

Review

Recycling of Petroleum-Based Lubricants into High-Value Petrochemicals and Carbon-Based Materials

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Abstract

Waste lubricating oils (WLOs) represent a major stream of hazardous petroleum-based residues, with global generation exceeding 24 million tons annually. Improper disposal of WLOs poses risks to soil, water, and air quality, while their chemical composition makes them a potential secondary resource within circular economy frameworks. This review summarizes conventional, advanced, and emerging technologies reported for the recycling and valorization of WLOs into high-value petrochemicals and carbon-based materials. Established processes such as acid–clay treatment, solvent extraction, and vacuum distillation are discussed together with more recent approaches, including catalytic upgrading, hydrotreatment, membrane separation, and thermochemical conversion methods such as pyrolysis and catalytic cracking. Reported data on process performance, environmental considerations, techno-economic indicators, and life cycle assessment outcomes are comparatively analyzed to outline current trends, technical challenges, and future development directions in WLO recycling. Particular attention is given to thermochemical pathways capable of generating carbonaceous materials, including carbon black, porous carbons, and functional carbon nanostructures with potential applications in adsorption, catalysis, electrochemical systems, and tribological formulations. Hybrid and integrated process configurations described in the literature are highlighted for their potential to improve recovery efficiency, enhance product quality, and reduce environmental burdens. In addition, recent life cycle assessment (LCA) and techno-economic analysis (TEA) studies are reviewed to provide insight into the environmental and economic implications of advanced re-refining systems. Overall, the reviewed literature indicates that WLO recycling represents not only an important element of sustainable lubricant management but also a promising waste-to-carbon strategy for the production of value-added carbon-based materials and petrochemical products.



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1. Introduction

Lubricating oils (LOs) are refined products derived from crude oil and synthetic bases. They consist mainly of high-molecular paraffins, naphthenes, and aromatic hydrocarbons with carbon numbers from C₂₀ to C₄₀₊ and boiling points above 340 °C [1,2]. Owing to their physicochemical properties, LOs play a vital role in reducing friction and wear,

preventing corrosion, sealing, and dissipating heat in automotive, marine, and industrial engines [3,4]. They also aid in the removal of by-products such as soot and sludge formed during combustion. Key quality indicators include viscosity, viscosity index (VI), flash point, pour point, and oxidative stability [5].

Global demand for lubricants remains high, reflecting their indispensable role in transportation and industry. The global lubricants market remains a significant industrial sector, with recent market analyses estimating its value at approximately USD 178 billion in 2025 and projecting growth to about USD 204 billion by 2030, driven by continued demand from automotive, industrial, and manufacturing applications [6]. As lubricant consumption increases worldwide, the generation of waste lubricating oils (WLOs) also continues to rise. Approximately 50% of the consumed lubricants end up as WLOs, while the remainder is lost through combustion, evaporation, leakage, and container residues [7]. Each year, about 24 million metric tons of WLOs are generated from railways, automotive workshops, shipyards, and industrial equipment [8].

During service, lubricants undergo severe thermal and mechanical stresses. Additives degrade, viscosity decreases, and contaminants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and soot accumulate [1]. As a result, WLOs are classified as hazardous wastes. Their uncontrolled disposal leads to soil and water contamination, long-term persistence of toxic components, and greenhouse gas emissions. Their uncontrolled disposal can lead to soil and water contamination, long-term persistence of toxic components, and greenhouse gas emissions, highlighting the importance of environmentally sound management and resource recovery strategies [7,9].

At the same time, WLOs represent a valuable secondary resource. They can be recycled into base oils, regenerated into motor oils, or converted into valuable by-products such as carbon black and fuel fractions [8,10]. Studies show that 1 L of motor oil can be regenerated from only 1.6 L of WLOs, highlighting the efficiency of closed-loop recycling [9]. In the European Union, annual lubricant consumption is approximately 5.7 million tons, with 2.7 million tons considered technically recyclable [10].

Recent studies also indicate that waste lubricating oils can serve as alternative feedstocks for the production of carbon-containing materials through thermochemical conversion processes such as pyrolysis and catalytic cracking. Depending on the process conditions, these technologies can generate carbonaceous products including carbon black, solid carbon residues, and porous carbon materials alongside liquid fuel fractions [11,12]. Such products are of growing interest due to their potential applications in adsorption, catalysis, environmental remediation, and other industrial fields. Therefore, in addition to conventional recovery of fuels and base oils, the conversion of WLOs into carbon-based materials is increasingly considered a promising route for waste valorization and sustainable resource utilization.

The management of WLOs is aligned with the principles of the circular economy, which promotes resource efficiency, waste minimization, and emission reduction. Recycling reduces dependence on virgin crude oil, lowers environmental risks, and contributes to sustainable industrial development [10]. Consequently, the valorization of WLOs is both a technological challenge and a strategic opportunity for integrating economic and environmental objectives (Figure 1).

Several review articles have addressed waste lubricating oil (WLO) recycling and recovery technologies, including re-refining, pyrolysis, fuel production, and environmental aspects of waste oil management [3,5,13]. However, most studies focus on specific technological approaches or individual valorization pathways, which complicates direct comparison of their technical, economic, and environmental performance. Recent advances in life cycle assessment (LCA), techno-economic assessment (TEA), catalyst development,

and carbon-material production have significantly expanded the range of available WLO valorization technologies. Nevertheless, comparative evaluation of these approaches using consistent performance indicators remains limited. In particular, information on process efficiency, product quality, environmental impacts, economic feasibility, catalyst-related limitations, and scale-up challenges is often dispersed across the literature. Therefore, this review provides a comprehensive assessment of WLO valorization technologies, including conventional re-refining processes, thermochemical conversion routes, and emerging pathways for the production of carbon-based materials. Particular attention is given to the comparison of technical performance, techno-economic indicators, environmental metrics and catalyst deactivation challenges. The review also discusses recent developments in carbon-material production from WLO-derived feedstocks and identifies priority directions for future research and industrial deployment.

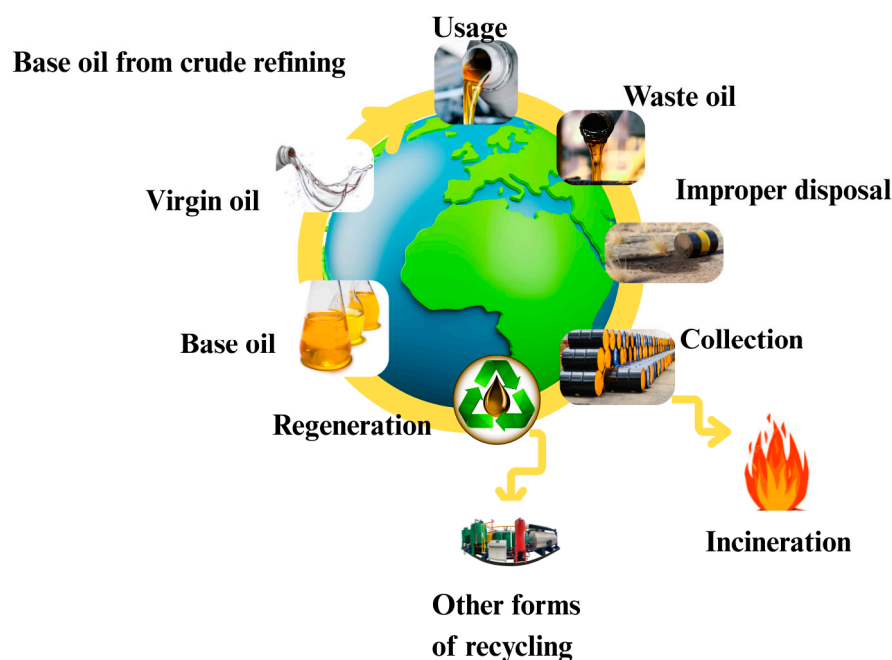


Figure 1. Circular economy concept for WLO management. Created by the authors based on information reported in [10].

2. Methods of Waste Lubricating Oil Recycling

The recycling of waste lubricating oils (WLOs) involves a series of technological processes aimed at restoring valuable fractions, primarily base oils, suitable for reuse in lubricant formulations or conversion into alternative products such as fuels and carbon materials. Several recycling technologies have been developed and implemented at various scales, ranging from traditional acid–clay treatment to advanced hybrid systems that combine distillation, extraction, and catalytic upgrading.

2.1. Acid–Clay Treatment

Acid–clay treatment remains one of the most widely applied methods for regenerating waste lubricating oils (WLOs) due to its efficiency, simplicity, and low cost [14]. The process includes filtration, dehydration, acid treatment, clay adsorption, and neutralization. Initially, filtration and centrifugation remove coarse impurities such as sand, metal particles, and sludge [15]. The oil is then dehydrated through atmospheric or vacuum distillation to eliminate water and low-boiling fractions, which prevents emulsion formation and reduces corrosive salts [16]. At the acid stage, asphaltenes, metal salts, resins, and other contaminants precipitate, producing an acid sludge that is separated and removed [17,18].

Commonly used acids include oxalic, sulfuric, acetic, and nitric acid (Table 1), often combined with activated clays for improved performance [19].

Table 1. Common acids applied in acid–clay treatment of waste lubricating oils.

Acid	Optimal Conditions	Clay Activation Method
Oxalic acid	45–50 °C; settling time 24 h	Sulfuric acid treatment
Sulfuric acid	Clarification at 110 °C; settling time 24 h	–
Acetic acid (glacial)	50 °C; settling time 24 h	1 mL oil per 4 g clay
Nitric acid	Settling time 24 h	Calcination at 800 °C for 5 h

Subsequent clay treatment adsorbs mercaptans, improves color, and enhances oil stability. Typically, about 0.4 lb of clay is applied per gallon of oil [20]. Neutralization is achieved with alkalis such as sodium hydroxide or lime, followed by water washing and filtration to remove residual acids and spent clay (Figure 2). In some cases, additional distillation or blending with additives restores properties to near-virgin quality [21].

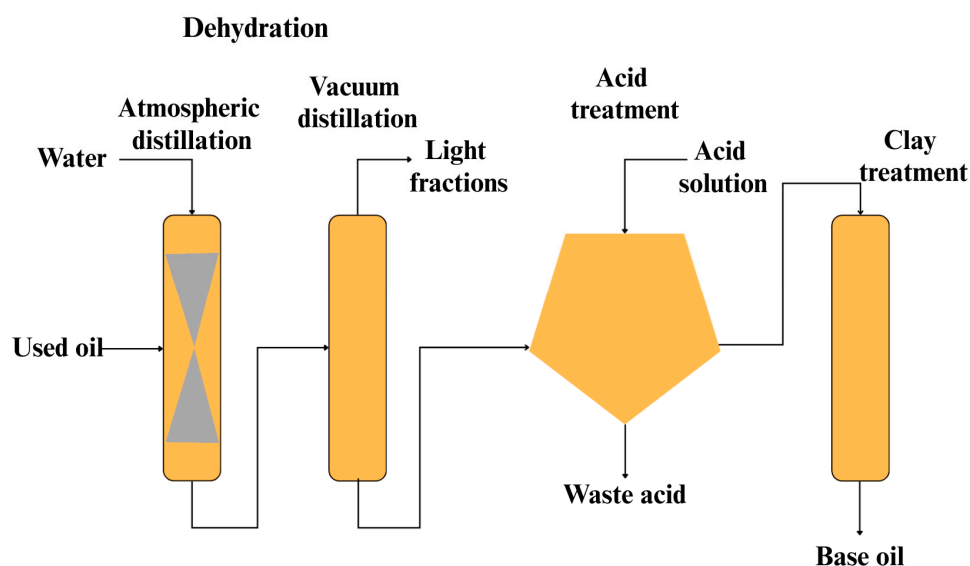


Figure 2. Process flow diagram of acid–clay treatment for waste lubricating oil regeneration. Created by the authors based on information reported in [13].

Despite its simplicity and low cost, acid–clay treatment produces significant quantities of hazardous sludge that require careful disposal. The method achieves moderate oil recovery (~65–70%) and improves color and stability, but residual heteroatoms can limit product quality. Economically, the process is favorable at small-to-medium scale, but scaling up requires management of acid waste and additional neutralization steps. Hybrid combinations with solvent extraction or membranes can enhance both recovery efficiency and environmental performance [22].

2.2. Solvent Extraction

Solvent extraction relies on solubility differences to separate base oil from contaminants, enabling regeneration under relatively mild conditions [23]. Its main advantage lies in resource conservation and reduced environmental impact compared with destructive disposal methods [24]. Pre-treated WLOs are first freed from water, sludge, and coarse solids via settling, filtration, or distillation (Figure 3) [25]. Solvent selection is critical; it

should dissolve base oils effectively but exhibit low affinity for additives and carbonaceous residues [26].

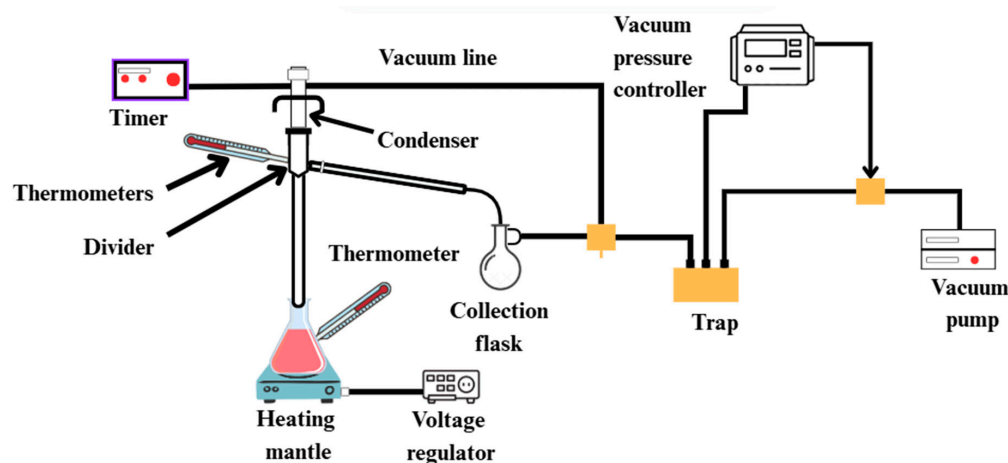


Figure 3. Pretreatment and solvent extraction methods for waste lubricating oil regeneration, redrawn and adapted from [27].

Common solvents include furfural combined with N-methyl-2-pyrrolidone, methyl ethyl ketone (MEK), isopropanol, and heptane. MEK is reported as the most efficient, while isopropanol is particularly effective in sludge removal. The oil–solvent mixture is processed in counter-current extractors or stirred reactors, yielding an oil-rich phase and a contaminant-rich phase. Experimental studies with heptane and 2-propanol have shown that 2-propanol exhibits superior sludge removal efficiency under optimized conditions (S/O ratio 1:6, 40 °C, 35 min), whereas heptane requires a higher temperature and longer mixing time to achieve comparable results, as illustrated in Figure 3, adapted from [27].

Phase separation is achieved by gravity settling or centrifugation [28]. The solvent is then recovered by low-pressure distillation, condensed, and recycled. Further polishing treatments such as hydrocracking, hydrotreating, deaeration, or adsorption on activated clay or carbon can enhance stability, remove metals, and improve color [29]. Solvent extraction reduces oil losses in the sludge phase by 10–14%, thereby increasing overall recovery efficiency [30].

Quantitative analysis shows solvent extraction achieves 70–80% base oil recovery. Trade-offs between solvent efficiency and operational cost must be considered, with MEK offering a higher yield and 2-propanol superior sludge removal. Combining solvent extraction with vacuum distillation or membranes improves overall recovery and product quality, making it a viable method for hybrid recycling systems.

2.3. Vacuum Distillation

Vacuum distillation is among the most widely applied modern methods for large-scale WLO re-refining. Operating under reduced pressure lowers the boiling points, enabling the separation of lube fractions without excessive thermal cracking [31]. The process involves pre-treatment (dehydration and degassing) and atmospheric distillation to remove light fractions, followed by vacuum distillation to obtain lube cuts [32]. Residual heavy fractions may be used as bitumen modifiers or fuel oils.

Distillates are typically subjected to post-treatment (e.g., clay adsorption or solvent refining) to meet base oil specifications. Vacuum distillation achieves recovery yields up to 84% of the original WLO, producing base oils that may meet API Group I–II standards [32]. When combined with hydrotreatment, the output can reach Group II–III quality. Its main disadvantages are high energy demand and capital investment, but it remains the backbone

of industrial WLO re-refining plants worldwide. Vacuum distillation has also found wide application beyond lubricating oil re-refining, particularly in the upgrading of bio-oils derived from plastic and food waste. A schematic representation of the process is shown in Figure 4, where operation under reduced pressure enables the separation of fractions at lower temperatures, thus preventing thermal degradation and improving product quality. Such examples highlight the versatility of vacuum distillation and reinforce its importance across diverse waste valorization pathways, including WLO re-refining [33].

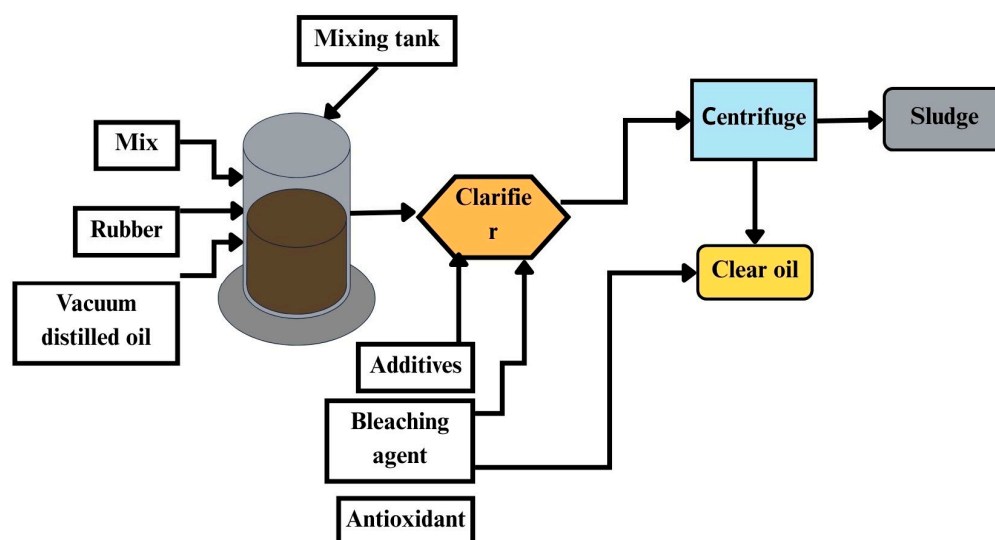


Figure 4. The schematic of the vacuum distillation process for the preparation of lubricating oil from waste oil, redrawn and adapted from [34].

Despite its high energy requirements and capital costs, vacuum distillation provides consistently high recovery (~84%) and high-quality base oils. TEA studies indicate that large-scale plants remain economically viable due to favorable yield and product value. Environmental assessments show that emissions are lower than chemical-based treatments, though energy-related CO₂ must be managed.

2.4. Hydrotreatment and Hydrofinishing

Hydrotreatment involves reacting WLO distillates with hydrogen in the presence of catalysts (Ni–Mo, Co–Mo, or noble metals) at elevated pressures (up to 15 MPa) and temperatures (350–450 °C). This process removes sulfur, nitrogen, oxygen, and metallic impurities, while simultaneously saturating aromatics [35]. Hydrofinishing further improves color, stability, and volatility characteristics, enabling production of base oils meeting API Group II–III standards, comparable to virgin refinery products [36]. Hydrotreatment significantly reduces PAHs and enhances oil performance in modern engines, making it the preferred upgrading method in advanced re-refining facilities [37]. However, high hydrogen consumption and expensive catalysts remain major challenges. Recent research highlights the potential of renewable hydrogen sources and nanostructured catalysts to reduce operational costs. A schematic representation of the hydrotreatment and hydrofinishing process is shown in Figure 5, adapted from [38].

The use of a trimetallic CoNiMo/ γ -Al₂O₃ catalyst derived from waste aluminum foil under optimized conditions (400 °C, 60 bar) significantly improved oil quality, reducing sulfur and acidity while increasing the viscosity index, thereby producing base oils comparable to API Group II–III. LCA studies indicate reduced environmental impacts compared with conventional chemical treatments. Despite higher operational costs due to

hydrogen and catalysts, advances in renewable hydrogen and nano-catalysts can improve techno-economic feasibility.

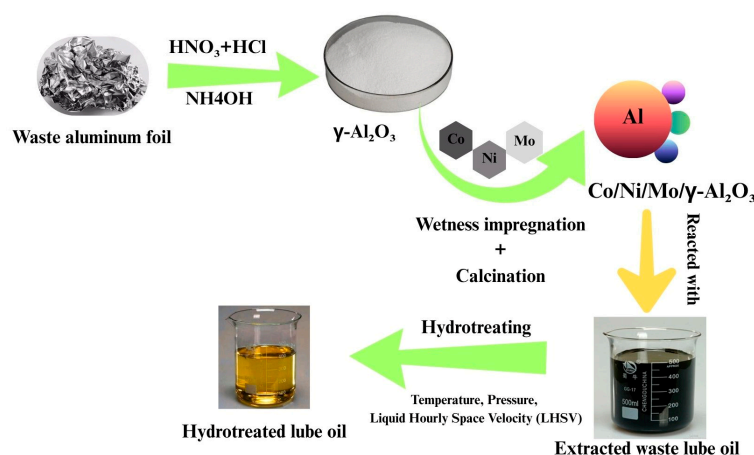


Figure 5. Schematic illustration of hydrotreatment and hydrofinishing of waste lubricating oil (WLO), redrawn and adapted from [38].

Catalyst Deactivation and Regeneration Challenges

Catalyst deactivation remains one of the major challenges limiting the industrial application of catalytic WLO upgrading processes, particularly hydrotreatment, hydrocracking, and catalytic cracking technologies. In fixed-bed systems, catalyst activity loss is commonly associated with coke deposition, accumulation of metallic contaminants, and structural changes in the catalyst, all of which reduce process efficiency and catalyst lifetime [39–41].

Coke deposition is one of the primary causes of catalyst deactivation. Carbonaceous deposits progressively cover active sites and obstruct catalyst pores, reducing catalyst activity and process efficiency [40,41]. In addition to catalyst deactivation, coke formation contributes to equipment fouling and pipe blockage. Recent studies have shown that metal-containing contaminants present in used lubricating oils can further accelerate coke formation and intensify fouling phenomena during catalytic upgrading processes [42].

The quality and composition of collected WLOs significantly influence the efficiency of downstream recycling and upgrading processes. Analysis of 30,242 WLO samples collected in Portugal revealed that 22.3% exceeded regulatory limits for water and sediment content, while approximately 60% showed contamination by glycol-containing compounds. These findings highlight the importance of feedstock quality control and pretreatment prior to regeneration and catalytic upgrading processes [43].

Another important challenge is catalyst poisoning by inorganic contaminants originating from lubricant additives and engine wear. Waste lubricating oils may contain Zn-, P-, Ca-, Mg-, Si-, and B-containing species that accumulate on catalyst surfaces and within pore structures, leading to pore blockage and irreversible activity losses [39]. A recent study of WLO hydrotreatment reported that pore blockage was the dominant deactivation mechanism during long-term operation. While carbonaceous deposits could be removed by calcination, silicon- and boron-containing compounds remained strongly bound to the catalyst surface after regeneration, causing permanent blockage of active sites and pores [39].

Catalyst regeneration is commonly achieved through oxidative treatment in air or oxygen atmospheres, typically at temperatures between 250 and 500 °C [40]. Although coke deposits can often be removed effectively, complete recovery of catalyst performance is not always possible because inorganic contaminants and structural modifications may persist after regeneration [39–41]. In addition to thermal regeneration, chemical rejuvenation

methods have also been reported. Sadeek et al. demonstrated that acid-leaching treatment of spent Ni–Mo/Al hydrotreating catalysts effectively removed deposited metals and restored hydrodesulfurization activity to a level approaching that of fresh catalysts [1].

To mitigate catalyst deactivation, several process-oriented strategies have been proposed, including feed pretreatment, demetallization, guard-bed systems, and multi-stage reactor configurations. For example, a three-reactor hydrogenation process incorporating a protective layer significantly reduced contaminant deposition on the primary catalyst and improved long-term catalyst stability during WLO upgrading [39]. Similarly, pretreatment technologies designed to suppress coke precursor formation enabled stable continuous operation for more than 600 h in pilot-scale WLO processing systems [42].

Catalyst deactivation through coking, fouling, pore blockage, and contaminant deposition remains a major challenge for catalytic WLO recycling technologies. Future developments should focus on contamination-resistant catalysts, efficient regeneration strategies, and advanced feed pretreatment methods to improve process stability and economic viability [39–42].

2.5. Membrane Filtration

Membrane-based technologies such as microfiltration, ultrafiltration, and nanofiltration are increasingly applied as pre-treatment or polishing steps in WLO recycling. These processes rely on selective pore sizes to separate suspended solids, water, and polar compounds without chemical additives [44]. Ceramic and polymeric membranes have demonstrated high efficiency in removing trace metals, oxidation products, and particulates, thereby extending catalyst life in downstream hydrotreatment [45].

While membrane fouling and high costs remain challenges, integrating membranes into hybrid systems with distillation or solvent extraction offers promising results in terms of energy savings and process intensification. Recent studies have demonstrated that hydrophobic polypropylene ultrafiltration membranes can effectively remove water, ash, carbon residue, acidity, and trace metals from WLO, thereby improving viscosity, density, and color quality of the treated oil [46]. As illustrated in Figure 6, such membrane systems highlight the potential of polymeric membranes not only as polishing units but also as standalone treatment steps under optimized operating conditions. Membrane filtration can achieve metal retention up to ~96% and maintain permeate flux at ~79% after cleaning, improving overall oil quality. Although membrane fouling and high costs are challenges, combining membranes with distillation or solvent extraction enhances energy efficiency and recovery rates. This makes membranes valuable both as polishing units and in hybrid recycling systems.

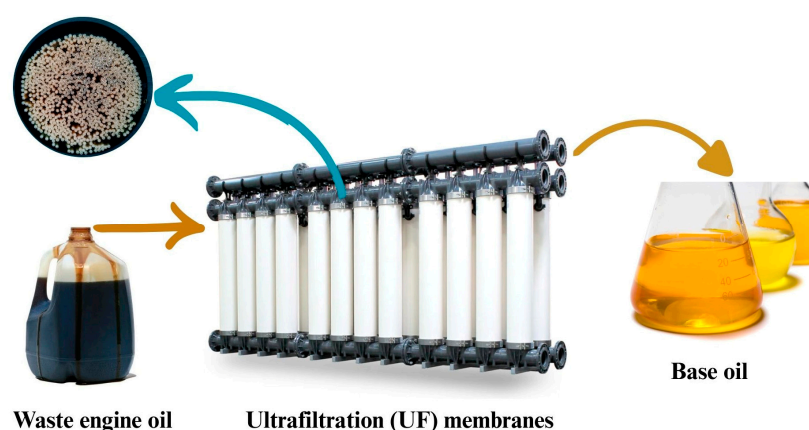


Figure 6. Schematic representation of waste engine oil ultrafiltration using hydrophobic polypropylene membranes. Created by the authors based on information reported in [46].

2.6. Pyrolysis and Catalytic Cracking

Thermochemical conversion processes such as pyrolysis and catalytic cracking decompose WLOs into lighter hydrocarbons under oxygen-free conditions [47]. The products include liquid fuel fractions (diesel- and gasoline-like), carbon black, and combustible gases. Catalysts such as zeolites, silica–alumina, and metal oxides improve product selectivity and reduce process temperature [48].

Although primarily employed for fuel production rather than lubricant re-refining, pyrolysis contributes to waste minimization and resource recovery, aligning with circular economy principles. Recent studies emphasize that reactor configuration and catalyst selection strongly influence the efficiency and sustainability of these thermochemical conversion processes. Figure 7 shows conventional and catalytic pyrolysis processes, emphasizing reactor configurations and catalyst effects on product yields and environmental performance. Fixed-bed reactors are often highlighted for their cost-effectiveness and simplicity, while catalytic systems, particularly with zeolite-based materials, improve liquid fuel quality and reduce emissions. In this review, a detailed discussion of pyrolysis products such as carbon black and fuel fractions is presented in Section 3. Moreover, emerging alternatives such as electrically heated pyrolysis have demonstrated potential for improving combustion efficiency and reducing environmental impacts compared with conventional thermal processes, although further validation under industrial operating conditions is still required [49]. Pyrolysis can achieve liquid product yields of approximately 80–87% while also generating potentially valuable by-products such as carbon black. Catalytic pyrolysis may improve product selectivity and reduce emissions; however, catalyst costs, deactivation, and process optimization remain important challenges. Available techno-economic studies indicate that fuel production from WLO pyrolysis can be economically feasible under specific operating conditions, whereas re-refining remains the preferred option when the objective is the recovery of high-quality lubricant base oils. Although emerging electrically heated pyrolysis technologies have shown potential for improving energy efficiency and environmental performance, further research is needed to establish reliable reactor designs, operating parameters, and long-term industrial viability.

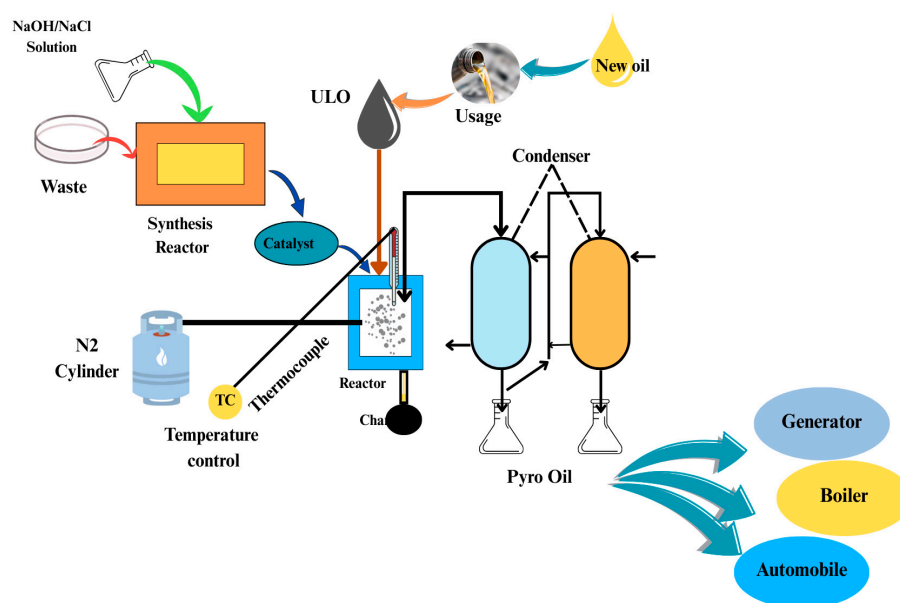


Figure 7. Schematic representation of pyrolysis and catalytic cracking pathways for waste lubricating oil conversion into liquid fuels, redrawn and adapted from [48].

2.7. Hybrid and Emerging Technologies

Recent research emphasizes the combination of traditional methods with advanced innovations. Examples include solvent extraction coupled with vacuum distillation, hydrotreatment integrated with membrane polishing, and plasma-assisted processes for contaminant degradation [50]. These hybrid approaches enhance product yields, minimize waste generation, and improve the sustainability of re-refining [51]. Novel methods such as supercritical fluid extraction and ionic liquid-based separation are under investigation, offering potential breakthroughs in selectivity and energy efficiency [52]. An illustrative example of such integration is the sequential application of solvent treatment followed by membrane filtration, which combines efficient sludge removal with fine purification of oil fractions (Figure 8). This hybrid configuration demonstrates how coupling conventional and membrane-based techniques can significantly improve overall recovery efficiency and product quality.

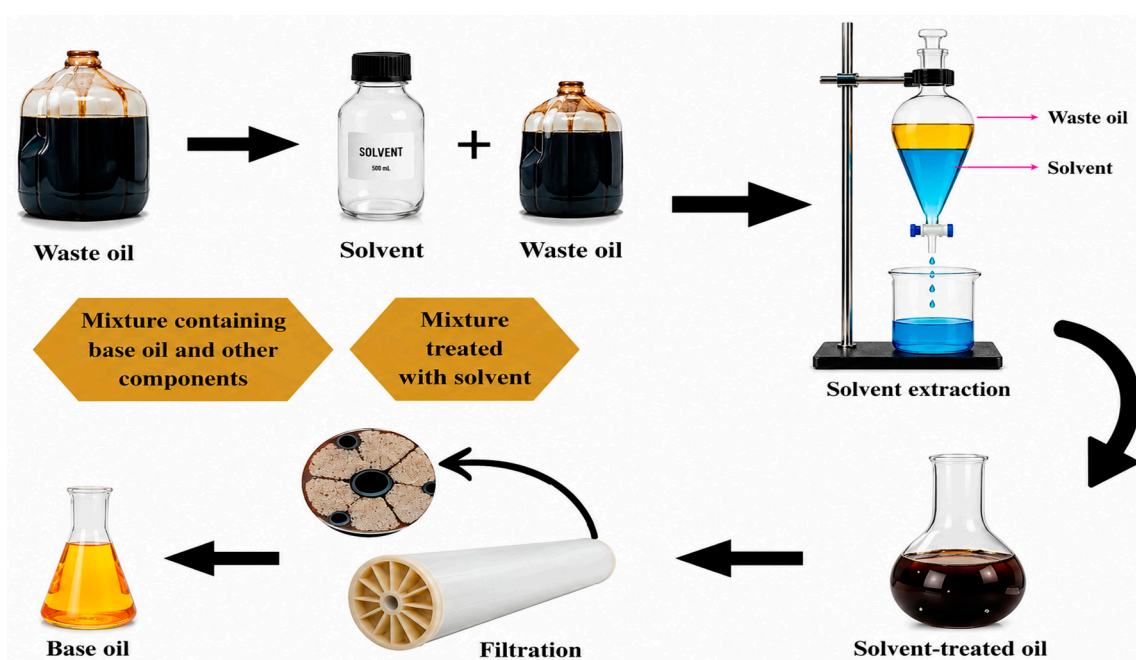


Figure 8. Hybrid re-refining process combining solvent extraction and membrane filtration. Created by the authors based on information reported in [13].

To provide a comprehensive comparison of the principal Waste Lubricating Oil (WLO) recycling methods, a comparative summary of the principal WLO recycling technologies is presented in Table 2.

Table 2. WLO recycling methods.

Technology	Yield (%)	Product Quality	Main Advantages	Main Limitations	Industrial Readiness
Acid–Clay Treatment	50–70	API Group I	Simple, low-cost process	Acid sludge generation, poor sustainability	Commercial [13]
Solvent Extraction	Up to 90	API Group I–II	High oil recovery, reduced sludge formation	Solvent recovery required	Commercial [53,54]
Vacuum Distillation	80–85	API Group I–II	Mature, scalable technology	High energy demand	Commercial [55]

Table 2. *Cont.*

Technology	Yield (%)	Product Quality	Main Advantages	Main Limitations	Industrial Readiness
Hydrotreatment & Hydrofinishing	75–90	API Group II–III	High-quality base oils and fuels	Hydrogen consumption, catalyst deactivation	Commercial [56,57]
Integrated Solvent Extraction–Hydrotreatment	Up to 80	Comparable to Group II	Improved product quality, reduced OAC	Process complexity	Commercial/Pilot [34]
Membrane Filtration	Pretreatment technology	Improved oil properties	Low energy consumption	Membrane fouling, low flux	Pilot [34]
Pyrolysis & Catalytic Cracking	Up to 96.5	Fuels + carbon products	Product diversification, high conversion	Scale-up and economic challenges	Pilot–Demonstration [58,59]
Hybrid & Emerging Technologies	Up to 90	High-quality recovered fractions	Enhanced resource recovery	Technology integration complexity	Laboratory–Pilot [60]

As shown in Table 2, WLO recycling technologies differ considerably in terms of recovery efficiency, product quality, process complexity, and industrial applicability. Conventional approaches such as acid–clay treatment and solvent extraction remain attractive due to their simplicity and relatively low operating costs, whereas vacuum distillation and hydrotreatment provide higher-quality products suitable for reuse as base oils. Emerging technologies, including pyrolysis, catalytic cracking, membrane filtration, and hybrid processing schemes, offer additional opportunities for resource recovery and product diversification; however, challenges related to energy consumption, catalyst stability, process integration, and large-scale implementation remain to be addressed. To further illustrate recent technological developments, Table 3 summarizes representative advances and performance benchmarks reported for major WLO recycling routes. The selected studies highlight significant improvements in oil recovery, contaminant removal, catalyst stability, and product quality, demonstrating the ongoing transition from conventional regeneration methods toward more efficient and sustainable recycling strategies [61].

Table 3. Representative recent advances and performance benchmarks in WLO recycling.

Technology	Representative Advancement	Key Performance Indicator	Ref.
Acid–Clay Treatment	Optimized acid–clay regeneration process	69% oil recovery; recovery cost 0.15 USD/L	[61]
Solvent Extraction	DEA–n-butanol solvent–flocculant system	85.27% oil recovery; regenerated oil met commercial standards	[62]
Three-Reactor Hydrotreating	Multi-reactor catalyst protection strategy	Catalyst life doubled; >80% S, N and Cl removal maintained for 10 weeks	[39]
CoNiMo/ γ -Al ₂ O ₃ Hydrotreating	Circular-economy catalyst support derived from waste aluminum foil	Viscosity index increased from 78 to 129; sulfur reduced from 6752 to 543 ppm	[38]
Hybrid Recovery System	Integration of centrifugation, solvent extraction and thermal treatment	90–94% oil recovery; energy consumption 400–600 kWh/t	[63]

The comparative evaluation of the reviewed recycling technologies (Tables 2 and 3) highlights clear differences in process efficiency, product quality, environmental performance, and industrial applicability. Processes such as acid–clay treatment remain among the simplest and lowest-cost options; however, they generate substantial quantities of hazardous sludge and offer limited scalability [14,15]. Solvent extraction improves oil recovery and product purity but requires efficient solvent recovery systems and careful control of emissions [27]. Vacuum distillation and hydrotreatment produce higher-quality base oils suitable for industrial reuse, although these technologies are associated with higher energy consumption, hydrogen demand, and capital investment [33].

Pyrolysis and catalytic cracking represent promising valorization pathways because they enable the conversion of waste lubricating oils into both liquid fuels and carbonaceous products while potentially reducing the consumption of chemical reagents and the generation of secondary waste compared with some conventional treatment methods [64]. For instance, a two-step pyrolysis process achieved WLO conversion of up to 96.5%, producing fuel fractions with sulfur content as low as 0.24 wt % [65]. In addition, the reuse of gaseous products for process heating may improve overall energy efficiency and reduce external energy demand [66]. However, despite these advantages, challenges associated with reactor design, catalyst stability, process optimization, product consistency, and economic feasibility continue to limit large-scale industrial implementation. Therefore, although pyrolysis and catalytic cracking demonstrate considerable potential within circular economy frameworks, further scale-up studies and comprehensive techno-economic assessments are required before their competitiveness relative to established re-refining technologies can be fully assessed [32,67].

Economic considerations play a crucial role in selecting appropriate WLO recycling technologies. Low-cost approaches, such as acid–clay treatment and solvent extraction, generally achieve moderate recovery yields and produce lower-value products, but they require relatively low capital investment and simple operating procedures [15,26]. These methods also exhibit comparatively low energy requirements, making them attractive for small- and medium-scale applications. In contrast, advanced technologies such as vacuum distillation, hydrotreatment, and pyrolysis enable the production of higher-value base oils and carbon-rich by-products suitable for industrial applications. However, these processes typically require higher capital investment, increased energy consumption, specialized catalysts, and stricter operating conditions to achieve optimal performance and product quality [33,65,67].

Consequently, the selection of an appropriate recycling strategy requires balancing product value, process complexity, energy demand, environmental performance, and overall economic feasibility. In this regard, integrated and hybrid approaches that combine pretreatment technologies with advanced upgrading processes may provide an effective pathway for improving resource recovery while maintaining acceptable operational costs and product quality. Such integrated systems are increasingly being considered as practical solutions for sustainable large-scale WLO recycling.

3. Valuable Products Obtained from Waste Lubricating Oils

Pyrolysis and catalytic cracking are key thermochemical technologies applied to WLOs, as discussed in Section 2.6. These processes generate several valuable products that can be recovered and utilized.

The major valuable products obtained from WLOs can be broadly classified into four groups: carbon black, regenerated base oils, fuel fractions, and secondary by-products (Figure 9). The subsequent discussion focuses on each of these categories individually, highlighting their properties, production methods, and industrial relevance.



Figure 9. Valuable petrochemical products and carbon-based materials obtained from waste lubricating oils (WLOs).

3.1. Carbon Black

Carbon black is a fine, amorphous carbon material obtained from the partial combustion or thermal decomposition of hydrocarbons [68]. Its micro- and nanoscale structure imparts unique reinforcing, conductive, and adsorptive properties, making it indispensable in the production of tires, rubber goods, coatings, and plastics. Recent research highlights the strategic potential of producing carbon black from WLOs, oily sludge, and waste tires as alternative feedstocks [69]. Such valorization not only addresses environmental concerns but also supports the demand for sustainable materials [70]. In addition to conventional applications, carbon black derived from waste streams such as waste lubricating oils is increasingly considered a valuable functional carbon material with potential use in advanced composites, energy systems, and environmental technologies. This shift reflects a broader transition from petroleum-derived fillers toward circular carbon resources obtained via waste-to-carbon pathways. Structurally, carbon black consists of more than 90% elemental carbon with surface-bound oxygen-containing functional groups such as carboxyl, quinone, lactone, phenolic, and ketonic groups [71]. These functionalities influence its reactivity and surface interactions. The primary particles, typically spherical and 10–100 nm in diameter, form fused aggregates in the range of 100–800 nm or larger, resulting in branched, three-dimensional morphologies [72,73]. This nanoscale architecture underpins its technological versatility across diverse sectors, including its role as a pigment, reinforcing filler, and conductive agent and precursor for functional carbon materials [74,75]. The predominant method for producing carbon black from WLOs is pyrolysis, a thermochemical process performed in the absence of oxygen. Unlike combustion, pyrolysis prevents complete oxidation of carbon to CO_2 , yielding solid carbon residues and liquid hydrocarbons [76]. In recent studies, such carbonaceous residues have also been explored as precursors for further activation processes to obtain porous and high-surface-area carbon materials, expanding their value beyond traditional carbon black applications. Accordingly, pyrolysis can serve as a resource recovery pathway rather than solely a waste disposal method, enabling the conversion of waste lubricating oils into valuable carbonaceous products and contributing to circular economy and sustainable development objectives [77].

3.2. Base Oils

Base oils are complex mixtures of paraffinic and naphthenic hydrocarbons with minor amounts of nitrogen- and sulfur-containing species [78]. They account for 70–90% of lubricating oil formulations and determine critical performance parameters such as viscosity, oxidation stability, and load-bearing capacity [79]. The re-refining of WLOs into base oils involves dehydration, vacuum distillation to obtain lube cuts, and subsequent hydrotreating to remove heteroatoms and improve product stability [80]. Re-refining technologies achieve yields of 75–84% of high-quality base oil from the initial WLO volume, meeting API Group I–III standards [81]. Vacuum distillation offers yields of approximately 84%, while solvent extraction provides around 78% [82]. Solvent-based approaches, using methyl ethyl ketone (MEK), 2-propanol, or 1-butanol, enable selective recovery of base oils followed by adsorption or filtration steps, achieving yields of 75–78% [83]. These methods demonstrate that regenerated base oils can fully replace virgin products in lubricant formulations while conserving natural resources.

3.3. Fuel Products from Pyrolysis and Co-Pyrolysis

Fuel fractions obtained from WLO recycling include diesel-like and gasoline-like liquids, light hydrocarbons, and heating oils. These products are commonly obtained through pyrolysis or co-pyrolysis with polymeric wastes, which have been reported to improve liquid yields and fuel properties under specific operating conditions. For instance, co-pyrolysis of WLOs with waste plastics at 450 °C can achieve up to 92.5% liquid yield with octane numbers reaching 96, surpassing conventional gasoline [84]. Thermal and catalytic pyrolysis under optimized conditions have been reported to yield approximately 60% diesel-like fractions, while additives such as CaO may contribute to sulfur reduction and improved combustion characteristics [85]. Microwave-assisted pyrolysis has demonstrated the potential to increase oil recovery to approximately 88% while producing fuels with high calorific value and reduced PAH content [86]. Catalytic and co-pyrolysis routes have demonstrated the potential to increase liquid product yields and improve selected physicochemical fuel properties; however, the observed performance strongly depends on catalyst characteristics, feedstock composition, reactor configuration, and operating conditions [87,88].

3.4. Secondary By-Products

Besides base oils, fuels, and carbon, WLO processing can generate valuable secondary products. These include bituminous residues that may serve as modifiers in asphalt binders, improving rutting resistance and durability of pavements [89,90]. Moreover, sulfur-containing compounds removed during WLO upgrading may be recovered as sulfur-rich streams, including hydrogen sulfide, which can subsequently serve as feedstocks for sulfur recovery processes in the chemical industry [91].

The integration of WLO-derived products into industrial chains contributes to circular economy principles. Life cycle assessment (LCA) studies indicate that regeneration of waste lubricating oils into base oils results in substantial greenhouse gas emission savings—approximately 344–537 kg CO₂-eq per tonne of WLO—compared with other waste oil management routes such as combustion or conversion to fuel [92]. Although direct comparisons with virgin base oil production depend on system boundaries, regeneration consistently demonstrates lower life cycle greenhouse gas emissions and energy demand [93]. Similarly, substituting WLO-derived fuels reduces dependency on fossil feedstocks and minimizes solid waste generation [93]. Economically, the valorization of 1 ton of WLOs can yield products worth USD 600–900, depending on the technology and

market conditions [94]. This dual benefit of environmental protection and resource recovery positions WLO recycling as both an ecological necessity and a profitable industrial practice.

3.5. Functional Carbon-Based Materials Derived from Waste Lubricating Oils

Thermochemical conversion of waste lubricating oils (WLOs), particularly via pyrolysis and catalytic cracking, generates carbonaceous solid residues that can serve as precursors for functional carbon-based materials. Depending on reaction conditions and catalyst type, these materials range from amorphous carbon and carbon black-like structures to partially graphitized and porous carbon frameworks with tunable physicochemical properties.

Recent studies further demonstrate that waste-derived hydrocarbons, including waste engine oils, heavy oil residues, waste plastics, scrap tires, and glycerol, can serve as alternative low-cost carbon precursors for the synthesis of nanostructured carbon materials. Depending on synthesis conditions and catalytic systems, these feedstocks can be converted into carbon nanotubes, carbon nanofibers, nanowhiskers, carbon microspheres, and porous carbon materials with tunable structural and surface properties. Such approaches are attracting increasing attention because they simultaneously address waste management and reduce the production cost of advanced carbon nanomaterials compared with conventional fossil-derived precursors [95].

The formation of such carbon materials is governed by dehydrogenation, aromatization, and polycondensation reactions occurring during thermal decomposition of hydrocarbons. At elevated temperatures, progressive structural rearrangement promotes the development of aromatic and microcrystalline carbon domains, whereas catalytic systems facilitate graphitization and pore formation. Consequently, the physicochemical properties of WLO-derived carbons strongly depend on process temperature, residence time, catalyst composition, and activation strategy.

WLO-derived carbon residues can be further upgraded through physical and chemical activation processes using CO_2 , steam, KOH, or H_3PO_4 , leading to a significant increase in surface area, porosity, and surface functionality. Recent studies demonstrated that phosphoric acid activation of oil-containing sludge at relatively low temperatures (600°C) produced mesoporous carbon materials with BET surface areas of approximately $70\text{ m}^2/\text{g}$ after only 30 min of treatment. Although this surface area is relatively low compared with highly activated carbons, the material was obtained under mild activation conditions and may still exhibit useful adsorption properties owing to its surface chemistry and the presence of iron oxide species. The pore development was strongly dependent on the H_3PO_4 impregnation ratio, while acid-washing further enhanced pore structure compared with water-washing due to more efficient removal of residual minerals and inorganic phases. In addition, activated carbons derived from hydrocarbon-rich waste streams may achieve significantly higher surface areas ($>500\text{--}1200\text{ m}^2/\text{g}$) under optimized activation conditions [11,96].

Morphological and compositional analyses using SEM and EDS revealed that the obtained carbon materials possessed porous structures enriched with iron oxides, imparting magnetic properties to the resulting adsorbents. Such characteristics are particularly attractive for environmental applications, since magnetic carbon materials can be easily separated and regenerated after adsorption processes. Due to their developed pore structure and surface reactivity, WLO-derived carbon materials demonstrate strong potential for adsorption of heavy metals, dyes, and organic pollutants, as well as for capture of CO_2 and volatile organic compounds (VOCs). Furthermore, their conductive carbon framework and defect-rich structure make them promising candidates for electrochemical applications, including supercapacitors and battery electrodes.

Beyond adsorption and electrochemical applications, waste-derived carbon materials also demonstrate strong potential as functional lubricant additives in tribological systems. Recent studies reported that activated carbon nanoparticles (ACNPs) produced from recycled waste streams significantly improved the tribological performance of lithium grease formulations. The incorporation of 0.025–1 wt % ACNPs reduced the coefficient of friction from 0.15–0.17 for base grease to as low as 0.03–0.06, while simultaneously decreasing wear scar diameter by 30–36% and improving load-carrying capacity by approximately 20–30%. These results indicate that waste-derived carbon nanomaterials can contribute to friction reduction, energy savings, and sustainable lubrication technologies while simultaneously valorizing hydrocarbon-containing waste streams [97].

From a sustainability perspective, the conversion of WLOs into functional carbon materials represents an advanced waste-to-carbon strategy aligned with circular economy principles. Unlike conventional disposal or combustion routes, this approach enables simultaneous waste minimization and production of value-added carbon materials with potential industrial applications. However, challenges related to feedstock heterogeneity, reproducibility of carbon structure, and optimization of large-scale activation processes still limit broader industrial implementation.

Overall, waste lubricating oils should be regarded not only as a source of fuels and regenerated base oils, but also as a promising precursor for high-value functional carbon-based materials, thereby significantly expanding the valorization potential of petroleum-derived waste streams [98].

4. Technological Innovations in Waste Lubricating Oil (WLO) Recycling

4.1. Techno-Economic and Sustainability Assessment

Recent studies increasingly incorporate life cycle assessment (LCA) and techno-economic assessment (TEA) to evaluate the feasibility of modern WLO recycling technologies. In addition to technical performance, environmental impacts, energy consumption, and economic viability have become important criteria for technology selection. Several studies have demonstrated that integrated recycling schemes combining pretreatment and upgrading processes may reduce environmental burdens while improving resource recovery efficiency [99,100].

TEA analyses indicate that the economic performance of WLO recycling is strongly influenced by plant capacity, feedstock quality, and utility costs, particularly hydrogen and electricity prices [101]. At larger processing capacities (approximately 50,000 t/year), waste oil re-refining technologies may become economically attractive, with reported production costs ranging from 198 to 349 USD/t depending on the selected process configuration [102]. Sensitivity analyses further indicate that profitability is significantly affected by electricity prices and catalyst lifetime, highlighting the importance of energy integration and catalyst regeneration strategies [103].

From an industrial perspective, technology readiness levels vary considerably among recycling routes. Plasma-assisted and membrane-based technologies remain primarily at pilot or demonstration scales (TRL 5–6), whereas hydrotreatment and vacuum distillation are closer to commercial deployment. Integration with existing refinery infrastructure is feasible for catalytic and distillation-based processes, enabling the utilization of existing equipment and operational expertise. However, several barriers to commercialization remain, including catalyst deactivation, feedstock variability, process scalability, and strict operational control requirements [22,32].

Therefore, integrating LCA and TEA perspectives provides a valuable framework for evaluating not only technical performance but also the environmental and economic

sustainability of emerging WLO recycling technologies. Comparative techno-economic and sustainability indicators reported in the literature are summarized in Table 4.

Table 4. Comparative techno-economic and sustainability indicators of waste lubricating oil (WLO) management and recycling pathways.

Reference	Technology	Economic Performance	Environmental Performance	Main Outcome
[92]	Regeneration vs. energy recovery	236–357 €/t savings	344–537 kg CO ₂ -eq/t reduction	Regeneration outperformed energy recovery pathways
[104]	Increased regeneration rates	€124–330 million societal savings	0.6–1.7 Mt CO ₂ -eq avoided	Environmental gains with moderate economic benefits
[9]	Re-refining	Energy demand 6144 MJ/t	363 kg CO ₂ -eq/t base oil	Lower impacts than virgin lubricant production
[93]	Re-refining and co-processing	34,300 t oil-eq savings/year	22,100 t CO ₂ -eq savings/year	Integrated management provided the highest overall benefits
[105]	Solvent extraction recycling	ROI 40%; production cost \$1.47/L	Reduced waste disposal burden	Economically feasible recycling route
[106]	KTI re-refining process	Production cost \$238/t refined oil	Reduced environmental burden from waste oil disposal	Re-refining showed favorable economic performance

The comparative analysis presented in Table 4 demonstrates a consistent trend across recent studies: waste lubricating oil re-refining generally provides the most balanced combination of environmental and economic performance compared with direct combustion and energy recovery routes. Regeneration technologies have been reported to achieve greenhouse gas emission reductions ranging from 344 to 537 kg CO₂-eq per tonne of waste oil, with solvent extraction and hydrotreatment exhibiting the most favorable environmental profiles [92]. Similarly, re-refining processes generated approximately 363 kg CO₂-eq per tonne of base oil and required 6144 MJ of energy per tonne of product while still providing lower environmental impacts than conventional lubricant production from crude oil [9].

At a broader system level, integrated waste oil management strategies have been shown to achieve annual savings of up to 22,100 t CO₂-equivalent and 34,300 t oil-equivalent. Although no single treatment pathway performed best across all impact categories, re-refining technologies consistently provided superior fossil resource conservation compared with combustion-based alternatives [93].

From an economic perspective, techno-economic evaluations confirm the commercial viability of waste oil recycling. Solvent extraction technology achieved a return on investment (ROI) of approximately 40% and a production cost of 1.47 USD/L of recovered base oil [105]. Likewise, the KTI re-refining process was identified as one of the most economically attractive commercial technologies, with an estimated production cost of approximately 238 USD/t of refined oil [106]. These results suggest that waste oil regeneration can provide competitive production costs while simultaneously reducing environmental burdens associated with improper disposal.

The socio-economic implications of increasing waste oil regeneration have also been investigated. Increasing the regeneration rate from 61% to 85% could avoid approximately

1.7 Mt CO₂-equivalent emissions and generate societal savings of up to €330 million. However, the overall benefits may be partially offset by administrative and regulatory implementation costs, indicating that economic feasibility depends strongly on regional policy frameworks and market conditions [104].

Despite the promising environmental and economic indicators reported in the literature, several challenges continue to limit the large-scale deployment of advanced recycling technologies. The overall performance of waste oil re-refining remains highly dependent on feedstock quality, collection efficiency, energy prices, catalyst lifetime, and process integration. Furthermore, environmental outcomes may vary according to the selected impact categories, allocation methods, and local energy mixes used in life cycle assessment studies. Therefore, future development of waste lubricating oil recycling technologies should be guided by integrated techno-economic and life cycle assessment approaches to ensure both environmental sustainability and long-term economic competitiveness. Overall, the available evidence supports re-refining as one of the most promising pathways for advancing circular economy objectives and reducing the environmental footprint associated with waste lubricating oil management.

Overall, the available literature indicates that re-refining technologies offer the most favorable balance between environmental sustainability and economic viability. Nevertheless, ongoing technological innovation is required to further improve process efficiency, catalyst durability, and operational flexibility.

4.2. *Emerging Technologies for WLO Recycling*

In recent years, conventional recycling approaches such as acid–clay treatment, solvent extraction, vacuum distillation, and hydrotreatment have been complemented by several emerging technologies aimed at improving process efficiency, product quality, and environmental performance. Among the most actively investigated approaches are plasma-assisted conversion, nanocatalyst-based hydroprocessing, hybrid integrated systems, and membrane-based separation technologies. These innovations seek to enhance resource recovery while reducing waste generation and energy consumption.

Plasma-assisted pyrolysis and gasification have attracted increasing attention as alternative thermochemical conversion technologies for producing fuels and carbonaceous materials from WLOs. Plasma technologies utilize high-energy arcs or microwave-induced plasmas to decompose complex hydrocarbons into lighter fractions and carbon-rich products [107]. Compared with conventional pyrolysis, plasma-assisted processes have been reported to achieve higher reaction rates, lower residual waste generation, and improved control of product composition under certain operating conditions. However, large-scale implementation of these technologies may be limited by process complexity, energy requirements, and the need for additional upgrading steps to obtain high-quality base oils [108]. Vacuum distillation and hydrotreating processes have achieved oil recovery yields of up to 84%, producing high-quality re-refined base oils suitable for further industrial applications [33]. In addition, plasma reactors may reduce the formation of undesirable by-products, contributing to improved environmental performance [109]. Nevertheless, energy consumption, reactor scale-up, and long-term operational stability remain important challenges for industrial deployment.

The use of nanostructured catalysts has significantly advanced hydrocracking and hydrotreating technologies for WLO recycling. Catalysts based on transition metal nanoparticles (Ni, Mo, Co, and Fe) supported on mesoporous materials such as SBA-15, MCM-41, and zeolites enhance cracking activity, sulfur removal, and aromatic hydrogenation [110]. These catalysts improve selectivity toward middle distillates and high-quality base oils while reducing energy requirements compared with conventional heterogeneous catalysts [111].

Furthermore, their high surface area and tunable pore structure promote improved interaction between active sites and WLO feedstocks, facilitating cleaner product streams [112]. However, catalyst stability and regeneration remain critical challenges for long-term industrial operation.

Hybrid approaches combining two or more treatment processes are increasingly being investigated as scalable recycling solutions [113]. Systems integrating solvent extraction with vacuum distillation, hydrofinishing, or catalytic upgrading have demonstrated improved oil recovery, enhanced additive removal, and reduced operating costs through energy integration. For example, solvent extraction followed by hydrofinishing can produce API Group II+ base oils with oxidative stability comparable to virgin lubricants [65]. Similarly, catalytic pyrolysis using zeolite-based catalysts generates gasoline- and diesel-like fuels with reduced polyaromatic content while simultaneously recovering carbon black as a value-added co-product [114]. Despite these advantages, maintaining consistent product quality and process stability remains a major challenge during scale-up.

Membrane-based technologies, including ultrafiltration, nanofiltration, and pervaporation, are increasingly applied as pretreatment and polishing stages in WLO recycling [115]. These processes enable the selective removal of water, asphaltenes, and metal-containing additives, thereby improving feed quality for downstream upgrading processes [116]. Recent developments in ceramic and polymeric membranes with enhanced thermal stability have enabled continuous operation under harsh processing conditions [117]. When integrated with conventional refining technologies, membrane systems may reduce overall process energy consumption by approximately 20–30%. Nevertheless, membrane fouling, long-term operational reliability, and scale-up remain important considerations for industrial implementation [118].

A comparative overview of the principal emerging technologies and their characteristics is presented in Table 5.

Table 5. Comparison of Emerging Technologies for WLO Recycling.

Technology/ Approach	Typical Operating Conditions	Key Performance Indicators	Main Products	Main Challenges	Ref.
Plasma-Assisted Processing	0–20 kV, 15–25 kHz	Liquid yield >80%; calorific value up to 44.38 MJ/kg; low S and N content	Liquid fuels, syngas, carbon black	High energy demand; scale-up and reactor economics	[118]
Nanocatalyst-Based Re-Refining	250–350 °C; 6–10 bar; LHSV 1–3 h ^{−1}	Enhanced HDS/HDN efficiency; improved conversion and base oil quality	Group II–III base oils, middle distillates	Catalyst deactivation and regeneration	[119]
Hybrid & Integrated Systems	Extraction + distillation + hydrofinishing	Oil recovery up to 90%; reduced operating costs through process integration	Base oils, diesel fractions, light fuels	Process complexity and optimization	[120]
Membrane Filtration & Separation	30–60 °C; 0.4–1.2 bar	Viscosity reduced by 2.1–14.2%; density reduced by 0.3–0.6%; improved feed quality	Pre-treated WLO for downstream refining	Membrane fouling and long- term stability	[45]

The emergence of plasma-assisted processing, nanocatalyst-based upgrading, hybrid integrated systems, and membrane-based separation technologies reflects the ongoing

evolution of WLO recycling toward higher resource efficiency and improved product quality. These approaches offer significant opportunities to enhance hydrocarbon recovery, reduce waste generation, and expand the range of value-added products obtained from waste lubricating oils.

Recent assessments indicate that most advanced WLO recycling technologies remain at pilot or demonstration stages (TRL 5–6), demonstrating technical feasibility but still requiring further optimization for large-scale deployment [3]. Integration with existing refinery infrastructure appears particularly promising for hybrid configurations that combine solvent extraction, hydroprocessing, and vacuum distillation, enabling more efficient utilization of existing processing facilities [22].

Nevertheless, several technical and economic barriers continue to limit commercialization. These include catalyst deactivation, feedstock variability, energy consumption, process complexity, and scale-up challenges. Future research should focus on catalyst regeneration strategies, process intensification, energy integration, and comprehensive techno-economic assessments to improve both process stability and industrial competitiveness. Addressing these challenges will be essential for the successful transition of emerging WLO recycling technologies from pilot-scale demonstrations to full-scale industrial implementation.

5. Conclusions

The recycling of petroleum-based lubricants has been increasingly addressed in the literature as an element of sustainable waste management and resource recovery. Conventional processes, including acid–clay treatment and distillation, continue to be applied; however, numerous studies report environmental and regulatory limitations associated with these approaches. Advanced recycling techniques such as hydrotreatment, solvent extraction, membrane separation, and catalytic cracking have been investigated for improving base oil quality and reducing environmental impacts. Reported results indicate that, under optimized conditions, these processes can produce re-refined oils meeting higher performance classifications, although outcomes strongly depend on feedstock variability and process configuration. In parallel, thermochemical pathways, including pyrolysis and plasma-assisted conversion, have been explored for the generation of fuels, carbonaceous materials, and other co-products, expanding the range of potential valorization routes for WLOs. Recent studies further demonstrate that waste lubricating oils can serve not only as a secondary source of fuels and regenerated base oils, but also as promising precursors for functional carbon-based materials, including carbon black, porous carbons, and nanostructured carbon materials. The development of waste-to-carbon strategies opens new opportunities for the production of adsorbents, catalyst supports, electrochemical materials, and tribological additives from petroleum-derived waste streams.

Comparative analysis of the reviewed studies highlights the importance of process integration and hybrid systems in enhancing recovery efficiency and mitigating environmental burdens. Recent life cycle assessment (LCA) and techno-economic assessment (TEA) studies reviewed in this work indicate that advanced WLO recycling technologies have the potential to combine environmental sustainability with economic feasibility, supporting their future industrial implementation and contributing to circular economy objectives. The comparison of available technologies further demonstrates that no single recycling route is universally optimal; rather, technology selection depends on product quality requirements, economic constraints, environmental considerations, and process scale.

Overall, the literature indicates that WLO valorization represents a technically feasible pathway for reducing hazardous waste generation and recovering valuable resources within circular economy frameworks. Future research should focus on improving process scalability, energy efficiency, catalyst stability, feedstock flexibility, and the reproducibility of carbon

material properties. In addition, greater attention should be devoted to integrated techno-economic and environmental assessments to support the development, optimization, and industrial deployment of next-generation waste-to-carbon and re-refining technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

WLOs	Waste lubricating oils
PAHs	Polycyclic aromatic hydrocarbons
MEK	Methyl ethyl ketone
API	American Petroleum Institute
LCA	Life cycle assessment
TEA	Techno-economic assessment

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