with the broader goals of circular economy and green processing where process optimization not only enhances product quality but also reduces waste and energy consumption. Emerging technologies, particularly those integrating renewable solvents, enzymatic catalysis, and low-temperature separations offer opportunities to redefine the sustainability paradigm in oil refining. The present review offers a comprehensive, integrative assessment of deacidification technologies for vegetable oils, bridging the divide between traditional and emerging processes. Its novelty lies in the cross-sectoral comparison of chemical, physical, enzymatic, membrane-based, and supercritical CO_2

deacidification approaches alongside the evaluation of advanced systems employing ionic liquids, deep eutectic solvents, and electrochemical methods. This work provides a unified analysis encompassing food, cosmetic, and biofuel applications unlike previous reviews that address isolated techniques or specific oil types. It further investigates the implications of deacidification on minor bio actives, oxidative stability, and sensory characteristics, offering insights into process-structure-function relationships critical for product optimization. The overview of deacidification of oils via methods, evaluations, comparative assessment and future outlook is shown Fig. 1. This review aims to provide a scientific framework for optimizing by synthesizing recent developments and establishing comparative performance benchmarks for deacidification practices, guiding both academic research and industrial innovation in line with sustainable food chemistry principles.

2. Fundamentals of deacidification

2.1. Significance of deacidification

Oilseeds represent a cornerstone of global agricultural production, serving as the major source of essential fatty acids (EFA) such as linoleic (C18:2) and α-linolenic acid (C18:3), along with fat-soluble vitamins A and E. In 2023, global oilseed production reached 612.79 million metric tons, while vegetable oil utilization was estimated at 186 million metric tons (FAO, 2023). Edible oils contribute approximately 25–30 % of total dietary energy intake in many developing countries, providing 9 kcal/g, and are widely incorporated into processed foods such as margarine, dressings, bakery products, and fried goods (Yang et al., 2013). Beyond nutrition, vegetable oils are valued industrially for their lubricating, textural, and heat-transfer properties during cooking and food processing. Crude oils derived from oilseeds contain a complex mixture of triacylglycerols (TAGs), diacylglycerols (DAGs), monoacylglycerols (MAGs), free fatty acids (FFA), phospholipids, sterols, tocopherols, and pigments (Chew & Nyam, 2020). Among these, TAGs account for approximately 95–98 % of total lipids, whereas FFA levels in freshly extracted crude oils typically range between 0.3 % and 5 %, depending on seed quality and handling.

The formation of FFA primarily occurs through lipase-catalyzed hydrolysis of TAGs, where lipase enzymes cleave ester bonds between glycerol and fatty acids in the presence of water and heat (Vaisali et al., 2014). This reaction is accelerated post-harvest due to cellular disruption, enzyme activation, and moisture uptake during storage. The mechanism can be summarized as:

$$\text{Triacylglycerol} + \mathbf{H_2O} \rightarrow \mathbf{Diacylglycerol} + \mathbf{FFA}$$

Repeated hydrolysis steps lead to monoacylglycerol and glycerol formation. Uncontrolled lipolysis significantly elevates FFA content, compromising oil stability. FFA are chemically more reactive than their parent TAGs due to their free carboxyl groups, which accelerate autoxidation and rancidification (Dunford, 2022a, 2022b). Elevated FFA (>2 %) promote the formation of hydroperoxides, aldehydes, and ketones, contributing to undesirable off-flavors, color degradation, and shortened shelf life. Oxidation of FFA is particularly problematic in polyunsaturated oils, where double bond conjugation enhances radical propagation. In addition, FFA catalyze metal ion oxidation reactions, further promoting the degradation of tocopherols and carotenoids, thus diminishing the nutritional value and oxidative stability of edible oils.

Oil refining encompasses pretreatment, degumming, neutralization/deacidification, bleaching, and deodorization, aimed at removing phosphatides, FFA, and oxidation products (Yang et al., 2013). Deacidification, the most critical and cost-intensive step, directly targets FFA removal. In chemical refining, FFA are neutralized using alkali solutions (e.g., NaOH) to form soap stock, which is subsequently separated from the neutral oil. Alternatively, physical refining employs steam distillation at 230–260 °C under 2–6 mbar vacuum to volatilize FFA, reducing their content to <0.05 % in refined oils (Shihab et al., 2022). Although high temperatures improve FFA removal efficiency, prolonged heating can induce thermal oxidation and polymerization of unsaturated fatty acids. Thus, optimizing residence time and temperature is crucial for maintaining sensory and nutritional quality. The deodorization step, often coupled with physical refining, eliminates volatile compounds responsible for undesirable odours and flavours, improving oil organoleptic properties. According to Codex Alimentarius (2023), refined olive oil should contain ≤0.3 % FFA, while cold-pressed and virgin oils may reach 2.0 %. Exceeding these thresholds negatively affects compliance with edible oil standards and consumer acceptability. High-FFA byproducts and waste oils pose environmental challenges, as their acidic nature complicates recycling and biodiesel conversion (Chew & Ali, 2021). Innovative approaches, including enzymatic deacidification, membrane separation, and supercritical CO_2 extraction, are emerging as sustainable alternatives to conventional refining, aiming to minimize chemical use and improve recovery of bioactive compounds such as tocopherols and phytosterols.

In summary, the formation and removal of FFA are central to the physicochemical stability, flavour, and market value of edible oils. Efficient refining processes such as balancing thermal control, energy input, and chemical minimization are essential to achieving FFA levels below regulatory limits while preserving nutritional integrity. The future advancements in green refining technologies will be crucial for addressing both economic efficiency and environmental sustainability in the global edible oil industry.

2.2. Fundamentals of deacidification process

In conventional edible oil refining, alkaline deacidification also known as chemical neutralization, is the predominant method used to remove free fatty acids (FFA). The process employs an alkaline solution, typically sodium hydroxide (NaOH), to neutralize FFAs and produce soap (saponified salts of fatty acids) and glycerol through the reaction:

$$RCOOH + NaOH \rightarrow RCOONa + H_2O$$

This saponification effectively converts FFAs into soaps that can be separated from the neutral oil phase. However, under alkaline conditions, triglycerides (TAGs) can also undergo alkaline hydrolysis, forming diacylglycerols (DAGs), monoacylglycerols (MAGs), and glycerol, leading to neutral oil loss (Wang et al., 2023). The reaction rate and efficiency depend on factors such as alkali concentration, temperature, mixing intensity, impurity content, and oil-soap phase separation efficiency. Although chemical refining is efficient and can reduce FFA content to below 0.05 %, it has notable drawbacks. Pan et al. (2019) reported that soap stock generated during neutralization can retain up to 50 % of its weight as entrained oil, resulting in substantial oil loss and reduced yield. Additionally, side saponification of TAGs contributes to waste generation that requires extensive wastewater treatment to meet environmental regulations. In contrast, physical refining—based on steam distillation under vacuum (230–260 °C, 2–6 mbar) is preferred for highly acidic oils (>5 % FFA) since it minimizes soap formation and oil loss. However, its high operating temperature promotes the formation of polymers and trans-fatty acid isomers, which degrade nutritional quality and oxidative stability (Shi et al., 2018).

The alternative approaches such as solvent extraction–based deacidification have been investigated but face challenges including limited mass transfer, difficult solvent recovery, and high capital costs due to the need for explosion-proof and enclosed systems. Consequently, these methods are not widely adopted industrially. Overall, traditional deacidification methods are constrained by oil loss (up to 2–3 %), soap stock disposal, wastewater load, and energy consumption. Over the past five decades, research has increasingly focused on developing sustainable, low-energy alternatives which includes enzymatic deacidification, membrane-assisted separation, and supercritical CO_2 extraction to improve FFA removal efficiency while minimizing byproduct formation and environmental impact (Xu et al., 2021).

2.3. Chemical composition of vegetable oils and sources of FFAs

The fatty acid composition of vegetable oils determines their nutritional quality, oxidative stability, and industrial applicability. Palm oil, one of the most widely produced edible oils, contains a higher proportion of saturated fatty acids (SFAs), particularly palmitic acid (C16:0, 42–47 %), along with oleic acid (C18:1, 37–41 %) as its major monounsaturated fatty acid (MUFA) component (Wang et al., 2021). In contrast, safflower oil a premium edible oil is characterized by a high linoleic acid (C18:2) content exceeding 70 % and a negligible linolenic acid (C18:3) level (<0.5 %), which enhances oxidative stability. Groundnut (peanut) oil is rich in oleic acid (C18:1, ~57 %) and linoleic acid (C18:2, ~20 %), with smaller fractions of palmitic (C16:0), stearic (C18:0), and arachidic (C20:0) acids, making it about 93 % total fat and predominantly unsaturated. Sesame oil similarly exhibits a favourable fatty acid profile with oleic acid (C18:1, 40 %), linoleic acid (C18:2, 42 %), and a minor proportion of palmitic acid (C16:0, 9 %), accounting for roughly 80 % unsaturated lipids (Flores et al., 2020). Among tropical oils, coconut oil is unique for its exceptionally high saturated fat content (~90 %), dominated by medium-chain fatty acids (MCFAs), notably lauric acid (C12:0, 49 %), myristic acid (C14:0, 18 %), and palmitic acid (C16:0, 8 %) along with smaller quantities of caprylic (C8:0, 7 %), capric (C10:0, 5 %), and stearic (C18:0, 2 %) acids. It contains only 2 % linoleic (C18:2) and 6 % oleic (C18:1) acids giving it high oxidative stability but low essential fatty acid content. Conversely, sunflower oil is abundant in polyunsaturated fatty acids (PUFAs), primarily linoleic acid (C18:2, 59–69 %) and oleic acid (C18:1, 20–30 %), with minor contributions from stearic (C18:0, 6–7 %) and palmitic (C16:0, 5–6 %) acids. Rapeseed (canola) oil contains the most balanced profile, with oleic acid (C18:1, 50–60 %), linoleic acid (C18:2, ~20 %), and linolenic acid (C18:3, 6–14 %), while saturated fatty acids remain below 7 %, making it nutritionally favourable and low in atherogenic fats (Wang et al., 2021).

Vegetable oils are generally classified based on the dominance of palmitic, oleic, or linoleic acids, the three principal fatty acids influencing stability and function. Oils rich in unsaturated fatty acids (UFA) (particularly MUFAs and PUFAs) are increasingly preferred due to their cardioprotective and hypocholesterolaemia effects (Dudi et al., 2021). However, a high PUFA content particularly of linolenic acid may increase susceptibility to oxidative rancidity. Beyond their lipid profile, vegetable oils are important dietary sources of essential fatty acids and liposoluble vitamins (A, D, E, and K), which contribute to their nutraceutical value. During extraction and processing undesirable components such as free fatty acids, heavy metals, hydrocarbons, glycolipids, proteins, resins, and mucilage's may co-exist with triglycerides. The refining process is therefore designed to eliminate these impurities while minimizing damage to triacylglycerols (TAGs) and preserving bioactive micronutrients. Structurally, the dominant fatty acids in most vegetable oils are C16 and C18 chains such as palmitic (C16:0), stearic (C18:0), oleic (C18:1), linoleic (C18:2), and linolenic (C18:3) which typically undergo esterification with glycerol to form triglycerides, the major energy-storing and functional component of edible oils (Kumar et al., 2019).

2.4. Fatty acids sources and classification

The occurrence of double or triple bonds allows the naturally occurring fatty acids to be divided into two major classes, known as saturated and unsaturated.

2.4.1. Saturated fatty acids

Saturated fatty acids (SFAs) are classified according to their carbon chain length into short-chain (C4:0-C10:0), medium-chain (C12:0-C14:0), and long-chain (C16:0-C26:0) categories each exhibiting distinct physicochemical and metabolic properties. Short-chain saturated fatty acids (SCFAs) such as butyric acid (C4:0) and caproic acid (C6:0) are primarily found in milk fats from cows, sheep, and goats, where they contribute to characteristic flavour and digestibility. Medium-chain fatty acids (MCFAs), including caprylic (C8:0), capric (C10:0), and lauric acid (C12:0), are abundant in tropical oils such as coconut and palm kernel oil and are valued for their rapid metabolic oxidation and antimicrobial properties (Lee et al., 2021). Myristic acid (C14:0) and lauric acid (C12:0) are key components of seed lipids from the Lauraceae and Myristicaceae plant families, from which their trivial names are derived (Kumar et al., 2019).

The dominant long-chain SFAs in edible oils include palmitic acid (C16:0) and stearic acid (C18:0). Palmitic acid typically representing 40–47 % of total fatty acids in palm oil, is also widely present in fish oils, milk fats, and vegetable fats, where it influences melting behaviour and texture. Stearic acid (C18:0) although constituting a minor fraction (~2–5 %) of most vegetable oils is a major component of ruminant tallow, imparting higher solid fat content and oxidative resistance. Other long-chain SFAs such as arachidic (C20:0), behenic (C22:0), lignoceric (C24:0), and cerotic (C26:0) occur in small quantities (<1 %) in certain seed oils and waxes, contributing to their high melting points and industrial utility. Propionic acid (C3:0), while present in trace amounts in animal fats, plays a greater role in microbial lipid metabolism than in edible oil composition. Only a few rare seed oils, such as those from Gossypium and Acer species, contain significant amounts of very-long-chain saturated fatty acids (≥C20), which are of interest for specialized applications in lubricants and cosmetics. Overall, SFAs provide oxidative stability and structural rigidity to oils, but excessive dietary intake (particularly of long-chain forms) has been associated with elevated low-density lipoprotein (LDL) levels, whereas shorter-chain and medium-chain variants are metabolized more rapidly and exhibit neutral or beneficial lipid effects (Wang et al., 2021).

2.4.2. Unsaturated fatty acids

Unsaturated fatty acids (UFAs) are characterized by one or more carbon-carbon double or triple bonds within their hydrocarbon chains and are broadly classified as monounsaturated fatty acids (MUFAs), polyunsaturated fatty acids (PUFAs), or acetylenic fatty acids depending on the number and type of unsaturation's. Fatty acids containing only double bonds are termed alkenoic (ethanoic or olefinic) acids whereas those containing triple bonds are referred to as alkenoic (ethanoic or acetylenic) acids (Coniglio et al., 2023). The degree of unsaturation is indicated by numerical prefixes (such as di-, tri-, tetra-, etc.) attached to the suffix -enoic to denote the number of double bonds as in linoleic acid (C18:2) and linolenic acid (C18:3). Structurally, the configuration of double bonds in UFAs may be either cis or trans, depending on the relative orientation of the hydrogen atoms around the double bond (Frančáková et al., 2015). In naturally occurring lipids, more than 90 % of double bonds exist in the cis configuration, which introduces kinks into the carbon chain, lowering melting points and maintaining fluidity in biological membranes. In contrast, trans fatty acids (TFAs) with hydrogen atoms on opposite sides of the double bond exhibit a linear conformation that increases packing density and mimics the physicochemical properties of saturated fats.

Industrially, partial hydrogenation of vegetable oils is performed to convert liquid oils into semisolid fats for products such as margarine and shortening, improving texture, flavour stability, and oxidative resistance. However, this process inadvertently induces isomerization, converting some cis double bonds into trans configurations and shifting their positions along the carbon chain. As a result, both positional (e.g., Δ9 to Δ10) and geometric (cis to trans) isomers are formed. Although hydrogenation enhances shelf life it also increases the trans fatty acid content often up to 25–45 % of total fatty acids in partially hydrogenated oils contributing to adverse health effects such as elevated LDL cholesterol and reduced HDL cholesterol levels. Consequently, modern food processing trends favour enzymatic interesterification and selective hydrogenation technologies that minimize trans-fat formation while maintaining oxidative stability and desirable physical characteristics (Ma et al., 2022; Wang et al., 2021).

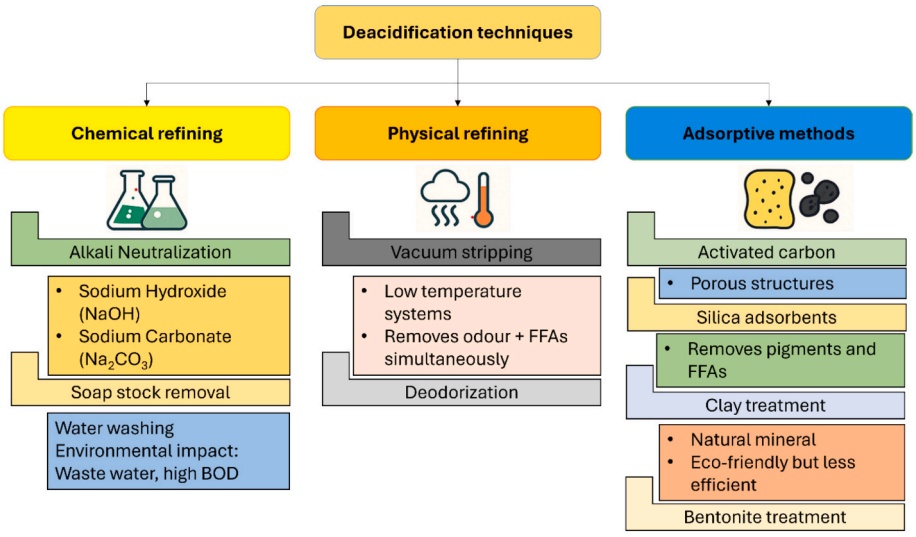


Fig. 2. Overview of conventional deacidification techniques employed.

2.4.2.1. Monounsaturated fatty acids. Monounsaturated fatty acids (MUFAs) are characterized by the presence of a single cis double bond in their hydrocarbon chain, which introduces a bend that keeps them liquid at ambient temperature while maintaining moderate oxidative stability. MUFAs are abundant in plant-based oils including olive oil (55–83 % oleic acid, C18:1), canola oil (50–60 % C18,1), as well as in nuts, seeds, and avocados (Dudi et al., 2021). Their consumption is associated with cardioprotective effects, including reduced low-density lipoprotein (LDL) cholesterol, increased high-density lipoprotein (HDL) cholesterol, and improved endothelial function, making them a key component of the Mediterranean diet. MUFAs also exhibit greater oxidative stability than polyunsaturated fatty acids (PUFAs), which allows their widespread use in cooking oils and processed foods without rapid rancidity (Wang et al., 2021).

2.4.2.2. Polyunsaturated fatty acids. Polyunsaturated fatty acids (PUFAs) are defined by the presence of two or more double bonds in their hydrocarbon chains, which introduce multiple kinks and render them liquid at room temperature, although they may partially solidify upon cooling. PUFAs are commonly classified as omega-3 (n-3) or omega-6 (n-6) fatty acids based on the position of the first double bond from the methyl end of the chain. They are essential fatty acids, meaning they cannot be synthesized endogenously and must be obtained through diet. Omega-3 fatty acids, such as α-linolenic acid (C18:3), eicosapentaenoic acid (EPA, C20:5), and docosahexaenoic acid (DHA, C22:6), are abundant in flaxseed, walnuts, and fatty fish, whereas omega-6 fatty acids, primarily linoleic acid (C18:2), are found in sunflower, corn, and soybean oils (Mengistie et al., 2018). PUFAs play critical roles in cell membrane fluidity, eicosanoid synthesis, and neurodevelopment, and their consumption is associated with cardiovascular protection, anti-inflammatory effects, and cognitive health. However, their multiple double bonds also make PUFAs more susceptible to oxidative degradation, which can generate lipid peroxides unless stabilized by antioxidants or controlled processing.

2.5. Factors influencing oil acidity (oxidation, hydrolysis, enzymatic activity)

The Total Acid Number (TAN) a key indicator of oil acidity, reflects the concentration of free fatty acids (FFAs) generated through oxidation, hydrolysis, and enzymatic activity. Oil quality deterioration is accelerated by temperature, light exposure, oxygen content, and the presence of pro-oxidants such as transition metals, which promote auto-oxidation (Zio et al., 2020). Hydrolysis, catalyzed by heat, moisture, or lipases, cleaves triglycerides into mono- and diacylglycerols, glycerol, and FFAs, while oxidation forms hydroperoxides and low-molecular-weight volatiles including aldehydes, ketones, carboxylic acids, and short-chain alkanes/alkenes (Chew & Nyam, 2020). During high-temperature cooking or frying, further reactions lead to the formation of dimers and polymers, increasing viscosity and generating off-flavors. Enzymatic hydrolysis is influenced by temperature, pH, substrate type, enzyme specificity, and concentration, all of which affect the rate and extent of FFA accumulation. The maintenance of low TAN through careful storage, controlled processing, and antioxidant protection is therefore essential to ensure the safety, stability, and organoleptic quality of edible oils (Alajtal et al., 2018).

2.6. Quality parameters affected by FFAs

The majority of edible oils used for cooking, frying, and food formulation are plant-derived, primarily from oilseeds such as peanuts, soybean, canola, sunflower, and cottonseed. These oils are predominantly triacyl glycerides, composed of three fatty acids esterified to a glycerol backbone, and are liquid at room temperature due to a high content of unsaturated fatty acids, in contrast to animal fats (Moser & Mehta, 2015). The type and proportion of fatty acids determine the physical, chemical, and nutritional properties of the oil. Trace constituents, including phytosterols, tocopherols, and waxes, typically account for less than 1 % of the oil, yet can influence antioxidant capacity and stability.

Oil quality is commonly monitored through free fatty acid (FFA) content, peroxide value (PV), and p-anisidine value (AV), which collectively reflect acidity and primary and secondary oxidation products (Dudi et al., 2021). FFAs, generated by hydrolysis or enzymatic activity, are more oxidation-prone than triglycerides, accelerating rancidity, off-flavor development, and acidity (Brahmi et al., 2020). Elevated FFA levels can shorten shelf life, increase losses during refining, and in extreme cases, cause digestive discomfort. The susceptibility of high-unsaturation oils to oxidative degradation under processing, storage, and cooking underscores the importance of careful handling and stabilization, including antioxidant supplementation and controlled storage conditions (Gharby, 2022).

3. Conventional deacidification techniques

The deacidification of vegetables oils is a crucial process in the edible oil industry to ensure the quality and stability of oils used for human

Table 1
Comparative performance of free fatty acid (FFA) removal and refining techniques for edible oils.

S. No.	Technique	Description	Key features / Pros & Cons	Common oils treated	FFA removal yield (%)	Nutrient retention (%)	Energy demand (kWh t^{-1} oil)	Oil loss (wt%)	Carbon footprint (kg CO_2-eq t^{-1})	References
1	**Neutralization (Alkali refining)**	• Alkali (NaOH or KOH) neutralizes FFAs forming soaps and aqueous phase.	• Simple and economical. • Widely used industrially • Produces soapstock and wastewater. • Moderate oil/nutrient loss.	Soybean, Sunflower, Palm	95–99	84–95	40–100	1–3	3500-4500	Gharby, (2022)
2	**Physical refining**	• FFAs removed by steam distillation under vacuum (no alkali).	• No chemicals. • Suitable for high-FFA oils. • Thermally intense and energy-demanding.	Palm, Coconut, Palm kernel	98–99	88–96	100–350	0.5–2	3000-4000	Sharma et al. (2022) and Sharma, Barthwal, Saini, & Rawat (2022)
3	**Degumming**	• Removal of phospholipids ("gums") via water or acid prior to deacidification.	• Improves clarity and stability. • Minimal effect on FFA. • Minor nutrient loss.	Soybean, Canola	<10	89–96	10–30	0.2–0.5	2500-3000	Gaber et al. (2020), Zufarov and Serkayev (2023)
4	**Solvent deacidification**	• Selective extraction of FFAs using organic solvents (ethanol, hexane, etc.).	• High FFA removal; effective for poor-quality oils. • Solvent recovery required. • Environmental and safety concerns.	Cottonseed, Corn	90–98	80–90	200–300	1–2	4000-5000	Riaz et al. (2023)
5	**Adsorption (Activated carbon)**	• Adsorption of FFAs and pigments onto porous carbon.	• Mild conditions • Low chemical use • Adsorbs some desirable components. • Disposal of spent adsorbent.	Soybean, Sunflower, Palm, Cottonseed, Corn	80–90	85–95	50–100	0.5–1	3000-3500	Mahmud et al. (2023)
6	**Fractionation**	• Thermal crystallization separates components by melting point differences.	• Preserves nutritional quality. • Not primarily for deacidification. • Possible minor nutrient losses.	Palm, Sunflower	–	90–98	100–150	0.2–0.8	3000	Chisca et al. (2022)
7	**Enzymatic deacidification**	• Lipase-catalysed hydrolysis of FFAs under mild conditions.	• Environmentally friendly. • Selective and excellent oil quality. • Costly enzymes and longer reaction times.	Soybean, Sunflower, Palm, Cottonseed, Corn	95–98	90–98	30–80	0.3–1	2500-3000	Baena et al. (2022)
8	**Supercritical CO_2 extraction**	• FFAs extracted using supercritical CO_2 at 25–35 MPa and 40–80 °C.	• Solvent-free. • Minimal oxidation. • High efficiency and requires high pressure and CAPEX.	Soybean, Sunflower, Palm, Cottonseed, Corn	97–99	92–99	200–400	0.2–0.5	2000-3000	Afzal et al. (2022)
9	**Steam distillation**	• FFAs removed with direct steam at elevated T (≥220 °C) under reduced pressure.	• Efficient for high-FFA feedstocks. • High thermal stress. • High steam demand.	Coconut, Palm	97–99	80–90	142–375	1–2	4000-4500	Ifa et al. (2022)
10	**Membrane filtration**	• Separation of FFAs by semi-permeable polymeric membranes.	• Low-energy, non-thermal. • High selectivity. • Membrane fouling and replacement cost.	Canola, Sunflower	80–95	90–98	20–50	0.2–0.8	2500-3000	Baena et al. (2022)

consumption. High acidity levels in oils affect the flavour and nutritional properties and lead to undesirable chemical reactions resulting in poor shelf life and oxidative stability. Deacidification refers to the removal of free fatty acids (FFAs) from oils through existing numerous methods but conventional techniques remain as the backbone of industrial applications (Gharby, 2022). The overview of the conventional deacidification techniques used in oil is shown in Fig. 2. Table 1 presents the comparative performance of free fatty acid (FFA) removal and refining techniques for edible oils used for oil deacidification.

3.1. Chemical refining

Chemical refining remains a dominant deacidification method in the vegetable oil industry, primarily designed to remove FFAs that compromise flavour, oxidative stability, and storage life. The process typically relies on alkali neutralization in which FFAs react with sodium hydroxide or sodium carbonate to form water-soluble soaps that can be separated from the neutral oil phase. The reaction follows the stoichiometric relationship:

$$R–COOH + NaOH \rightarrow R–COONa + H_2O$$

where one mole of alkali neutralizes one mole of FFA. Industrial operations often maintain a slight alkali excess (5–10 %) to ensure complete neutralization resulting in FFA reductions from 3 to 10 % in crude oil to below 0.1 % in the refined product. Although highly effective and relatively fast, this method generates large volumes of soap stock typically 6–8 % of the processed oil mass which requires further acidulation or disposal. These by-products contribute to higher wastewater loads and environmental concerns highlighting the need for more sustainable alternatives such as physical refining or enzymatic deacidification (Chen & Sun, 2023).

3.1.1. Alkali neutralization

Alkali neutralization also referred to as alkali refining, remains a fundamental step in the chemical refining of vegetable oils. The process aims to eliminate free fatty acids (FFAs), which adversely affect sensory quality, oxidative stability, and storage life. In this operation, an alkaline reagent like sodium hydroxide (NaOH) or sodium carbonate (Na_2CO_3) is introduced into the crude oil where it reacts stoichiometrically with FFAs to form soaps and water through a saponification mechanism. The resulting soap stock, being insoluble in the oil phase, is removed via centrifugation, washing, or decantation (Gharby, 2022; Gumus et al., 2023). This separation step not only purifies the neutral oil but also facilitates subsequent refining operations such as bleaching and deodorization. Sodium hydroxide is the most commonly applied reagent due to its strong alkalinity and high reactivity, which enable rapid FFA neutralization. However, excessive alkalinity can induce co-removal of neutral oil and degradation of minor constituents such as tocopherols, sterols, and other antioxidants. Sodium carbonate, by contrast, is a weaker base and reacts more gradually, leading to lower saponification losses and improved retention of thermolabile micronutrients. Its use is often favored in the processing of premium or specialty oils, where compositional integrity is prioritized (Susik & Ptasznik, 2023). Quantitative assessments underscore these trade-offs. de Sa et al. (2022) reported that alkali refining of soybean oil achieved an approximately 90 % reduction in FFA content, lowering acidity from ~1.5 % to below 0.15 %, which significantly enhanced taste and oxidative stability. However, the study also demonstrated that NaOH concentrations exceeding 0.2 % *w*/w caused marked degradation of tocopherols up to 30 % loss highlighting the importance of optimizing alkali dosage. The authors identified the range of 0.05–0.15 % NaOH (*w*/w) as optimal, balancing FFA reduction efficiency with nutrient preservation.

The Complementary findings by Gumus et al. (2023) on sunflower oil confirmed these mechanistic and compositional trends. NaOH treatment yielded the highest FFA removal (~92 %), whereas Na_2CO_3 achieved a moderate reduction (~75 %). Nevertheless, NaOH also induced greater tocopherol degradation (>35 % loss) compared to Na_2CO_3 (<15 % loss), indicating that a milder alkali system can better maintain the oil's bioactive profile despite lower deacidification efficiency. Overall, the performance of alkali neutralization is governed by a delicate interplay between reaction kinetics, alkali strength, and process parameters such as temperature and mixing time. Optimal control of these variables is essential to achieve high deacidification efficiency while minimizing neutral oil loss and preserving the nutritional and functional quality of refined oils. Continued optimization and the integration of mild chemical or hybrid refining strategies may offer a path toward more sustainable and nutritionally favourable oil processing.

3.1.2. Soap stock formation and removal

The formation of soap stock is an inherent outcome of alkali refining and represents both a functional necessity and an environmental challenge. Soap stock comprises a complex mixture of soap salts (sodium or potassium carboxylates), water, residual free fatty acids (FFAs), and trace neutral oil. During the neutralization process, the alkaline reagent (NaOH or Na_2CO_3) reacts with FFAs to form soaps that are insoluble in oil. Once saponification occurs, efficient phase separation becomes critical to prevent contamination of the refined oil and ensure product stability. The separation is typically accomplished by centrifugation, filtration, or water washing. Centrifugation at high rotational speeds facilitates the stratification of oil and soap phases while filtration can remove fine soap particles that remain suspended. Water washing is often employed as a polishing step to eliminate residual soaps and alkali traces yielding an oil with improved clarity and lower alkalinity (Shah & Patel, 2022). Despite its necessity, this step generates considerable volumes of soap stock sludge and alkaline wastewater posing major environmental management concerns.

The soap stock disposal is problematic due to its high chemical oxygen demand (COD) and lipid content from an environmental perspective. Typical COD values exceed 40,000 mg L^{-1}, which, if discharged untreated, can severely deplete dissolved oxygen in aquatic systems, leading to eutrophication and fish mortality (Elsayed et al., 2024). Moreover, landfilling or direct discharge of soap stock can cause soil contamination and increase the burden on local wastewater treatment systems. Amaral et al. (2023) reported that conventional disposal practices in palm oil refining resulted in significant ecological degradation, including aquatic toxicity and soil nutrient imbalance. The recent studies have emphasized the valorization of soap stock through recovery and conversion technologies to mitigate these impacts. Transesterification and hydrolysis have emerged as promising strategies to transform soap stock into biodiesel, glycerol, and other value-added products effectively turning a high-pollution by-product into a renewable resource (Amaral et al., 2023). The biodiesel yield from soap stock can reach 85–90 % conversion efficiency depending on catalyst type and FFA content offering both environmental and economic benefits. Similarly, the recovery of sterols, tocopherols, and other bio actives from soap stock enhances the overall sustainability of refining operations (Bida et al., 2022; Shah & Patel, 2022).

The Emerging biotechnological approaches further expand these possibilities. Microbial consortia have been investigated for their ability to degrade soap stock into biodegradable polymers and biosurfactants by minimizing waste accumulation and promoting circular bioeconomy principles (Ayyildiz et al., 2023; Jach & Malm, 2022). These methods provide an eco-friendly alternative to traditional disposal reducing COD loads while generating secondary metabolites of industrial relevance. Overall, chemical refining particularly alkali neutralization using NaOH or Na_2CO_3 remains one of the most effective techniques for FFA reduction, the environmental management of soap stock remains a critical sustainability challenge. Integrated waste treatment and recovery systems that combine chemical, biological, and thermal valorization pathways represent the most promising direction for future development. These strategies not only address pollution control but also

contribute to resource efficiency aligning with global sustainability goals in the edible oil industry (Gautam et al., 2023; Gharby, 2022).

3.2. Physical refining

Physical refining is a widely adopted alternative to chemical refining, particularly suitable for oils rich in polyunsaturated fatty acids (PUFAs) such as sunflower, soybean, and palm oils. Unlike alkali neutralization, this method eliminates free fatty acids (FFAs) through distillative removal rather than chemical neutralization by avoiding soap stock formation and reducing chemical waste (Marsol-Vall et al., 2022). The process involves heating the oil to high temperatures (typically 220–270 °C) under high vacuum conditions (below 3–5 mbar) while introducing stripping steam to facilitate the volatilization and removal of FFAs. The key operations include steam distillation, vacuum stripping, and deodorization which collectively remove FFAs, volatile odour compounds, and other minor impurities. The efficiency of FFA removal depends on both temperature and steam flow rate as higher energy input enhances mass transfer but may accelerate thermal degradation of sensitive bioactive compounds.

In an optimized study on palm oil deacidification, Ashaari et al. (2021) demonstrated that operating at 240–260 °C, vacuum pressures below 3 mbar, and steam flow rates of 1.0–1.5 % *w*/w reduced FFA levels from an initial ~5 % to below 0.1 %, meeting refined oil standards. The study further revealed that physical refining preserved a higher proportion of carotenes and tocopherols resulting in an improved oxidative stability index (OSI) and extended shelf life relative to chemically refined counterparts (Rhazi et al., 2022). This nutrient retention is primarily attributed to the absence of strong alkaline reagents and minimal aqueous contact, which reduces the leaching of lipid-soluble antioxidants. Despite these advantages, physical refining presents notable energy and environmental trade-offs. The high temperatures required for effective distillation significantly increase energy consumption and operational costs, while potentially elevating the process's carbon footprint. Energy demand for physical refining can be 20–30 % higher than for chemical neutralization if heat recovery and process integration are not optimized (Ashaari et al., 2021). Advanced system designs incorporating multi-effect evaporators, heat exchangers, and vacuum energy recovery have been proposed to enhance efficiency and mitigate these drawbacks.

Overall, physical refining offers a chemical-free, environmentally favourable route for deacidification especially for oils with low phosphatide content and high FFA levels. The balance between energy efficiency, oxidative stability, and nutrient preservation remains central to ongoing research with current trends focusing on process optimization, hybrid refining systems, and renewable energy integration to further improve the sustainability of this refining approach.

3.2.1. Steam distillation

Steam distillation is a central operation in the physical refining of vegetable oils primarily employed for the removal of FFAs and other volatile impurities without the use of chemical reagents. In this process, the oil is heated under vacuum conditions while steam is introduced to facilitate the volatilization and separation of FFAs from the non-volatile triglyceride matrix (Kaya & Hung, 2021). The introduction of steam effectively lowers the partial pressure of volatile components by reducing their boiling points and enabling distillation at moderate temperatures that minimize thermal degradation of sensitive nutrients. The process involves co-distillation of FFAs with steam at elevated temperatures typically 240–270 °C and vacuum pressures of 2–5 mbar (Gharby, 2022). Under these conditions, FFAs and other volatile compounds vaporize and are subsequently condensed and collected in a separate phase, while the deacidified oil remains in the refining vessel. The vacuum environment plays a dual role by (i) lowering the vaporization temperature of FFAs and (ii) preventing oxidative deterioration by preserving the oil's quality and color.

The empirical studies underscore the efficiency and quality advantages of steam distillation. Oo et al. (2024) reported that optimized steam distillation achieved up to 90 % reduction in FFA content in palm oil reducing acidity to below 0.2 %, and substantially enhancing oxidative stability and sensory attributes. Similarly, Onn et al. (2023) observed that the process preserved higher levels of antioxidants and sterols which are often degraded during chemical refining. It leads to superior nutritional retention and longer oxidative stability index (OSI) values. These findings highlight steam distillation's capability to deliver high-purity, high-quality oils while maintaining their bioactive profiles. However, the process's major limitation lies in its energy intensity. The combination of high operational temperatures and continuous vacuum generation results in elevated thermal and electrical energy consumption by increasing operational costs and the carbon footprint of large-scale refining plants. The estimates suggest that steam distillation can consume 20–40 % more process energy than chemical neutralization if waste heat recovery and energy optimization are not implemented (Oo et al., 2024). Consequently, recent research has focused on hybrid refining systems combining physical distillation with mild chemical or enzymatic pre-treatments and energy integration techniques such as heat exchangers and vapor recompression to improve process sustainability.

In summary, steam distillation represents a chemically clean and quality-preserving method for vegetable oil deacidification offering distinct advantages in nutrient retention and environmental compatibility. Its broader industrial adoption, however, will depend on advancements in energy-efficient design and process integration to ensure economic viability alongside environmental performance.

3.2.2. Vacuum stripping

Vacuum stripping represents a crucial step in the physical refining sequence typically following steam distillation to remove residual FFAs and other volatile compounds. This process operates under reduced pressure enabling the volatilization of FFAs at substantially lower temperatures than would be required under atmospheric conditions by minimizing thermal degradation of heat-sensitive oil constituents (Jamoussi et al., 2022; Gharby, 2022). Vacuum stripping relies on the reduction of the oil's internal vapor pressure which decreases the boiling points of FFAs and other volatiles. When subjected to controlled heating under vacuum, these components evaporate and are subsequently condensed and separated from the bulk oil. This results in a product with significantly reduced acidity and enhanced oxidative and nutritional stability (Atta et al., 2024). The process is typically conducted at temperatures between 180 and 220 °C and vacuum pressures below 10 mbar allowing efficient deacidification while preserving vital micronutrients such as tocopherols, phytosterols, and polyunsaturated fatty acids (PUFAs) (Gharby, 2022; Mayayo et al., 2024).

The experimental evidence underscores the method's effectiveness and selectivity. Mayayo et al. (2024) demonstrated that vacuum stripping reduced the FFA content in sunflower oil to below 0.5 % achieving standards suitable for premium edible oils. The study also highlighted that, under optimal operating parameters the process maintained high levels of nutritional and bioactive compounds while preventing oxidative deterioration. The retention of PUFAs and antioxidants was attributed to the lower operating temperatures afforded by vacuum conditions which minimize exposure to oxygen and heat-induced degradation. Despite its advantages, vacuum stripping is highly sensitive to process control. Overheating or inadequate vacuum can lead to the loss of volatile flavour compounds and degradation of delicate nutrients. Conversely, insufficient energy input may result in incomplete FFA removal. Therefore, precise regulation of temperature, pressure, and residence time is critical to achieving the desired balance between deacidification efficiency and product quality (Mayayo et al., 2024).

In summary, vacuum stripping offers a mild, solvent-free, and environmentally favourable approach for the final purification of vegetable oils. When integrated with steam distillation and deodorization, it forms

a robust physical refining system capable of producing high-quality, low-acid oils with superior sensory and nutritional attributes. The future developments focus on energy optimization and process automation could further enhance its industrial scalability and sustainability.

3.2.3. Deodorization

Deodorization represents the final and most critical stage of the physical refining process serving both sensory and functional purposes in the production of edible vegetable oils. The operation aims to remove volatile odour- and flavour-causing compounds such as aldehydes, ketones, short-chain fatty acids, and oxidation products by improving the oil's sensory quality and extending its shelf life (Chen & Sun, 2023). Deodorization involves passing steam through the oil to strip off volatiles when conducted under high vacuum (1–5 mbar) and at temperatures ranging from 180 to 270 °C. The stripped vapours are then condensed and removed while the treated oil is cooled to preserve stability and minimize post-process oxidation (Czarnota et al., 2023). Deodorization functions as a steam distillation process under vacuum where injected steam reduces the partial pressure of volatile compounds enabling their removal at lower effective temperatures. This minimizes oxidative and thermal degradation of bioactive components such as tocopherols and phytosterols. Additionally, the process contributes to the final reduction of residual FFAs ensuring compliance with international standards for refined edible oils (<0.1 % FFA).

A recent study by Jamoussi et al. (2022) demonstrated that deodorization conducted at moderate temperatures (180–220 °C) and low vacuum pressures (1–3 mbar) effectively eliminated odour compounds in soybean oil while retaining essential nutrients including tocopherols and polyunsaturated fatty acids (PUFAs). The authors emphasized that such optimized parameters are particularly important for oils prone to oxidative deterioration during storage. However, exposure to excessive temperatures or prolonged treatment can lead to thermal degradation of volatile antioxidants resulting in reduced oxidative stability and shelf life. Hence, precise control of temperature, pressure, and steam flow rate is critical for achieving a balance between sensory improvement and nutritional preservation. Physical refining overall presents notable advantages over chemical refining. The absence of alkali and other reagents eliminates soap stock formation, minimizes chemical waste, and improves environmental sustainability (Colonia et al., 2023). Moreover, by reducing exposure to reactive chemicals, the process better preserves heat-sensitive micronutrients such as carotenoids, tocopherols, and phytosterols. However, these benefits are offset by high energy demands, particularly for maintaining elevated temperatures and deep vacuum conditions in steam distillation, vacuum stripping, and deodorization units. Energy consumption can increase by 20–40 % compared to chemical refining, and the specialized equipment required (e.g., vacuum pumps, steam generators, and heat exchangers) raises capital and operational costs (Atta et al., 2024).

The recent advances have therefore focused on enhancing the energy efficiency and selectivity of physical refining. Innovations such as membrane-based separation and supercritical CO_2 extraction have emerged as promising low-temperature alternatives for deacidification and deodorization. In a study by Sharghi et al. (2024), membrane distillation was applied to sunflower oil refining and achieved substantial reductions in energy use by operating at 50–90 °C, significantly lower than the 240–270 °C typically required for conventional steam distillation. This approach not only reduced thermal energy consumption but also preserved higher levels of bioactive compounds including tocopherols, phytosterols, and PUFAs. Despite these advantages, the technology faces challenges such as membrane fouling, complex equipment design, and high initial investment, which currently limit large-scale adoption. Physical refining particularly with innovations such as membrane distillation and supercritical CO_2 techniques is expected to remain a cornerstone of the vegetable oil industry as global demand for sustainably produced and nutritionally superior edible oils continues to rise (Meijaard et al., 2024; Gharby, 2022). The continued research aimed at energy optimization, waste heat recovery, and process integration will be essential to enhance both the economic and environmental sustainability of this refining approach.

3.3. Adsorptive methods

Adsorptive methods are increasingly gaining attention in the vegetable oil industry as an effective, ecofriendly and cost-effective alternative to conventional chemical refining techniques. These methods relay on adsorbent materials to remove impurities such as FFA's, colour pigments, odours, and other contaminants from crude vegetable oils. Activated carbon, silica-based adsorbents, clay or bentonite treatment are among the most widely used adsorptive materials in the oil deacidification process (Wan Osman et al., 2024).

3.3.1. Activated carbon and silica-based adsorbents

Adsorptive deacidification has emerged as an efficient alternative to traditional chemical and physical refining methods particularly for preserving the nutritional and sensory qualities of high-value vegetable oils. Among the various adsorbents evaluated, activated carbon and silica-based materials are the most widely applied due to their high surface area, large adsorption capacity, and selectivity toward FFAs and polar impurities (Yi et al., 2023). These materials operate primarily through physical adsorption, enabling effective impurity removal without inducing undesirable chemical transformations in the oil. Activated carbon is a microporous material characterized by extensive internal pore networks and reactive surface functional groups which facilitate the adsorption of FFAs, pigments, and trace contaminants. Adsorption occurs through Van der Waals forces and surface interactions between carboxylic groups in FFAs and oxygen-containing functionalities on the carbon surface. Once equilibrium is reached the purified oil is separated from the carbon via filtration yielding a product with significantly reduced acidity (Channei et al., 2025). In a recent study, Aniobi et al. (2023) demonstrated that activated carbon achieved up to a 75 % reduction in FFA content during the deacidification of soybean oil with moderate acidity levels making it a viable option for oils containing 1–3 % FFAs. However, adsorption capacity was found to decrease sharply for oils with higher acidity due to rapid surface saturation. This limitation highlights the need for adsorbent regeneration to maintain performance and cost efficiency. Regeneration can be accomplished through thermal desorption or chemical treatment restoring adsorption capacity and extending adsorbent lifespan over multiple cycles. Despite its efficiency, activated carbon use must balance adsorbent cost, regeneration frequency, and adsorption kinetics to remain economically sustainable for large-scale refining.

Silica gel and modified silica materials constitute another important class of adsorbents used for oil deacidification. Owing to their high specific surface area, tunable pore structure, and chemical stability, silica adsorbents effectively remove polar impurities including FFAs, pigments, and trace metals while preserving essential nutrients and sensory quality (Soylu et al., 2025). Adsorption occurs through hydrogen bonding and Van der Waals interactions between the hydroxyl groups of silica and carboxylic acid groups in FFAs. A study by Wang et al. (2023) reported that silica gel achieved an 85 % reduction in FFA content during the refining of peony oil while maintaining high levels of tocopherols and polyphenols demonstrating its selectivity and mildness compared with alkali refining. The study also noted that temperature strongly influences adsorption efficiency with elevated temperatures (>70 °C) reducing FFA uptake due to desorption effects. Thus, precise control of adsorption parameters (including temperature, contact time, and adsorbent dosage) is essential for optimal deacidification and nutrient preservation. Silica-based systems are often combined with other refining steps (such as mild degumming or filtration) to enhance overall purification efficiency and reduce energy consumption. Their mild operating conditions and minimal chemical input make them

particularly suitable for refining premium and specialty oils sensitive to oxidative or thermal degradation. Both activated carbon and silica-based adsorbents demonstrate strong potential for sustainable deacidification in vegetable oil refining. Activated carbon offers broad adsorption capabilities but requires efficient regeneration strategies while silica materials provide higher selectivity and better nutrient preservation (Yi et al., 2023). The continued research into adsorbent modification, regeneration methods, and process optimization including the development of composite adsorbents and nanostructured materials is expected to further enhance the economic and environmental sustainability of adsorptive deacidification in the vegetable oil industry.

3.3.2. Clay and bentonite treatment

Clay, bentonite, activated carbon, and silica-based adsorbents are widely used in adsorptive deacidification methods due to their high surface area, adsorption capacity, and ability to remove impurities from vegetable oils while preserving essential nutritional and sensory qualities. These materials offer an environmentally friendly alternative to chemical refining since they operate without chemical reagents, reducing environmental impact and preserving sensitive compounds such as antioxidants, tocopherols, and phytosterols (Akhtar et al., 2024; Gharby, 2022). Activated carbon is highly porous which allows it to adsorb free fatty acids (FFAs) and other polar impurities from oils. The adsorption occurs through physical interactions between the FFA molecules and the carbon's surface functional groups, and the purified oil is separated from the carbon after treatment (Channei et al., 2025; Yi et al., 2023). Aniobi et al. (2023) demonstrated that activated carbon could reduce FFA content in soybean oil by up to 75 %, making it a viable option for oils with moderate acidity. However, its effectiveness decreases for high-acid oils due to saturation, and the carbon must be regenerated via thermal or chemical methods to maintain efficiency and reduce long-term costs.

Silica-based adsorbents, including silica gel and modified silica materials are effective in removing polar impurities (such as FFAs, pigments, and trace metals) without affecting the oil's flavour or nutritional quality. Adsorption occurs via hydrogen bonding and Van der Waals interactions between the oil molecules and the silica surface (Soylu et al., 2025). Wang et al. (2023) reported that silica gel could reduce FFA content in peony oil by 85 % while preserving antioxidants such as tocopherols and polyphenols. The method is particularly advantageous for oils sensitive to nutrient loss, but its efficiency depends on precise control of temperature, contact time, and adsorbent amount. Clay, including fuller's earth is widely used for deacidification and decolorization of vegetable oils due to its availability, low cost, and ability to be regenerated. Activated clay adsorbs FFAs, pigments, phospholipids, and trace metals through surface adsorption mechanisms, leaving behind cleaner oil (Soylu et al., 2024; Asbbane et al., 2024). Anyikwa et al. (2021) found that activated fuller's earth reduced FFA content in crude palm oil by 60–70 % without significant losses of tocopherols and phytosterols highlighting its ability to preserve nutritional properties. The adsorption efficiency can be influenced by the oil type and presence of other impurities emphasizing the need to optimize parameters such as contact time, temperature, and clay dosage.

Bentonite composed mainly of montmorillonite is particularly effective for oils with high impurity content or as a post-treatment following alkali refining. Its adsorption efficiency is enhanced by its high surface area and cation-exchange properties which allow it to bind FFAs, pigments, and trace metals (Badran et al., 2023). Kwaśnica et al. (2022) demonstrated that bentonite could reduce FFA content in hemp oil by 50–60 % making it suitable for oils with high initial acidity. However, its fine particle size necessitates additional filtration steps, which can increase processing time and operational costs. Despite their effectiveness, adsorptive methods have limitations. Adsorbents have finite capacity requiring regeneration or replacement to maintain efficiency and their performance can be limited for very high-acid oils (Sharma, Barthwal, et al., 2022; Sharma, Sharma, et al., 2022). Operational conditions such as temperature, contact time, and adsorbent concentration must be carefully controlled to optimize deacidification while preserving oil quality. The recent advances have focused on enhancing adsorption capacity through nanomaterials, modified adsorbents, biodegradable or recyclable materials, and hybrid combinations of activated carbon, silica, and clay (Gharby, 2022; Kumar et al., 2020; Yuan et al., 2023). Integration with techniques such as membrane filtration also shows promise for improving efficiency, reducing energy consumption, and producing high-quality, environmentally sustainable oils.

Overall, adsorptive deacidification using activated carbon, silica-based adsorbents, clay, and bentonite provides an effective, environmentally friendly, and nutritionally preserving alternative to chemical refining. While challenges related to adsorbent capacity, regeneration, and high-acid oils remain, ongoing research and technological innovations continue to improve the applicability and sustainability of these methods in industrial oil refining (Gharby, 2022; Akhtar et al., 2024; Yuan et al., 2023).

4. Advanced deacidification technologies

4.1. Enzymatic deacidification

Enzymatic deacidification has become an efficient and sustainable approach for reducing FFA content in high-acid oils under mild reaction conditions. Unlike chemical neutralization, which often causes triglyceride loss and generates soap stock, enzymatic methods employ lipases or esterases to selectively catalyze the esterification or transesterification of FFAs, converting them into neutral glycerides with minimal alteration of the triacylglycerol (TAG) profile (Dunford, 2022a, 2022b; Xu et al., 2021, b). Immobilized lipases such as *Candida antarctica* lipase B (CALB) operate at the oil-solvent interface promoting the reaction between FFAs and short-chain alcohols (e.g., ethanol or glycerol). The enzymatic reaction rate is governed by substrate diffusion and water activity, enabling control over reaction selectivity and minimizing oxidation or hydrolysis side reactions (Li, Deng, et al., 2022; Li, Wang, et al., 2022; Liu et al., 2024). For instance, Xu et al. (2021, b) reported that under optimal conditions (40 °C, 200 rpm, 5 % water content), FFA levels in α-linolenic acid-enriched oil decreased from 12.8 % to below 0.3 % within 6 h, while maintaining over 98 % of the original TAG composition.

Continuous-flow and immobilized reactor systems further enhance catalytic efficiency and scalability. Xu et al. (2022a, 2022b) demonstrated a tandem continuous-flow enzymatic reactor for rice bran oil deacidification, achieving over 95 % FFA removal with a productivity of 1.2 kg FFA converted h^{-1} g^{-1} enzyme and stable activity over 20 cycles. Similarly, Liu et al. (2024) showed that immobilized CALB@MCM-41-C8 lipase achieved 90 % FFA reduction in rapeseed oil at 45 °C, while preserving desirable aroma compounds, indicating minimal structural disruption of the lipid matrix. Process conditions and feedstock composition significantly influence enzyme performance. Feng et al. (2023) found that the catalytic efficiency of immobilized lipase decreased by 15–20 % when processing crude oil with higher phospholipid content due to enzyme fouling but could be restored by optimizing temperature (50 °C) and substrate flow rate (0.8 mL min^{-1}). Moreover, the introduction of glycerol-based deep eutectic solvents as reaction media enhanced substrate solubility and reduced interfacial tension, improving FFA conversion from 82 % to 96 % while retaining over 90 % enzyme activity after 10 cycles (Li, Deng, et al., 2022; Li, Wang, et al., 2022).

These findings demonstrate that enzymatic deacidification offers precise control over acid removal through biocatalytic mechanisms that maintain oil quality. Quantitatively, most systems achieve >90 % FFA reduction, preserve >95 % TAG integrity, and retain >85 % enzyme activity across multiple cycles parameters that underscore the industrial potential of enzyme-assisted oil processing (Dunford, 2022a, 2022b; Liu

et al., 2024; Xu et al., 2022a, 2022b). Beyond deacidification, enzymatic treatments offer targeted cleaning and stain removal due to their substrate specificity, reducing collateral damage to sensitive fibers. Effective application requires optimization of enzyme type, concentration, temperature, and pH to balance activity and material safety (Xu et al., 2024). The development of multifunctional nanocellulose-based composites represents a significant step toward holistic conservation. These materials can integrate deacidification, structural reinforcement, antimicrobial activity, and environmental resilience (e.g., UV and humidity protection), enabling long-term preservation under variable storage conditions.

In summary, enzymatic deacidification combines specificity, mild reaction conditions, and adaptability through nanocellulose-based composites offering a quantitatively measurable reduction in cellulose degradation while preserving artifact integrity. The continued research into enzyme selection, nanoparticle incorporation, and material engineering promises increasingly efficient, reversible, and multifunctional conservation strategies.

4.1.1. Lipase-catalyzed esterification and hydrolysis

Lipases, hydrolase enzymes capable of catalyzing esterification and hydrolysis are central to industrial biocatalysis due to their high specificity and ability to operate under mild conditions. These properties enable applications across food, pharmaceuticals, biofuels, and sustainable chemical processes. Lipases catalyze the nucleophilic attack of hydroxyl or carboxyl groups on ester bonds allowing selective formation or cleavage of esters without harsh reagents. In esterification, lipases facilitate environmentally friendly syntheses. Singhania et al. (2021) demonstrated selective ester formation from primary alcohols and carboxylic acids in aqueous micellar media using TPGS-750-M surfactant enabling one-pot, multi-step reactions with negligible organic solvent use. Similarly, lipase-catalyzed polymerization of levoglucosan-based monomers has produced biobased polyesters providing a sustainable alternative to conventional petrochemical routes (Bassut et al., 2022). These examples highlight lipase versatility in constructing both small-molecule esters and complex polymers. Lipase-mediated hydrolysis exhibits remarkable chemo selectivity. Vilas Bôas (2022) reviewed the selective cleavage of ester bonds to generate aromatic, emulsifying, and lubricant esters under mild conditions a process often unattainable with traditional chemical methods. This precision is particularly valuable in synthesizing unsymmetric biphenyl esters and other complex molecules.

Industrial applications further underscore lipase efficacy. Monteiro et al. (2024) achieved >95 % conversion in the enzymatic esterification of castor oil fatty acids with 2-ethyl-1-hexanol using Eversa Transform 2.0 producing bio lubricants with improved oxidative stability and tribological performance. In the food sector, two-step, solvent-free lipase-catalyzed esterification of lauric acid generated esters with antimicrobial and antioxidative properties, enhancing emulsion stability and food safety. Lipases also function in unconventional media. Nanomicelle-assisted aqueous esterification enables reactions traditionally restricted to organic solvents aligning with green chemistry principles (Singhania et al., 2021). Overall, lipases combine efficiency, selectivity, and environmental compatibility, enabling sustainable production of esters, polymers, lubricants, and functional food additives. Ongoing research continues to expand their mechanistic understanding and industrial applicability, reinforcing their role as versatile and eco-friendly biocatalysts.

4.1.2. Enzyme immobilization techniques for industrial applications

Enzyme immobilization, the attachment of enzymes to solid supports, enhances stability, reusability, and facilitates separation from reaction mixtures, making it a cornerstone of industrial biotechnology. Immobilized enzymes often retain activity over extended periods, tolerate broader pH and temperature ranges, and enable continuous production, reducing operational costs and aligning with sustainable practices. Immobilization stabilizes enzyme conformation, prevents denaturation, and can protect active sites from harsh conditions. The common strategies include adsorption where weak interactions anchor enzymes to carriers such as activated carbon. Covalent binding which forms chemical bonds for enhanced stability but may partially reduce activity. Entrapment and encapsulation confine enzymes in gels or semipermeable membranes while allowing substrate diffusion while crosslinking aggregates enzyme molecules via agents like glutaraldehyde for industrial robustness (Mohidem et al., 2023). Ideal carriers are inert, biocompatible, and high-surface-area. Nanomaterials particularly magnetic nanoparticles which enable facile recovery and can increase enzyme half-life by 2-3fold (Cavalcante et al., 2024). Renewable agrowaste-derived supports provide cost-effective and sustainable alternatives.

The operational benefits are substantial: immobilized laccase on magnetic nanoparticles retained >80 % activity after five reuse cycles in dye degradation, while keratinase immobilized on chitosan-β-cyclodextrin showed enhanced thermal stability and extended shelf life. Applications span textile processing, food, pharmaceuticals, biofuels, and environmental remediation, including wastewater treatment where immobilized enzymes achieve high pollutant removal efficiency. The challenges persist, including activity loss during immobilization, mass transfer limitations, and support material costs. Advanced solutions such as nanostructured carriers, hybrid supports, metal-organic frameworks, and 3D-printed entrapment matrices are under development to address these issues. As industrial demand for sustainable, cost-effective biocatalysis grows, enzyme immobilization continues to offer versatile and scalable solutions (Bassut et al., 2022; Baena et al., 2022; Cavalcante et al., 2024).

4.2. Supercritical Fluid Extraction (SFE)

Supercritical Fluid Extraction (SFE) has emerged as a sustainable and efficient method for oil deacidification, using supercritical carbon dioxide (SC-CO_2) as a green solvent. Operating above CO_2's critical temperature (31.1 °C) and pressure (7.38 MPa), SC-CO_2 combines gas-like diffusivity with liquid-like solvating power, enabling selective removal of free fatty acids (FFAs) while preserving triglycerides and bioactive compounds. The tunable density of SC-CO_2 allows precise control of solvating strength by adjusting temperature and pressure, achieving efficient deacidification at relatively low temperatures, thereby minimizing thermal degradation of sensitive nutrients (Wang et al., 2024). Rice bran oil which naturally contains elevated FFAs, has been effectively refined via SFE. Dunford (2022) reported that optimized SC-CO_2 conditions reduced FFA content by over 70 % improving both edibility and shelf life while retaining tocopherols and other antioxidants. Similarly, wheat germ oil, rich in bioactive compounds, benefits from SFE's mild conditions; counter-current column setups selectively extract FFAs, yielding oil with significantly lower acidity without compromising tocopherol content.

The recent innovations integrate SFE with membrane separation to enhance FFA removal and minimize oil losses. For example, soybean oil processed through SFE-membrane hybrids demonstrated improved deacidification efficiency while maintaining overall yield. SC-CO_2 extracts FFAs based on polarity and molecular size, and membranes further concentrate and separate these acids, resulting in a synergistic, solvent-free refining process (Huang et al., 2024). Overall, SFE provides a versatile, eco-friendly approach for producing high-quality, minimally processed oils. Its ability to selectively remove FFAs, preserve nutrients, and adapt to diverse oil matrices makes it particularly valuable for food, nutraceutical, and pharmaceutical applications. The continued optimization of pressure, temperature, and hybrid processing strategies promises to broaden SFE's applicability and efficiency in sustainable oil refinement.

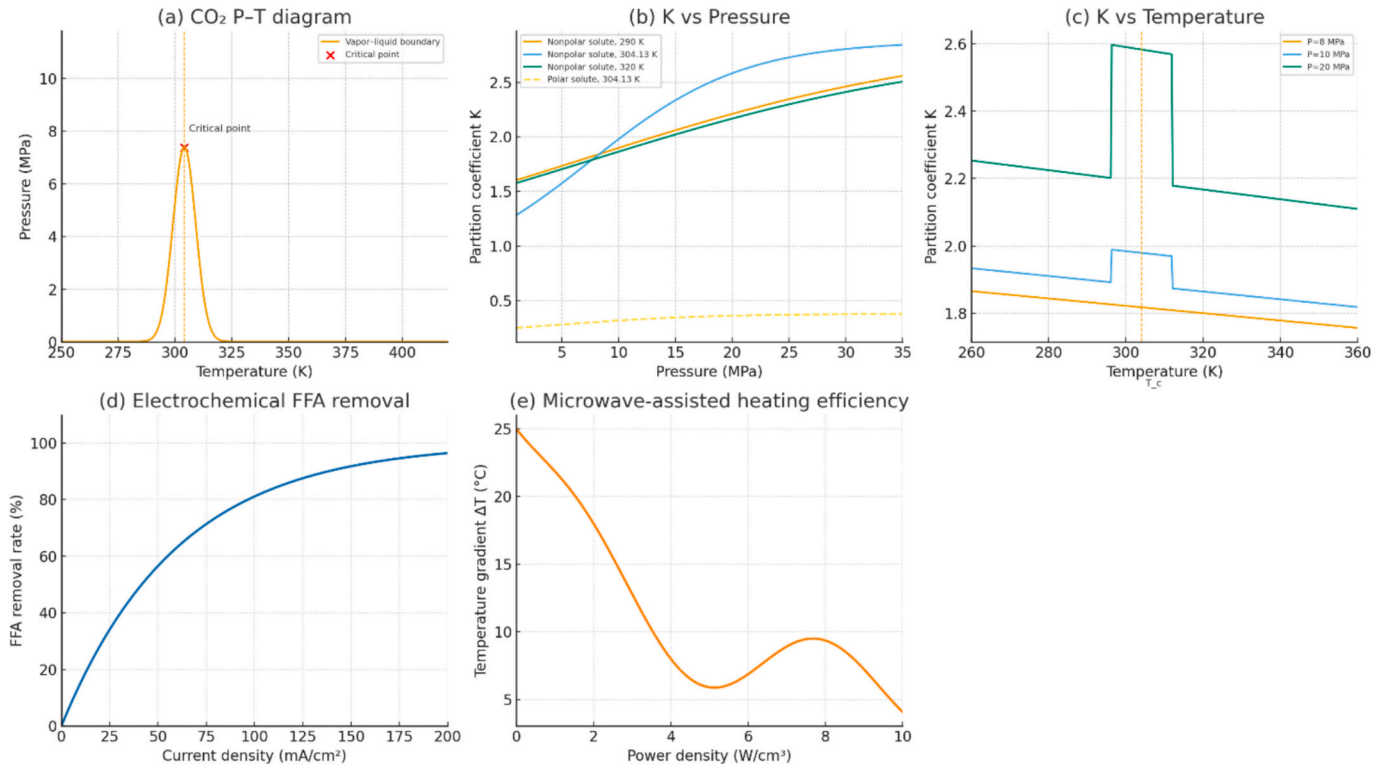


Fig. 3. a, b, c. Supercritical CO_2 process: pressure-temperature-partition coefficient curves, d. Electrochemical methods: current density versus FFA removal rate plots, and e. Microwave-assisted processes, power density versus temperature gradient.

4.2.1. *CO_2-based FFA removal*

The removal of FFAs is a critical step in oil refining essential for improving stability, sensory quality, and shelf life. Traditional chemical deacidification methods (such as alkali refining) are effective but often produce undesirable by-products including soap stock, glycerol losses, and wastewater, raising environmental and economic concerns. These limitations have driven the development of greener, more selective techniques, with CO_2-based methods emerging as particularly promising. Supercritical CO_2 (SC-CO_2) extraction utilizes CO_2 above its critical temperature and pressure, a state in which the fluid exhibits gas-like diffusivity and liquid-like solvating power. These properties allow SC-CO_2 to penetrate oil matrices efficiently and selectively solvate FFAs without disrupting triglycerides or thermally sensitive bioactives such as tocopherols, carotenoids, and polyunsaturated fatty acids. Studies have shown that SC-CO_2 can reduce FFA content by 60–80 % in oils such as rice bran and wheat germ under optimized conditions while retaining over 90 % of tocopherols, demonstrating both selectivity and mild processing conditions (Huang et al., 2024).

The ability to tune CO_2 density via pressure and temperature adjustments allows precise control over solvation strength, balancing deacidification efficiency with nutrient preservation. Hybrid systems combining subcritical CO_2 extraction with membrane technologies have been developed to further enhance performance. In these setups, CO_2 selectively solubilizes FFAs while membranes separate acids from triglycerides. This approach reduces operational pressures and energy requirements while improving FFA removal efficiency. For example, studies on soybean oil using CO_2-membrane hybrids achieved up to 75 % FFA reduction with minimal oil loss, outperforming conventional solvent extraction in both yield and selectivity. Innovative solvent strategies have also expanded CO_2-based deacidification. CO_2-responsive deep eutectic solvents (DESs) can reversibly change polarity under CO_2 exposure, enabling tailored extraction of FFAs from oils with complex compositions (Wang et al., 2024).

Zhou et al. (2024) reported up to 85 % FFA removal in crude oils while preserving antioxidant activity, highlighting the potential of tunable, green solvent systems to enhance selectivity and efficiency. Biological approaches, such as photo biocatalysis offer an alternative route by enzymatically converting FFAs into hydrocarbons under light exposure. The utilization of enzymes like fatty acid photo decarboxylases, this method achieves substantial FFA reduction (65–80 %) under mild conditions without chemical solvents or high temperatures, preserving triglyceride integrity (Wenjian et al., 2022). Overall, CO_2-based deacidification encompasses SC-CO_2 extraction, CO_2-membrane hybrids, DES-assisted extraction, and photo biocatalysis represents a versatile, sustainable strategy for oil refining. These methods achieve high FFA removal while maintaining nutritional and sensory qualities, reduce chemical waste, and can be adapted for a wide range of oils, including rice bran, wheat germ, soybean, and palm oils. Ongoing research focuses on optimizing CO_2 flow rates, pressures, solvent compositions, and continuous processing designs to improve scalability and cost-effectiveness. As consumer demand for minimally processed, high-quality oils grows and environmental regulations tighten, CO_2-based deacidification is poised to play a central role in next-generation, sustainable oil refining technologies (Huang et al., 2024; Wang et al., 2024).

4.2.2. *Selectivity and efficiency considerations*

Supercritical CO_2 (SC-CO_2) exhibits unique physicochemical properties that make it an effective solvent for selective deacidification of oils. Above its critical temperature and pressure, CO_2 displays gas-like diffusivity and liquid-like solvating power, which can be finely tuned by adjusting temperature and pressure. This tunability enables selective solubilization of FFAs over triglycerides (TAGs), primarily due to differences in molecular weight, polarity, and intermolecular interactions. By optimizing operational parameters, SC-CO_2 can extract FFAs efficiently, producing deacidified oils with minimal loss of desirable nutrients such as tocopherols, carotenoids, and polyunsaturated fatty acids. Reported studies show FFA reductions of 60–80 % in rice bran,

soybean, and wheat germ oils under pressures of 15–25 MPa and temperatures of 40–60 °C, while retaining over 90 % of key bioactive components (Dunford, 2022). SC-CO_2 extraction has been integrated with membrane separation technologies to enhance both selectivity and efficiency. Hybrid systems combining SC-CO_2 with nanofiltration membranes exploit the solvating ability of CO_2 and the molecular sieving effect of membranes to separate FFAs from TAGs more effectively. This approach reduces processing time, improves oil purity, and minimizes solvent use. For example, studies on soybean oil have demonstrated that SC-CO_2/nanofiltration hybrids can achieve FFA removal efficiencies exceeding 75 %, surpassing conventional supercritical extraction alone. The combination also facilitates continuous processing, which is advantageous for industrial-scale operations (Huang et al., 2024).

Subcritical CO_2 extraction, conducted below the supercritical point but above the gas phase, offers a gentler alternative suitable for heat-sensitive oils such as palm and soybean oil. Operating at lower pressures and temperatures, subcritical CO_2 maintains oil quality while effectively reducing FFA content. Petračić et al. (2022) reported that subcritical CO_2 could achieve up to 65 % FFA reduction in soybean oil without significant losses in tocopherols or other bioactives, highlighting its suitability for mild processing environments. This method also contributes to energy savings and operational simplicity, making it an attractive option for smaller-scale or low-temperature refining processes. The efficiency of CO_2-based deacidification depends on multiple process variables, including CO_2 flow rate, extraction time, temperature, and pressure. Optimizing these parameters is critical to maximize FFA removal while minimizing oil loss. Experimental design techniques such as response surface methodology (RSM) have been employed to model the interactions between these factors, enabling the identification of optimal conditions tailored to specific oil types. For instance, RSM studies indicate that increasing CO_2 density through higher pressures enhances FFA solubility, but excessively high pressures may reduce selectivity by partially solubilizing TAGs. Likewise, extended extraction times improve FFA removal but may lead to minor losses of sensitive nutrients, highlighting the need for precise process control (Wang et al., 2024). The Fig. 3. a, b, c. explains the pressure-temperature-partition coefficient curves of supercritical CO_2 process. Overall, CO_2-based deacidification including SC-CO_2, subcritical CO_2, and hybrid membrane-assisted processes offers a green, efficient, and tunable approach for improving oil quality. These methods address both environmental and nutritional concerns, providing a scalable and sustainable alternative to conventional chemical refining by selectively removing FFAs while preserving essential components.

4.3. Membrane-based techniques

4.3.1. Ultrafiltration, nanofiltration, and pervaporation

The deacidification of edible oils is a vital stage in refining that determines product quality, stability, and shelf life. Conventional chemical neutralization with alkaline solutions effectively removes free fatty acids (FFAs) but often results in 2–5 % oil loss, substantial wastewater generation, and high energy consumption. To address these limitations, membrane-based separation technologies (namely ultrafiltration (UF), nanofiltration (NF), and pervaporation (PV)) have emerged as sustainable alternatives offering selective separation, reduced environmental impact, and compatibility with existing refining operations. Ultrafiltration utilizes semi-permeable membranes with pore sizes ranging from 0.01 to 0.1 μm, functioning primarily through size exclusion to remove macromolecules such as phospholipids, proteins, and mucilaginous substances that cause turbidity and oxidative instability in crude oils. UF facilitates the physical retention of colloidal impurities without affecting triglyceride composition. The studies on crude canola oil have shown that UF can reduce phospholipid levels by over 80 %, markedly improving clarity and oxidative resistance while enhancing downstream processing efficiency. Nanofiltration, employing membranes with pore sizes of approximately 1–10 nm and molecular weight cutoffs between 200 and 1000 Da separates small solutes such as FFAs from triglycerides via diffusion and charge-based repulsion. The process operates at moderate pressures (1–4 MPa) and offers high selectivity due to differences in molecular size and polarity. In soybean oil systems, NF has demonstrated FFA rejection rates exceeding 90 %, reducing the acid value from 4.5 to below 0.5 mg KOH/g while preserving over 95 % of triglycerides (Bolto et al., 2020). This quantitative improvement underscores NF's capability for effective deacidification with minimal oil loss and without chemical additives.

Pervaporation, in contrast operates on the principle of differential sorption and diffusion through a dense membrane followed by vapor-phase transport enabling the separation of volatile components based on their affinity to the membrane material. In edible oil processing, PV has been applied for solvent recovery and the removal of volatile impurities. When integrated into deacidification systems, PV can recover up to 95 % of organic solvents such as hexane or ethanol used in extraction, thereby lowering operational costs and reducing environmental emissions. A hybrid system combining UF, NF, and PV provides a comprehensive and intensified approach to deacidification. Abdorrezaee and Raisi (2021) reported that sequential integration of these membrane processes achieved efficient deacidification of crude canola oil while enabling solvent recycling. In this configuration, UF eliminates macromolecular impurities, NF selectively separates FFAs, and PV recovers solvents and volatile fractions. The integrated membrane system not only enhances deacidification efficiency with overall FFA reductions exceeding 90 % but also reduces total energy consumption by 30–40 % compared to chemical neutralization, aligning with sustainable refining principles.

Despite these advantages, membrane fouling, limited lifespan, and scale-up challenges continue to constrain industrial application. The current research focuses on developing fouling-resistant and high-permeability membranes through surface modification, nanocomposite incorporation, and optimization of hydrodynamic conditions. Advances in material science and module design are expected to further improve the durability, selectivity, and economic feasibility of membrane-based deacidification, positioning UF, NF, and PV as integral components of next-generation edible oil refining processes.

4.3.2. Polymeric and ceramic membrane performance in FFA separation

Polymeric and ceramic membranes have been widely explored for edible oil deacidification due to their tunable surface properties, separation efficiency, and operational adaptability. Among polymeric materials, polyvinylidene fluoride (PVDF) is particularly valued for its chemical resistance, mechanical strength, and thermal stability. However, its inherent hydrophobicity limits FFA rejection and promotes fouling. To mitigate this, surface modification strategies have been developed. For example, coating PVDF membranes with chitosan (CS) enhances hydrophilicity and introduces amine groups capable of electrostatic interactions with FFAs, improving selectivity. Crosslinking the CS layer with glutaraldehyde (GA) increases film integrity and reduces swelling, resulting in enhanced FFA rejection and superior antifouling behaviour (Baig & Waheed, 2023). Quantitatively, such modifications have been shown to increase FFA rejection efficiency by up to 25–40 % and prolong membrane life by nearly twofold under continuous operation. Polymeric membranes fabricated from polyether sulfone (PES), PVDF, or polysulfone (PS) typically feature pore sizes of 0.2–0.5 μm and thicknesses between 100 and 200 μm operating effectively at 1–4 bar and temperatures up to 60 °C. These moderate conditions make them suitable for cost-sensitive and batch-scale operations. However, fouling remains a critical limitation primarily caused by hydrophobic interactions and pore blockage by phospholipids, proteins, and oxidation products. This results in declining flux and selectivity over time with reported flux reductions of 20–50 % after prolonged use. Strategies such as hydrophilic surface coatings, periodic backwashing, and cleaning-in-place (CIP) protocols are employed to restore performance and extend

operational lifespan.

Ceramic membranes composed of inorganic materials like alumina (Al_2O_3), zirconia (ZrO_2), or titania (TiO_2) exhibit superior thermal and chemical resilience. It functions with the pore sizes of 0.1–0.3 μm, thicknesses of 1–2 mm, and operating capacities up to 10 bar and 300 °C which is suited for harsh industrial environments. Their rigid, smooth structure resists organic fouling and inorganic scaling more effectively than polymeric counterparts allowing stable flux and higher recovery rates. Pilot-scale studies using ceramic membranes for rice bran oil deacidification achieved substantial FFA reductions while retaining bioactive components like oryzanol (Huang et al., 2023). Additionally, using low-cost precursors such as coal fly ash has been explored to lower fabrication expenses while maintaining comparable permeability and selectivity. Despite their robustness, ceramic membranes can still experience fouling from residual oils, proteins, and mineral salts, particularly when processing crude or unrefined feedstocks. These effects are typically mitigated through high-temperature backflushing and aggressive chemical cleaning, which ceramic membranes can withstand due to their structural stability. Although ceramic systems incur higher initial costs, their longer lifespan and tolerance to severe cleaning protocols make them economically favourable in continuous operations. In contrast, polymeric membranes remain preferable for lower-cost, small- or medium-scale applications under mild process conditions (Baig and Waheed, 2023).

The hybrid membrane systems have been developed to exploit the complementary advantages of both types. For instance, employing a polymeric membrane for preliminary FFA removal followed by a ceramic membrane for final polishing enhances overall deacidification efficiency and product purity. Further improvements have been demonstrated by coating ceramic membranes with polypyrrole (PPy), which increases hydrophilicity and oil rejection while maintaining mechanical strength. Such hybrid and surface-modified configurations have reported overall FFA removal efficiencies exceeding 90 %, with improved permeate flux stability and reduced fouling rates. The ongoing advancements in membrane materials and design continue to drive improvements in oil deacidification performance. Emerging research focuses on mixed-matrix membranes (MMMs) incorporating nanoparticles, graphene oxide, or zeolites to enhance selectivity and flux, as well as bio-based polymers to improve environmental sustainability. The key challenges ahead involve scaling up these systems, optimizing long-term fouling control, and integrating membranes into existing refining operations (Huang et al., 2023). The continued material innovation and process intensification, membrane-based technologies are poised to play a central role in developing energy-efficient and sustainable edible oil deacidification processes.

4.4. Electrochemical methods

4.4.1. Electrochemical neutralization and electrodialysis

Electrochemical neutralization represents an emerging, reagent-free approach for edible oil deacidification, utilizing electric currents to drive redox reactions that neutralize free fatty acids (FFAs) without producing chemical waste. The process involves the generation of hydroxyl ions at the cathode and hydrogen ions at the anode which react with acidic and basic components, respectively, facilitating in situ neutralization. Unlike conventional chemical methods, electrochemical neutralization can be precisely controlled through current density and electrode configuration, enabling selective targeting of FFAs while preserving triglyceride integrity. A notable variation, electrocoagulation has been widely applied in petroleum refinery wastewater treatment where the electrolytic dissolution of metal electrodes generates coagulant species such as $Fe(OH)_3$ or $Al(OH)_3$ that adsorb and precipitate emulsified oil and organic contaminants. Abbas and Asel (2023) reported that electrocoagulation achieved substantial reductions in chemical oxygen demand (COD) and oil content often exceeding 90 % removal efficiency (Shown in Fig. 3. d) demonstrating its potential as a clean, controllable neutralization technique. Though traditionally used for aqueous systems these same electrochemical principles can be adapted for oil deacidification, particularly when integrated with mild emulsification to enhance FFA ionization and transfer toward reactive sites.

Electrodialysis (ED) extends electrochemical principles to membrane-based ionic separation. It employs alternating cation- and anion-exchange membranes under an applied electric field to selectively transport charged species. In oil deacidification, FFAs, present as carboxylate anions ($RCOO^-$), can be efficiently separated from the oil matrix. Luo et al. (2023) demonstrated that ED removed over 99 % of acids from corncob acid hydrolysate, simultaneously recovering valuable by-products such as proteins and phenolic compounds highlighting its potential for resource recovery alongside deacidification. However, membrane fouling remains a key limitation, caused by the accumulation of organic and inorganic species on the membrane surface, which elevates electrical resistance and decreases ion transport efficiency. In this study, fouling was primarily linked to lignin-carbohydrate complexes and protein aggregates necessitating periodic chemical cleaning to restore performance. To address fouling, current research focuses on developing fouling-resistant ion-exchange membranes, optimizing electric field strength, and incorporating hydrodynamic turbulence promoters to minimize concentration polarization. Quantitatively, such optimizations can reduce energy consumption by 15–25 % and extend membrane lifespan by up to 30 %, significantly improving process economics.

A major advantage of electrochemical deacidification technologies lies in their compatibility with renewable energy sources. Alkhadra et al. (2022) demonstrated that electrodialysis and related electrochemical systems can operate efficiently under intermittent power inputs making them ideal for coupling with solar or wind energy. This adaptability can lower the carbon footprint of refining operations and contribute to sustainable process intensification. Additionally, the modular nature of ED systems allows for scalable and customizable configurations accommodating varying oil feedstocks and production capacities (Luo et al., 2023). The future advancements in electrochemical deacidification are expected to focus on developing hybrid systems that combine neutralization and separation within a single electro-membrane module. Further emphasis should be placed on techno-economic assessments, optimization of energy efficiency, and validation at pilot and industrial scales. These next-generation systems hold promise for transforming edible oil refining into a cleaner, more efficient, and sustainable process by merging electrochemistry with membrane technology.

4.4.2. Impact on oil quality and energy efficiency

Electrochemical deacidification processes, particularly electrodialysis (ED), have emerged as promising alternatives to traditional chemical neutralization for refining edible oils. These processes efficiently reduce FFA content while preserving the nutritional and sensory integrity of the oil (Luo et al., 2023). Unlike alkali neutralization, which often removes beneficial minor components such as tocopherols, sterols, and phenolics, ED operates under mild thermal and chemical conditions, minimizing oxidative degradation and nutrient loss. This ability to maintain oil quality is critical for retaining both the health-promoting attributes and consumer acceptance of edible oils. Electrochemical deacidification offers substantial efficiency advantages from an energetic standpoint. Electrodialysis relies on ion migration across selectively permeable membranes driven by an applied electric potential, rather than by thermal or chemical gradients. As a result, energy consumption is markedly lower typically 30–50 % less than conventional chemical neutralization since the process operates at near-ambient temperatures and eliminates the need for extensive heating or reagent preparation. This improved energy profile not only reduces operational costs but also contributes to environmental sustainability by lowering carbon emissions associated with energy-intensive refining stages. Despite these benefits, challenges remain, most notably membrane

fouling in ED systems (Luo et al., 2023).

Fouling arises from the deposition of organic materials, residual oils, and inorganic salts on the membrane surface leading to reduced ion transport efficiency and elevated energy demand. The studies have shown that flux decline due to fouling can reach 20–40 % during extended operation, depending on feed composition and process conditions. To mitigate these effects, regular cleaning protocols, including chemical rinsing and polarity reversal, are essential to maintain system performance. Ongoing research focuses on developing fouling-resistant ion-exchange membranes incorporating surface modifications such as hydrophilic coatings or nanoparticle additives, and optimizing operational parameters such as current density and flow hydrodynamics to enhance long-term stability. A key advantage of electrochemical deacidification lies in its compatibility with renewable energy sources. ED systems can function effectively under intermittent power inputs making them well suited for integration with solar or wind energy (Alkhadra et al., 2022). This adaptability can significantly reduce the carbon footprint of oil refining and aligns with global efforts toward sustainable and low-emission manufacturing. Furthermore, the modular design of electrodialysis units enables scalability and customization, allowing the technology to be tailored for diverse oil feedstocks and production capacities.

The future advancements in electrochemical deacidification are expected to focus on hybridizing ED with other separation processes (such as ultrafiltration or pervaporation) to enhance efficiency and product purity. Parallel developments in membrane engineering, energy optimization, and process integration will be crucial to realize industrial viability. Comprehensive techno-economic and life-cycle assessments are also essential to evaluate cost-effectiveness and environmental impact at scale. Collectively, these innovations position electrochemical deacidification as a transformative, energy-efficient, and sustainable approach for next-generation edible oil refining (Luo et al., 2023).

4.5. Ionic liquids and deep eutectic solvents (DESs)

4.5.1. Emerging solvents for selective FFA removal

Ionic liquids (ILs) and deep eutectic solvents (DESs) have emerged as innovative green solvents for the deacidification of edible oils offering environmentally benign alternatives to conventional chemical refining. Ionic liquids are salts composed of bulky organic cations (such as imidazolium, pyridinium, or cholinium) and various inorganic or organic anions that remain liquid at room temperature. Their distinctive physicochemical properties including negligible vapor pressure, high thermal stability, and tunable polarity, make them ideal for selective free fatty acid (FFA) extraction. ILs interact with FFAs through acid-base pairing, hydrogen bonding, and electrostatic interactions, facilitating their separation from triglycerides without inducing hydrolysis or oxidation. The recent research has focused on cholinium-based ILs, derived from natural and biodegradable precursors, which exhibit low toxicity and enhanced biocompatibility. For example, cholinium oleate demonstrated high selectivity in extracting FFAs from vegetable oils reducing acid values by up to 80–90 % while preserving essential nutritional compounds such as tocopherols and sterols (Fabiane et al., 2023). These results highlight the potential of IL-based systems to achieve effective deacidification under mild conditions, maintaining oil quality and sensory attributes.

Deep eutectic solvents (DESs) composed of a hydrogen bond donor (HBD) and hydrogen bond acceptor (HBA) form eutectic mixtures with melting points significantly lower than those of their individual components. DESs share many advantageous characteristics with ILs (such as low volatility, high solvation capacity, and chemical tunability) but are typically more cost-effective, biodegradable, and easier to prepare. Natural DESs (NADESs), formulated from renewable constituents like betaine, glycerol, or polyalcohol's, have demonstrated comparable or superior performance to ILs in edible oil deacidification. For instance, NADESs based on betaine-polyol systems effectively reduced FFAs in palm oil while preserving bioactive minor compounds such as carotenoids and tocotrienols (Sander et al., 2022). When comparing ILs and DESs, both solvent systems exhibit high selectivity and extraction efficiency often achieving FFA reductions exceeding 85 %. However, DESs generally hold advantages in environmental sustainability, biodegradability, and economic feasibility. Their preparation typically involves simple mixing of natural, low-cost precursors without additional purification steps. The selection between ILs and DESs depends on parameters such as oil composition, targeted FFA profile, desired product purity, and process economics.

The success of IL- and DES-based deacidification relies on optimizing solvent-to-oil ratios, phase separation dynamics, and solvent recovery strategies for industrial application. Process integration studies have demonstrated that extractive deacidification using DESs can be incorporated into existing refining lines with minimal modifications, achieving efficient solvent regeneration and reuse over multiple cycles with >90 % solvent recovery. These characteristics significantly enhance process sustainability and reduce waste generation (Fabiane et al., 2023). The ongoing advancements in task-specific solvent design where ILs or DESs are tailored for selective interaction with particular FFA structures promise to further improve separation performance and recyclability. Future research should emphasize molecular-level modelling to predict solvent-FFA interactions, life-cycle and techno-economic assessments to evaluate large-scale viability, and integration with hybrid refining systems such as membrane or electrochemical technologies. Collectively, ILs and DESs represent a transformative step toward sustainable, energy-efficient, and low-emission edible oil deacidification processes (Sander et al., 2022).

4.5.2. Mechanistic insights and sustainability aspects

The efficacy of ionic liquids (ILs) and deep eutectic solvents (DESs) in free fatty acid (FFA) removal is closely tied to their distinctive molecular interaction mechanisms. ILs, consisting of bulky organic cations and diverse anions, can be molecularly engineered to selectively interact with FFAs through hydrogen bonding, π–π stacking, electrostatic attraction, and van der Waals forces. These interactions facilitate the complexation or solubilization of FFAs while maintaining triglyceride stability. In contrast, DESs formed by mixing hydrogen bond donors (HBDs) and acceptors (HBAs) establish an extensive hydrogen-bonding network that enhances the solvation and selective extraction of FFAs from oil matrices. This tunable hydrogen-bond framework underpins their high deacidification efficiency and mild extraction behaviour, ensuring the preservation of beneficial components such as tocopherols, carotenoids, and sterols. Although ILs and DESs are often promoted as green solvents, their sustainability profiles require nuanced evaluation. ILs exhibit advantageous characteristics (such as low volatility, high thermal stability, and strong solvent power) yet concerns persist regarding toxicity, limited biodegradability, and high synthesis costs. Conversely, DESs, particularly natural DESs (NADESs) synthesized from benign components such as choline chloride, betaine, and carboxylic acids, offer greater biodegradability, lower toxicity, and cost-effectiveness (Aditi & Ranjan, 2023). Their facile preparation through simple mixing without complex purification steps and their potential for recycling and regeneration further strengthen their environmental and economic appeal.

The comparative studies indicate that both ILs and DESs can achieve substantial FFA reductions, often exceeding 80–90 %, depending on solvent composition and oil type. For instance, deacidification of palm oil using betaine monohydrate–carboxylic acid DESs achieved significant acid value reduction while maintaining oxidative stability and sensory quality. Similarly, ILs have demonstrated high selectivity in extracting FFAs from biodiesel feedstocks and vegetable oils, with reported acid value decreases of up to 85 % under optimized solvent-to-oil ratios. The choice between ILs and DESs ultimately depends on factors such as feedstock characteristics, target purity levels, economic constraints, and environmental impact considerations (Fabiane et al.,

Table 2
Removal of FFA from vegetable oil by advance non-thermal techniques.

S. No	Technique	Type of oil / initial acid value / throughput	Method	FFA removal / conversion	Vitamin E / antioxidant retention	Energy / water / waste flows	References
1	Microwave-Assisted Treatment (Microwave irradiation)	• Non-edible oil or waste oil (oleic acid model)	• 150 W microwave power; • Ethanol:oleic acid molar ratio 2:1; $T = 473$ K; $t = 6$ h	• 97.62 % conversion of oleic acid to ester under specified conditions	–	• Energy: microwave process noted as more energy-efficient vs conventional heating Water: reaction produces water (esterification byproduct)	Nguyen et al. (2020)
2	Microwave pre-treatment (seed heating)	• Canola seeds / flaked seeds	• Microwave heating: 110 °C, 300 s, 190 kJ/kg	• Reduction of lipase activity thus preventing FFA formation. • FFA content reduced (initial 8.17 % FFA of WCO) to 0.082 % in one WCO microwave-esterification study.	–	• Energy: in WCO study ~250 W microwave, 35 s; energy lower than conventional.	Gaber et al. (2021)
3	Microwave-assisted Interesterification	• Waste cooking oil	• Microwave-assisted catalysis at 30–60 °C (details modest)	• Modification of triglyceride structure by reaction with alcohol; • Reduces FFA content before biodiesel conversion.	–	• –	Pop (2018)
4	DBD Cold Plasma	• Vegetable oil	• 15 % H_2: 85 % He gas mix; 12h exposure.	• In palm oil hydrogenation study, linolenic acid decreased by 86.6 %, linoleic by 69.2 %.	• Tocopherol stability was affected • Tocopherol stability significantly higher in stripped corn oil than medium-chain TAG after plasma treatment	• Plasma treatment reduced moisture content by ~20 % after 6 min	Puprasit (2021), Puprasit et al. (2020)
5	DBD Cold Plasma	• Soybean oil	• Electrical discharge in H_2 gas - (iodine value dropped from 128 ppm to 99.6 ppm).	• Reduction in iodine value (thus unsaturation) but explicit FFA removal not given	–	–	Wang et al. (2020)
6	DBD Cold Plasma	• Palm oil -initial acid value ~67.16	• Plasma treatment of palm oil with glycerol as hydrogen donor; • Iodine value reduced from 67.16 to 31.61; • No trans-fat formed	• FFA removal not specified; • Iodine value drop implies unsaturation reduction rather than direct FFA removal	–	–	Priyanti et al. (2024)
7	Plasma-Assisted Catalytic Trans-esterification	• Vegetable oil	• Atmospheric plasma, CaO/ZnO catalyst, methanol at room temperature.	• Enhanced FFA conversion to methyl esters; improved biodiesel yield	–	–	Palm et al. (2022)

2023). Industrial-scale deployment of IL and DES systems requires addressing process integration, solvent recovery, and scalability. The recent engineering advances have enabled their incorporation into existing refining lines with minimal retrofitting, employing techniques such as phase separation-assisted extraction, vacuum stripping, and solvent regeneration to enhance economic viability. Efficient recycling protocols have achieved solvent recovery rates exceeding 90 %, substantially reducing waste generation and operating costs. The modular and tunable nature of IL and DES-based systems further supports process customization, allowing flexibility across varying production capacities and oil types (Sander et al., 2022).

The current research continues to refine these solvent systems focusing on the design of task-specific ILs and DESs with enhanced FFA selectivity, reduced cytotoxicity, and improved biodegradability. The exploration of novel hydrogen bond donors and acceptors derived from renewable feedstocks such as amino acids, sugars, and organic acids offers promising routes to more sustainable formulations. The future efforts should integrate molecular modelling, techno-economic assessments, and life cycle analyses to fully evaluate the industrial potential and environmental impact of IL- and DES-based deacidification technologies. Collectively, these innovations highlight the growing potential of green solvent systems as viable, energy-efficient, and sustainable alternatives for next-generation edible oil refining (Aditi & Ranjan, 2023).

4.6. Plasma-assisted and microwave techniques

The innovative methods for selective deacidification of oils include non-thermal approaches that avoid high temperatures, preserving the oil's quality while effectively removing FFAs. Various non-thermal methods have been developed for selective deacidification of oils, each offering distinct advantages in terms of efficiency and sustainability (Wadhwani, 2022). The Table 2 represents some advanced technologies for removal FFA from oil.

4.6.1. Plasma-assisted techniques

Plasma-assisted deacidification represents (Shown in Fig. 4) an advanced non-thermal technology that utilizes ionized gases to initiate targeted chemical reactions capable of reducing FFAs and modifying

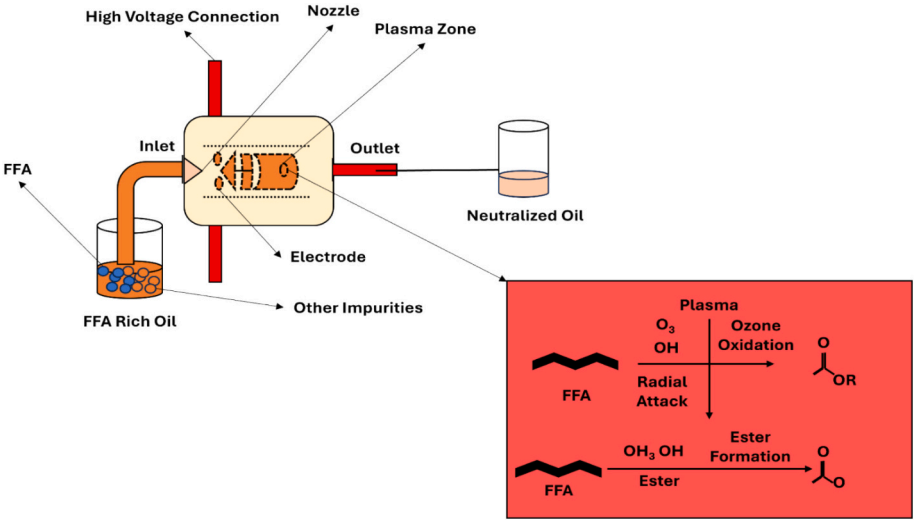


Fig. 4. Plasma assisted technique.

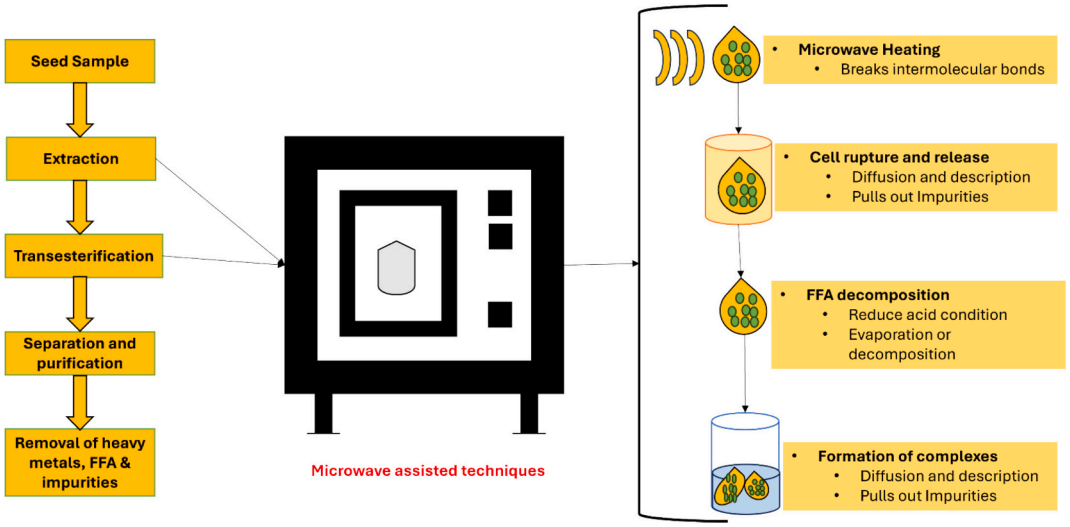


Fig. 5. Microwave assisted technique.

lipid structures while preserving the oil's nutritional integrity (Machmudah et al., 2025). Unlike conventional thermal or catalytic treatments that often induce oxidation or nutrient loss, plasma systems operate at near-ambient temperatures relying on energetic electrons, ions, and radicals to drive reactions selectively. Palm et al. (2022) explored a plasma-assisted catalytic transesterification route for oil processing at 20–22 °C employing a dielectric barrier discharge (DBD) system operating at ~5 kV under atmospheric pressure. The combination of plasma activation with CaO-ZnO catalysts significantly enhanced transesterification kinetics achieving high ethyl acetate conversion within shorter reaction times compared to conventional catalysis. Plasma-generated high-energy electrons activate methanol molecules into reactive intermediates (-CH_3, CH_3O-), which more readily react with triglycerides and FFAs to form methyl esters (biodiesel) and glycerol. This process simultaneously decreases FFA content in waste oils and improves their fuel properties, demonstrating plasma's dual deacidification and upgrading functionality.

Thirumdas (2023) investigated DBD cold plasma for partial hydrogenation of vegetable oils under mild conditions (<50 °C; 20 kV; 2–10 min exposure). Even short treatments of 2–4 min effectively reduced FFA levels and initiated selective hydrogenation, whereas prolonged treatments (8–10 min) led to diminishing returns and minor quality degradation. The plasma generated reactive oxygen and nitrogen species (ROS/RNS) that oxidized FFAs into volatile compounds and, in the presence of hydrogen donors such as glycerol, promoted selective hydrogen addition to double bonds. This enabled the formation of more stable saturated lipids without trans-fat generation, addressing a major limitation of conventional hydrogenation processes. Furthermore, plasma treatment inactivated lipase enzymes, preventing further FFA formation and thereby extending shelf life (Hernández-Torres et al., 2022). Puprasit (2021) optimized DBD cold plasma treatment parameters for palm oil using a H_2-He gas mixture (15 % H_2, 85 % He). The study examined the effects of hydrogen concentration (25–100 % H_2), input power (20–80 W), gas flow (0.25–1.5 L min^{-1}), electrode gap (0.25–1 cm), and reaction time (0–15 h). Helium served as the carrier gas due to its superior ionization capability while nitrogen was excluded to avoid forming hazardous nitrides or cyanides. The shorter treatment times (2–4 min) yielded optimal FFA reduction and enzyme deactivation confirming the process's high efficiency under non-thermal conditions. Compared with chemical antioxidant or enzymatic lipase inhibition treatments plasma technology demonstrated superior FFA removal and lipid stabilization, without introducing synthetic additives or requiring high energy input. The similar studies by Birania et al. (2022), Jafari and Therdthai (2022), and Sarangapani et al. (2018) corroborate plasma's

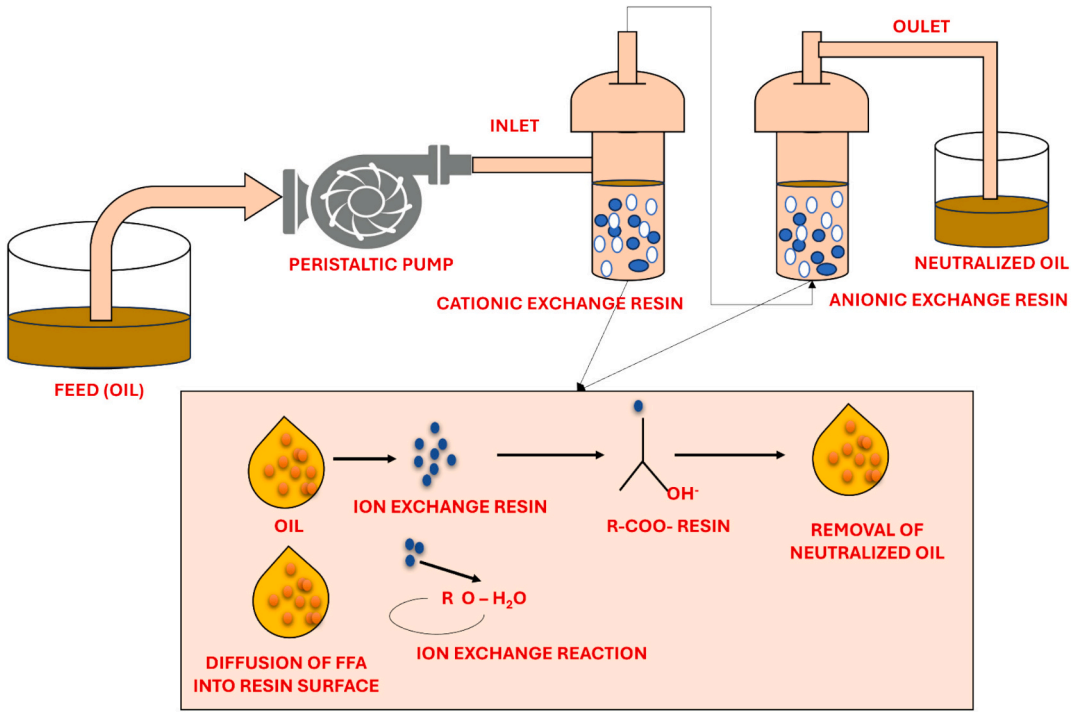


Fig. 6. FFA removal by Ion exchange resin.

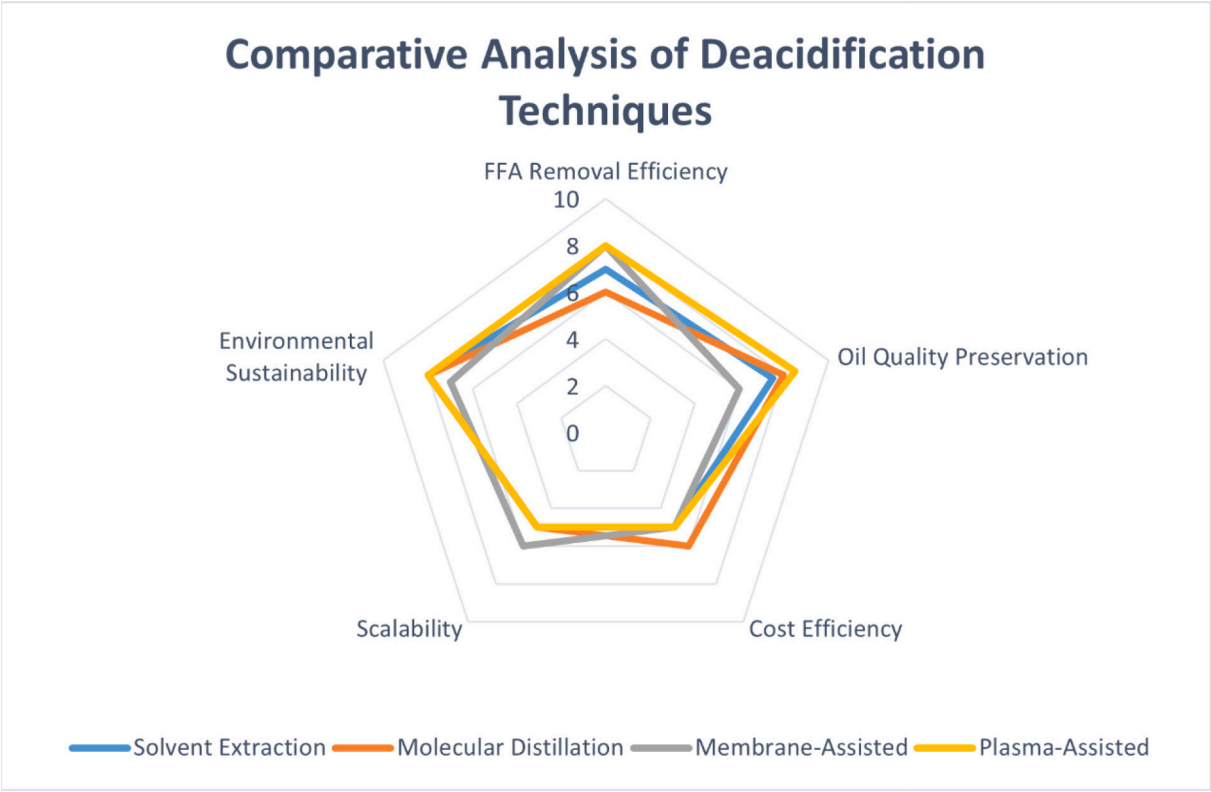
multifunctional role in improving lipid quality, oxidative stability, and food safety.

Priyanti et al. (2024) applied DBD plasma using glycerol as a hydrogen donor to produce trans-fat-free margarine from palm oil. The setup featured a helium flow rate of 1 L min^{-1}, 35 W discharge power, 10 mm electrode gap, and ambient temperature operation enabled selective saturation of unsaturated fatty acids without cis-to-trans isomerization. While a 12 h treatment achieved the desired solid fat consistency, it raised concerns regarding process scalability and productivity. Additionally, the reliance on helium, though beneficial for plasma stability, presents economic and sustainability limitations for large-scale implementation. Future optimization should address energy efficiency, carrier gas substitution, and assessment of the oxidative stability and sensory properties of plasma-treated fats for industrial adoption. Collectively, plasma-assisted deacidification and hydrogenation offer a solvent-free, non-thermal, and energy-efficient approach to improving oil quality. The technology effectively reduces FFA content, inactivates lipolytic enzymes, and enables controlled lipid modification without generating trans fats or compromising nutritional components. Nonetheless, challenges remain in controlling hydrogenation selectivity, scaling up reactor designs, and monitoring volatile by-products to ensure safety and consistency (Birania et al., 2022). Addressing these issues through advances in reactor engineering, process automation, and real-time plasma diagnostics could accelerate the transition of plasma-assisted oil processing from laboratory research to industrial-scale sustainable applications.

4.6.2. *Microwave techniques*

Microwave treatment represents (Shown in Fig. 5) an advanced thermal processing approach that utilizes electromagnetic radiation (300 MHz-300 GHz) to generate internal heating through dipolar rotation and ionic conduction, enabling rapid and uniform temperature elevation within the material (Pattnaik & Mishra, 2020). In oil refining, these mechanisms accelerate free fatty acid (FFA) degradation and enhance reaction kinetics in esterification and neutralization steps, thereby improving deacidification efficiency. For example, microwave exposure at 700 W for 2–6 min achieved substantial FFA reduction while minimizing thermal gradients and preserving heat-sensitive nutrients (Chen et al., 2024). Despite its benefits, large-scale application faces challenges in ensuring uniform energy distribution, as localized overheating can lead to nutrient loss and oxidative degradation. Microwave-assisted extraction (MAE) further enhances oil recovery from seeds and nuts by disrupting cellular matrices and increasing membrane permeability (Zamanhuri et al., 2021). This process reduces solvent consumption and extraction time compared with conventional Soxhlet extraction while facilitating neutralization through improved FFA reactivity with alkalis. The controlled microwave exposure preserves bioactive compounds (such as tocopherols, polyphenols, and omega fatty acids) by limiting exposure time and preventing prolonged oxidation. This retention of antioxidants improves both nutritional and oxidative stability though optimal energy and time parameters remain critical to avoid localized overheating.

Microwave-assisted hydrogen peroxide digestion (MW-AHPD) has been investigated for both multi-elemental analysis and refining. Under optimized conditions (2.0 mol L^{-1} H_2O_2, 156 °C, 50 min) it achieved efficient digestion with residual carbon contents of 0.84–1.60 % (m/m) (Munjanja et al., 2025). At these temperatures, partial thermal degradation of FFAs occurs, reducing oil acidity while promoting neutralization with alkali agents. However, maintaining precise temperature control is vital to prevent degradation of bioactive constituents. Microwave pretreatment prior to extraction enhances both yield and bioactive preservation, as shown by Yang et al. (2013) in rapeseed processing. Treatment at 600 W for 6 min ruptured cell structures and increased solvent penetration outperforming conventional preheating (90 °C for 20 min) in tocopherol and phenolic retention. Nevertheless, excessive exposure (>6 min) caused degradation, underscoring the need for matrix-specific optimization to balance extraction intensity and nutrient stability. Microwave-assisted esterification has proven highly effective for high-FFA oils. Trinh et al. (2017) reduced the FFA content of rubber seed oil from 40.14 % to 0.79 ± 0.02 % under optimal conditions: 60 °C, methanol-to-oil ratio 19.94:1, 7.93 wt% H_2SO_4, and 23 min reaction time. Methanol concentration was the dominant variable driving equilibrium toward methyl ester formation while excessive catalyst addition yielded diminishing returns. Although efficient, solvent recovery and



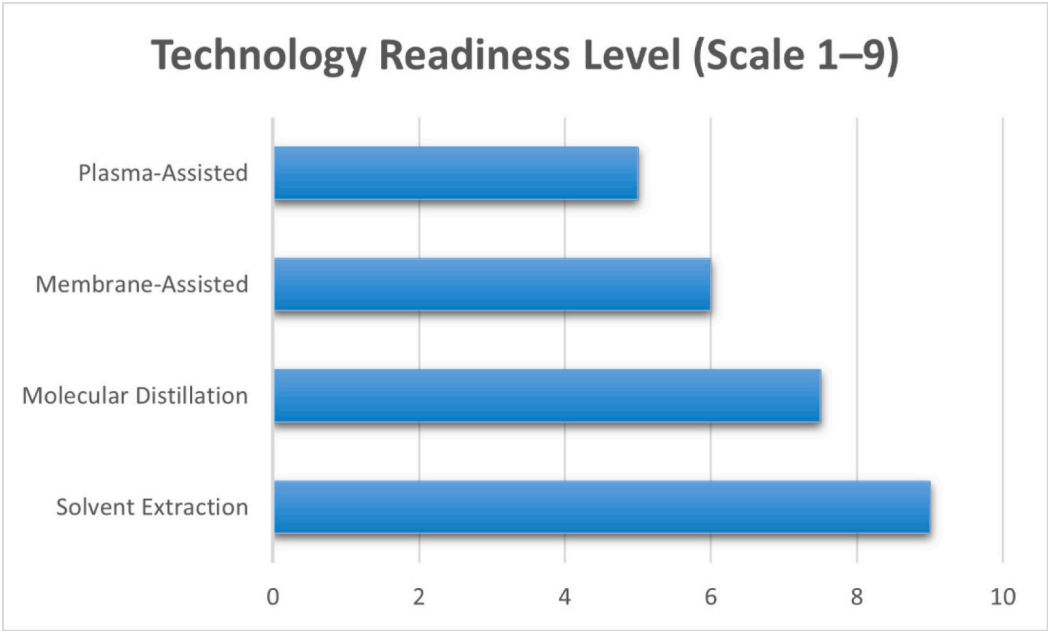


Fig. 7. Comparative analysis and technology readiness level of deacidification techniques.

long-term oil stability warrant further investigation to ensure environmental and quality compliance.

Microwave-assisted extraction of flaxseed oil (Koubaa et al., 2016) at 450 W for 3–5 min demonstrated improved retention of phenolics and lower peroxide and anisidine values compared to conventional extraction. The volumetric and non-contact heating of microwaves promoted rapid mass transfer without extended thermal stress. Yet, power levels exceeding 600 W or prolonged exposure caused localized degradation, emphasizing the importance of intermittent or pulsed heating strategies. Microwave stabilization also extends to grains and brans. Adebowale et al. (2020) observed that microwave treatment of sorghum flour (36–90 kJ / 100 g) significantly decreased fat acidity and anisidine values, attributed to lipase inactivation and reduced lipid oxidation, enhancing flavour stability during storage. Similarly, Patil et al. (2016) optimized rice bran stabilization at 4 W/g for 5 min effectively reducing FFAs while maintaining oil quality. However, excessive power (6 W/g) caused charring and oxidation, demonstrating the narrow operational margin between stabilization and degradation. These studies highlight that while microwave heating can effectively inactivate lipolytic enzymes, uniform energy distribution and residual enzyme assays are

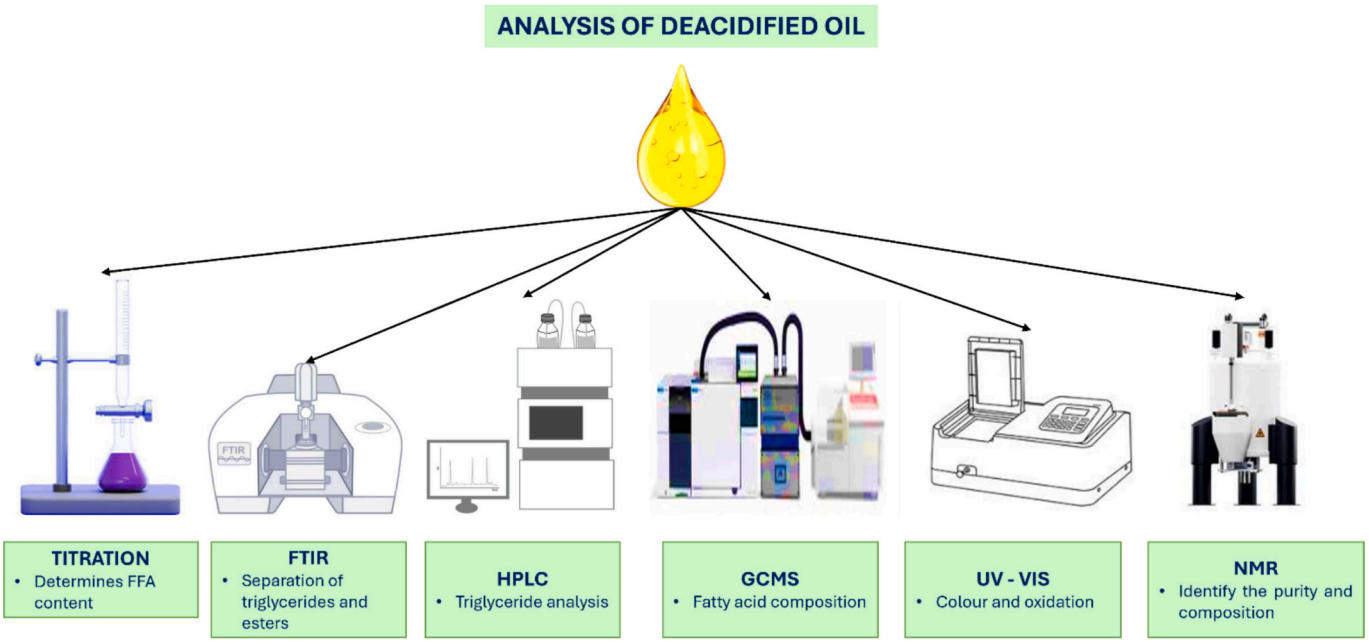


Fig. 8. Different analytical approaches used for characterisation of de-acidified oils.

crucial for validating process efficiency. Li, Wang, et al. (2022) and Li, Deng, et al. (2022) found that microwave treatment of white and red sorghum at 900 W for 40 s increased total phenolic and flavonoid content and enhanced antioxidant capacity (DPPH, ABTS). Prolonged exposure (>60 s) reversed these effects due to thermal degradation, illustrating the time-sensitive nature of microwave-induced bioactive enhancement. Liu et al. (2021) reported similar trade-offs in rice bran, where brief exposure (1–2 min) reduced antinutrients (phytates, oxalates) but extended heating (3 min) diminished vitamin E and phenolic content, reducing antioxidant activity.

Overall, microwave-assisted technologies for deacidification, extraction, stabilization, or hydrogenation offer substantial advantages in processing speed, energy efficiency, and bioactive retention. They promote rapid volumetric heating, enhancing molecular motion, reaction rates, and enzyme inactivation kinetics without the extended exposure associated with conventional methods. However, process optimization remains critical to balance FFA reduction with the preservation of nutritional and sensory qualities. The key challenges include ensuring uniform field distribution, scalability, and real-time temperature monitoring in industrial systems. Future research should focus on modelling heat and mass transfer dynamics, integrating sensor-based control systems, and validating performance through long-term storage and sensory evaluations to enable the safe and sustainable application of microwave processing in edible oil refining.

4.7. Ion exchange resin-based deacidification

The adsorptive removal of FFAs from oils using ion exchange resins (shown in Fig. 6) exploits the chemical properties of FFAs and the functional architecture of resins. FFAs (R-COOH) are polar, acidic compounds formed via triglyceride hydrolysis, and their removal is critical to improve oil quality. Ion exchange resins are cross-linked polymers bearing charged functional groups capable of selective ion binding. Anion exchange resins with positively charged sites, such as quaternary ammonium groups, interact electrostatically with dissociated FFAs ($R\text{-}COO^-$), exchanging them with counterions like OH^- or Cl^-. This exchange is enhanced by COOH ionization in the presence of moisture or mild heat. Conversely, cation exchange resins with negatively charged sites can bind FFAs via proton exchange forming soap-like complexes. Hydrophobic polymer matrices additionally stabilize FFAs through van der Waals and hydrophobic interactions enabling selective removal without affecting desirable oil components (Khedkar et al., 2020). This non-thermal process preserves oil quality, and resins can be regenerated offering a cost-effective and environmentally friendly alternative to chemical neutralization (Deboni et al., 2018). KP et al. (2025) evaluated FFA removal from high-acid coconut oil using three resins: Amberlyst A26, Amberlite IRA 400 (AMT), and Dowex WGR-2 (DOX). Amberlyst A26 achieved the highest removal efficiency at 98.02 %, attributed to strong base properties, high porosity, and hydrophobicity facilitating electrostatic binding to $R\text{-}COO^-$ ions. AMT removed 85.92 % of FFAs, while weak base DOX achieved 75.4 % (KP et al., 2025). Hydrophobic interactions further contributed to adsorption. Challenges for industrial scale-up include resin cost, regeneration needs, fouling, and sensitivity to moisture and temperature (Machmudah et al., 2025).

Juera-Ong et al. (2022) demonstrated FFA reduction in sludge palm oil using Amberlyst 15. Under optimized heterogeneous conditions (44.7 wt% methanol, 38.6 wt% catalyst, 360 min), FFAs decreased from 89.16 wt% to 1.26 wt%, while homogeneous sulfuric acid reduced FFAs to 1.03 wt% in 79.7 min but required more methanol (58.4 wt%) and generated wastewater. Amberlyst 15 was reusable for nine cycles with conversion decreasing from 97.7 % to 90.3 %, demonstrating environmental and economic advantages despite longer reaction times. Singh et al. (2021) examined strong and weak base resins for FFA removal from refined soybean oil, identifying Amberlite FPA 51 (secondary amine, weak base) as the most effective under 8 h of treatment. The mechanism involved electrostatic attraction of $R\text{-}COO^-$ to positively charged sites and stabilization via hydrophobic interactions. Ethanol washing desorbed 86.55 ± 5.19 % of FFAs, showing good renderability. Limitations include slow adsorption kinetics and variable performance with different oil matrices, which may affect industrial feasibility. Chung et al. (2018) treated peanut oil with strong base resins A26OH and IRA900Cl achieving up to 85 % FFA removal. Elevated temperatures (25–45 °C) improved diffusion and adsorption fitting both Langmuir and Freundlich isotherms, indicating monolayer electrostatic and multilayer hydrophobic adsorption. Oil quality was preserved, though long-term resin stability and regeneration were not fully evaluated.

Susik and Ptasznik (2023) compared ion exchange resins and NaOH neutralization for post-fermentation corn oil. Ion exchange resins operated under milder conditions (60 °C, 60 min) and retained bioactive

Table 3
Deacidification methods, mechanisms, analytical techniques, advantages, limitations, and quantitative aspects in deacidification of oils.

Method / Technique	Mechanism	Analytes / Parameters Measured	Advantages	Limitations	Quantitative Range / Data	References
Titrimetric FFA Estimation	• Neutralization of free fatty acids with NaOH/KOH; color change via indicator	• FFA, Acid Value	• Simple, cost-effective, routine lab use	• High reagent use, time-consuming, low selectivity, no dynamic info	• FFA typically 0.2–8 %	Di Pietro et al., 2020
Automated Flow Titration (FIA)	• Oil reacts with indicator in flow system; neutralization detected by spectrophotometer	• FFA, acid neutralization kinetics	• Rapid, online monitoring, customizable flow/volume	• Solvent selection critical, dense/high-viscosity oils may clog	• Comparable to titration, real-time monitoring	Pereira et al., 2020; Nurulain et al., 2021
Gas Chromatography (GC)	• Fatty acids derivatized to methyl esters, separated by column based on polarity	• Fatty acid profile, individual FFA	• High resolution, reliable separation	• High temperature, sample prep needed	• Accurate quantification of individual fatty acids	KP et al., 2025
GC-MS (Mass Spectrometry)	• GC separation + MS for mass-dependent structural identification	• Fatty acids, hydrocarbon/oxygenated hydrocarbons	• Structural elucidation, MIQ reduces calibration	• Expensive, requires standards	• Peak comparison with library; MIQ allows multi-ion quantification	Guerrero-Esperanza et al., 2023
HPLC	• Separation via stationary/mobile phase interactions	• Heat-labile bio actives (tocopherols, tocotrienols)	• Sensitive, avoids thermal degradation	• Requires pre-treatment (TLC/column)	• Quantifies individual phytochemicals; retention compared pre- and post-deacidification	Xu et al., 2020; Xin et al., 2022
UPLC	• High-pressure, sub-2 μm particles for ultra-fine separation	• Phenolic compounds, minor bio actives	• Very sensitive, rapid, small sample	• High-pressure equipment, cost-intensive	• Detects ultra-low concentration compounds	Wang et al., 2023
FTIR Spectroscopy	• IR absorption by functional groups; C=O and OH bands indicate FFA/glycerides	• Free fatty acids, glycerides	• Non-destructive, rapid, minimal sample prep	• Low sensitivity for very low FFA; triglyceride interference	• FFA detection 0.2–8 %; 1711 cm^{-1} marker for FFA	Bai et al., 2022; Ma et al., 2024; Lu et al., 2022
Raman Spectroscopy	• Inelastic light scattering to detect chemical bonds	• Hydrolyzed/oxidized fatty acids	• Non-destructive, complementary to FTIR	• Expensive, lower throughput	• Semi-quantitative, qualitative structural info	Wang et al., 2023
NMR Imaging	• Magnetic resonance of nuclei in molecules	• Hydrolyzed/oxidized fatty acids	• Non-destructive, structural insight	• Costly, complex data analysis	• Quantitative for molecular composition	Santos et al., 2018

compounds, whereas NaOH caused soap formation and minor component losses, highlighting the selectivity and environmental advantage of resin-based methods. Resin-based deacidification relies on FFA dissociation in neutral-to-alkaline conditions allowing $R\text{-}COO^-$ ions to replace weaker counterions on the resin. Hydrophobic resin matrices stabilize the hydrocarbon chains via van der Waals interactions. While batch studies show effective FFA removal and feasible regeneration (Singh et al., 2021; Chung et al., 2018), scalability challenges remain, including resin fouling, long-term stability, and economic viability for continuous industrial operation. Ion exchange resins provide a selective, non-thermal, and environmentally friendly approach for FFA removal from diverse oils. Their effectiveness depends on resin type, functional groups, porosity, and hydrophobicity, with strong and weak base anion exchange resins achieving up to 98 % FFA reduction under optimized conditions. While batch studies confirm high efficiency and renderability, industrial application requires addressing resin cost, fouling, and long-term stability to ensure sustainable large-scale operations (Singh et al., 2021).

5. Comparative analysis of deacidification methods

A comparative analysis of deacidification methods for vegetable oils reveals distinct advantages and limitations across various approaches. This comparative analysis based on the few criteria are efficiency in FFA removal, impact on oil quality (color, taste, nutritional properties), cost and scalability considerations, and environmental sustainability of each approach.

5.1. *Efficiency in FFA removal*

Membrane-assisted deacidification offers high selectivity in FFA removal due to engineered pore sizes and surface properties that allow targeted separation of FFAs while retaining beneficial components such as vitamins, antioxidants, and essential fatty acids. Techniques such as ultrafiltration (UF), nanofiltration (NF), and microfiltration (MF) can be tailored to specific molecular sizes and properties, enhancing selectivity. Operating under mild conditions, these membranes prevent thermal or oxidative degradation, maintaining oil quality, colour, flavour, and nutritional properties (Werth & Skiborowski, 2018). Plasma-assisted deacidification utilizes ionized gases to generate reactive species like ozone and hydroxyl radicals, which oxidize FFAs into simpler compounds. This process achieves targeted FFA removal without chemical solvents, preserving oil integrity and offering an environmentally friendly alternative to conventional deacidification (Okpo & Edafiadhe, 2024).

Molecular distillation effectively reduces FFA content by exploiting high vacuum to lower boiling points of FFAs and other volatiles, enabling separation at temperatures that minimize thermal degradation. This preserves essential fatty acids, tocopherols, and antioxidants. The studies show that molecular distillation can reduce FFA levels to below 1 %, with efficiencies exceeding 92 % in *Camelina sativa* oil under optimized conditions: evaporator temperature ~ 173.5 °C, wiper speed 350 rpm, and feed flow rate 2 mL/min (Ştefan et al., 2021; Avram et al., 2015). Elevated temperatures enhance FFA volatility, the wiper speed ensures uniform turbulent flow and prevents surface film formation, and controlled feed flow maintains optimal mass and heat transfer, collectively maximizing FFA removal while preserving oil quality (Lopresto et al., 2024). The non-chemical advanced methods including membrane filtration, plasma-assisted treatment, and molecular distillation enable precise and efficient FFA removal while maintaining oil nutritional and sensory quality. Membrane processes excel in mild, selective separation; plasma-assisted methods provide solvent-free, reactive removal; and molecular distillation achieves high FFA reduction (>92 %) under controlled thermal and hydrodynamic conditions making these methods suitable alternatives to conventional high-temperature or chemical refining techniques.

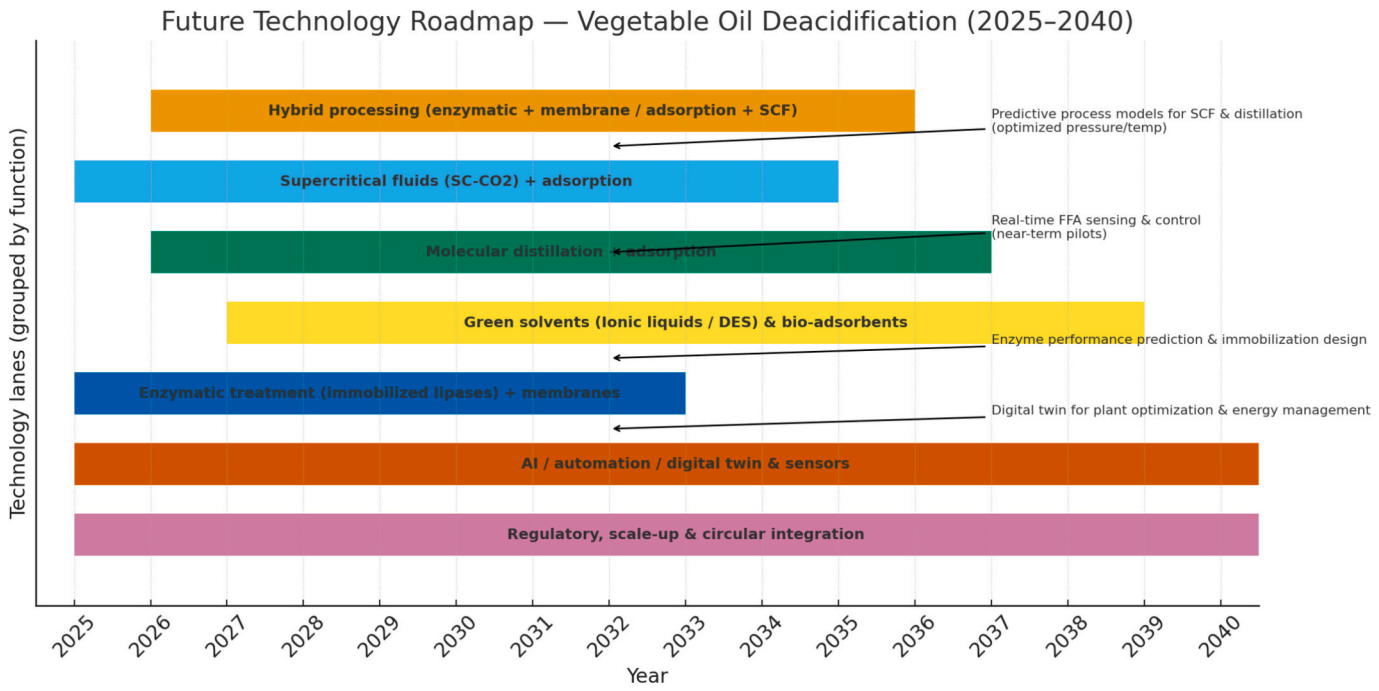


Fig. 9. Future Technology Roadmap (2025–2040) for vegetable oil deacidification.

5.2. Impact on oil quality

Deacidification methods differ markedly in their mechanisms, efficiencies, and effects on oil quality, particularly regarding free fatty acid (FFA) removal, colour, taste, and retention of bioactive compounds. Enzymatic deacidification employs lipases to selectively hydrolyse or esterify FFAs converting them into neutral compounds while leaving triglycerides intact. This selectivity preserves carotenoids, tocopherols, and phytosterols, maintaining nutritional value and sensory attributes. The reported FFA reduction efficiencies range from 85 % to 95 %, depending on enzyme type, substrate, and reaction conditions (Han et al., 2019; Ma et al., 2024). Mild operating conditions minimize oxidation and colour changes, though longer reaction times and enzyme costs may limit scalability unless immobilized or reusable enzymes are used. Molecular distillation achieves FFA removal by exploiting volatility differences under high vacuum enabling selective evaporation of FFAs without excessive thermal degradation of the oil. Efficiencies often exceed 90 %, as shown in *Camelina sativa* oil, where optimized parameters such as evaporator temperatures around 173–175 °C, wiper speeds of 350 rpm, and feed flow rates of 2 mL/min enhanced mass transfer, prevented surface fouling, and promoted uniform FFA removal (Ştefan et al., 2021; Avram et al., 2015). While highly effective, slight changes in colour and flavour may occur due to heat exposure, and operational costs are higher than enzymatic or membrane-based methods.

Solvent extraction removes FFAs by selective dissolution, achieving 85–95 % efficiency depending on solvent properties. However, this approach can extract lipophilic bioactive compounds, reducing nutritional value and altering flavour, and generates chemical waste, which raises environmental concerns (Busto & Vera, 2019). Membrane-assisted techniques including ultrafiltration (UF), nanofiltration (NF), and microfiltration (MF), provide high selectivity by separating FFAs based on molecular size and surface interactions while retaining beneficial compounds. These methods operate under mild, non-thermal conditions, preserving oil color, taste, and nutritional integrity (Werth & Skiborowski, 2018). Limitations include potential membrane fouling and replacement costs, but continuous processing options improve scalability. Plasma-assisted deacidification employs ionized gases to generate reactive species, such as ozone and hydroxyl radicals, which selectively oxidize FFAs into simpler compounds. This process avoids harmful solvents and preserves triglycerides and bioactive molecules, offering a sustainable and eco-friendly alternative (Okpo & Edafiadhe, 2024). Precise control of plasma parameters is essential to ensure consistent performance.

Overall, enzymatic and membrane-assisted methods excel in preserving oil quality, while molecular distillation and solvent extraction achieve maximal FFA reduction. Plasma-assisted approaches combine selectivity with sustainability. Optimizing parameters such as reaction time, temperature, and contact efficiency is crucial to balance FFA removal with retention of nutritional and sensory properties, making method selection dependent on the oil type, desired purity, and processing constraints.

5.3. Cost and scalability considerations

Deacidification methods vary significantly in capital investment, operational costs, and scalability, reflecting differences in technology complexity and process requirements. Membrane-assisted processes, including ultrafiltration (UF) and nanofiltration (NF), require moderate initial investment due to specialized membranes and pressure-driven systems, with estimated capital costs ranging from US $15,000–25,000 for pilot- to small-scale units. Operational costs are relatively low typically US $1.68–2.88 per cubic meter of treated oil, because these systems operate under mild conditions without high thermal energy input making them energy-efficient compared to traditional thermal or distillation methods (Marsol-Vall et al., 2022). The selective separation occurs as membranes with tailored pore sizes and surface properties allow FFAs to pass or be retained while preserving triglycerides and bioactive compounds. Membrane modules are inherently modular enabling scalable design by adding units to match production demand. Challenges include membrane fouling which necessitates periodic cleaning and replacement, and pretreatment requirements such as coarse filtration to maintain integrity and optimize lifespan. Despite these considerations, membrane-assisted deacidification offers a combination of moderate costs, high scalability, and reproducible performance.

Solvent extraction technologies generally have lower upfront

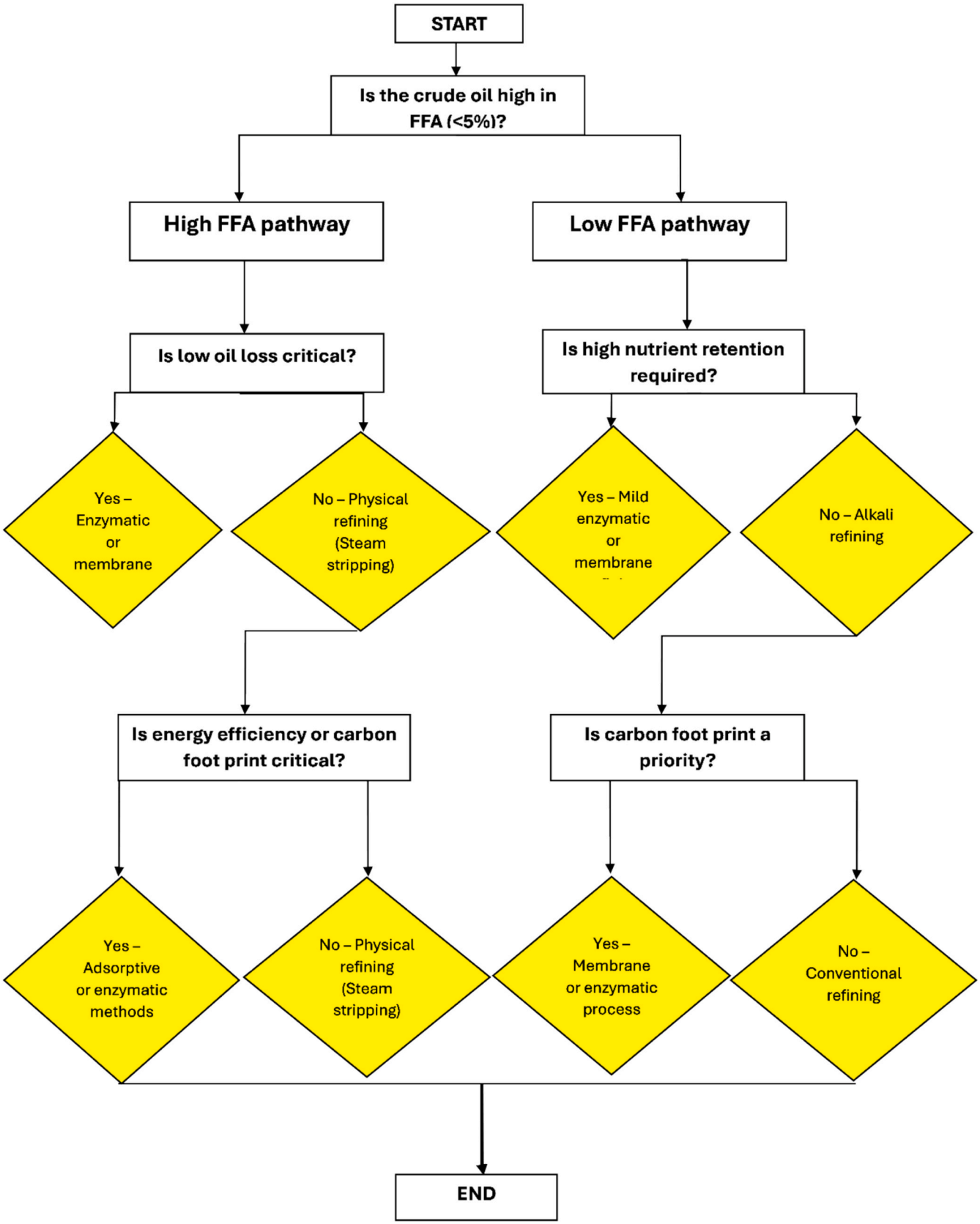


Fig. 10. Decision tree at the end of each section to guide technology selection.

equipment costs (~US $5000–10,000 for batch systems), but operational expenses are considerably higher, accounting for 47–77 % of total costs due to solvent procurement, recovery, and energy-intensive recycling (Ramirez et al., 2022; Busto & Vera, 2019). Ethanol-based systems demonstrate superior continuous operation performance, achieving FFA reductions exceeding 85 %, compared to methanol, while also lowering solvent-related environmental impact. The process relies on the selective solubility of FFAs in the chosen solvent allowing their separation from triglycerides, but large-scale operations require sophisticated handling, containment, and recovery strategies. Integrating adsorption or ion-exchange steps has been shown to enhance FFA removal efficiency and reduce solvent losses. Plasma-assisted deacidification is a non-thermal approach that employs reactive species (such as ozone and hydroxyl radicals) generated in ionized gases to break down FFAs selectively preserving triglycerides and sensitive bioactive compounds. Capital costs are high due to complex plasma reactor designs, estimated at US $50,000–80,000 for pilot systems, although modular micro plasma arrays offer potential for improved scalability. Operational efficiency remains a concern, as energy consumption is significant, requiring optimization for large-scale industrial deployment (Srivastav & Karunanithi, 2024).

Molecular distillation excels in FFA removal while preserving tocopherols, carotenoids, and polyunsaturated fatty acids. However, it demands substantial capital investment (~US $33,600 for small to medium-scale units) and high operational costs (~US $2.10–2.34 per kg of deacidified oil) due to energy requirements for high-vacuum maintenance, heating, and wiper evaporator mechanisms (Ştefan et al., 2021; Avram et al., 2015). Mechanistically, under high vacuum FFAs and other volatiles evaporate at lower temperatures separating from the oil while minimizing thermal degradation of bioactive compounds. Scalability is limited, making it more suitable for specialty oils or small- to medium-scale production. The studies on *Camelina sativa* and hazelnut oil have achieved FFA reductions exceeding 90 % while maintaining nutritional and sensory quality, and optimization in enzyme-assisted aqueous extraction oils, such as soybean oil, has demonstrated precise control over deacidification efficiency and bioactive retention (Altuntas et al., 2018). The consideration on both cost efficiency and operational stability, membrane-assisted deacidification emerges as the most balanced solution for industrial-scale applications. It combines moderate capital and operational expenses with high scalability, consistent performance, and gentle, non-thermal processing conditions that preserve oil quality, making it a practical, sustainable, and economically feasible technology for large-scale FFA removal.

5.4. Environmental sustainability

Deacidification methods differ markedly in environmental sustainability due to variations in energy consumption, chemical use, and waste generation. Membrane-assisted deacidification is the most environmentally friendly operating under mild, non-thermal conditions, requiring no chemical reagents, and producing minimal waste. The process selectively separates free fatty acids (FFAs) through membranes while retaining triglycerides and bioactive compounds, reducing post-processing and disposal needs. Energy consumption is comparatively low, estimated at $\leq$0.3 kWh/kg oil, with negligible wastewater generation, highlighting its efficiency and sustainability (Marsol-Vall et al., 2022). In contrast, solvent extraction relies heavily on chemical solvents such as hexane, ethanol, or methanol, which can leave residues, contribute to air and water pollution, and require energy-intensive recovery and recycling. Even with process optimization, such as using ethanol in continuous extraction, FFA reduction can exceed 85 %, but energy use is substantially higher, and solvent recovery produces significant waste streams (Ramirez et al., 2022; Xin et al., 2022).

Plasma-assisted deacidification provides a sustainable alternative by generating reactive species from ionized gases to degrade FFAs under non-thermal conditions. This approach preserves sensitive oil constituents, minimizes energy use (~0.1–0.3 kWh/kg oil), and produces negligible waste. The studies indicate reductions in greenhouse gas emissions by 21–35 % demonstrating high potential for large-scale sustainable application (Srivastav & Karunanithi, 2024). Molecular distillation, although effective in achieving over 90 % FFA removal and preserving nutritional and sensory qualities is less sustainable due to elevated temperature requirements (~173 °C), high vacuum operation, and specialized equipment, resulting in energy consumption of approximately 0.25 kWh/kg oil and negligible wastewater, compared to solvent-based or alkali processes which can generate 0.7 kg waste/kg oil (Ştefan et al., 2021; Altuntas et al., 2018). Overall, membrane- and plasma-assisted deacidification offer the greatest environmental benefits by minimizing chemical use, waste, and energy consumption, whereas solvent extraction and molecular distillation carry higher ecological costs despite their efficiency in FFA removal. The comparative analysis and technology readiness level of deacidification techniques is shown in Fig. 7. The selection of a deacidification method thus requires balancing oil quality, processing efficiency, and sustainability to ensure industrial feasibility with minimal environmental impact.

6. Analytical techniques for deacidification efficiency

Deacidification is a critical and cost-intensive step in edible oil refining, as minor deviations can adversely affect oil stability and brand reputation. Physical (Seifollahi et al., 2024), chemical (Jiang et al., 2023), and enzymatic (Xu, Zhang, Zivkovic, and Zheng, 2022) methods are commonly employed to reduce non-saponifiable and non-triglyceride components with the goal of enhancing oil stability while preserving bioactive nutrients. The method selection should be guided by robust analytical characterization to ensure efficacy. Traditionally, FFA content is measured before and after deacidification to justify process effectiveness; however, the demand for real-time and online monitoring has driven the adoption of molecular and biochemical assessment techniques beyond simple colorimetric assays (shown in Fig. 8). Table 3 shows the deacidification methods, mechanisms, analytical techniques, advantages, limitations, and quantitative aspects in deacidification of oils. The conventional titrimetric method relies on neutralization of hydrolyzed fatty acids with NaOH or KOH, indicated by a color change (Di Pietro et al., 2020). The acid value proportional to FFA content serves as a proxy for oil stability with lower FFA indicating more stable oils. While cost-effective, this method is time-consuming, consumes significant reagents, and lacks insight into dynamic fatty acid release. Automated flow titration using flow injection analysis (FIA) accelerates neutralization reactions and allows online monitoring via spectrophotometry, with calibration tailored to oil volume, solvent compatibility, and flow rate (Nurulain et al., 2021; Pereira et al., 2020). High-viscosity oils may present flow challenges due to clogging, highlighting the importance of solvent selection.

High-performance liquid chromatography (HPLC) and gas chromatography (GC), often coupled with mass spectrometry (MS) are employed to determine fatty acid composition and retention of liposoluble bioactive such as tocopherols and tocotrienols (Xu et al., 2020). In GC, fatty acids are converted to methyl esters separated in packed columns based on polarity, and detected via flame ionization. The coupling with MS allows structural elucidation and quantification of individual fatty acids with multiple ion quantification (MIQ) reducing calibration needs (Guerrero-Esperanza et al., 2023). For example, resin-dependent variations in treated coconut oil demonstrated significant differences in caprylic acid composition (KP et al., 2025). HPLC is preferred for heat-labile bio actives, with pre-treatment steps (TLC or column chromatography) enhancing separation and quantification. Ultrasound-assisted ethanol extraction has been shown to retain higher α-tocopherol levels compared to alkali deacidification, improving antioxidant capacity and delaying oxidation (Xin et al., 2022). Ultra-performance liquid chromatography (UPLC), operating at 15,000 psi with sub-2 μm particle columns, enables sensitive detection of

phenolic compounds in medicinal oils (Wang et al., 2023).

FTIR spectroscopy provides rapid, non-destructive assessment of functional groups associated with FFA. In the mid-IR region (4000–400 cm^{-1}), carbonyl stretching at 1711 cm^{-1} serves as a marker for free fatty acids while OH stretching (3600–3200 cm^{-1}) corresponds to glycerides (Bai et al., 2022; Ma et al., 2024). Interference from triglyceride esters at 1746 cm^{-1} can be mitigated by protective agents generating secondary peaks at 1570 cm^{-1}. The chemometric methods such as PLSR, PCA, and MLR enhance predictive accuracy of FFA content. Raman spectroscopy (Wang et al., 2023) and NMR imaging (Santos et al., 2018) have further advanced detection of hydrolyzed or oxidized fatty acids. FTIR detection ranges for FFA typically span 0.2–8 % providing quantitative insight into deacidification efficiency (KP et al., 2025). Deacidification reduces free fatty acids by converting them to glycerides or derivatives stabilizing the oil against hydrolysis and oxidation. Harsh conditions (such as elevated temperature or pressure) can degrade thermolabile bio actives highlighting the importance of mild enzymatic or ultrasound-assisted methods. Analytical monitoring thus serves a dual role: confirming FFA reduction and preserving nutraceutical compounds. Quantitative analysis via chromatographic or spectroscopic methods allows correlation of process parameters with bioactive retention providing a mechanistic framework for optimizing deacidification.

7. Future perspectives and challenges

The future of vegetable oil deacidification is moving toward innovations that improve both process efficiency and environmental sustainability. Conventional refining methods are limited by high energy consumption, oil losses, and degradation of bioactive compounds. Consequently, there is a growing demand for next-generation approaches aligned with green chemistry and Industry 4.0 principles (Usman et al., 2022; Nehmeh et al., 2022). Hybrid deacidification technologies are emerging as promising strategies that combine the strengths of multiple methods. For instance, coupling enzymatic treatments with membrane filtration allows selective hydrolysis or esterification of FFAs followed by efficient separation of reaction products, enhancing FFA removal while preserving oil quality and generating valuable byproducts (Biundo et al., 2023; Pervez et al., 2022). Similarly, supercritical fluid (SCF) extraction combined with adsorption has demonstrated significant potential for preserving thermally sensitive compounds while effectively lowering FFA levels. These hybrid approaches provide tailored solutions for low-grade or high-acidity feedstocks (Esmi et al., 2022). The quantitative evidence supports these benefits. Vicentini-Polette et al. (2024) reported that supercritical CO_2 (SC-CO_2) extraction reduced FFA in sunflower oil by up to 85 % under optimized conditions (60 °C, 250 bar) while maintaining tocopherol content, an important antioxidant for nutritional and oxidative stability. Likewise, Maziero et al. (2024) demonstrated that molecular distillation of crude palm oil at 170 °C under vacuum efficiently removed FFAs and retained carotenoids and vitamin E, with subsequent activated clay treatment enhancing clarity and stability. These studies highlight the dual objectives of hybrid systems: effective deacidification and nutrient preservation.

Green solvents, including ionic liquids and deep eutectic solvents are increasingly explored for FFA extraction due to their tunable polarity, low volatility, and recyclability. Bio-based adsorbents and immobilized enzymatic processes also offer pathways for low-energy, low-waste refining (Onn et al., 2023; Marsol-Vall et al., 2022; Zulqarnain et al., 2021). Despite their potential, challenges related to toxicity, regulatory approval, and cost must be addressed before large-scale adoption. Integration of automation and artificial intelligence (AI) is reshaping oil deacidification. Real-time monitoring of FFA concentrations and quality parameters allows dynamic optimization of process conditions, enhancing efficiency and consistency. Machine learning models support predictive control, fault detection, and resource optimization, while digital twin models enable simulation-based testing without disrupting operations (Nehmeh et al., 2022). Despite these technological advances, regulatory and commercial adoption remain significant hurdles. Novel methods using SCF, enzymes, or green solvents require rigorous safety testing before approval for food-grade or cosmetic-grade oils. Regulatory bodies such as the FDA, EFSA, and Codex Alimentarius impose strict guidelines that can slow commercialization. Additionally, industrial facilities are cautious in investing in new equipment without clear cost-benefit validation. Pilot-scale studies, technology transfer programs, and economic feasibility analyses are essential to bridge this gap (Abdalla et al., 2024).

The trajectory of vegetable oil deacidification points toward hybrid, green, and digitally optimized solutions. Enzymatic, physical, and separation-based methods integrated into multifunctional systems can achieve selective FFA removal while preserving bioactives. Sustainable solvents and low-impact processes reduce environmental footprint, and AI-driven automation enhances precision and resource efficiency. The Future Technology Roadmap (2025–2040) for vegetable oil deacidification is shown in Fig. 9 along with decision tree at Fig. 10. Overcoming regulatory, economic, and scale-up challenges will be crucial, with ongoing research and interdisciplinary collaboration likely to enable next-generation deacidification strategies that are efficient, sustainable, and aligned with global quality standards (Abdalla et al., 2024).

8. Conclusion

Vegetable oil quality is critical for the food, cosmetic, and biofuel sectors yet degradation from FFAs necessitates efficient deacidification strategies. This review highlights the progression from traditional chemical and physical methods to advanced approaches that include enzymatic, supercritical fluid, membrane, and ionic liquid-based techniques offering enhanced efficiency, selectivity, and sustainability. The future of deacidification lies in hybrid systems that integrate the strengths of multiple methods, alongside green, AI-driven processes that align with global sustainability goals. While challenges in scalability, regulatory approval, and cost persist, ongoing innovation and interdisciplinary collaboration promise to overcome these barriers. Ultimately, vegetable oil deacidification is poised for transformation: emerging technologies are not merely alternatives but represent the next frontier in smarter, cleaner, and more adaptable refining for the industries of tomorrow.

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G. Jeevarathinam: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization. **R. Rahul:** Writing – review & editing, Writing – original draft, Methodology. **J. Deepa:** Writing – review & editing, Writing – original draft. **N. Sharath Kumar:** Writing – original draft. **C.S. Neethu:** Writing – original draft. **G. Sarojini:** Writing – original draft. **V. Siva Shankar:** Writing – original draft. **Punit Singh:** Writing – original draft. **Davinder Pal Singh Oberoi:** Writing – original draft. **Sarvesh Rustagi:** Writing – original draft. **Syed Mohammed Basheeruddin Asdaq:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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