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RECENT ADVANCEMENTS AND CHALLENGES IN RECYCLING WASTE ENGINE OIL FOR ENVIRONMENTAL SUSTAINABILITY

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ABSTRACT

Recycling Waste Engine Oil (WEO) is essential for addressing sustainability, economic, and health concerns arising from improper disposal. This article provides insights from a comprehensive discussion on various techniques and technologies utilised in WEO recycling. It highlights the importance of WEO recycling in reducing environmental pollution, conserving resources, and promoting sustainability. Traditional methods like acid/clay treatment, vacuum distillation, and solvent extraction are discussed along with their limitations and challenges. Recent advancements in WEO recycling techniques such as membrane filtration, bioremediation, and adsorption techniques are emphasised for their potential to enhance recycling efficiency. The article also highlights the economic benefits of adopting circular economy principles and the production cost reduction gains associated with base oils. It explores the ecological advantages of WEO recycling, including pollution mitigation and ecosystem preservation to maintain sustainability. However, challenges like acidic sludge generation and the search for cost-effective bio-based materials are acknowledged. This article offers a concise overview of current WEO recycling technologies, addressing both advancements and persistent challenges in this crucial field, while emphasising its pivotal role in fostering sustainability and environmental care.

Introduction

Waste management is critical, yet challenging, as many wastes are difficult to recycle, leading to extensive landfilling globally. Hazardous waste disposal contributes to pollution and greenhouse gas emissions without recovering toxic components (Zahir Hussain *et al.*, 2020). With modern society's reliance on cars, the demand for lubricants, particularly engine oil, has surged. The automotive industry accounts for 57% of global engine oil consumption in 2016 (Patel & Shadangi, 2020). The increase in vehicle numbers has generated around 20 billion tons of Waste Engine Oil (WEO), posing environmental concerns treated ineffectively (Pinheiro *et al.*, 2021; Z. Yang *et al.*, 2021). About 95% of WEO is either incinerated or disposed of in landfills and wastewater streams (Makwana *et al.*, 2020; Zgheib & Takache, 2021).

According to recent studies, the global Used Engine Oil Recycling market was valued at USD 2268.3 million in 2023, projected to reach USD 3414.4 million by 2030, with a CAGR of 6.0% (Information, 2023). Figure 1 presents the publication trends over the past 23 years, highlighting the emergence of studies focusing on WEO recycling. Notably, there is a substantial increase in relevance observed from 2006 to 2023. The analysis of the database indicates the importance and growing interest in the recycling of WEO.

Engine oil, the primary petroleum fraction, serves a critical role in vehicles and machines by reducing friction between moving parts and facilitating smooth operation (Osman *et al.*, 2018). It performs three functions—heat transfer, friction reduction, and corrosion resistance in automotive engines—essential for lubrication and cooling, and extending the lifespan of moving parts under varying conditions (Mishra *et al.*, 2020). Engine oil lubricants comprise approximately half the lubricant market. (Nour *et al.*, 2021). Despite its importance, decreasing fossil fuel reserves, increasing demand, and environmental hazards associated with WEO disposal have stirred debate about lubricant oils (Li *et al.*, 2020).

Additives, like antioxidants, anti-wear, thickeners, anti-foam, detergents, corrosion protection, dispersants, and high-pressure additives, in base oil enhance its performance (Mohammed *et al.*, 2013; Yash, 2015; Gunawan *et al.*, 2019). They introduce or enhance specific properties such as oxidation resistance and friction reduction. However, used oil contains contaminants like heavy metals (lead, cadmium, arsenic, chromium, nickel), sulfur, toluene, benzene, chlorinated paraffins, chlorinated solvents, polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAHs), posing environmental and health risks (Peng *et al.*, 2018; Anufriev *et al.*, 2019; Ramirez *et al.*, 2019; Zahir Hussain *et al.*, 2020; Gaur *et al.*, 2023). These contaminants can originate from additive degradation, wear debris, and external pollutants (Kheireddine *et al.*, 2013; Sadeek *et al.*, 2014). Due to its hazardous components, WEO can contaminate water sources, soil, and air if improperly disposed of (Yadav & Saravanan, 2015). Figure 2 illustrates the journey of engine oil from its initial unused state to its eventual fate of either disposal or recycling. Despite impurities, much of the base oil in WEO remains unexhausted, preserved by the stability of heavy compounds (Patel & Shadangi, 2020). Therefore, rigorous processing is essential before considering reuse or recycling.

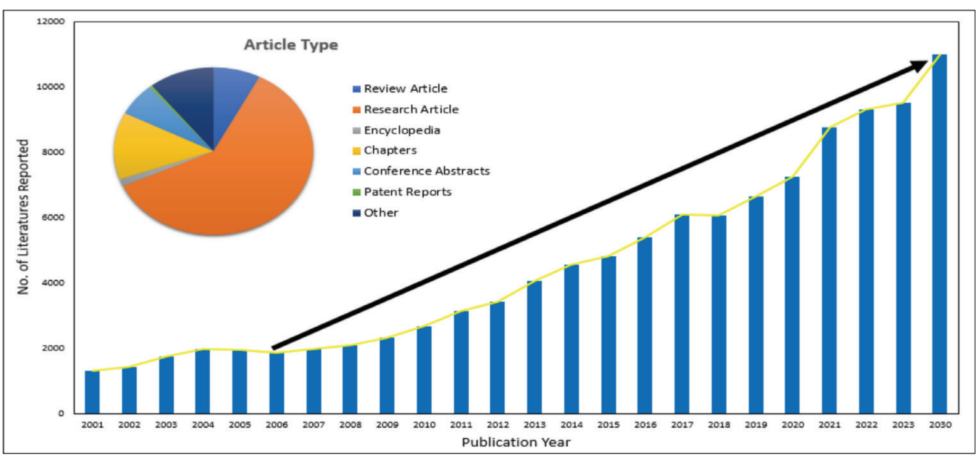

Figure 1: Number of scientific studies in the last twenty years about recycling of waste engine oil. Search conducted through Science Direct database on 16 March 2024 and forecast for up to 2030

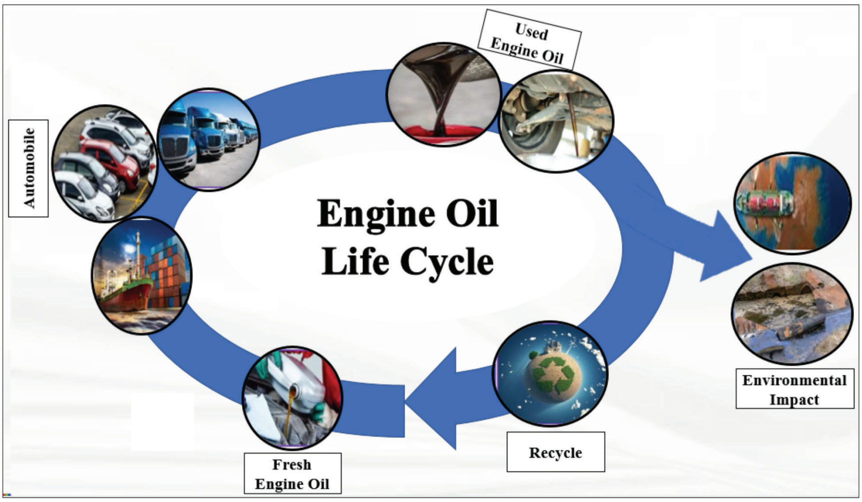

Figure 2: Schematic drawing of life cycle of engine oil from unused state to either recycled or disposal

Environmental Impact of Waste Engine Oil

Improper disposal of waste, including hazardous waste like WEO, poses significant threats to social, economic, and environmental sustainability (Tekin *et al.*, 2019). Various materials, including discarded tires, used automotive engine oil, and residue from automobile shredders, primarily from vehicles, contribute to this waste stream (Lam & Chase, 2012; Patel & Shadangi, 2020; Korchak *et al.*, 2021). Environmental concerns dictate that they require proper handling due to their hazardous nature (Widodo *et al.*, 2020). The significant volume of WEOs has economic and environmental impacts, the initial product costs millions to manufacture and the used material poses high pollution risks when improperly disposed of. Discharging WEO into water and land, or burning them as low-grade fuel can lead to severe pollution. Therefore, appropriate handling and disposal procedures are crucial to mitigate these risks and promote environmental sustainability.

Engine oil is a hazardous substance that poses significant threats to both the environment and human health. It contains a cocktail of metals and heavy polycyclic aromatic hydrocarbons, resulting from incomplete combustion and the wear process of engine components. These compounds have been linked to chronic hazards such as carcinogenicity and mutagenicity, potentially leading to increased cancer risk, bone marrow damage, and liver or kidney disease, upon prolonged exposure (McLoone *et al.*, 2021; Goyal *et al.*, 2022). These pollutants not only harm animal populations by adhering to their fins, feathers, and hair, but also disrupt ecosystems as affected animals migrate to other areas.

Additionally, the insolubility, persistence and slow degradation of engine oil compound its environmental danger over time (Ossai *et al.*, 2020). Moreover, modern engine oil additives heighten its toxicity in the environment. Thus, the proximity of polycyclic aromatic hydrocarbons, heavy metals, and polychlorinated biphenyls in used engine oil presents a grave threat to ecological balance and human well-being.

Importance of Recycling Waste Engine Oil

Recycling, reuse, energy recovery, and proper disposal is a must (Pinheiro *et al.*, 2021). WEO poses significant environmental risks, with just one gallon capable of contaminating a million gallons of groundwater. Even small concentrations of 50 ppm to 100 ppm in sewage treatment plants can disrupt the water treatment process (Adelowo *et al.*, 2006; Klamerus-Iwan *et al.*, 2015). The recycling of waste engine oil may offer a cost-effective alternative to incineration. Incineration and chemical treatment, while common is disposing of WEO, incur high costs and release a large amount of carbon dioxide emissions due to the energy-intensive equipment required. Consequently, about 55% of worldwide WEO are treated as municipal solid waste and dumped into landfills or waterways, due to lower processing costs (Sam *et al.*, 2020). UEO, a byproduct of vehicle servicing, contributes to millions of litres of waste annually (Patel & Shadangi, 2020; Afreen Nissar *et al.*, 2022). Proper treatment of WEO is necessary to mitigate health and environmental risks.

Recycling methodologies and waste management strategies have been implemented by several countries, including Japan, India, China, and Korea, as documented in previous literature (Ni & Chen, 2015; Osayi *et al.*, 2018; Arora *et al.*, 2019). These methods aim to address the environmental and health threats posed by WEO. Recycling involves cleaning the base oil, separating degraded additives and adding new ones to restore the oil to its original higher quality state. Conventional recycling methods such as distillation, are costly but serve economic, resource conservation, and environmental and health protection purposes (Hamawand *et al.*, 2013). Additionally, alternative fuel production from WEO not only reduces petroleum consumption but also protects the environment and minimises greenhouse gas emissions. The characteristics and environmental impacts of WEO, as well as the significance of recycling this material is illustrated in Figure 3.

Several reviews have examined the recycling processes and environmental impacts of waste lubricants and other oils. However, a comprehensive review specifically on the challenges in traditional engine oil recycling and recent advancements in engine oil recycling technology remains notably absent. Therefore, the objective of this review is to provide a comprehensive examination of engine oil recycling, encompassing both the challenges associated with traditional methods and recent advancements in recycling technology. This review aims to stimulate research on advanced WEO recycling techniques and generate innovative ideas for mitigating its environmental impact, improving fuel and lubricant quality,

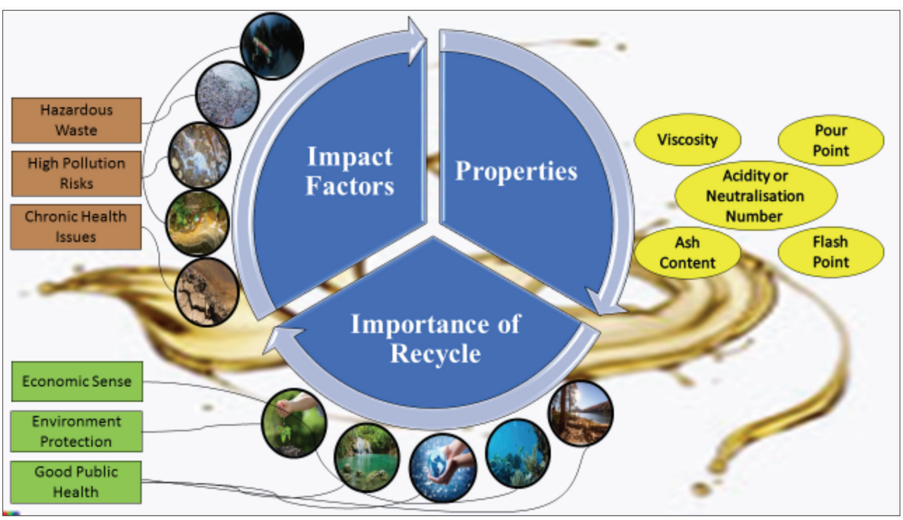

Figure 3: Properties and environmental impact of waste engine oil and importance of recycling

and implementing circular economy approaches in refining operations, while discussing the ecological and economic benefits of employing these technologies.

Overview of Engine Oil Recycling Process

Engine oil recycling is crucial for environmental sustainability and resource conservation, especially considering the damage caused by WEO when dumped into waterways, land, and sewers (Al-Khafaji *et al.*, 2018). Recycling involves the collection, pre-treatment, and re-refining of used oil. Additives may be blended with the recycled oil to enhance its performance characteristics, and quality control measures are implemented throughout the process to ensure compliance with regulatory standards (Hussain *et al.*, 2024). The detailed WEO recycling process, as depicted in Figure 4, shows the entire journey from the extraction and collection of used engine oil to its recycling, and finally, the assessment of its environmental impact post-recycling.

Engine oil recycling is guided by fundamental principles of minimising waste, conserving resources, and preventing environmental pollution (Pinheiro *et al.*, 2021). These principles drive the entire process, starting from collection to reprocessing and reuse. Oil recycling supports sustainability and resilience by preventing pollution, saving energy, generating economic benefits and embracing the principles of a circular economy. By keeping valuable materials in circulation, it contributes to a more sustainable and resilient environment. Public awareness and education initiatives play a vital role in promoting responsible oil management practices and increasing participation in recycling efforts. Through these principles, oil recycling contributes to environmental sustainability and resource efficiency, making it an integral part of sustainable development strategies.

Figure 4: Schematic illustration of stages in waste engine oil recycling
Source: Pictures adapted from Liu and Wang (2021), Sun *et al*. (2021) and Zulqarnain *et al*. (2021)

Historical Development in Recycling Processes

The growing attention towards recycling WEO is primarily driven by escalating environmental concerns stemming from increased pollution and the imperative to natural resources conservation. In some technologically advanced countries, as much as 50% of engine oils are sourced from recycled ones. In areas such as the European Union, the production of refined base oils from used engine oil accounts for only 13% of the total required base oils (Zimmermann & Jepsen, 2018). Exploring the historical development of WEO recycling techniques is crucial to gaining insights into addressing environmental concerns and improving resource efficiency over time. Table 1 showcases the chronological evolution of WEO recycling techniques. These advancements highlight the evolving landscape of WEO recycling, with efforts directed towards maximising resource recovery and minimising environmental impact.

Table 1: Chronological development of waste engine oil recycling techniques

Year	Technique	Development	References
Pre-20th Century	Rudimentary methods	Basic filtration and settling were used for WEO recycling.	Mekonnen (2014)
1930s	Initial recycling efforts	Initial efforts towards recycling WEO emerged, prompted by emerging environmental concerns.	Kramer *et al.* (2001), J. D. Udonne (2011)
1940s-1950s	Filtration, simple distillation	Basic re-refining techniques like filtration and simple distillation were commonly employed.	Parry (2019)
1960s-1970s	Vacuum distillation,	Advanced methods such as vacuum distillation, gained prominence for separating base oil from contaminants.	King *et al.* (1964)
1980s	Hydrotreating, bioremediation	Introduction of hydrotreating processes to improve oil quality.	Płaza *et al.* (2001), da Silva *et al.* (2012)
1990s	Solvent extraction	Solvent extraction techniques became prevalent, offering efficient removal of contaminants from used oil.	Dean and Xiong (2000)
2000s	Advanced re-refining technologies	Advancements in re-refining technologies led to improved efficiency and sustainability driven by stricter regulations.	Kupareva *et al.* (2013)
2010s	Hydrocracking, catalytic cracking, adsorption	Introduction of innovations like hydrocracking and catalytic cracking to further refine base oils.	Weitkamp (2012)
2020s	Emerging technologies, adsorption, bioremediation	Exploration of emerging technologies such as membrane filtration, adsorption and bio-based processes, including bioremediation.	Gogoi *et al.* (2022)

Main Processes Involved in Engine Oil Recycling

The journey of recycling waste oil starts with a basic step: Separating the different components. This is done by allowing impurities to settle below while the oil floats to the surface, based on their different densities. Once this separation is done, the waste oil goes through distillation to transform it into different fractions based on their boiling points. What's left after distillation is the reclaimed engine oil. The next stage involves acid treatment to get rid of any remaining impurities. The treated oil is then heated and mixed with sodium carbonate powder to remove acidic residues, make the oil cleaner, and more stable. Finally, the oil is passed through specialised filters to ensure it's pure and ready for use again. Figure 5 offers an overview of the key stages in engine oil recycling. Table 2 details the process of recycling WEO and the technologies utilised at laboratory scale are described below.

Traditional Engine Oil Recycling Techniques and Challenges

Acid/Clay Treatment

In this method, WEO is treated with various acids such as sulfuric, acetic, and formic acids, followed by clay absorption (Parekh *et al.*, 2022). Initially, the used oil is filtered to remove mechanical impurities, followed by distillation to eliminate water and light ends. The subsequent steps include more filtration to remove metallic particles and debris, reaction with sulfuric acid and clay inside a reactor at temperatures ranging from 475 K to 625 K for fuel production, and storage after re-filtering and cooling (Demirbas, 2008). The specific stages of the acid/clay treatment process involve heating the waste oil, introducing acid with continuous mixing, sedimentation for 24 hours, filtration to remove sludge residue, bleaching by heating and mixing with clay, neutralisation with sodium hydroxide to adjust pH, and final filtration after settling for 24 hours (J. Udonne & Bakare, 2013; Abu-Elella *et al.*, 2015; Hegazi *et al.*, 2017). Despite its simplicity, low capital investment and affordability, this method poses environmental threats due to the generation of acidic sludge as secondary contaminants. Additionally, it struggles to eliminate asphaltic impurities and presents challenges in the safe disposal of huge amounts of sulfuric acid sludge waste (Santhoshkumar & Ramanathan, 2020). Therefore, while this method offers

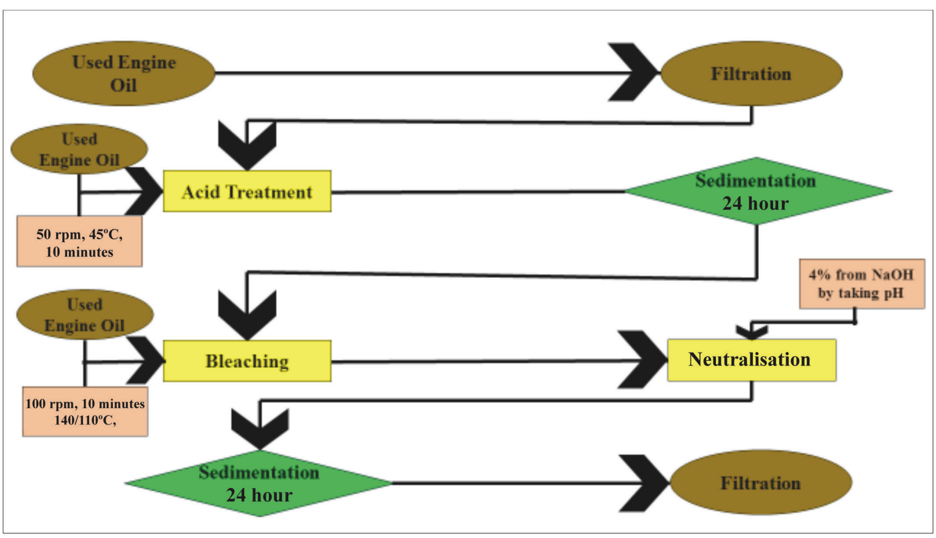

Figure 5: Illustration of main process with parameters involved in engine oil recycling

Table 2: Methods used to recycle used engine oil and the technologies involved in this process

Steps	Technologies	References
Pre-treatment	Filtration Distillation Centrifugation Magnetisation Heating Sedimentation	Li *et al*. (2020), Shanbhag *et al*. (2020), Widodo *et al*. (2020), Afreen Nissar *et al*. (2022), and A Nissar *et al*. (2023)
Recycling	Acid treatment Acid clay treatment Distillation/clay Solvent extraction Activated carbon/clay treatment	Santhoshkumar and Ramanathan (2020)
Re-refining	Vacuum distillation Atmospheric and vacuum distillations	Zeb *et al.* (2023)
Finishing	Filtration Sedimentation Neutralisation Adsorption	Aguilar *et al.* (2020)

a straightforward approach to oil recycling, its drawbacks underscore the need for more sustainable alternatives.

Vacuum Distillation and Clay Treatment

To address environmental concerns, vacuum distillation offers an effective method for treating waste engine oil. This widely adopted technique is instrumental in eliminating moisture and organic impurities accumulated in lubricants during engine usage. Vacuum distillation is often complemented by clay treatment, forming an integrated process aimed at refining waste oil (Hamawand *et al.*, 2013). The method has several key stages. Initially, waste oil is distilled at elevated temperatures to separate moisture and light hydrocarbons.

Subsequently, the dehydrated oil is subjected to high temperature and pressure, followed by condensation (Shri Kannan *et al.*, 2014). The process proceeds with vacuum distillation, utilising either thin film or conventional vacuum columns, to further refine the oil. In this phase asphalt minerals and organo-metallic compounds are separated, resulting in the fractionation of waste oil into three quantities. Following distillation, the distillate undergoes treatment with activated clay to mitigate colour, odour, and other undesirable components. A notable advancement in this process is the regeneration and recycling of spent clay for multiple treatments, contributing to sustainability. Lastly, heat treatment with clay enhances the characteristics of the separated oil fractions before concluding with pressure filtration (S. A. Ratiu *et al.*, 2020). While vacuum distillation and clay treatment offer significant benefits in waste oil refinement, challenges include the need for specialised equipment, skilled operators, high investment costs, and the usage of highly toxic materials.

Solvent Extraction

A viable solution to address this concern involves recovering the base oil from WEO through recycling processes that utilise cost-effective and non-toxic materials. Solvent extraction offers the advantage of producing high-quality base oils with lower impurities. However, it requires advanced operational setup and skilled personnel compared to other recycling methods (Parekh *et al.*, 2022). Solvent extraction is recognised as one of the cheapest and most effective methods for recycling used lubricating oils (Zgheib & Takache, 2021; N. Isa *et al.*, 2022). This technique involves using a solvent which extracts the base oil from contaminated oil while leaving contaminants behind. The efficiency of solvents is influenced by factors such as polarity, molecular interactions, and carbon chain length, with longer chains enhancing recovery rates. The process begins with filtering the oil and removal of solid residues, followed by solvent mixing. Separation of heavier compounds and asphaltic materials from the engine oil and the solvent takes place in a settling tank. Subsequently, a distillation process recycles the solvent and provides a stream of engine oil mostly for further vacuum distillation. Common solvents include propane, pentane and butane, although other chemicals may also be used (Adewole *et al.*, 2019). Figure 6 presents a basic flow of the solvent extraction process accompanied by an examination of both its advantages and obstacles.

Using solvent extraction is preferred over acid treatment when it comes to enhancing the viscosity/temperature and oxidative stability properties of base oils (Akanda *et al.*, 2022). The solvent dissolves only the extract that we don't want, leaving behind the desirable components, particularly saturated alkanes, in a separate phase (Vural, 2020). A blend of methyl ethyl ketone (MEK) and 2-propanol was utilised as a solvent to recover and reuse WEOs. However, its operation cost was high compared to recycling used engine oil through acid-clay treatment (Sarkar *et al.*, 2022). Another work used propane as a solvent. Propane is capable of dissolving asphaltenes, paraffinic or waxy material and intermediately dissolved

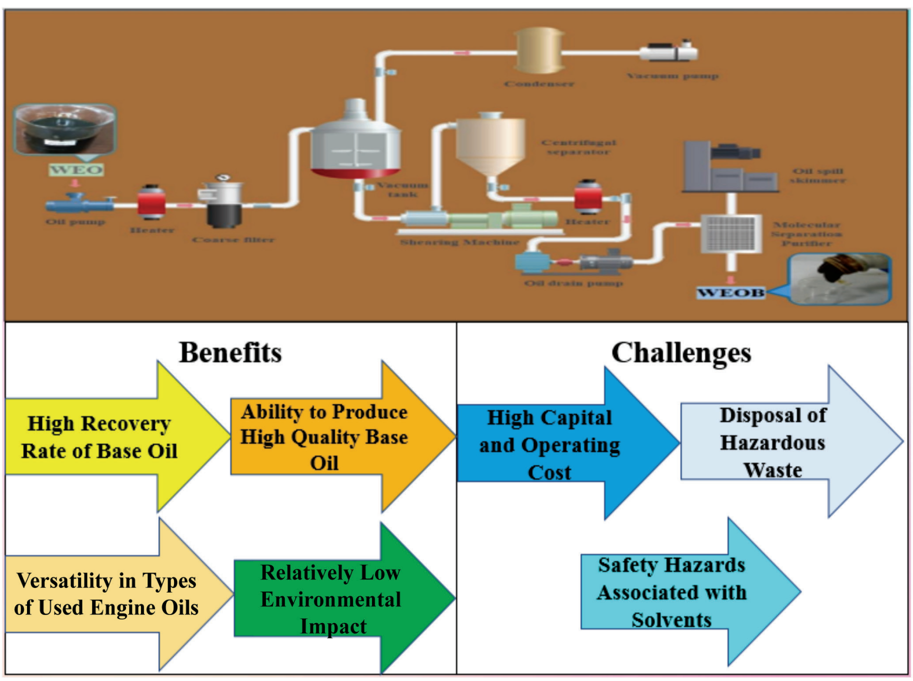

Figure 6: Simplified conceptual flow for the solvent extraction process with added benefits and challenges of solvent extraction process

Source: C. Liu and Wang (2021)

oxygenated material (Velasco-Calderon *et al.*, 2020). Since propane is dangerous and can catch fire easily, this procedure is considered hazardous. Extracting involves losing solvents and requires highly skilled operators to maintain. Additionally, extraction happens under high pressure, which makes building extraction plants costly. Moreover, it generates significant quantities of hazardous by-products (Yaseen *et al.*, 2021). The amount of recovery and quality of recycled oil can vary depending on the method used to process it.

Hydrotreating

Hydrotreating involves treating used oil with hydrogen under high temperature and pressure. Hydrotreating removes impurities, while hydrocracking breaks down the larger hydrocarbon molecules into smaller, more valuable ones (Speight, 2023). Nowadays, with the scarcity of crude oil supplies, there's a growing emphasis on recycling various materials, like WEO. Treatment technologies for WEO can be categorised into two main groups based on their primary products: Treatments that convert WEO into Re-refined Engine Oil (REO) and those that produce fuel (Q. Liu *et al.*, 2011). The re-refining process involves techniques like Vacuum Distillation (VD) with hydrofinishing, solvent extraction, and adsorption, which primarily focus on converting WEO into REO (Li *et al.*, 2020).

However, the capacity of existing re-refining plants worldwide, around 400 with a total capacity of 1.8 million tonnes/year, falls short of meeting global WEO recycling demand (K. Zhang *et al.*, 2017). Additionally, the re-refining process emits approximately 5,495 kg of CO_2 per tonne of WEO, contributing to global warming (H. Wei *et al.*, 2020). On the other hand, burning WEO as fuel presents challenges due to the high ash content (up to 1.5% wt.), which fouls furnace equipment, increases operating costs and poses health hazards due to submicron-size ash particles (Shen *et al.*, 2021). Given these limitations, there's a need for cleaner WEO recycling strategies to minimise environmental impact and enhance recycling efficiency. Hydrotreating improves the quality of engine oil and fuels. as it removes impurities like nitrogen, sulfur, and oxygen, using hydrogen gas, thereby reducing atmospheric pollutants produced by burning of fuels such as SOx and NOx (Xiaojie *et al.*, 2022; Islam *et al.*, 2023).

However, a drawback of hydrotreating is its high cost, primarily due to the significant hydrogen gas requirement. For instance, removing nitrogen to generate NH_3 as a byproduct necessitates twice the amount of hydrogen. Researchers like Antonina *et al.* (2013) have investigated WEO properties and the changes after hydrotreating, showing that the properties of REO are similar to fresh oil (Kupareva *et al.*, 2013). However, relying solely on hydrotreating for re-refining has its challenges due to the substantial requirement of hydrogen gas (Lam *et al.*, 2016). For instance, Liu *et al.* (2019) hydrotreated WEO to transform it into a diesel-like fuel, but with a higher calorific value of 48 MJ/kg. The resulting fuel had a nitrogen content of 0.04% by weight and a sulfur content of 0.03%.

Catalytic Cracking

Catalytic cracking, a well-established petroleum refining process, offers an efficient method for transforming WEO into valuable products like gasoline, kerosene and fuel oil. By rearranging hydrocarbon molecules, catalytic cracking produces lighter products such as LPG, gasoline, and heating oil while reducing residuals (Chen *et al.*, 2024). Despite its effectiveness, catalytic cracking requires sophisticated equipment and is energy-intensive, making it less competitive compared to simply using waste oil directly as fuel (Vargas *et al.*, 2016; Tekin *et al.*, 2019; Di Vito Nolfi *et al.*, 2021; Hoang *et al.*, 2021; Mishra *et al.*, 2021). Cracking reactions produce more than 80% wt of liquid hydrocarbons at mild operating conditions and with high reaction rates (Chi *et al.*, 2021; Miao *et al.*, 2021; Rodriguez Lamar *et al.*, 2021).

Table 3: The main technologies employed at an industrial scale for re-refining used engine oils

Recycling Method	Process	Advantages	Disadvantages
Acid–clay	1. Dehydration by preliminary distillation at low temperature. 2. Vacuum distillation. 3. Additional refining for eliminating hydrocarbons. 4. Adsorption with clay to reduce dark colour and odour.	• Proven effective and consistently yields high-quality base oils. • Simple process and does not need skilled workers to operate. • Low cost for production, requires minimal initial investment, making it profitable for small-scale operations. • Suitable for smaller capacities. • Low energy consumption.	• Incompatible with pollution control regulations. • Prohibited in many countries due to environmental concerns and regulations. • Low yield resulting from oil loss in mud and clay. • Increased maintenance costs and safety hazards. • Generates polluting waste.
Vacuum distillation and clay treatment	1. Distillation for separation of water particles and light hydrocarbons at high temperatures. 2. Vacuum distillation using conventional vacuum columns. 3. Activated clay treatment. 4. Pressure filtration.	• Enhanced efficiency. • Higher-quality recycled engine oil. • Reduced energy consumption, minimised use of chemicals. • Environmental benefits. • Easier management and maintenance of the recycling facility.	• Need for specialised equipment. • Require skilled operators. • Utilisation of potentially toxic materials. • High costs.
Solvent extraction	1. Dehydration: Removal of impurities like asphalt, resin, and metal compounds. 2. Removal of sludge as non-hazardous waste. 3. Vacuum distillation using conventional vacuum columns. 4. Adsorption with clay for reduction of odour and dark colour.	• Functions at ambient temperature without resulting in contamination. • Utilises recyclable solvent for efficient functional recovery, ensuring production of high-quality base oils. • Propane serves as a solvent for removing additives, tar, and metals.	• Operating at higher pressure. • Requires operating systems and qualified personnel. • May involve operating losses of solvent. • Propane can cause fires/explosions. • High energy consumption. • Economical only for high plant capacity.
Hydro-treatment	1. Dehydration. 2. Vacuum distillation with conventional vacuum column.	• Removal of impurities. • Improvement in recycled oil quality.	• Operates at elevated temperature and pressure. • High energy consumption.

	3. Treatment of oil using hydrogen with a catalyst to remove nitrogen, sulfur, and oxygen. 4. Solvent extraction enhances the oil quality. 5. Adsorption with clay.	• Corrects the colour and odour of the oil.	• Costly and unsafe. • Not suitable at small scale.
Catalytic cracking	1. Feedstock preparation and patalyst selection. 2. Cracking Reaction: Under elevated temperature and pressure conditions. 3. Product Separation: The cracked products, which include lighter hydrocarbons are separated from the reactor. 4. Product Refining: Undergo further refining processes through hydrotreating, distillation or other purification steps.	• Transforming WEO into valuable products like gasoline, kerosene, and fuel oil. • Sophisticated equipment and is energy-intensive.	• Catalyst deactivation due to fouling or coke deposition. • Higher energy consumption. • Reduced overall effectiveness. • Installation and operation costs are high. • Greenhouse gas emissions are generated.

Moreover, catalytic cracking, being an advanced pyrolysis technique, provides additional advantages in WEO treatment. It breaks down heavy residues rich in sulfur into lighter components, leaving behind coke (Fahim *et al.*, 2010). Materials like clays, zeolites, mesoporous silica, and amorphous silica enhance the reaction rate and produce lighter products with higher efficiency (Tamunaidu & Bhatia, 2007). One study conducted catalytic cracking of WEO using mesoporous aluminum silicate catalysts prepared under acidic and basic conditions and doped with metals like Mg, Zn, Cu, and Ni (Almeida Streitwieser *et al.*, 2023). Catalytic cracking holds promise for advancing a circular economy and addressing environmental and health concerns associated with WEO disposal. Catalytic methods are more efficient than thermal processes because they require less energy to get started and produce more liquid fuel, increasing yield from 63% to 90%. Catalytic cracking can yield diesel-like fuel meeting Diesel II requirements, indicating its potential for producing high-quality fuels adaptable to existing diesel engines without alterations (Vargas *et al.*, 2016). Table 3 lists all the industrialised primary technologies for recycling WEOs with detailed process steps and also with their advantages and disadvantages.

Combined Technologies

These advanced techniques integrate multiple conventional methods to effectively address the complex structure of contaminants found in waste oil. Due to the intricate nature of these contaminants, a singular method often fails to achieve the desired yield, prompting the establishment of various organisations with tailored procedures for managing and removing contaminants from used engine oil (Pinheiro *et al.*, 2021; Parekh *et al.*, 2022). However, these approaches demand expensive equipment, trained workers and meticulous practices. Vaxon Biotech has developed an economically promising technology for recycling WEOs that involves vacuum distillation and a finishing process such as solvent extraction or chemical treatment (Kupareva *et al.*, 2013). This innovative method effectively removes heavy metals, acidic components, and chloride by using alkali hydroxide and vacuum distillation to obtain base oil of varying viscosities. Notably, this advanced vacuum distillation process minimises oil cracking and is predominantly utilised in Europe. A key advantage of this method is the utilisation of a new distillation unit known as the vacuum cyclone flash evaporator, contributing to its efficacy.

Despite the attractiveness of solvent extraction or chemical treatment in recycling WEO, the resulting product quality tends to be mediocre or low, with yields limited to 65% to 70%. Additionally, a significant portion of residue is utilised as asphalt, leading to resource wastage and secondary environmental pollution. Rafie *et al.* (2013) recently explored an alternative solvent extraction method combined with solid adsorption for recycling WEO. Although this method offers lower operating and equipment costs, with half of the treatment process operating at ambient conditions, drawbacks include subpar REO quality and the generation of new liquid and solid waste (Li *et al.*, 2020). A technology introduced in 1992, the KTI process by Kinetic Technology International (KTI) combines vacuum distillation and hydrofinishing to recycle WEO. This method involves distillation under atmospheric conditions at 250°C to remove moisture and light hydrocarbons, followed by hydrogenation to eliminate metal components like nitrogen, sulphur and oxygenated complexes, resulting in high-quality recycled oil. While this process effectively removes contaminants, its high investment cost is a drawback (Oladimeji *et al.*, 2018; Toeipomthong, 2019).

Studi Tecnologie Progetti (STP), another technology also combines vacuum distillation and hydrofinishing techniques. This process involves dehydrating, vacuum distilling, separating the lubricating portion, and hydrofinishing to extract base oil from the remaining components, producing less hazardous waste (Parekh *et al.*, 2022). The Proterra recycling technology, an advanced oil refining process, combines solvent extraction and vacuum distillation. The secondary products generated by this method include extracts, light oils, and vacuum residues, along with wastewater that cannot condense (Aremu *et al.*, 2015; Oladimeji *et al.*, 2018). Figure 7 depicts

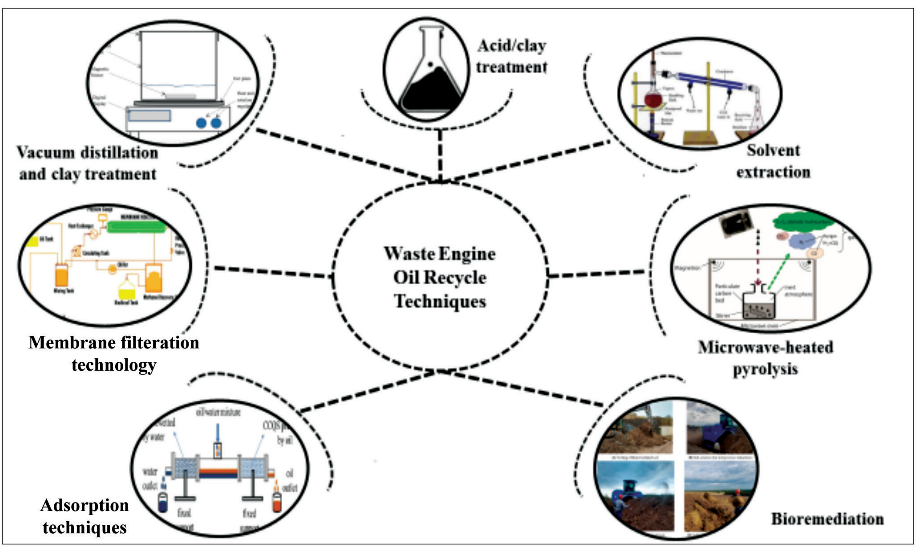

Figure 7: Various suggested techniques for the recycling of waste engine oils
Source: Pictures adapted from Lam and Chase (2012), Hamawand *et al.* (2013), Usman *et al.* (2021), Zulqarnain *et al.* (2021), Yinglong *et al.* (2022), Ameen *et al.* (2023), and Brejea *et al.* (2023)

various treatment and recycling technologies that exist to recycle and recover pure base oil from WEO.

Recent Advancement in Engine Oil Recycling Technology

The worldwide production of WEO is an estimated 40 million tons annually, presenting a significant challenge in terms of treatment and disposal (Santhoshkumar & Ramanathan, 2020). WEO, being highly contaminated, poses detrimental effects on both the environment and humans if not properly disposed of or managed. However, it also holds potential as a valuable source of high-grade fuel and feedstock due to its mixture of aromatic and aliphatic hydrocarbons, which if unrecovered, contribute significantly to organic waste liquids produced globally (Mishra *et al.*, 2021). Advanced technologies for refining WEO such as membrane technology, Pyrolysis Process (PP), adsorption techniques and bioremediation, are emerging as promising alternatives (Sarkar *et al.*, 2023).

Pyrolysis

Pyrolysis is an effective process for reclaiming fresh oil from WEO through thermal means. This thermal process involves heating waste materials at very high temperatures (ranging from 300°C to 1,000°C) under inert atmospheric conditions (Hasan *et al.*, 2021; Mikulski *et al.*, 2021). During pyrolysis, polymeric materials undergo thermal degradation, their macromolecular structures break down into smaller molecules and generate a number of hydrocarbons. The resulting pyrolytic products include a gas and a liquid fraction containing paraffins, naphthenes, olefins and aromatics, and solid residues (Campuzano *et al.*, 2021; Su *et al.*, 2022).

This process offers an alternative to incineration, as it yields valuable products. Pyrolysis techniques have demonstrated economic and environmental advantages, as waste materials after thermal cracking are decomposed into an inert atmosphere, producing pyrolysis oils and gases for use as high-grade fuel or chemical feedstock, or char for substitute of activated carbon (Zaman *et al.*, 2017). A study on recycling WEO into reusable diesel fuel through pyrolytic distillation, investigated the impact of two additives, sodium carbonate, and sodium hydroxide, on fuel purification. Optimal results were achieved with the addition of 2% sodium carbonate followed by two continuous distillations. These findings highlighted the efficacy of pyrolytic distillation in producing diesel fuel suitable for engine use (Maceiras *et al.*, 2017).

Diesel engines are suggested for the utilisation of pyrolysis fuel because of their high thermal efficiency and operational reliability. Blending pyrolysis fuel with diesel results in reliable engine performance (Arpa *et al.*, 2010). The literature suggests that a blend of diesel and 35% treated oil yields properties close to pure diesel (Beg *et al.*, 2010). However, pyrolysis oil blends may experience reduced BTE and increased CO, and smoke emissions due to viscosity issues (Geo *et al.*, 2018). To mitigate these challenges, lower viscous fuels and enhanced oxygen concentration are recommended. High-pressure fuel injection strategies are effective in enhancing air-fuel mixture and proper combustion, resulting in improved performance and reduced emissions (Jaichandar & Annamalai, 2013). The pyrolysis process yields gas, liquid and solid products, with yields dependent on various reaction parameters. Operating at higher temperatures typically reduces char yield and increases gas yield (Sekar *et al.*, 2022).

Furthermore, metal-char catalysts enhance heterogeneous reactions, facilitating quicker attainment of desired temperatures and sulfur absorption. Lam *et al*. (2015) investigated WEO pyrolysis employing a metallic char catalyst. Metal presence catalyses heterogeneous reactions, enhancing methane decomposition and rapidly achieving necessary temperatures (Lam *et al.*, 2015). Furthermore, metals transform into oxides, absorbing sulfur from the oil (Lam *et al.*, 2010). Microwave Pyrolytic

Processes (MPP) are commonly employed due to their efficiency and effectiveness in waste conversion.

Microwave Assisted Pyrolysis

Microwave Assisted Pyrolysis (MAP) is an innovative method initially pioneered by Tech-En Ltd. United Kingdom (Lam *et al.*, 2010). This anaerobic thermal treatment employs microwave-heated particulate carbon beds, demonstrating effectiveness in recovering valuable chemicals from various waste materials like plastics. It starts with combining WEO with particulate carbon, a highly microwave-absorbent material, and then heating the mixture under microwaves. The engine oil undergoes thermal cracking without oxygen, leading to the formation of shorter hydrocarbon chains. The gaseous products are subsequently condensed into pyrolysis oils, which exhibit diverse compositions dependent on the characteristics of the original substances and the conditions under which the reaction occurs (Santhoshkumar & Ramanathan, 2020).

Microwave Assisted Pyrolysis (MAP) of WEO generates valuable chemical feedstock, including hydrocarbon gases and liquid oils containing Benzene, Toluene, Xylene (BTX) and other aromatic hydrocarbons (Widodo *et al.*, 2018). However, despite its potential, the economic value of the chemical feedstock produced by pyrolysis is often lower than that of the original engine oil (Li *et al.*, 2020). In choosing methods for WEO recovery and disposal, environmental safety, feedstock quality, and economic benefits must be carefully considered (Verma *et al.*, 2020). Microwave pyrolysis, employing a bed of microwave-absorbent materials like activated carbon, particulate carbon and mesoporous aluminosilicate, enhances process efficiency (Rex *et al.*, 2020). Suriapparao and Vinu (2015) explored fly ash, silicon carbide, and activated carbon as susceptors in polypropylene microwave pyrolysis, yielding liquid percentages of 32%, 29% and 21%, respectively. Salema and Ani (2012) conducted oil palm shell microwave pyrolysis with varying mass ratios of activated carbon, observing no pyrolysis without a susceptor.

Ramanathan and Santhoshkumar (2019) noted a 40% activated carbon requirement to elevate pyrolysis temperature with a reduction in specific energy consumption, necessitating further investigation to compare fuel quality with conventional methods. Microwave-assisted pyrolysis emerges as a promising approach for converting waste into fuel at high temperatures (400°C to 800°C) under inert conditions, at lower energ consumption, reduced production costs and faster heating rates (Lam Mahari *et al.*, 2016; Beneroso *et al.*, 2017; M Y. Zhang *et al.*, 2018). Intensive research efforts have focused on MAP's impact on alkanes, viscosity, calorific value, heavy metals and H/C ratio. Mahari *et al*. (2018) observed that MAP at 500°C with 50°C/minutes heating rate increased gaseous and liquid yields by 18% and 81%, respectively. Phetyim and Pivsa-Art (2018) achieved highest pyrolysis oil yield between 400°C to 425°C, while Tripathi *et al.* (2015) investigated abundant saturated hydrocarbons in waste engine oil pyrolysis between 350°C to 400°C. Activation energy requirements vary with temperature and heating rate.

Membrane Filtration Technology

Membrane technology, while costly, offers a high-quality and high-yield method for base oil production compared to other techniques. In this process, waste engine oil undergoes filtration through hollow fiber polymer membranes where heavy metal particles and carbon residue are removed. Common membrane materials include polyacrylonitrile (PAN), polyethersulphone (PES), polyvinylidenefluoride (PVDF), and polyvinylidene fluoride-glass fiber (PGF) (Rouzegari *et al.*, 2020; Widodo *et al*., 2020). This continuous operation effectively enhances the liquidity and flash point of recovered oils by removing impurities. However, the expense of modern high-temperature polymeric membranes is a drawback, as they can be damaged and soiled by larger particles.

Membrane technology offers energy efficiency benefits over traditional methods (M. H. M. Isa *et al.*, 2012). The choice of membrane material is crucial for optimal separation performance. Hydrophobic materials, such as polyethylene (PE), polypropylene (PP), polytetrafluoroethylene (PTFE), or PVDF are preferred for oil filtration due to their low water adsorption and high affinity for non-aqueous solutions like oils (Chamani *et al.*, 2021). PP, known for its stability and affordability, exhibits promising potential as a membrane material for purifying waste engine oils due to its low surface energy. The experimental setup of the membrane filtration process is illustrated in Figure 8. Previous studies have demonstrated that highly hydrophobic PP membranes show increased oil permeability. However, further research is needed to explore the capabilities of PP membranes in waste engine oil purification and evaluate their impact on the efficiency of treated oils (Wenten *et al.*, 2019). A study explored the potential of using polypropylene as a promising membrane material for ultrafiltration of WEO. Assessments were conducted to observe alterations in membrane surface's hydrophobicity and oleophilicity, alongside analysing the characteristics of the treated waste engine oils (Widodo *et al.*, 2020).

Due to these benefits, membrane filtration has found applications in various sectors such as textile wastewater treatment, waste lube oil processing, and palm oil processing with zero-sludge (Widodo *et al.*, 2018; Sepehri & Sarrafzadeh, 2018; Fathali *et al.*, 2019; Gunawan *et al.*, 2019; Wenten *et al.*, 2020). Material selection plays a crucial role in membrane performance, with research focusing on innovative materials like carbon nanotubes, graphene, aquaporins, and zeolites, to enhance membrane efficiency (Roy *et al.*, 2020). In waste oil treatment, ceramic membranes are also preferred. Ceramic membranes excel in extreme operating conditions, offering high temperature and pressure tolerance for increased flux rates. However, they lack hydrophobicity and can be costly to fabricate (Psoch *et al.*, 2004; Himma *et al.*, 2019). To optimise removal efficiencies and productivity, careful consideration of membrane materials is essential.

Adsorption Techniques

Adsorption techniques in waste oil recycling involve using adsorbent materials to remove impurities and contaminants from the oil

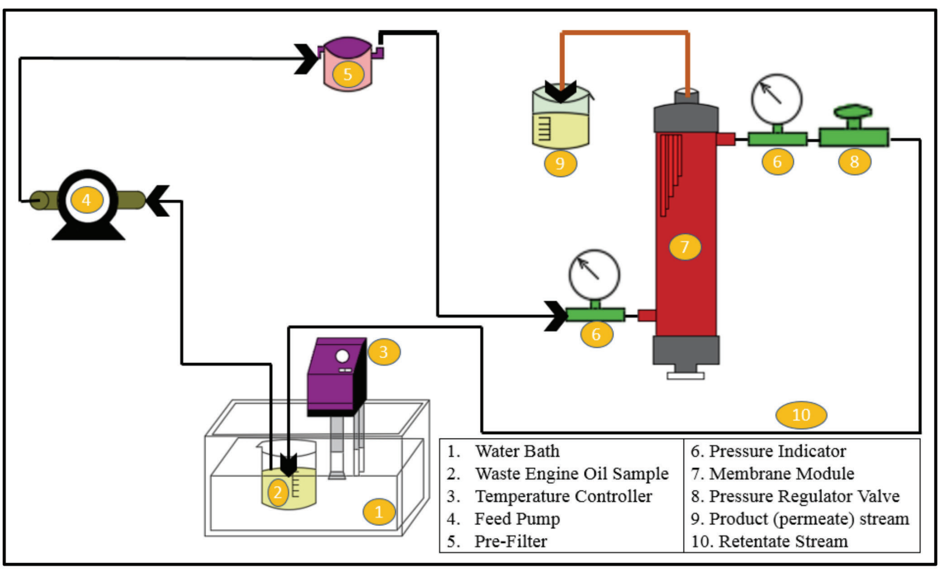

Figure 8: Experimental setup of membrane filtration technology for used engine oil recycling

(Mohammed *et al.*, 2013; Sabadash, 2023). The final stage in WEO purification is known as finishing, during which substances like chlorine, sulfur, nitrogen, oxygen, and peroxides are removed. These substances contribute to the oil's aesthetics and play a role in increasing its acidity. After this stage, the WEO appears clearer, with properties similar to fresh engine oil (Jafari & Hassanpour, 2015). Finishing can be achieved through adsorption processes with various materials, including natural clay, silica, activated clay, and activated carbon. Evaluations suggest that clay is a more cost-effective option compared to other materials (Aguilar *et al.*, 2020).

Bentonite clay is a widely used adsorbent material in waste oil recycling. Activated bentonite offers additional benefits in oil recycling by reducing sludge volume as residue and minimising oil loss (Mekonnen, 2014). Oduola and Kwonna employed Ukpor clay activated with sulfuric acid to extract heavy metals and trace elements from WEO (Oduola & Okwonna, 2016). The adsorption capacity of bentonite depends on various activation conditions such as acid concentration, contact time, temperature, acid/clay ratio, particle size, mixing speed, and pH (Pawar *et al.*, 2016). Therefore, it is essential to ascertain the most favourable operational parameters for every variety of bentonite deposit found within a region. In the treatment of used engine oil, varying amounts of bentonite powder is incorporated into specific volumes of oil, and the mixture is homogenised under predetermined conditions (Benk, 2021). In addition, serpentine is widely available worldwide and contains valuable ores like nickel, chromium, and magnesium. One study aims to utilise serpentine for the bleaching of waste engine oil. The objective is to remove impurities and odours from the WEO, involving pre-cleaning by solvent extraction followed by bleaching using heat and/or acid-treated serpentine (Huang *et al.*, 2017).

Activated carbon, silica gel and zeolite are also popular adsorption media for removing impurities from WEO. Activated carbon, known for its high porosity and surface area, effectively adsorbs a wide range of organic compounds found in waste oil. The oil is passed through a bed of activated carbon, where impurities adhere to the surface of the carbon particles (Li *et al.*, 2020). Additionally, activated carbon derived from agricultural by-products can be employed for remediating oil-spilled environments, making it a suitable adsorbent material for treating crude oil-polluted water (Ogbodo *et al.*, 2021). Zeolites, with its highly porous structure and large surface area, also serve as effective adsorbents for removing organic compounds, heavy metals, and other contaminants from waste oil (Mamaghani *et al.*, 2022). Silica gel, often combined with other adsorbents, effectively removes impurities from WEO. Recycled Polyethylene Terephthalate (RPET) aerogels derived from plastic bottle waste and waste Nitrile Rubber (NBR) show promise in oil spill cleaning applications (Le *et al.*, 2020). Silica aerogels address limitations in oil absorption capacity and stability, providing a solution for oil spill cleanup (Thai *et al.*, 2020). Hydrophobic biobased aerogels are also utilised for oil absorption due to their low density and high porosity.

Adsorption Using Hydrophobic Biobased Aerogels

Hydrophobic biobased aerogels have emerged as effective oil absorbents, leveraging their low density, high porosity, and expansive specific surface area (Ravi & Vadukumpully, 2016; Meng *et al.*, 2017; Xu *et al.*, 2019; Abdul Khalil *et al.*, 2023). One significant advantage of these biomass-derived materials is their ready availability at no cost, coupled with their renewable nature and minimal maintenance requirements (Abdul Khalil *et al.*, 2020). Their super hydrophobic properties, alongside remarkable porosity and ultralow density, make them invaluable for addressing environmental challenges, particularly oil spillage (Leng *et al.*, 2021).

Bioaerogels, a subclass of aerogel materials originated from biodegradable and renewal biopolymers, like cellulose, starch, chitosan, proteins, and alginate, blend the distinctive features of aerogels with the sustainability of biopolymers (Yahya *et al.*, 2021; Mawardi *et al.*, 2024). This synergy renders them as eco-friendly, potentially biodegradable, and sustainable materials suitable for bioremediation and oil spill clean-up (Chhajed *et al.*, 2019; ben Hammouda *et al.*, 2021). Depending on the level of contamination and the method employed, bioaerogel-based sorbents can be reusable. Variants such as cellulose aerogels, alginate aerogels, and carrageenan aerogels are notable options (Nešić *et al.*, 2019; S. Wei *et al.*, 2020; Abbasi *et al.*, 2023; Muhammad *et al.*, 2023; J. Yang *et al.*, 2024). Moreover, surface modification techniques or nanoparticle integration further enhance the efficacy of bioaerogels for oil spill clean-up applications.

Bioremediation

Bioremediation of WEO refers to the use of biological organisms such as microorganisms (e.g., bacteria, fungi) to degrade, detoxify, and eliminate contaminants present in used or discarded engine oil (Ahmed & Fakhruddin, 2018). Bioremediation harnesses the natural metabolic activities of microorganisms to break down these contaminants into simpler, less harmful substances, thereby reducing the environmental impact of WEO (Adams *et al.*, 2014; Gaur *et al*., 2023). Bioremediation offers an efficient strategy to expedite clean-up by stimulating microbial growth (Dangi *et al.*, 2019). The addition of nitrogen-rich nutrients (biostimulation) enhances bioremediation by overcoming limitations such as lack of essential nutrients. Evidence has shown that nitrogen supplementation has beneficial impacts on microbial activity and the breakdown of petroleum hydrocarbons. Banana skin, spent mushroom compost, and brewery-spent grain have shown potential in improving biodegradation of waste engine oil in soil as alternatives to inorganic fertilisers (Abioye *et al.*, 2010).

Bioremediation, a non-invasive, cost-effective, and eco-friendly technique, modifies environmental conditions to encourage the proliferation of naturally occurring microorganisms capable of breaking down pollutants, conserving soil texture and essential characteristics. This is achieved through aeration, addition of nutrients, pH control, moisture content, and temperature regulation (Hamoudi-Belarbi *et al.*, 2018). While physicochemical technologies have limitations such as potential environmental damage and destruction of soil characteristics, bioremediation is an economic, efficient, and versatile environmental treatment (Sharma *et al.*, 2018; Padhan *et al.*, 2021). Compost bioremediation, despite receiving little attention has potential for remediating heavily contaminated sites, with the dung from cows, camels, donkeys, and horses being applied to enhance the treatment process (Abdulkarim *et al.*, 2019).

Fungi and bacteria also play a crucial role in biodegrading hydrocarbons, with filamentous fungi showing promise due to their ability to attach quickly to substrates and secrete extracellular enzymes for digestion. Fungal bioremediation offers simplicity, cost-effectiveness, and ease of maintenance compared to physical-chemical techniques, requiring minimal energy input while preserving soil structure (Ramírez-García *et al.*, 2019). Various species such as *Aspergillus*, *Penicillium*, *Fusarium*, *Rhizopus*, *Alternaria*, and *Cladosporium* have been identified as effective hydrocarbon degraders. In a study on bioremediation of soil contaminated with spent engine oil, indigenous fungi isolated from hydrocarbon-contaminated soils from mechanic workshops were investigated. Three isolated fungi, namely *Aspergillus glaucus*, *Trichoderma polysporum*, and *Talaromyces flavus*, were identified using the API 20C method. *T. flavus*, and *A. glaucus* demonstrated high potential for bioaugmenting the bioremediation process of WEO-contaminated soils, suggesting their effectiveness in restoring the soil to its original state quickly (Abdulkarim *et al.*, 2019). Table

Table 4: Table summarising various recent technologies in engine oil recycling, highlighting their advantages and challenges

Technology	Advantages	Challenges	References
Acid/clay treatment	Efficient process, widely used	Generation of acidic sludge, cost inefficiencies	Hegazi *et al.* (2017)
Vacuum distillation	Effective in removing impurities	Energy-intensive, high initial investment	Shri Kannan *et al.* (2014)
Solvent extraction	High purity extraction, widely applicable	Costly solvents, environmental concerns	Zgheib and Takache (2021)
Pyrolysis	Versatile, effective in breaking down hydrocarbons	Equipment complexity, product quality control	Hasan *et al.* (2021)
Microwave assisted pyrolysis	Rapid process, high yield	Energy consumption, equipment complexity	Verma *et al.* (2020)
Hydrotreating	High efficiency in sulfur and nitrogen removal	High operating pressures and temperatures	Li *et al.* (2020)
Membrane filtration	Selective separation, minimal chemical use	Membrane fouling, high operating costs	Widodo *et al.* (2020)
Bioremediation	Environmentally friendly, natural process	Slow kinetics, limited applicability	Gaur *et al.* (2023)
Adsorption techniques	Versatile, cost-effective, easy implementation	Adsorbent regeneration, selectivity	Sabadash (2023)

4 provides a comparative summary of recent technologies in engine oil recycling, emphasising their respective benefits and hurdles.

Global Current Technologies for Recycling WEO

Apart from environmental benefits, recycling used engine oil also reduces pollution. It offers significant economic advantages and financial gains for companies implementing recycling processes and technologies. As a result, WEO recycling is widely practiced globally, with various methods and techniques utilised by established companies and those in development. Table 5 below outlines some of the technologies currently applied worldwide.

Environmental Impact and Product Quality Enhancement

Due to its significant content of harmful impurities such as acids, heavy metals, PAHs, and PCBs, WEO is categorised as a hazardous material. Improper handling and disposal of this waste can lead to groundwater and soil contamination, posing risks to ecosystems and human health. Given these concerns, a specialised management approach is essential (Pichtel, 2016; Bahadori, 2020). Recycling used engine oil is strongly advocated both for ecological preservation and economic reasons. This review explores various recycling technologies that have been traditionally and currently utilised worldwide. These technologies exemplify responsible management practices. Preventing the release of oils into the environment preserves ecosystems and promotes sustainable development. Ongoing improvements in these technologies aim to increase the volume of recycled oil and enhance the capability of the recycling process. The recycling process of used engine oil offers several advantages that are universally applicable across all technologies used worldwide. These advantages, whether ecological or economic, vary depending on the context in which the analysis is conducted.

Table 5: Cutting-edge technologies for recycling waste engine oil currently implemented globally

Name of Technology	Principle Based	Procedure	Novelty/Key Factor	Company Name
HyLube technology	Direct Contact Hydrogenation (DCH)	1. Engine oil that has been treated with a heated hydrogen mixture is transferred to a separating flash to remove remaining soluble metals. 2. A catalytic reactor is utilised for hydroprocessing to refine the used oil, followed by the separation of water and gases from the oil fraction.	The lubricant undergoes treatment within a pressurised hydrogen atmosphere without prior preparation.	PURAGLOBE Holding GmbH, Germany
Revivoil technology	Thermal de-asphalting and hydrofinishing	1. Heating the filtered used oil that contains additives. 2. Cooling the blend to separate water and light hydrocarbons through condensation. 3. Sending the dehydrated oil to a Thermal De-Asphalting unit (TDA). 4. Separating the diesel fraction from the top and the asphalt fraction from the bottom. 5. Finishing oil cuts by exposing them to hydrogen over a catalyst to remove impurities.	Recycled waste engine oil quality superior to market and largest reproduction capacity.	Itelyum Regeneration (Viscolube), Italy
Mohawk technology	Vacuum distillation and hydrofinishing	1. Chemical processing to prevent impurities. 2. Distillation to separate moisture and light hydrocarbons. 3. High vacuum distillation to separate diesel fuel. 4. Transfer of heavy particles to a heavy asphalt flux stream.	99% of engine oil recovery and creates near-perpetual cycle of use.	Southern Oil, Australia

Safety Kleen technology	Thin film evaporation and hydrogenation	1. Atmospheric dehydration enhances thermal stability, colour, and odour. 2. Distillation under higher vacuum recovers oil base stock. 3. Residues are repurposed as asphalt extenders or fuel. 4. Hydrogen treatment removes impurities, and corrects odour, colour, and corrosion issues.	Variety of used oil products recycling services.	Clean Harbors Inc., United States
Bechtel MP extraction	Solvent extraction process	1. N-methyl-2-pyrrolidone (MP) to remove unwanted components. 2. Solvent extraction tower under specific parameters. 3. Solvent recovery section. 4. Removal of MP.	Enhanced viscosity index, thermal, and oxygen stability, improved colour of the recycled oil, recirculation of the solvent for added sustainability to the process.	Bechtel, United States
STP technology	Vacuum distillation and chemical treatment/ hydrofinishing	1. Preheating utilised on used oil precedes its passage through a drum flash. 2. Removal of residual gas oil is achieved through the stripping process. 3. Heavy impurities are isolated via high vacuum distillation conducted in a thin-film evaporator. 4. Product quality is enhanced through the final fractionation process.	Over 40,000 tons of recycled oil are produced annually.	Afriquia SMDC, Morocco
Lwart technology	Thermal De-Asphalting and solvent extraction	1. Initially, atmospheric dehydration extracts water from the used engine oil. 2. Light hydrocarbons are removed through flash distillation. 3. The thermal de-asphalting process effectively eliminates heavy contaminants. 4. Additional purification and neutralisation of the finished product are achieved through solvent treatment.	The plant handles 140,000 tons of used oil annually, averting the need for burning and reducing reliance on imported base oil.	Lwart Lubrificantes, Brazil

Source: S. Ratiu *et al.* (2022)

Ecological benefits of WEO recycling include minimising the volume of oil reaching the environment, thereby curbing pollution (Madanhire & Mbohwa, 2016). Additionally, it reduces the release of substantial contaminants into the environment, thereby reducing the risk of contamination in water bodies. Eliminating toxic emissions generated from waste oil incineration also mitigates atmospheric pollution (Ogunkunle & Ahmed, 2021). Furthermore, WEO recycling will also reduce the extraction of petroleum products and its resulting pollution. In addition, there are economic advantages, including fostering a regenerative economy and supporting a sustainable future. Less will be spent on disposing of WEO and the establishment of recycling facilities offers employment opportunities for a significant workforce. Ultimately, it enhances the economic value of the system by stimulating the growth of the used engine oil recycling industry.

Future Outlook and Challenges

As the petroleum industry continues to evolve, WEO disposal has become a growing challenge, posing significant threats to social, economic, and environmental sustainability. The impact of heavy metals, heteroatomic compounds, polycyclic aromatic hydrocarbons, and other toxic pollutants on animal and human health, as well as the ambient ecological surroundings, cannot be ignored. Consequently, there is increasing attention on the development of waste recycling methods. Numerous techniques have emerged for resource recovery and safely treating recycled waste engine oil. Globally, common WEO treatment methods include acid/clay treatment, vacuum distillation, solvent extraction, and membrane filtration technology. Although the traditional acid/clay method is effective, it generates acidic sludge, posing as a secondary pollutant. There is limited research on modifying this process to reduce acidic sludge generation (Ruzali *et al.*, 2022).

Additionally, the refining process is expensive, often involving the use of costly nanomaterials and membranes (Widodo *et al.*, 2018). Investigating more economical materials is essential to enhance the cost-effectiveness of the process. Adsorption offers a straightforward, cost-efficient and convenient method for regenerating waste engine oil. Clay is frequently utilised for adsorption purposes in eliminating impurities from used engine oil, owing to its high adsorption capacity and widespread availability. Conducting Polymers (CPs) also exhibit excellent adsorption efficiency and attractive electrical and electrochemical properties. While CPs have been used to remove toxic pollutants and heavy metals from wastewater, there is limited research on their application in treating waste engine oil (Hu *et al.*, 2013). Hence, it is crucial to investigate CPs as promising adsorbents for pretreating waste oil to minimise the formation of acidic sludge.

Recycling WEO is imperative and widely practiced across the globe. However, one of the major challenges is the lack of awareness among some individuals regarding the harmful effects of improperly disposed of WEO. Many people unknowingly discard it before it can be collected for recycling, leading to its contamination of water bodies and the formation of oily acidic sludge, which poses even greater harm to the environment. Addressing this issue requires raising awareness about the detrimental effects of WEO and instilling a sense of responsibility among consumers to properly dispose of it.

In addressing this issue, the primary challenge lies in effectively separating the emulsified oil-water mixture present in oily sludge, particularly for solid-liquid and oil-water separation processes. Therefore, it becomes imperative to integrate principles of environmental conservation, energy efficiency and minimised resource consumption, harnessing the interdisciplinary benefits offered by physics, chemistry, and biology. Different processes for recovery and treatment of crude oil should be optimised or combined based on the type of oily sludge, with continuous efforts in technical optimisation, demulsification, quality enhancement, advancement in economy, efficiency and equipment research, and development. Figure 9 presents the challenges

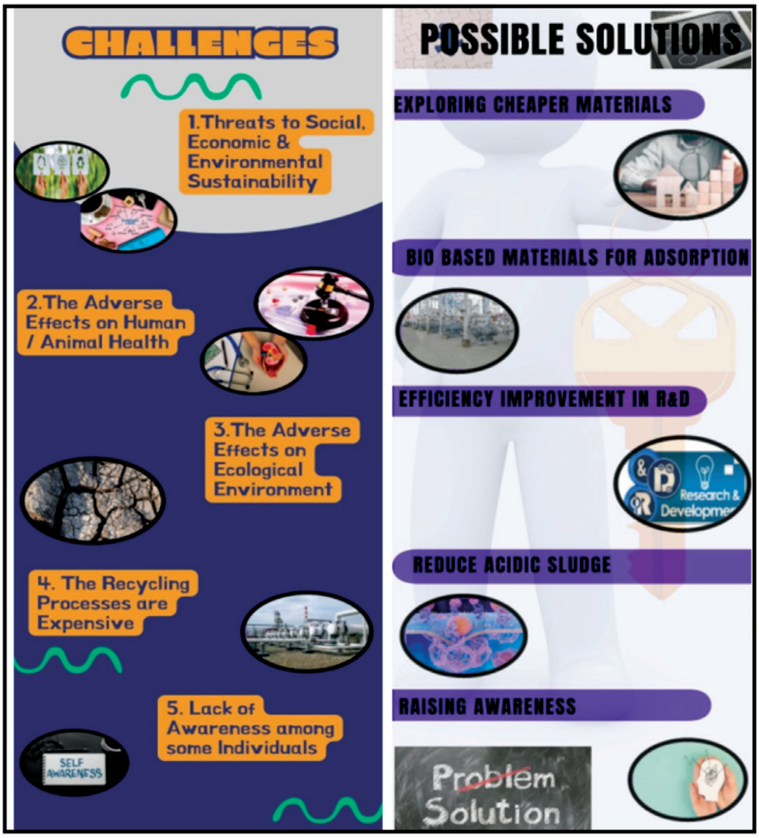

Figure 9: Infographic illustration highlighting challenges and possible solutions in the future of WEO recycling

and potential solutions pertaining to the future of recycling WEO. Overall, WEO recycling offers a sustainable and environmentally friendly alternative to traditional refinery methods, aiding in pollution reduction.

Conclusions

In conclusion, the recycling of WEO is a critical practice in environmental protection, economic sustainability, and public health preservation. This review discussed the environmental impact and importance of recycling, as well as the range of recycling techniques and technologies, emphasising their pivotal role in pollution mitigation, resource conservation and sustainable development. Although traditional methods such as acid/clay treatment, vacuum distillation, and solvent extraction were examined, they encountered challenges such as acidic sludge generation and cost inefficiencies. In contrast, recent advancements like microwave-assisted pyrolysis, membrane filtration, bioremediation, and adsorption techniques offer promising solutions to enhance WEO recycling efficiency.

Additionally, the adoption of circular economy principles and cost reduction strategies in virgin oil production offers significant economic benefits. Despite notable progress, challenges like acidic sludge generation and the quest for cost-effective materials persist, highlighting the need for ongoing research and innovation. This review provides valuable insights into the current state of WEO recycling, emphasising the importance of continued efforts to overcome obstacles and propel further advancements in this crucial field. Overall, engine oil recycling promotes sustainability, conserves resource, and reduces environmental pollution associated with oil consumption, contributing to the longevity of machinery and equipment in automotive and industrial sectors.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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