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A REVIEW OF EMERGING TECHNOLOGIES FOR USED ENGINE OIL TREATMENT

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Abstract: The escalating global generation of used engine oil and its inherent environmental hazards emphasize the need for advanced recycling solutions within a circular economy framework. This article aims to provide a review of five emerging technologies for used engine oil treatment: advanced membrane ultrafiltration, supercritical fluid extraction, nanotechnology, electrochemical de–oiling and hydroprocessing. Each technology offers distinct mechanisms for contaminant removal and oil valorization. While these technologies present substantial advantages in efficiency, product quality, and environmental footprint, common challenges include high capital costs, membrane fouling, process optimization for diverse feedstocks and the need for thorough life cycle assessments of novel materials. The synergistic integration of these technologies into multi–stage processes is identified as the most effective pathway to maximize resource recovery and overcome individual limitations.
Keywords: emerging technologies, used engine oil, internal combustion engine, circular economy

1. INTRODUCTION

The global lubricant market, estimated at 35.7 million metric tons in 2017 and projected to reach 37.4 million metric tons by 2023, represents a continuous and substantial source of used engine oil. Lubricants, typically comprising 70–90% base oil and the remainder as additives, are essential for machinery operation [1]. However, during normal use, these oils accumulate impurities such as dirt, metal scrapings, water, and various chemicals, which degrade their performance and render them unsuitable for continued application [2].

The environmental repercussions of improperly managed used engine oil are profound. This material is insoluble, persistent, and slow to degrade, containing toxic chemicals and heavy metals that pose severe threats to ecosystems. It adheres readily to surfaces, from beach sand to bird feathers, and is a significant source of contamination for waterways and drinking water sources; even a single quart of oil can contaminate up to two million gallons of water [2]. Furthermore, the original production of lubricating oils introduces toxic substances like heavy metals, chlorine, and sulfur, which, along with high temperatures and oxidation during use, can generate harmful compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs). A fundamental understanding underpinning the drive for recycling is that engine oil does not inherently "wear out"; it merely becomes contaminated. This perspective shifts the focus from waste disposal to resource management. The core lubricating properties of the oil remain intact, implying a high potential for regeneration and retention of material value. This conceptualization directly supports the economic incentive for re–refining, as it represents a more efficient use of resources compared to producing virgin oil, saving energy and crude oil [2].

The purpose of this paper is to explain the distinct mechanisms for contaminant removal and oil valorization that are offered by emerging technologies, analyzing both benefits and challenges. The future of used engine oil recycling lies in integrated, multi–stage systems that leverage the complementary strengths of these technologies, supported by evolving regulatory frameworks and a growing market acceptance for re–refined products.

2. EMERGING TECHNOLOGIES FOR USED ENGINE OIL TREATMENT

The landscape of used engine oil recycling is rapidly evolving, moving beyond conventional methods such as acid–clay treatment, vacuum distillation or solvent extraction. This evolution is propelled by the imperative for more efficient, environmentally sound, and economically viable solutions. Newer

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techniques include advanced membrane ultrafiltration, supercritical fluid extraction (SFE) or supercritical CO_2 extraction, nanotechnology, electrochemical de–oiling and hydroprocessing.

A notable trend among these emerging technologies is the increasing emphasis on hybrid or integrated processes. For instance, ultrafiltration is often followed by other processes like reverse osmosis or ion exchange, and hybrid coagulation–ultrafiltration processes have been investigated to enhance efficiency. Similarly, hydrotreating frequently serves as a final purification step after distillation, and nanofiltration is integrated into solvent–refining stages [4]. The recognition that a dual–stage process combining solvent extraction and hydrotreating can be optimal further illustrates this trend [5]. This indicates that no single emerging technology is a universal solution. Instead, optimal used oil recycling systems are likely to involve a sequence of complementary technologies, each addressing specific contaminants or achieving particular purification levels. This approach allows for synergistic process design, leading to more robust and efficient systems that maximize resource recovery and minimize environmental impact.

Advanced membrane ultrafiltration

Advanced membrane ultrafiltration (UF) is a green physical separation process that typically operates without the need for additional chemical agents. It employs semi–permeable membranes with pore sizes typically averaging around 0.01 μm [4]. The core principle of UF is size exclusion, where the liquid to be treated is applied against the membrane surface under controlled conditions of pressure and flow. The membrane permits water and smaller molecular components to pass through as permeate, while retaining and concentrating larger particles and contaminants. For used engine oil, UF membranes primarily facilitate the efficient removal of solid particles like carbon black, particles from friction and wear, and polymerization and condensation products [6]. This filtration process results in a lighter oil color, reduced ash residue, and decreased viscosity. The removal of solid particles can also indirectly reduce the content of water and certain metals, such as zinc and calcium, which originate from the degradation of additives in the used oil [6].

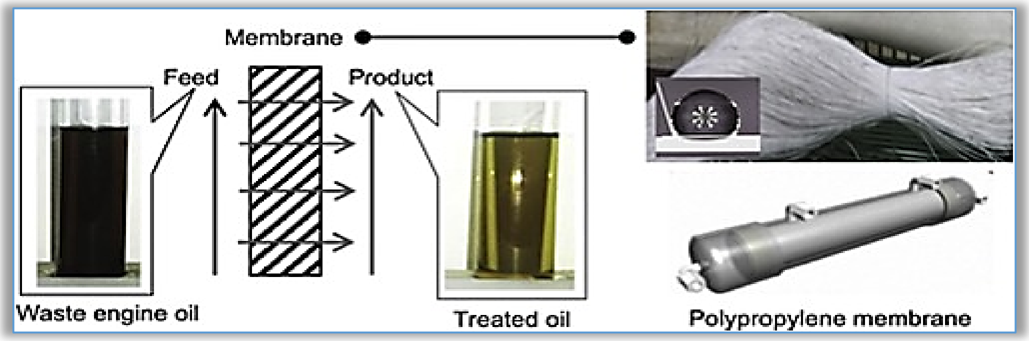

Figure 1. The process of treating used engine oil through membrane ultrafiltration [7]

The established presence of UF in water treatment provides a robust foundation for its application in used oil recycling. The principles of separating suspended solids and emulsified oils from water are being adapted to the more complex matrix of used engine oil. This transfer of expertise from water treatment to oil re–refining leverages existing knowledge, equipment, and research into membrane materials and fouling, potentially accelerating the maturity and reducing the research and development costs for oil applications.

For used engine oil re–refining specifically, UF is actively being researched and demonstrated at pilot and semi–works scales. A typical ultrafiltration system designed for emulsified oily waste often includes pre–treatment, the ultrafiltration stage itself, and post–treatment, which may involve settling for recycling or incineration if the oil cannot be reused [8]. Such systems can dewater emulsified oil waste by up to 95%. Performance data from laboratory tests, pilot plants, and operational systems in various metalworking industries (e.g., cutting oils, wash waters, rolling mill coolants) have been collected, demonstrating the technology's effectiveness [8].

A notable example is a unique membrane filtration system, V*SEP (Vibratory Shear Enhanced Process), which uses a microfiltration membrane module and was installed in July 2001 at a major waste oil re–refining operation in Portland, Oregon. This system was capable of processing up to 80% of dewatered waste oil, demonstrating stable and reproducible permeation rates with periodic cleaning, processing 20,000 gallons in approximately 1.75 days per modular unit. More recently, ceramic membranes are being actively pursued for waste oil re–refining, coal tar oil clean–up, and FCC slurry upgrading, capitalizing on their superior thermal and chemical stability [9]. A ceramic membrane hybrid process has been successfully demonstrated at a semi–works scale for used oil re–refining, processing over 70,000 gallons of used oil over a 12–month period. This semi–works facility achieved impressive results, producing approximately 6,000 gallons per week of membrane–treated oil (permeate) and between 1,600 and 2,000 gallons per week of high–quality base oil from the membrane permeate. The process yielded membrane efficiencies of 73–78% and decolorization efficiencies of 83–85%, with an overall process yield ranging from 61–66.3%. The re–refined oil produced through this process demonstrated quality parameters comparable to or even superior to virgin base oil, with metals reduced to below 1 ppm [9].

Supercritical fluid extraction (SFE)

Supercritical Fluid Extraction (SFE) is a sophisticated method that utilizes a supercritical fluid as an extraction medium to isolate target components based on their differential solubilities. A supercritical fluid (SCF) is defined as any substance maintained above its critical temperature and critical pressure, at which point it forms a homogeneous phase exhibiting properties characteristic of both a gas and a liquid. This unique state endows SCFs with gas–like low viscosity and high diffusivity, enabling them to easily penetrate material matrices and facilitate rapid mass transfer during extraction. Concurrently, their liquid–like density provides significant solvating power [10].
Carbon dioxide (CO_2) is the most widely favored supercritical fluid for SFE processes, primarily due to its relatively low critical temperature (31 °C) and pressure, its non–toxic and non–flammable nature, and its ready availability from existing industrial activities. As a lipophilic solvent, supercritical CO_2 ($scCO_2$) is particularly effective at dissolving lipid–soluble or low–polar compounds. A key advantage of SFE is the tunability of $scCO_2$'s solvating power, which can be precisely adjusted by manipulating temperature and pressure. Elevating pressure typically increases compound solubility by boosting the fluid's density. Conversely, while raising the temperature can increase the vapor pressures of solutes, potentially enhancing yields, it may simultaneously decrease the solvent's density, which can reduce solubility [10].

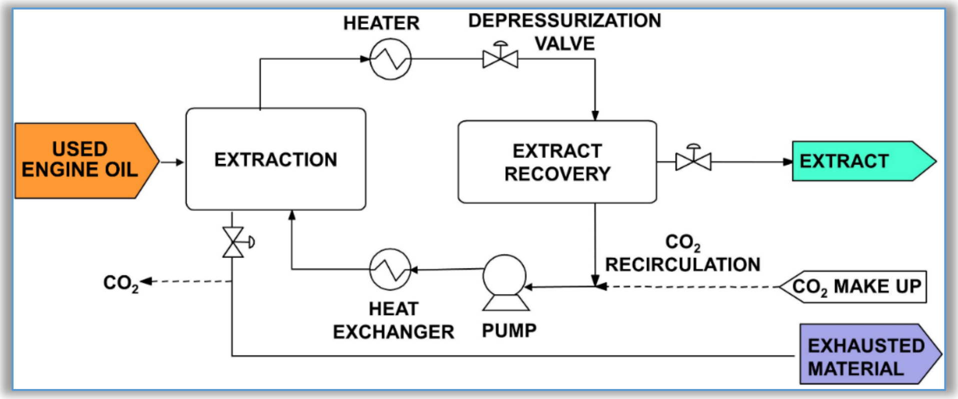

Figure 2. The process of treating used engine oil through supercritical fluid extraction [11]

The application of SFE specifically for used engine oil re–refining is predominantly in the research and pilot demonstration phases. While it is recognized as a "possible application" for refining used oil, studies have focused on optimizing laboratory and pilot–scale conditions. For instance, research has explored optimal pressure and temperature ranges for used oil recovery, identifying conditions such as 150–210 bar and 35–65°C, with 210 bar and 45°C being optimal for achieving the highest efficiency in some studies [12]. Dynamic extraction of used oil using CO_2 has been carried out in packed column extractors at 313K (40°C) across pressures ranging from 9.0 MPa to 12.0 MPa. Notably, oil extracted at 313 K and 9.0 MPa has been found to be similar to virgin lubricating oil, although the yield at this specific condition was lower compared to extractions at higher pressures. The overall efficiency of extraction for used oil has been reported to be approximately 90% in some cases [13].

Nanotechnology and nanofilters

Nanofiltration (NF) is a pressure–driven membrane technology, alongside microfiltration, ultrafiltration, and reverse osmosis that employs semi–permeable membranes to reject dissolved and suspended solids. NF membranes are characterized by extremely fine pore sizes, typically ranging from 1 to 10 nanometers, and a molecular weight cut–off (MWCO) between 100 and 2000 Daltons. The separation mechanisms in NF are a combination of charge effect repulsion, solution diffusion, and physical sieving through these micro/nano–pores, with sieving and charge effects being the dominant mechanisms. This allows NF membranes to preferentially reject multivalent ions over monovalent ions (e.g., 95% rejection of multivalent ions versus only 20% of monovalent ions). They are relatively impermeable to divalent ions, dissolved organic matter, pesticides, and other macromolecules, while allowing monovalent ions to pass through [14].

A specialized application within this domain is Organic Solvent Nanofiltration (OSN), which utilizes chemical–resistant hollow nanofiber membranes with pores finer than one nanometer. These OSN membranes function as "molecular sieves," selectively allowing the base oil to pass through while retaining solvents and other impurities. This precise molecular sieving action, combined with charge repulsion, enables the separation of contaminants at a much finer scale than ultrafiltration, leading to high–purity separation. Beyond filtration, nanotechnology extends to the use of nanomaterials as catalysts, nano–emulsions, or nanocomposites. For instance, nanomaterials such as graphene nanoplatelets, γ–Fe_2O_3, and ZnO nanoparticles have been shown to improve the kinetics of pyrolysis processes for used lubricating oil recovery. Magnetic nanoparticles based on iron oxide, with their high surface–to–volume ratio, reproducibility, selectivity, and reusability, are emerging as powerful tools for the efficient valorization of waste into fuels, offering the added advantage of magnetic harvesting for easier separation [3].

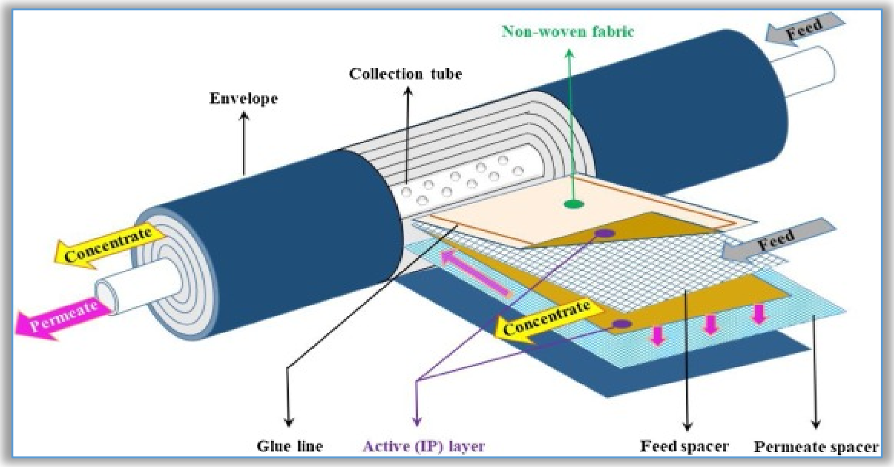

Figure 3. The operating principle of nanotechnology / nanofilters [15]

The specific application of Organic Solvent Nanofiltration (OSN) in used engine oil re–refining is an emerging field, with companies like SepPure Technologies pioneering and actively developing commercial solutions. SepPure's RE(SOLV) process, based on GreenMem chemical–resistant hollow nanofiber membranes, is presented as an "emerging solution" for cleaner waste oil re–refining. NF's potential to replace RO membranes due to its lower operating pressure, reduced

energy consumption, and lower investment, operational, and maintenance costs makes it an attractive alternative [14].
Beyond filtration, nanomaterials are actively being researched for their catalytic properties to enhance pyrolysis processes, offering an alternative pathway for used oil valorization into fuels. Research on nanomaterial–assisted pyrolysis has shown promising results in recovering lighter hydrocarbon cuts (C8–C15) from used lubricating oil, with γ–Fe_2O_3 nanoparticles proving particularly effective [3]. Nanomaterials are also finding broader applications within the oil lifecycle, such as in automotive products (e.g., fuel additives for cleaner exhaust, nanotechnology–enabled lubricants for reduced wear) and as catalysts in petroleum refining and automotive catalytic converters. Furthermore, studies indicate that nanoparticles can enhance oil recovery in Enhanced Oil Recovery (EOR) techniques by 10–15% [16].

Electrochemical de–oiling

Electrochemical de–oiling encompasses a range of technologies that leverage electrical energy to treat oil–contaminated streams, primarily focusing on water purification but also showing potential for direct oil upgrading. Electrocoagulation (EC) is a broad–spectrum treatment technology highly effective in removing total suspended solids (TSS), turbidity, metals, and oils from water. The fundamental principle of EC involves the destabilization of soluble organic pollutants and emulsified oils in aqueous media through the introduction of highly charged species. This is achieved by passing an electric current through sacrificial electrodes submerged in the wastewater [17].
The EC apparatus typically consists of a sacrificial anode, which releases coagulant metal ions (commonly aluminum or iron due to their low cost and non–toxicity), and a cathode, usually made of metal plates. On the cathode surface, water undergoes hydrolysis, producing hydrogen gas and hydroxyl groups. Simultaneously, electrons flow freely, destabilizing the surface charges on suspended solids and emulsified oils. As the reaction proceeds, these destabilized particles and oil droplets agglomerate to form large flocs, which effectively entrain suspended solids, heavy metals, and emulsified oils. Coagulation primarily occurs by reducing the net surface charge of colloidal particles, allowing Van Der Waals forces to promote their aggregation [17]. An additional mechanism, known as "sweep flocculation", involves the trapping of impurities within the amorphous hydroxide precipitate generated during the process. The microbubbles of hydrogen and oxygen produced at the electrodes adhere to these flocs, aiding in their separation and lifting them to the surface (electroflotation). The final solids separation step can then be achieved using conventional methods such as settling tanks, media filtration, or ultrafiltration [17].
Beyond the physical separation achieved by EC, electrochemical methods are being explored for direct chemical transformation of contaminants. For instance, sulfur can be removed from liquid hydrocarbon oils by subjecting a mixture of the oil and an electrolyte to a direct current field, inducing oxidation, reduction, or other electrochemical reactions of the sulfur–containing material to facilitate its separation.

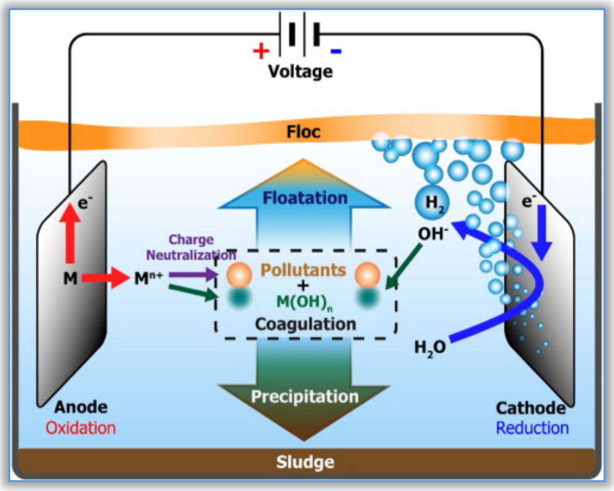

Figure 4. The operating principle of electrochemical de–oiling [19]

A particularly promising development is electrochemical hydrogenation (ECH), which operates at low temperatures (below 80 °C) and ambient pressure, crucially without requiring an external hydrogen source. This makes ECH an environmentally and economically favorable alternative to conventional thermochemical upgrading processes that typically demand high temperatures and pressures. Research also investigates the electro–oxidation potential of waste engine oil for direct use in fuel cells, demonstrating the basic feasibility of this process on a platinum electrode in an acid electrolyte within a temperature range of 20–80 °C [18].

The direct commercial application of electrochemical de–oiling specifically for the re–refining of used engine oil into base oil, rather than just water purification from oil contamination, appears to be more in the research and development phase. Research is actively exploring the electro–oxidation potential of waste engine oil emulsion on a platinum electrode in an acid electrolyte, demonstrating its basic feasibility within a temperature range of 20–80°C for potential use in fuel cells [18]. Similarly, electrochemical hydrogenation (ECH) is being developed as a promising alternative for bio–oil upgrading, operating under mild conditions. The strong foundation and commercial success of EC in treating oily wastewater provide a valuable knowledge base and technological infrastructure that can be adapted for used engine oil re–refining [18].

Hydroprocessing

Hydroprocessing is a fundamental set of processes in the oil refining industry, encompassing hydrogenation, hydrocracking, and hydrotreating. These processes are critical for producing modern energy and transportation fuels, and increasingly, for re–refining used engine oil. The core mechanism involves reacting used oil with hydrogen gas at high pressure and temperature in the presence of a catalyst [5].

Hydrotreating (HDT) is primarily aimed at removing impurities such as sulfur, nitrogen, and metals, thereby enhancing the purity of the feedstock [5]. The catalysts typically employed are metal oxides or sulfides, such as cobalt–molybdenum (Co–Mo) or nickel–molybdenum (Ni–Mo), supported on an alumina base. In this catalytic environment, hydrogen reacts with these contaminants, converting them into gaseous compounds that can be easily separated: sulfur is converted to hydrogen sulfide (H_2S), nitrogen to ammonia (NH_3), and unsaturated hydrocarbons become saturated. This process is essential for achieving a cleaner, higher–quality final product [5].

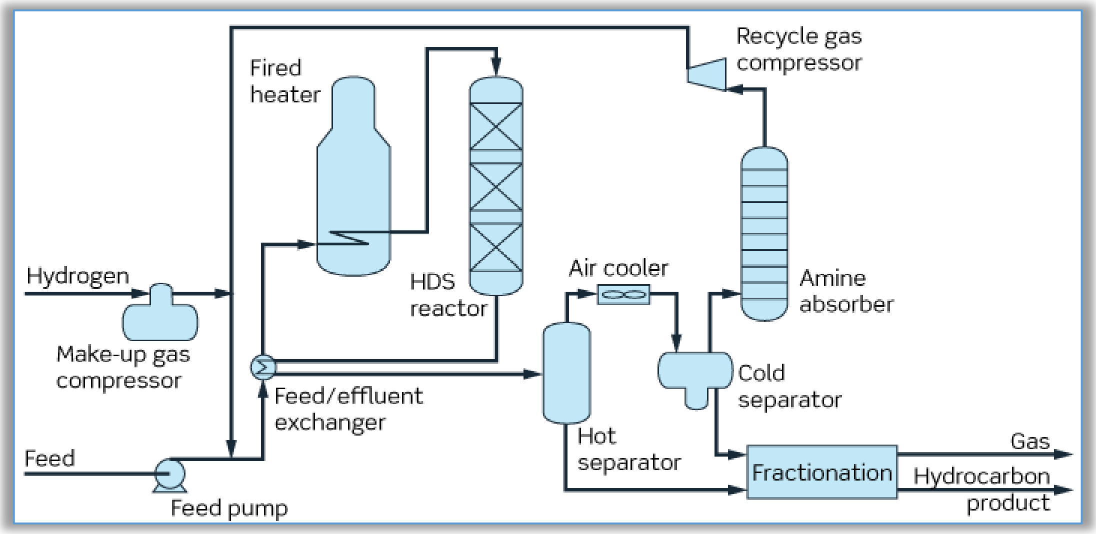

Figure 5. The operating principle of hydroprocessing [20]

Hydrocracking (HCK) is another key hydroprocessing step that breaks down large, complex hydrocarbon molecules into smaller, more valuable ones through hydrogenation. This yields lighter and more stable base oils. Hydroisomerization, a related process, rearranges molecular structures without breaking them down, specifically to improve viscosity and oxidation stability, producing high–performance base oils [21]. Hydrogenation also plays a crucial role in improving the viscosity index of refined oil by reacting hydrogen with impurities like sulfur, nitrogen, and oxygen, forming H_2S, NH_3, and water, which are subsequently removed. Hydrofinishing, a type of hydrotreating, specifically targets improvements in the color and odor of the refined oil by reacting hydrogen with unsaturated compounds and aromatics to form saturated compounds. Poly–nuclear aromatics (PNAs), which are formed during the high–temperature and high–pressure combustion process in engines, are effectively removed by the hydrogenation process during re–refining. The entire process is typically carried out in a trickle bed reactor containing the catalyst bed, operating under precise conditions of temperature (e.g., 350°C), pressure (e.g., 50 Kg/cm²), and a controlled hydrogen to oil ratio [21].

Hydroprocessing is a well–established and commercially vital technology in the re–refining of used engine oil, playing a central role in producing high–quality base oils that meet modern lubricant standards. It is considered an essential preliminary step for achieving a cleaner, higher–quality final product [21]. The re–refining process, which frequently incorporates hydrotreating, effectively removes a broad spectrum of contaminants, including metals, dirt, and harmful byproducts, yielding re–refined oil that meets the same stringent American Petroleum Institute (API) standards as virgin oil. Major industry players extensively employ hydroprocessing. GFL Environmental, for instance, operates a non–hazardous used oil refinery in Columbus, Ohio, that uses catalytic hydrotreating to convert vacuum gas oil (VGO) into high–purity Group II+ base oil and diesel fuel additive. This facility has the capacity to process 1,500 barrels of used motor oil per day and annually produces 28 million liters of base oil. Safety–Kleen, recognized as the largest re–refiner of used oil in North America, integrates hydrotreating as the final critical step in its process. This stage removes residual impurities such as sulfur, nitrogen, chlorine, and heavy metals, while also correcting issues related to odor, color, and corrosion performance. Safety–Kleen processes over 200 million gallons of used oil annually, demonstrating the industrial scale of hydrotreating in re–refining [22].

3. ECONOMIC VIABILITY AND ENVIRONMENTAL FOOTPRINT CONSIDERATIONS

The economic viability and scalability of emerging technologies for used oil recycling differ considerably, shaping their potential for widespread adoption. Advanced membrane ultrafiltration generally shows favorable economics thanks to its low energy demand, high recovery rates, simple maintenance, and small footprint, making it cost–effective even at smaller capacities of about one million gallons per year.

Demonstrations indicate that a facility processing two million gallons annually can achieve a capital payback in just over a year, though membrane replacement remains the most significant operating cost. Supercritical fluid extraction, on the other hand, is hindered by high capital and operating costs due to the specialized high–pressure equipment it requires. These costs are a key barrier to industrial implementation, though automation is beginning to reduce expenses, and the technology becomes more economically viable at higher capacities where economies of scale can be realized. The price of CO_2 also plays a major role in the overall cost [21].

Nanotechnology, particularly organic solvent nanofiltration, offers clear economic advantages, with energy savings of up to 90% and operational cost reductions of up to 50% compared to traditional thermal separation. Each SepPure system, for example, can save around $4 million annually by recycling 8,000 tons of solvents. Nanofiltration typically operates at lower pressures and costs than reverse osmosis, while nanomaterial–assisted pyrolysis is also considered economically sound. Electrochemical de–oiling is commercially applied in produced water treatment but remains under evaluation for direct re–refining of used engine oil, mainly due to high costs. Hydroprocessing requires significant investment in high–pressure vessels and hydrogen infrastructure and involves high operational expenses due to demanding temperature and pressure conditions and the continuous supply of hydrogen. However, innovations such as extended catalyst life help reduce costs, and the method ultimately proves advantageous by enabling the production of high–value products [23].

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4. ADVANTAGES AND TECHNICAL CHALLENGES

Each of the emerging technologies for used engine oil treatment offers distinct advantages and poses a series of technical challenges, illustrated in Table 1.

Table 1. Advantages and technical challenges of emerging technologies for treating used engine oil

Technology	Advantages	Technical challenges
Advanced membrane ultrafiltration	Energy efficient, high recovery rates, small footprint, minimal chemical usage. Effective at removing suspended solids, bacteria, endotoxins, plastics, proteins, protozoa, silica, silt, smog, viruses. High rejection rates for polymerization products and metals (96.3%). Can reduce ash residue (90–99%), water content (78–82%), carbon particles (66%), calcium (50–59%), and zinc (28–43%). Modular and economical at smaller scales (e.g., 1 million GPY). Produces microparticulate–free product for subsequent adsorption. Green and environmentally friendly cleaning methods developed [6].	Inability to reliably remove the smallest particles. Susceptible to damage and fouling by larger particles, leading to decreased permeability. Membrane replacement can be a significant operating cost (e.g., 1–1.2 years lifespan for some modules). Does not allow for complete restoration of physicochemical properties or selective recovery of specific base oil components, often requiring further downstream processing. Lack of comprehensive data on waste oil composition hinders optimal method formulation. Long–term performance reliability is a key limitation due to aggressive contaminants [6].
Supercritical fluid extraction	Faster extraction times. Drastically reduces solvent usage (up to 30 times less). Lower environmental impact due to minimal residue and non–toxic solvents (CO_2). Superior efficiency and selectivity due to high diffusivity and mass transfer. Non–flammable and non–toxic CO_2 makes it safer. Low critical temperature of CO_2 (31°C) suitable for temperature–sensitive substances. Simpler solvent removal post–extraction. Avoids acidic resin residues from acid–clay methods. Eliminates solvent waste incineration. Tunable density allows for highly selective extraction. Can enhance catalytic operations [12].	High initial setup cost. High capital and operating costs, especially for compressors and high–pressure vessels. Energy loss during decompression step. Challenges with high–pressure materials and pumps. Difficulties in process control within the critical region due to high solvent compressibility. Safety considerations due to high pressure and temperature. Patent complexities and licensing costs. Scale–up challenges due to limited understanding of rate processes, requiring costly pilot studies. Optimizing yield requires meticulous parameter adjustment and balancing equilibrium/mass transfer kinetics. Optimal solvent flow rate is application–specific [12].
Nanotechnology	Effective oil removal, compact design, reduced need for chemical additives, stable effluent quality. Higher efficiencies in reducing COD and TDS compared to MF/UF. Lower operating pressures and energy consumption than RO, leading to lower investment, operation, and maintenance costs. OSN offers high separation efficiency, ease of scalability, reduced footprint, and superior product quality. Heatless, pressure–driven OSN can reduce energy consumption by up to 90% and operational costs by up to 50%. OSN membranes are chemically resistant to harsh organic solvents, acids, alkalis, and heat. Can be used for catalyst recycling and upgrading lube oil by removing consumed additives. Nanomaterials improve pyrolysis kinetics, leading to higher yields of desirable hydrocarbons (C8–C15) and lighter fuels. High surface–to–volume ratio, reproducibility, selectivity and reusability of nanomaterials. Magnetic nanoparticles allow for easier separation. Can reduce pyrolysis reaction time and improve product quality [3].	Primary critical issue is membrane fouling, requiring appropriate pre–treatment and cleaning strategies. Direct treatment of high oil concentration feed streams can be problematic for NF. Lack of fundamental knowledge regarding elemental transport phenomena in OSN membranes. Instability of traditional polymeric membranes (partially addressed). Finding a robust design for nanomaterial–assisted pyrolysis with a reliable range of operating parameters is challenging. Nanomaterial–assisted pyrolysis may not be suitable for all material types. "Green paradox" concerns: need for comprehensive life cycle assessment to understand potential environmental and human health impacts throughout their life cycle. Eco– and health–toxicology risks associated with nano–sized technologies persist [3].
Electrochemical de–oiling	Broad–spectrum treatment for turbidity, metals, oils and bacteria. Effectively destabilizes soluble organic pollutants and emulsified oils. Flocs produced are generally more robust, contain less bound water, and are more readily filterable. Utilizes cheap and non–toxic electrode materials (aluminum, iron). Can be integrated with other separation methods like ultrafiltration. Electrochemical hydrogenation (ECH) operates at low temperatures (<80°C) and ambient pressure, without external hydrogen source. ECH can combine renewable electricity with biomass conversion. Potential for direct energy production from waste oil via electro–oxidation [17].	High capital costs have historically limited widespread adoption. Sensitive to feed characteristics: does not perform optimally with low conductivity (<300 μS/cm), low suspended solids (<20 mg/L), or non–polar/monovalent contaminants. Operational parameters (temperature, pollutant concentration) significantly affect performance. Most electrochemical methods for direct re–refining of used engine oil are still in the research phase, with scaling–up challenges not fully detailed. Traditional upgrading methods (which ECH aims to replace) require high temperatures (200–400°C) and pressures (200 bar). Overall sustainability depends on the energy source (ideally renewable) [17].
Hydroprocessing	Produces high–quality, stable re–refined base oils with excellent oxidation stability, optimal viscosity, and superior low–temperature properties. Effectively removes sulfur, nitrogen, metals, unsaturated hydrocarbons, oxidation products, and PAHs. Hydrocracking breaks down large molecules into valuable smaller ones; hydroisomerization improves viscosity and oxidation stability. Modern catalysts offer higher activity, selectivity, and extended lifespans, reducing operational costs. Can achieve optimal results at lower temperatures and pressures, reducing energy consumption and carbon footprint. Generates primarily gaseous byproducts, which are easier to handle than liquid/solid waste. Versatile, processing various used oil sources and qualities [21].	Requires high operating pressures and temperatures. Higher operational costs due to substantial energy consumption and continuous hydrogen supply. Catalysts can deactivate over time, requiring regeneration or replacement. Less efficient at removing certain heavy metals, necessitating robust pre–treatment. Safe and efficient management of flammable hydrogen adds complexity. Substantial initial capital investment for facilities and hydrogen infrastructure. Market growth can be impacted by crude oil price fluctuations and high catalyst development costs. Stringent regulations for catalyst production and use can be a barrier for new entrants. Efficiency heavily relies on feedstock quality from upstream processes [21].

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Overall, the cost–effectiveness of these technologies depends strongly on scale. Membrane–based methods like ultrafiltration and nanofiltration are well–suited to smaller, decentralized recycling operations, which also reduce transport costs. In contrast, SFE and hydroprocessing, though expensive per unit of capacity, achieve significant economies of scale in large, centralized facilities, making them more competitive for high–volume processing. A sustainable circular economy for used oil will likely require a combination of smaller distributed pre–treatment units alongside larger re–refining plants, with the long–term success of each technology shaped by factors such as energy use, solvent recovery, and catalyst replacement [23].

Emerging technologies in used oil management aim to substantially reduce the environmental footprint compared to traditional disposal practices or low–value burning. Recycling used oil is recognized as environmentally beneficial, helping to lower greenhouse gas emissions, conserve crude oil resources, and prevent waste from reaching landfills. Re–refining processes, in particular, require significantly less energy than producing virgin oil, with the recycling of just one gallon preventing the release of 3.4 kilograms of carbon dioxide [24].

Advanced membrane ultrafiltration is a green physical process that relies on little to no chemical use, lowering both water and energy consumption. Its sustainability is further enhanced by the development of environmentally friendly membrane cleaning methods. Life Cycle Assessment studies of re–refining processes that include membrane technology confirm reduced reliance on natural energy resources. Supercritical fluid extraction also offers notable environmental advantages, producing minimal residues while using safe, non–toxic carbon dioxide in place of harmful organic solvents. This method prevents the formation of acidic resin residues and leaves no hazardous effluent, aligning with Green Chemistry principles. Life Cycle Assessment research suggests that SFE can deliver significant environmental savings when compared to conventional techniques [24].

Nanotechnology, particularly organic solvent nanofiltration, contributes by cutting energy consumption by up to 90 percent and reducing emissions, with the potential to save as much as 100 million tons of carbon dioxide annually. Nanomaterial–assisted pyrolysis also adds value by preventing the release of persistent hydrocarbons and converting waste into useful fuels. However, the environmental impact of manufactured nanomaterials throughout their full life cycle remains insufficiently studied, raising concerns about a possible "green paradox," in which technologies designed to solve environmental problems may inadvertently create new ones. Electrochemical de–oiling supports sustainability by enabling the treatment and reuse of water on–site, while electrochemical hydrogenation offers an additional benefit by pairing renewable electricity with biomass conversion. Life Cycle Assessment continues to be an essential tool for evaluating the environmental effects of such approaches [25].

Hydroprocessing further strengthens environmental performance by producing cleaner lubricants with lower emissions through the efficient removal of sulfur and other contaminants. The enhanced durability and stability of hydroprocessed base oils help reduce both oil consumption and waste. Compared to burning used oil as fuel, hydroprocessing significantly lowers greenhouse gas and heavy metal emissions while also reducing strain on landfills and waterways [25].

5. CONCLUSIONS

In conclusion, used engine oil, though contaminated, remains a valuable resource whose sustainable management is essential for conserving crude oil, reducing energy use, and limiting environmental pollution. The analysis of emerging technologies: advanced membrane ultrafiltration, supercritical fluid extraction, nanotechnology, electrochemical de–oiling and hydroprocessing, shows that each contributes distinct advantages, from energy–efficient pre–treatment and selective contaminant removal to high–quality re–refining comparable with virgin oils. However, no single method can fully address the complexity of used oil treatment. The most

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promising solution lies in integrated, multi–stage systems that combine the strengths of these technologies, such as membranes for initial separation and hydroprocessing or SFE for advanced purification. This approach enhances efficiency, improves product quality, and minimizes environmental impact, supporting a truly sustainable circular economy for used oil.

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