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Reclamation of Base Oil from Depleted Engine Oil by Solvent Extraction Process: An Insightful Review

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Abstract

Lubricating oils are viscous hydrocarbon liquids obtained from crude oil, are essential for lubricating the moving parts of various machines. Used lubricants are classified as hazardous waste due to their elevated concentrations of environmentally dangerous organic substances, including Polychlorinated Biphenyl (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), and heavy metals. These contaminants, originating from the integrity of lubricating oil, are significantly affected by wear and tear, additive breakdown, thermal cracking, and oxidation during their operational life, necessitating their replacement. Direct disposal of this used oil into the environment causes substantial pollution. Incineration of used oil generates significant ash and carcinogenic byproducts, further contributing to environmental contamination. Recycling lubricants, through the application of physical-chemical processes, enables the recovery of base oil, a valuable reusable raw material in lubricant production. Numerous studies have investigated oil reuse and used oil re-refining. Research consistently validates solvent extraction, frequently enhanced using adsorption, as a more performant and efficacious technique for recycling used lubricating oil. The present review offers a thorough analysis of the solvent extraction procedure for this application.

Keywords: *regeneration used oil, Solvent Extraction for Oil Recycling, Base Oil, Waste Oil Management*

1. Introduction

The most stable, least volatile, and highest-boiling component of crude petroleum is lubricating oil. Consisting primarily of hydrocarbons, its molecules typically contain between 20 and 70 carbon atoms and fall into three main categories: paraffinic, naphthenic, and aromatic. The molecular structure of paraffinic compounds is primarily characterized by straight-chain alkanes, resulting in properties like waxiness, elevated pour point, favorable viscosity, and superior temperature stability. Naphthenic compounds differ structurally, incorporating linear chains with a significant presence of pentamerous rings and a lesser proportion of hexagonal rings. This leads to a low pour point, making them suitable for applications such as refrigeration oils. However, due to their high carcinogenic potential, their use in engine oils is limited. Aromatic molecules consist of linear chains that include hexagonal benzene ring structures. In fact, the distinction between these groupings is sometimes obscured, as numerous lubricating oil molecules are hybrid structures containing varied quantities of these different hydrocarbon kinds [1]. The high boiling point of lubricating oil (exceeding 400°C) distinguishes it from other crude oil fractions [2], with molecular weights ranging from 250 to 1000 [3]. The primary functions of lubricating oil include minimizing friction, inhibiting corrosion, providing a medium for heat transfer, and acting as a suspending agent for contaminants [4, 5]. The chemical makeup of lubricating oils typically comprises 80–90% base stock and 10–20% chemical additions and other compounds [6]. A typical lubricating oil composition is illustrated in Figure 1. Notwithstanding the detrimental impact of spent oil on the environment, it is regarded as a significant energy resource, a subject that has been well investigated. Spent oil can be rerefined into base lubricant oil by eliminating pollutants and can be processed into fuel oil, combusted to generate energy, or utilised as feedstock for the manufacture of different petroleum-derived goods. The recycling of spent lubricating oil is an established process that has undergone continuous enhancement, resulting in the development of several ways, and these include: vacuum distillation, solvent extraction, solvent extraction followed by adsorption, de-slugging, and adsorption process [7]. The use of solvent extraction has been studied as an alternative method that involves the use of reduced energy levels relative to alternative approaches, as indicated by several researchers [8, 9]. Solvent extraction is a refining technique employed for spent lubricating oils, relying on the solvent's capacity to remove basic oil constituents derived from discarded lubricating oil selectively. The solvent will eliminate impurities and additives existing in used oil and will precipitate according to gravitational forces. The solvent can be reconstituted using distillation for reutilization. The extraction of oil is contingent upon the properties of both the solvent and the oil, the temperature of extraction, and the duration of contact between the solvent and the feed [8]. This essay aims to emphasise the significance of solvent extraction as a method for recycling spent synthetic lubricating oils in Iraq. This will help address the sustainable development goals related to good health, a clean environment, and environmental sustainability and preservation.

2. Definition of used oil

The term "used oil" designates petroleum-derived or manufactured lubricant that has served its lubricating function and is no longer capable of performing its original intended purpose. Lubricating oil ages, deteriorates, and loses efficacy owing to contamination with foreign substances, including metal particles, filings, other oils, and additives [2]. Figure 2 illustrates the lubricating oil return cycle.

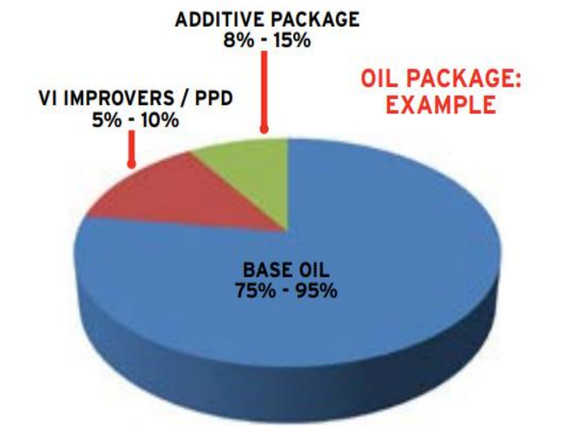

Fig. 1: Typical Lubricating Oil Composition [10].

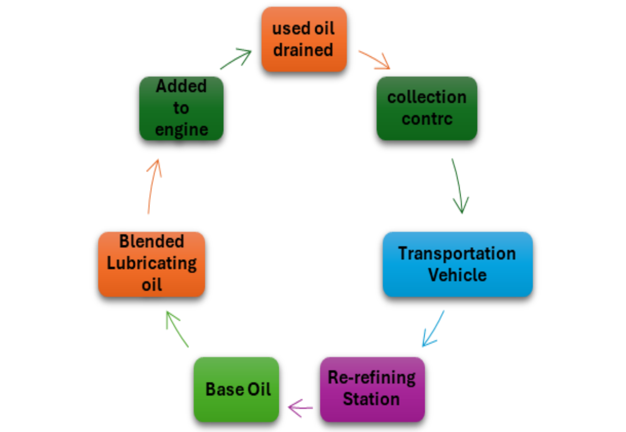

Fig. 2: Recycling process of re-refined lubricating oils [11].

3. Substances Contaminating Used Oil

The accumulation of various contaminants during operation leads to a decline in the effectiveness of automotive lubricating oil. These contaminants can be broadly categorized as follows:

3.1. Extraneous Contaminants

Emanate from the external environment and metal particulates produced within the engine. Environmental pollutants comprise dusts, dirt, and humidity. Air can also be regarded as a pollutant due to its capacity to cause oil foaming. Engine-derived contaminants include:

1. Metallic particulates originating from engine abrasion.
2. Carbonaceous particulates arising from inadequate burning of fuel.
3. Metallic oxides generated as corrosion byproducts of metallic components.
4. Water infiltrated through leaks in the system cooling.
5. Water generated as a byproduct of burning of fuel, along with fuel, fuel additions, or its derivatives, which may infiltrate the engine crankcase [12].

3.2. Products of Oil Deterioration

Oil deterioration leads to the formation of several byproducts, including:

1. **Sludges:** a complex mixture of oil, water, dusts, dirt, and carbonaceous debris. This sludge can either accumulate on engine parts or remain colloidally suspended within the oil.

2. **Lacquer:** The exposure of oil-borne sludge to high operating temperatures leads to the formation of varnish, a rigid or viscous accumulation on engine components.
3. **Oil-Soluble Compounds:** These are the byproducts residuals of oil oxidation dissolved in the oil and can't be eliminated using standard filtration methods. These soluble compounds may subsequently accumulate on motor components. The quantity and allocation of engine deposits fluctuate considerably based on engine operating criteria. At decreased crankcase the temperatures, carbon deposits predominantly arise due to incomplete combustion of gasoline rather than from the lubricating oil. Conversely, at elevated temperatures, the lubricating oil significantly contributes to the creation of increased lacquer and sludge deposits [12,13].

4. Causes of Lubricating Oil Degradation

Any lubricating oil, regardless of whether it is sourced from crude or synthetic origins, that has been tainted by chemical or physical contaminants during its application is classified as wasted lubricating oil, occasionally designated as spent engine oil or waste oil. Rammohan [14] emphasizes that infrequent oil changes permit the accumulation of pollutants such as dirt within the engine, obstructing adequate lubrication of moving components. Aljabiri [15] delineated the principal mechanisms contributing to the depletion of lubricating oil additives, including thermal deterioration, oxidation, neutralization, shearing, hydrolysis, aqueous cleansing, particle purification, filtration, contamination, frictional interaction, surface adsorption, condensation, settling, and evaporation. Three principal variables lead to the breakdown of lubricating oil: severe heat, excessive cold, and prevalent pollutants [14, 2]. Additional contributing factors encompass entrained air, humidity, incompatible gases, process constituents, inside or outside radiation pollution, and unintentional fluid blending. Water, frequently originating from condensation, can lead to engine corrosion, a process that is expedited in elevated temperature oil due to heightened chemical reactivity. The extended presence of water in lubricating oil can result in emulsification, creating a caustic mixture that may evolve into sludge, potentially obstructing oil passageways or filters [15]. The degradation process entails the reaction of hydrocarbons with oxygen during an initial phase, resulting in the formation of extremely reactive peroxide radicals. Hydroperoxides degrade into oxygenated molecules, which then react to generate large-molecule organic acids and polymeric compounds. The subsequent polymerization and polycondensation of certain substances lead to the production of insoluble sludge, which may form as a thin layer, formulating lacquers or varnishes for application on both hot and cold metal substrates [16]. Prolonged exposure to elevated temperatures hastens the deterioration of lubricating oil characteristics, requiring its extraction and substitution [17]. Used lubricating oil comprises many metals, as lead, zinc, barium, arsenic, chromium, and cadmium [18, 19]. The principal constituents of old lubricating oil include deteriorated additive, base oil, metallic particulates, carbon particulates, and oxidation byproducts. A variety of additives are employed to improve lubricant performance; however, these additives diminish in efficacy with time. Furthermore, lubricating fluid collects various metals due to component wear. While in storage, lubricating oil may become polluted with chlorinated solvents, water, uncombusted fuel, carbon, and dust [20]. Moreover, lubricating oil serves as a corrosion-resistant, cooling, and cleansing agent, accumulating numerous contaminants and additional constituents [21]. These impurities immediately disrupt the lubricant's viscosity, thereby diminishing its efficacy and execution. Figures 3 the percentage contribution of used oils.

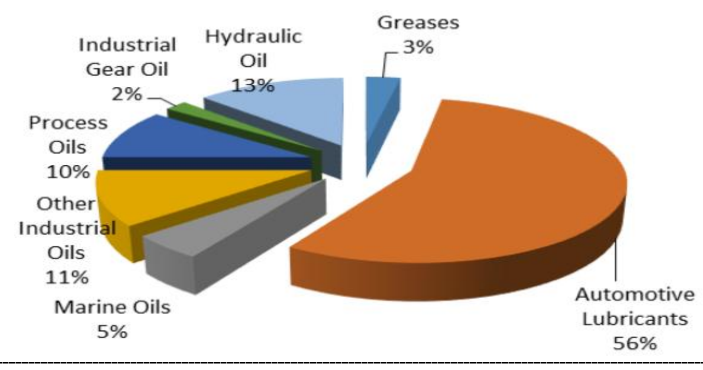

Fig. 3: Percentage contribution of used oils [20].

5. Ecological Consequences of Spent Lubricating Oil

The pollutants in used oil have harmful effects on the environment and public health. Degraded additives, contaminants, and degradation byproducts render waste oil significantly more toxic and detrimental to people's health and the environment than virgin oil bases. These pollutants can elicit a range of harmful health effects in humans and other mammals by inhalation, ingestion, or dermal exposure. These effects include respiratory conditions like lipid pneumonia and lipid granuloma in the pulmonary system. Inappropriate disposal of spent oil, including the discharge into stormwater drainage systems or sewage systems, can adversely influence aquatic ecosystems and marine coastlines. When discarded in soil or landfills, spent oil can infiltrate ground and surface water via multiple land treatment mechanisms. Moreover, improper disposal of used oil endangers flora and fauna, potentially resulting in economic detriment to industries such as recreation and fishing [20]. Nwachukwu et al. assert that one liter of spent lubricating oil can pollute one million liters of water, underscoring the considerable risk of water pollution [23]. The UN claimed in 2016 that about six million deaths each year are linked to air pollution, highlighting the extensive effects of pollutants. Even minimal amounts of oil in wastewater, 50 - 100 ppm, entering sewage treatment facilities can disrupt and compromise treatment operations. Used oil drainage is reported to constitute over 40% of overall oil pollution in American rivers, being the predominant source of this contamination. Emetere [24] indicated that the combustion of used lubricating oil emits aerosols and greenhouse gases into the environment, capable of dispersing at significant velocities (10-12 m/s). Table 1, used by Nwachukwu et al. encapsulates several local applications of used oil along with their direct and indirect detrimental consequences.

Table 1: Assessment of the local environmental impact applications of spent motor oil [23]

Local use of spent oil	Application	Ecological impact
Road construction	On the ground	Contamination of soil
Rust prevention	On a metal device	Contact stains
Emergency lubrication for vintage engines	Automobiles, generators	Air pollution, waste
Timber preservation	Timber; roofing, fencing	Soil contamination
Combined with lubricant for gear oil	Gear box lubricant	Contaminants; Soil degradation
Manufacture of grease	Automobile lubricant	Stain upon touch
Combustion, Boilers, furnaces	Burners, bakery, incinerators	Off-gas, air pollution
For the management of pests, weeds, and dust	Garden, workshops	Soil pollution
Hydraulic oil	Props, Lifts, Jacks	Stain upon touch
Ball joint oil and nuts losing oil	Ball and socket joints, fasteners	Emissions, atmospheric contamination
Block and Balustrade mold lubricant	Block, bricks, balustrade molds	Spills
Medication	Wound and cuts	Spills Supplementary Health Impact
Dust and tick control	Land, floor	Soil contamination, discoloration

6. Spent Lubricating Oil Management

The management of old lubricating Oils encompasses three principal methods: recovery, reprocessing, and regeneration (or re-refining) [25]. Reprocessing focuses on removing impurities from spent lube oils through various physical treatments, including heat treatment, precipitation, filtration, dehydration, and centrifugation [2]. Recovery, a similar process, entails the separation of particles and water from used lubricating oils by physical methods, resulting in a product resembling the original oil but still containing some metallic contamination [2]. Regeneration, also known as re-refining, is a more comprehensive procedure designed to yield base oils with optimal contamination removal, rendering them appropriate for the formulation of new lubricants. The regeneration process generally comprises multiple phases, such as water removal, pollutant dirt separation, treatment with acids, solvent extraction, clay treatment, hydrogenation, or their combinations [26]. The re-refining process is generally implemented through four discrete unit operations: pre-treatment (dehydration and particulate removal), regeneration (removal of oxidation products and other contaminants), fractionation (the separation of light-end hydrocarbons), and finishing. (Odor and colour enhancement of the re-refined base oil) [27]. Table 2 presents commonly employed re-refining methods at the laboratory scale, while Figure 4 provides a schematic summary of the sequential steps involved in these processes.

Table 2: Protocols for the re-refinement of old oils and the employed technology [25]

	Technologies	Country
Pre-Treatment	Filtering, centrifuging, Decantation, and sedimentation Distillation	Egypt [28], South Africa [29]
	Filtration	Egypt [30]
	Sedimentation, magnetization, heating, and agitation	Nigeria [31]
The Regeneration	Acid treatment	Iran [32], Nigeria [33], Colombia [34], Romania [35]
	Caustic treatment	Ghana [36]
	Activated carbon/clay treatment	
	Distillation/clay	South Africa [29]
	Acid clay treatment	
	Irradiation and ultrasonic adsorption	Kazakhstan [37]
	Solvent extraction	Spain [38], UAE [39], Egypt [28], Iraq [40], Nigeria [31], Portugal [41], Egypt [30]
Separation of the Bases	Distillation using vacuum	UAE [39], Iraq [40], Ghana [36], Egypt [30], Ukraine [42]
	Atmospheric and vacuum distillations	Spain [38]
Finishing	Adsorption, neutralization, Sedimentation, and filtration	Nigeria [31], Romania [35]
	Filtration and heating	South Africa [29]
	Filtration	Colombia [34]

Adsorption	UAE [39], Iraq [40], Nigeria [31], Iran [32], Kazakhstan [37], Egypt [30]

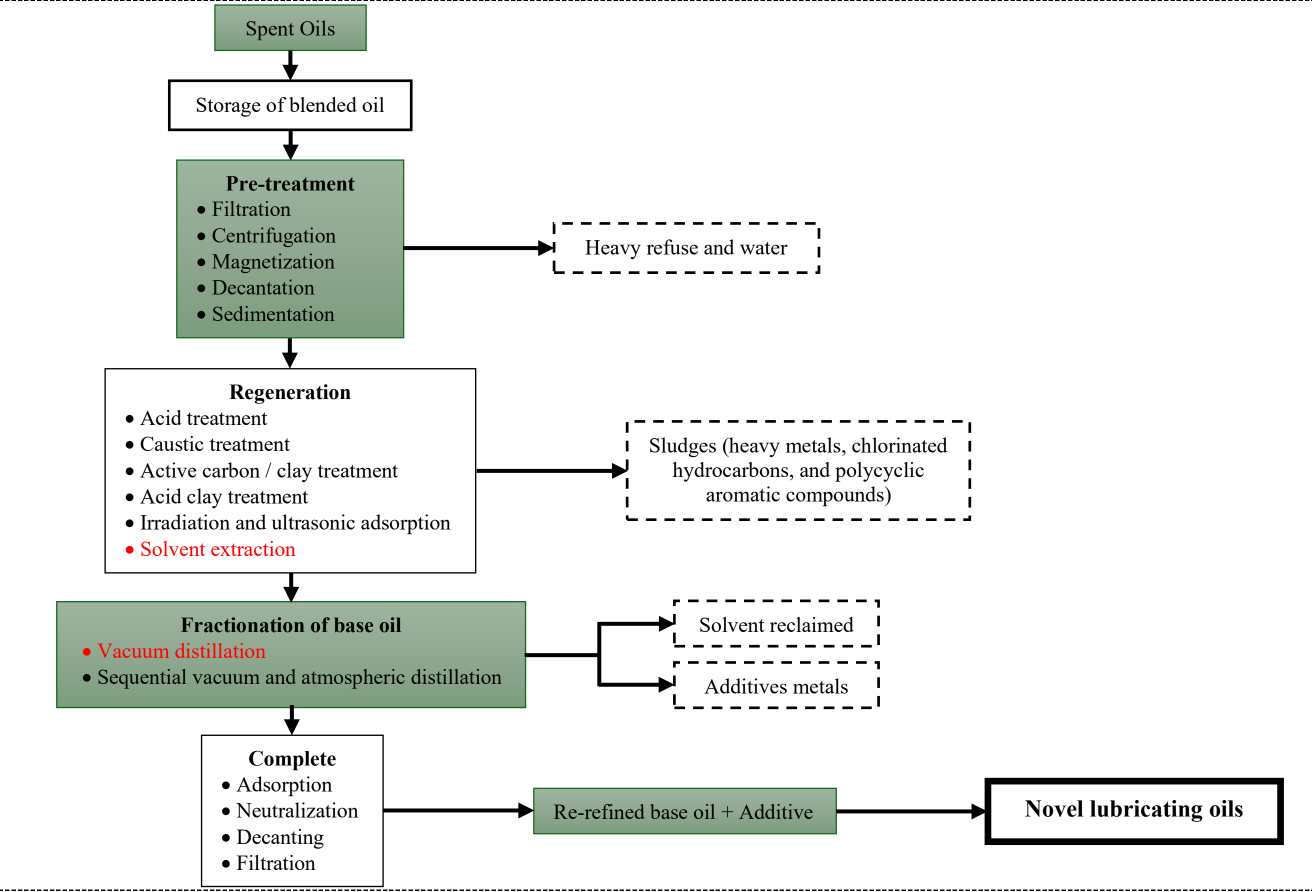

Fig. 4: Basic processes in the re-refinement of used oils [27].

7. Methods for Re-Refining Spent Oils

The primary methods utilized for the re-refinement of spent oils on an industrial basis are (a) the acids/clay method, (b) the active clays method, (c) Thin Film evaporation (TFE) utilizing distillation using vacuum, (d) the solvent extraction method, and (e) the hydrotreatment method [2,43,44]. Figure 5 delineates the procedures for every re-refining technique, together with the associated recoverable yields. Re-refining typically comprises four distinct stages: pre-treatment (extraction of water and solid particulates), renewal (removal of degradation byproducts), separation of base oils (separation of lighter hydrocarbons), and finish (enhancement of the colour and Odor of the processed oil) [27, 28, 45]. Table 3 summarizes the methods of the process with their advantages and disadvantages.

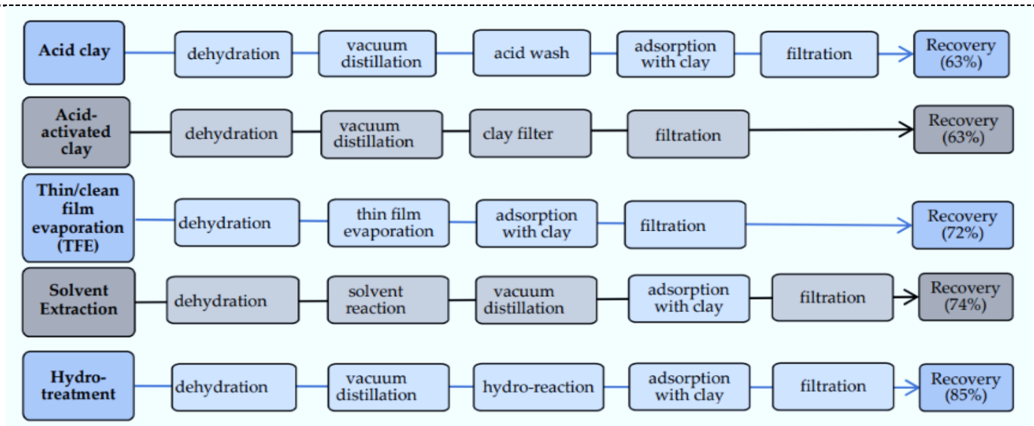

Fig. 5: Overview of the technologies utilized in the industrial re-refinement of old lubricating oil [43, 46].

Table 3: The primary technologies utilized at an industrial level for the re-refinement of old lubricating oils

Method	Process	Advantages	Disadvantages
Acid–clay [23,47]	Dehydration (elimination of contaminants, water, antifreeze, and solvents through initial low-temperature distillation). Vacuum distillation. Sulfuric acid treatment involves the reaction with oxygen, sulphur, and nitrogen to produce sludge. Further purification to exclude paraffinic and naphthenic hydrocarbons. Clay adsorption to mitigate Odor and discoloration	Established technology; minimal production expenses; uncomplicated and direct procedure; does not necessitate highly experienced personnel; appropriate for small-scale enterprises; low capital outlay; lucrative for small facilities; reduced energy usage; generates high-quality base oils	Produces contaminating waste; induces equipment deterioration; diminished production due to oil depletion in mud and clay; fails to adhere to contemporary pollution control standards; banned in numerous nations
Activated clay [23,47]	Dehydration. Vacuum distillation employing a standard vacuum column. Adsorption utilizing activated clay at 120°C for a duration of 2 hours. Filtration	Eliminates the necessity for acid treatment; straightforward procedure; appropriate for small-capacity facilities; yields high-quality base oils	Excessive clay consumption; comparatively poor efficacy; variable quality; environmental issues associated with the disposal of substantial amounts of used clay; dependence on particular clay varieties, which may not be easily accessible
Thin film evaporation (TFE) [28,47]	Dehydration. Thin-film evaporation using vacuum distillation, isolating volatile substances from high-boiling distillates that contain heavy metals. Two finishing alternatives: (a) hydraulic finishing (for the elimination of chlorine, nitrogen, oxygen, and sulphur compounds) or (b) clay adsorption (for the removal of pollutants including heavy metals and breakdown byproducts)	Appropriate for large-capacity facilities; thin-film evaporators function under high vacuum and are ideal for high-value products; reduces contamination; yields superior quality base oils	Requires high operating temperatures and high vacuum; economically viable only for high-capacity plants; high energy consumption
Solvent extraction [47,46,48]	Dehydration. Removal of impurities by mixing with solvents (except sulfuric acid) that precipitate insoluble and suspended materials (e.g., asphalt, metal compounds, and resins), yielding non-hazardous sludge waste. Vacuum distillation employing a standard vacuum column. Clay adsorption for the mitigation of Odor and discoloration. Propane may serve as a solvent	Recyclable solvent; reduces contamination; facilitates functional recovery of base oils; yields high-quality base oils; propane effectively removes additives, metals, and tar; operable at ambient temperature	Economical only for large-scale plants; requires higher operating pressures; necessitates sophisticated operating systems and qualified personnel; potential for solvent losses; risk of fire/explosion with propane; high energy consumption
Hydro-treatment [43,47,46]	Dehydration. Vacuum distillation employing a standard vacuum column. Treatment involving hydrogen and a catalyst to eliminate sulphur, nitrogen, and oxygen. Integrating this with solvent extraction can further improve oil quality. Clay adsorption	Enhances oil colour and aroma; distillation efficiently eliminates sulphur, nitrogen, metals, and unsaturated hydrocarbons	Elevated expenses; safety issues; inappropriate for small-scale operations; significant energy consumption; necessitates high operating temperatures and pressures

The selection of an appropriate re-refining process for spent lubricating oil is contingent upon the consideration of three major criteria: technical viability and reliability, safety and health, environmental (HSE) considerations, implications, and economic viability. Solvent extraction, frequently employed in conjunction with adsorption, has been identified as a particularly efficacious method for spent lubricating oil regeneration [30]. A critical factor in the efficacy of solvent extraction lies in the selection of appropriate solvents. These solvents must demonstrate a high solubility parameter to facilitate efficient base oil reclamation [49,50,51]. While exhibiting limited solvency for additive and carbon-based constituents [49].

8. A COMPREHENSIVE ANALYSIS OF THE SOLVENT EXTRACTION PROCESS

The Solvent extraction involves mixing spent lubricating oil with a solvent capable of selectively extracting the base oil while causing impurities to flocculate. Several recent studies have investigated this technique, often in connection with other methods, to improve the recovery and quality of re-refined base oil. Araromi et al. (2016) [52] employed two individual solvents (ethanol C_2H_6O and 1-butanol $C_4H_{10}O$) and a binary solvent mixture (1-butanol+ethanol mixture) for the refinement of used lubricating motor oil at 35°C, 45°C, and 50°C. The solvent efficacy was examined at solvent-to-oil ratios from 1:1 to 7:1, using percentage oil yield as an efficiency metric. 1-Butanol proved to be the most efficacious single solvent in the extraction method, followed by the 1-butanol-ethanol mixtures. The overall best presentation for both solvents was achieved at a temperature of extraction of 50°C.

Abdulaziz and Mahmood (2016) [53] examined the extraction and distillation method for the regeneration of base oil from used lubricating oil. Multiple solvents, such as 1-butanol $C_4H_{10}O$, 2-propanol C_3H_8O, ethanol C_2H_6O, and binary solvent mixtures (heptane C_7H_{16} + methyl ethyl ketone C_4H_8O) combined with acetone C_3H_6O, were analysed. According to their findings, 1-butanol achieved the highest oil recovery (93.7%) and solvent recovery (96.2%) under optimal conditions of a 4:1 solvent-to-oil ratio and temperature of extraction of 40°C.

Epelle et al. (2017) [54] studied how well three cleaning liquids—phenol C_6H_6O, furfural $C_5H_4O_2$, and N-Methyl Pyrrolidone-NMP C_5H_9NO could remove bad stuff from used oil to improve its viscosity index (VI). At a solvent-to-oil ratio of 4:1 and a heat of 100°C, NMP demonstrated the best performance in terms of VI improvement, achieving the highest value of 105, outperforming both furfural and phenol. However, furfural provided the optimal performance in relation to raffinate yield (90%), surpassing NMP and phenol in this metric.

Osman et al. (2018) [30] conducted experimental work on refining spent oils using novel solvent extraction blends. The execution of three ternary combinations was assessed: (A) {toluene $C_6H_5CH_3$ + butanol C_4H_9OH + methanol CH_3OH }, (B) {toluene $C_6H_5CH_3$+ butanol C_4H_9OH + ethanol C_2H_6O }, and (C) {toluene $C_6H_5CH_3$+ butanol C_4H_9OH + isopropanol C_3H_8O }. Proportions of oil to solvent varying from (1:1 to 1:3). The findings validated that solvent mixture A had the greatest efficacy in sludges elimination. The highest percentage of sludges removal enhanced with rising solvent-to-oil ratios. Combination A eliminated the greatest proportion of sludges (52%), followed by combination B (36.7%), while mixture C removed the least (18.9%). The disparities were ascribed to the solubility of the base oil in the corresponding solvents and their dielectric constants.

Ramadhan and Wiyanti (2018) [55] investigated the remediation of used lubricating oil utilizing butanol C_4H_9OH (solvent), kaolin (adsorbent), and KOH (coagulant). They observed significant reductions in Ca^{2+} (99.98%), Mg^{2+} (97.31%), Pb^{2+} (79.59%), and Cr^{6+} (33.33%), but an increase in Fe^{2+} (112.78%). The ideal circumstances consisted of a 3:1 solvent-to-oil ratio, 1.5 g of kaolin, and 2.0 g of KOH. Higher butanol and KOH concentrations were found to be more effective in reducing metal content.

In their investigation of solvent extraction/adsorption for spent lubricating oil regeneration, Oladimeji et al. (2018) [56] identified optimal process conditions. Employing methyl ethyl ketone C_4H_8O and propan-2-ol C_3H_8O as solvents, they determined that a 4:1 solvent-to-oil ratio with methyl ethyl ketone yielded the most advantageous physical-chemical features in the regenerated base oil. The oil yield increased with higher solvent-to-oil ratios and mixing speeds, reaching an optimal temperature of 50°C, beyond which the quality declined. The solvent-to-oil ratio was identified as the primary factor influencing the quality of the regenerated base oil.

Adewole et al. (2019) [57] evaluated regenerated base oil from composite solvent extraction (hexane C_6H_{14} /butanol C_4H_9OH solvent, KOH flocculant) for reuse potential. The regenerated oil's flash point (222°C) was slightly below SAE 20 (224°C), SAE 30 (226°C), and SAE 40 (268°C) standards, while its 40°C kinematic viscosity (138.92 cSt) exceeded these grades (SAE 20: 37 cSt, SAE 30: 88 cSt, SAE 40: 110 cSt). Further viscosity and flash point improvements were recommended.

Santos et al. (2019) [58] investigated the impact of engine usage on recovered base oil quality. They observed two engines utilizing the identical oil type, one for roughly 5,000 km and the other for 10,000 km. Base oil was extracted from the utilized lubricant utilizing polar organic solvents (1-butanol $C_4H_{10}O$, 2-propanol C_3H_8O, and methyl ethyl ketone C_4H_8O) and subsequently characterized via physical-chemical and thermal analysis (TG/DTG/DTA). Methyl ethyl ketone provided the highest base oil yields (approximately 80%), followed by 1-butanol (just above 70%). 2-Propanol yielded unsatisfactory results.

Nour et al. (2021) [59] compared isopropyl alcohol C_3H_8O (single solvent) with ethanol C_2H_6O /isopropyl alcohol C_3H_8O /toluene $C_6H_5CH_3$ (composite solvent) for used engine oil recycling. Both reduced calcium, alkaline, and zinc contamination from additives. At 40°C, isopropyl alcohol showed better viscosity, VI, and FTIR results than the composite solvent. Zeolite was proposed for heavy metal removal.

Osman et al. (2021) [60] examined the effects of two changed ternary solvent mixtures: A (xylene C_8H_{10}, butanol $\underline{C_4H_9OH}$, methanol CH_3OH) and B (xylene C_8H_{10}, butanol C_4H_9OH, isopropanol C_3H_8O), subsequently subjected to bleaching using activated alumina as an adsorbent. The used oil was first allowed to settle for one hour, subsequently centrifuged at 1500 rpm for 30 minutes, and last filtered. The results showed that all tested ratios (1:1, 1:3, and 1:5) of solvent mixture A performed best, achieving the highest percentage of sludges removal. The sludges removal rate was higher with the methanol-containing mixture (A) compared to the isopropanol-containing mixture (B), attributed to methanol's higher solubility parameter (29 $J/m^3)^{1/2}$. Increasing the solvent-to-oil ratio also increased the sludges removal rate, with an optimum ratio of 3:1 at 70°C. The physicochemical properties of the base oils obtained using solvent mixture A at a 3:1 volume ratio at 70°C, subsequent to treatment with alumina activation, met the specifications of virgin base oil.

Ayeni et al. (2021) [61] regenerated used base oil using methyl ethyl ketone C_4H_8O extraction and unripe plantain peel-derived AC adsorption—a 3:1 solvent-to-oil ratio optimized contaminant removal, viscosity, and TBN, yielding a treated base oil. Extraction at 60°C increased TBN by 32% (6.90 to 10.21 mg KOH/g). Subsequent adsorption (15 wt% AC, 60°C) removed >91% of both calcium and zinc. The optimal conditions (3:1, 60°C) resulted in a regenerated oil with properties (90.23 cSt viscosity, 203 °C flashpoint, 0.909 g/ml density, 0.64 wt% sulphur) similar to fresh Ram SN500.

Dinesh et al. (2021) [62] explored lubricating oil refining using solvent extraction combined with vacuum distillation, employing three different solvents: 1-propanol C_3H_8O, n-butanol $C_4H_{10}O$, and ethanol C_2H_6O. Laboratory experiments were conducted based on a complete global design. The study found that the kinematic and dynamic viscosities of the recovered oil were higher using different separation methods at lower temperatures.

Benjamin et al. (2022) [63] compared the treatment of 3-month-old 5W-30 oil using 70:30 methanol CH_3OH /n-hexane C_6H_{14} (5:1 solvent-to-oil ratio), KOH coagulation (120°C), and activated charcoal adsorption (150°C, 1 hour, 300 rpm centrifugation). Eight physicochemical parameters of fresh used and treated oil were analysed. Treatment significantly improved all parameters (95% confidence), achieving 95.7% recovery. The method was deemed technically feasible, sustainable, and environmentally friendly.

Naife et al. (2022) [64] investigated the impact of various operating parameters on the solvent extraction process using heptane C_7H_{16} and 2-propanol C_3H_8O. The studied parameters included solvent-to-oil ratios (1:2, 1:4, 1:6, and 1:8), mixing time (20, 35, 50, and 65 minutes), temperature (30, 40, 50, and 60 °C), and mixing speed (500 rpm). The results confirmed that 2-propanol exhibited superior performance in sludges removal compared to heptane. Increasing the solvent-to-oil ratio enhanced waste removal, but economic considerations necessitate optimization. The research determined the ideal operating parameters for 2-propanol (35 minutes, 1:6 solvent-to-oil ratio, 40 °C) and heptane (50 minutes, 1:6 solvent-to-oil ratio, 50 °C).

Decote et al. (2023) [65] investigated ultrasound (25 °C, 24 kHz, 20% amplitude) and mechanical stirring (225 rpm, 25 °C), utilizing diverse alcohols (ethanol C_2H_6O, propan-2-ol C_3H_8O, 2-methylpropan-1-ol $C_4H_{10}O$, butan-1-ol $C_4H_{10}O$) for oil extraction (0.5, 1, and 5 minutes). Butan-1-ol yielded the highest recovery after 5 min with both ultrasound (91.4 wt%) and stirring (88.3 wt%). 2-Methylpropan-1-ol also showed good results (79.4 wt% with ultrasound, 59.8 wt% with stirring). Recovered oil viscosity with 2-methylpropan-1-ol and butan-1-ol (126.0 and 132.7 $mm^2\ s^{-1}$) approached fresh locomotive oil (150.6 $mm^2\ s^{-1}$). Ca, Cr, Fe, Mo, and Na concentrations were reduced.

Olaremu (2024) [66] investigated the use of two ternary solvent mixtures: Toluene $C_6H_5CH_3$, 1-butanol $C_4H_{10}O$, and methanol CH_3OH (TBM), and toluene $C_6H_5CH_3$, 1-butanol $C_4H_{10}O$, and ethanol C_2H_6O (TBE). In their experiments, the respective solvent mixture was added to the used engine oil at a 3:1 ratio, followed by one hour of stirring using a magnetic stirrer and a 24-hour settling period. The results indicated that the TBM mixture yielded re-refined oil with properties surpassing those of fresh virgin oil. Conversely, the TBE mixture produced comparatively poorer results.

Mu'azu et al. (2024) [67] explored a hexane C_6H_{14}/ methyl ethyl ketone C_4H_8O extraction followed by activated charcoal adsorption for used oil regeneration. Optimal conditions yielded 77.20% base oil recovery (0.29% ash, 11.25% sludges removal). Adsorption further reduced Zn^{2+} (88.88%) and Fe^{2+} (46.32%), with a slight yield loss (2.77%, 75.06% final yield). The regenerated oil's properties (0.8699 specific gravity, 26.1/7.3 cSt viscosity at 40/100°C, 192°C flash point) approached virgin SN 150 and met ASTM standards, except for slightly elevated TAN (0.96 mg KOH/g) and color. The process shows promise for safe oil reuse.

Table 4: Important studies on solvent extraction methods for used engine oil.

No.	Researcher (s)	Year	Title of the Research	Conclusion	Reference
1	Araromi et al.	2016	Application of Solvent Extraction Process for Revivification of Used Lubricating Engine Oil	1-butanol produced the best performance in Oil ratio of 5:1 at an extraction setting of 50ºC.	[52]
2	Abdulaziz and Mahmood	2016	Recovery of Base Oil from Spent Automobile Oil Using Elementary and Binary Solvent Extraction	1-butanol yielded the highest oil recuperation (93.7%) and solvent recuperation (96.2%) at 40°C with a weight ratio of 4:1.	[53]
3	Epelle et al.	2017	Improving the Viscosity Index of Used Lubricating Oil by Solvent Extraction	N-Methyl Pyrrolidone-NMP best solvent in terms of VI improvement, giving value 105. Furfural gave the best performance of raffinate production of 90% at a solvent-to-oil ratio of 4:1 at 100°C.	[54]
4	Osman et al.	2018	Recycling of used engine oil by different solvent	The solvent mixture (toluene, butanol, and methanol) exhibits optimal effectiveness for sludges removal at a solvent-to-oil ratio of 3:1.	[30]
5	Ramadhan and Wiyanti	2018	Treatment of Waste Lubricating Oil by Chemical and Adsorption Process Using Butanol and Kaolin	The best ratio of butanol to reduce iron, calcium, magnesium, lead, and chromium in used oil is 3:1, and the best ratio is 2 grams for KOH.	[55]
6	Oladimeji et al.	2018	Data on the treatment of used lubricating oil from two different sources using solvent extraction and adsorption	Methyl Ethyl Ketone exhibited superior performance, achieving the maximum sludges clearance; a 4:1 solvent-to-oil ratio produced the most favourable physicochemical characteristics in the regenerate base oil.	[56]
7	Adewole et al.	2019	Characterization and Suitability of Reclaimed Automotive Lubricating Oils Reprocessed by Solvent Extraction Technology	The binary mixture consisting of 70% butanol and 30% n-hexane, combined with 3 g of potassium hydroxide (KOH) at a solvent-to-oil ratio of 5:1 and a temperature of 60°C, resulted in enhanced characteristics of the recovered oil.	[57]
8	Santos et al.	2019	Recycling of lubricating oils used in gasoline/alcohol engines: Thermal characterization	The optimal solvents for base oil extraction are the methyl ethyl ketone, approximately 80%, and 1-butanol, slightly exceeding 70%.	[58]
9	Nour et al.	2021	Dataset on the recycling of used engine oil through solvent extraction	Optimal results were attained using isopropyl alcohol as the sole solvent at the temperature of extraction of 40°C.	[59]
10	Osman et al.	2021	Optimization of acidic activated conditions for natural clay and its application in waste oil bleaching	The spent oil was processed using solvent mixture (xylene, butanol, methanol) at a solvent-to-oil ratio of 3:1, thereafter subjected to bleaching utilising activated alumina and activated clay as adsorbent materials to produce base oil.	[60]
11	Ayeni et al.	2021	A two-stage coupling process for the recovery of base oils from used lubricating oils	Methyl ethyl ketone served as the extraction solvent, while activated carbon derived from unripe banana peels functioned as the adsorbent. The findings validated that a solvent-to-oil ratio of 3:1 at 60°C produced exceptional efficiency.	[61]

12	Dinesh et al.	2021	Recycling of Used Lubricating Engine Oil by A Solvent Extraction Process	The utilisation of ethanol as a solvent for oil treatment yielded extracts that facilitated simpler distillation in comparison to n-butanol and 1-propanol solvents.	[62]
13	Benjamin et al.	2022	Binary Solvent Pretreatment, Adsorption and Definite Characterization of the Used Engine Lubricants.	A binary solvent mixture (methanol/n-hexane) combined with activated charcoal shown efficacy as a hybrid formulation, restoring 95.7% of the quality parameters of degraded engine oil after three months of application.	[63]
14	Naife et al.	2022	Treatment of Used lubricant Oil by Solvent Extraction	The results indicate that the solvent 2-Propanol had superior efficacy in sludges removal compared to heptane.	[64]
15	Decote et al.	2023	Quality analysis of oil recovered from used locomotive engine oil using ultrasound assisted solvent extraction	The optimal outcomes for recovered oil were achieved using ultrasound (5 min); the yield of butan-1-ol was the highest (91.4 wt%), succeeded by 2-methylpropan-1-ol (79.4 wt%), propan-2-ol (12.1 wt%), and ethanol (3.6 wt%).	[65]
16	Olaremu	2024	Treatment and Recycling of Used Lubricating Oil in Nigeria: Solvent Extraction Approach	The results indicate that the mixture containing Toluene, 1-butanol, and Methanol (TBM) outperformed the properties of the fresh virgin oil.	[66]
17	Mu'azu et al.	2024	Optimization of Base Oil Regeneration Using Response Surface Methodology from Spent Lubricating Oil Through Binary Solvent Extraction Process	This paper examined the efficacy of Hexane and Methyl Ethyl Ketone as solvents, followed by adsorption utilising activated charcoal.	[67]

9. Conclusion

Energy and environmental concerns are paramount topics of discussion among environmental activists and organizations. Random disposal of used lubricating oil not only harms the environment but also represents a missed opportunity to utilize a valuable resource and forfeits potential economic benefits. Therefore, promoting sustainable used oil management should be prioritized and supported by environmental ministries through grants and incentives, recognizing it as an eco-friendly technology. Due to the significant health, economic, and ecological implications associated with spent lubricating oil, research efforts have focused on identifying technologies that maximize environmental protection and socioeconomic gains at minimal cost. Recycling of used lubricating oils is gaining increasing importance in the context of ecological conservation. Regeneration, or re-treatment processes, aim to produce base oils suitable for reuse. Solvent extraction has emerged as a viable alternative to conventional acid-clay and hydrotreatment methods within the research community. The appeal arises from several significant advantages, such as the generation of superior base oil, diminished pollution levels, solvent recyclability, and compliance with environmental regulations. Process parameters, including temperature, solvent-to-oil ratio, mixing speed, mixing duration, and solvent type, have been demonstrated to affect the efficacy of solvent extraction. Despite its demonstrated success, the economic viability of spent lubricating oil regeneration remains a key challenge. Therefore, to optimize the regeneration process from both financial and environmental perspectives, further research is needed to establish a systematic approach for solvent screening.

References

[1] Hsu, Y. L., & Liu, C. C. (2011). *Evaluation and selection of regeneration of waste lubricating oil technology*. Environmental monitoring and assessment, *vol.* 176, 197-212.

[2] Speight, J. G., & Exall, D. I. (2014). *Refining used lubricating oils.* CRC Press, Taylor & Francis Group, NW.

[3] Bhushan, Z. K., Anil, S. M., Sainand, K., & Shivkumar, H. (2016). *Comparison between different methods of waste oil recovery*. International Journal of Innovative Research in Science, Engineering and Technology, *vol.* 5(11), 2001-2009.

[4] Kannan, S. C., Kumar, M. K., Hussain, S. M., and Priya, D. N. (2014). *Studies on Reuse of Re-Refined Used Automotive Lubricating Oil*. Research Journal of Engineering Sciences, *vol.* 3(6), 8 - 14.

[5] Mynin, V. N., Smirnova, E. B., Katsereva, O. V., Komyagin, E. A., Terpugov, G. V., & Smirnov, V. N. (2004). *Treatment and regeneration of used lube oils with inorganic membranes*. Chemistry and technology of fuels and oils, *vol.* 40, 345-350.

[6] Rincon, J., Canizares, P., & Garcia, M. T. (2005). *Regeneration of used lubricant oil by polar solvent extraction*. Industrial & Engineering Chemistry Research, *vol.* 44(12), 4373-4379.

[7] Abu-Elella, R., Ossman, M. E., Farouq, R., & Abd-Elfatah, M. J. I. J. C. B. S. (2015). Used motor oil treatment: turning waste oil into valuable products. *International journal of chemical and biochemical sciences*, *vol.* 7, 57-67.

[8] Diphare, M., & Muzenda, E. (2013). Influence of solvents on the extraction of oil from waste lubricating grease: A comparative Study. *2nd International conference on agriculture, environment and biological sciences, Dec. 17 -18, Pattaya, Thailand*.

[9] Ayeni, A. O., Oyekunle, D. T., Adegbite, O., Alagbe, E., & Ejekwu, O. (2019). Physico-chemical remediation of polycyclic aromatic hydrocarbons contaminated soil. *Journal of Physics: Conference Series,* IOP Publishing. *vol.* 1299(1), p. 12121.

[10] Mustapha T., Surajudeen A., & Usman A. (2021). *Base Oil Regeneration from Spent Lubricating Oil Using Solvent Extraction Process: A Review*. IOSR Journal of Engineering (IOSRJEN), 11(11). 26-35.
[11] Parekh, K., Gaur, R., & Shahabuddin, S. (2022). Recent advances in reclamation of used lubricant oil. *Tailored Functional Materials: Select Proceedings of MMETFP 2021*, 273-282.
[12] Awaja, F., & Pavel, D. (2006). *Design aspects of used lubricating oil re refining*. 1st edition, Elsevier, Oxford, UK.
[13] Armioni, D. M., Raţiu, S. A., Benea, M. L., & Puţan, V. (2024, December). Overview on the environmental impact of used engine oil. In *Journal of Physics: Conference Series,* IOP Publishing. *vol.* 2927(1), p. 12007.
[14] Rammohan, A. (2016). *Engine's lubrication oil degradation reasons and detection methods: A review*. Journal of chemical and Pharmaceutical Sciences, *vol.* 9(4), 3363-3366.
[15] Aljabiri, N. A. (2018). *A comparative study of recycling used lubricating oils using various methods*. Journal of Scientific and Engineering Research, *vol.*5 (9), 168-177.
[16] Khuong, L. S., Zulkifli, N. W. M., Masjuki, H. H., Mohamad, E. N., Arslan, A., Mosarof, M. H., & Azham, A. (2016). *A review on the effect of bioethanol dilution on the properties and performance of automotive lubricants in gasoline engines*. RSC advances, *vol.* 6(71), 66847-66869.
[17] Cerón, A. A., Boas, R. N. V., Biaggio, F. C., & de Castro, H. F. (2018). *Synthesis of biolubricant by transesterification of palm kernel oil with simulated fusel oil: Batch and continuous processes*. Biomass and Bioenergy, *vol.* 119, 166-172.
[18] Udonne, J. D., & Bakare, O. A. (2013). *Recycling of used lubricating oil using three samples of acids and clay as a method of treatment*. International Archive of Applied Sciences and Technology, *vol.* 4(2), 8-14.
[19] Mekonnen, H. A., & Ababa, A. (2014). *Recycling of used lubricating oil using acid-clay treatment process*. PhD. Thesis submitted to Addis Ababa University - Ethiopia.
[20] Diphare, M. J., Muzenda, E., Pilusa, T. J., & Mollagee, M. (2013). *A comparison of waste lubricating oil treatment techniques*. In 2nd International Conference on Environment, Agriculture and Food Sciences (pp. 106-109).
[21] Abro, R., Chen, X., Harijan, K., Dhakan, Z. A., & Ammar, M. (2013). *A comparative study of recycling of used engine oil using extraction by composite solvent, single solvent and acid treatment methods*. International Scholarly Research Notices, 2013(1), 952589.
[22] Rodriguez-Hernandez, J., Andrés-Valeri, V. C., Calzada-Pérez, M. A., Vega-Zamanillo, Á., & Castro-Fresno, D. (2015). *Study of the raveling resistance of porous asphalt pavements used in sustainable drainage systems affected by hydrocarbon spills*. Sustainability, *vol.* 7(12), 16226-16236.
[23] Nwachukwu, M. A., Alinnor, J., & Feng, H. (2012). *Review and assessment of mechanic village potentials for small scale used engine oil recycling business*. African Journal of Environmental Science and Technology, *vol.* 6(12), 464-475.
[24] Emetere, M. E. (2017). *Investigations on aerosols transport over micro and macro-scale settings of West Africa*. Environmental Engineering Research, *vol.* 22(1), 75-86.
[25] Sánchez-Alvarracín, C., Criollo-Bravo, J., Albuja-Arias, D., García-Ávila, F., & Pelaez-Samaniego, M. R. (2021). *Characterization of used lubricant oil in a Latin-American medium-size city and analysis of options for its regeneration*. Recycling, *vol.* 6(1), 10.
[26] Diphare, J. M., Pilusa, J., & Muzenda, E. (2013). *The effect of degrading agents and diluents on oil recovery from Lithium based waste lubricating grease*. In 2nd International Conference on Environment, Agriculture and Food Science, Kuala Lumpur, Malaysia.
[27] Widodo, S., Ariono, D., Khoiruddin, K., Hakim, A. N., & Wenten, I. G. (2018). *Recent advances in waste lube oils processing technologies*. Environmental Progress & Sustainable Energy, *vol.* 37(6), 1867-1881.
[28] Emam, E., & Shoaib, A. (2012). *Re-refining of used lube oil. II-by solvent/clay and Acid/Clay-Percolation Processes*. ARPN J. Sci. Technol. vol. 2. 1034-1041.
[29] Abdulkareem, A. S., Afolabi, A. S., Ahanonu, S. O., & Mokrani, T. J. E. S. (2014). *Effect of treatment methods on used lubricating oil for recycling purposes. Energy Sources*, Part A: Recovery, Utilization, and Environmental Effects, *vol.* 36(9), 966-973.
[30] Osman, D. I., Attia, S. K., & Taman, A. R. (2018). *Recycling of used engine oil by different solvent*. Egyptian Journal of Petroleum, 27(2), 221-225.
[31] Isah, A., Abdulkadir, M., Onifade, K., Musa, U., Umar, G., Bawa, A., & Sani, Y. (2013). *Regeneration of used engine oil*. Lecture Notes in Engineering and Computer Science, World Congress on Engineering, WCE 2013, London, 3 July 2013-5 July 2013.
[32] Salem, S., Salem, A., & Babaei, A. A. (2015). *Preparation and characterization of nano porous bentonite for regeneration of semi-treated waste engine oil: Applied aspects for enhanced recovery*. Chemical engineering journal, 260, 368-376.
[33] Owolabi, R. U., Akinola, A. A., Oyelana, O. A., & Amosa, M. K. (2017). *Some Physico-Chemical and Adsorptive Reclamation Strategies of Spent Automobile Engine Lubricating Oil*. Journal of Engineering Research, 22(1), 98-106.
[34] Fong Silva, W., Quiñonez Bolaños, E., & Tejada Tovar, C. (2017). *Caracterización físico-química de aceites usados de motores para su reciclaje. Prospectiva*, 15(2), 135-144.
[35] Stan, C., Andreescu, C., & Toma, M. (2018). *Some aspects of the regeneration of used motor oil*. Procedia Manufacturing, 22, 709-713.
[36] Mensah-Brown, H. (2015). *Re-Refining And Recycling Of Used Lubricating Oil*.

[37] Syrmanova, K. K., Kovaleva, A. Y., Kaldybekova, Z. B., Botabayev, N. Y., Botashev, Y. T., & Beloborodov, B. Y. (2017). *Chemistry and recycling technology of used motor oil*. Oriental Journal of Chemistry, 33(6), 3195-9.

[38] Moya, L., & Botamino, I. (2010). *Desde el aceite lubricante usado hasta su puesta en el mercado tras su regeneración*. Madrid, España.

[39] Abdel-Jabbar, N. M., Al Zubaidy, E. A., & Mehrvar, M. (2010). *Waste lubricating oil treatment by adsorption process using different adsorbents*. International Journal of Chemical and Molecular Engineering, 4(2), 141-144.

[40] Mohammed, R. R., Ibrahim, I. A., Taha, A. H., & McKay, G. (2013). *Waste lubricating oil treatment by extraction and adsorption*. Chemical Engineering Journal, 220, 343-351.

[41] Pinheiro, C. T., Ascensão, V. R., Cardoso, C. M., Quina, M. J., & Gando-Ferreira, L. M. (2017). *An overview of waste lubricant oil management system: Physicochemical characterization contribution for its improvement*. Journal of Cleaner Production, 150, 301-308.

[42] Korchak, B., Hrynyshyn, O., Chervinskyy, T., & Polyuzhin, I. (2018). *Application of vacuum distillation for the used mineral oils recycling*. Chemistry & Chemical Technology, 12(3), 365-371.

[43] Kupareva, A., Mäki-Arvela, P., & Murzin, D. Y. (2013). *Technology for rerefining used lube oils applied in Europe: a review*. Journal of Chemical Technology & Biotechnology, 88(10), 1780-1793.

[44] Haro, C., De la Torre, E., Aragón, C., & Guevara, A. (2014). *Regeneración de arcillas de blanqueo empleadas en la decoloración de aceites vegetales comestibles*. Revista Politécnica, 34(1).

[45] García González, M.T.(2019). *Regeneración de Aceites Lubricantes Usados Mediante Extracción*.

[46] Ijadi Maghsoodi, A., Hafezalkotob, A., Azizi Ari, I., Ijadi Maghsoodi, S., & Hafezalkotob, A. (2018). *Selection of waste lubricant oil regenerative technology using entropy-weighted risk-based fuzzy axiomatic design approach*. Informatica, 29(1), 41-74.

[47] Jafari, A. J., & Hassanpour, M. (2015). *Analysis and comparison of used lubricants, regenerative technologies in the world*. Resources, Conservation and Recycling, 103, 179-191.

[48] Oladimeji, T. E., Sonibare, J. A., Omoleye, J. A., Emetere, M. E., & Elehinafe, F. B. (2018). *A review on treatment methods of used lubricating oil*. Int. J. Civ. Eng. Technol, 9(12), 506-514.

[49] Durrani, H. A., Panhwar, M. I., & Kazi, R. A. (2012). *Determining an efficient solvent extraction parameters for re-refining of waste lubricating oils*. Mehran University Research Journal of Eng. & Tech, 31(2), 265-270.

[50] Emam, E. A., & Shoaib, A. M. (2013). *Re-refining of used lube oil, I-by solvent extraction and vacuum distillation followed by hydrotreating*. Petroleum & Coal, 55(3).

[51] Kamal, A., & Khan, F. (2009). *Effect of extraction and adsorption on re refining of used lubricating oil*. Oil & Gas Science and Technology Revue de l'IFP, 64(2), 191-197.

[52] Araromi, D., Aremu, M., & Gbolahan, O. (2016). *Application of solvent extraction process for revivification of used lubricating engine oil*. American Chemical Science Journal, 10(4), 1-7.

[53] Abdulaziz, Y. I., & Mahmood, S. M. (2016). *Recovery of base oil from spent automobile oil using elementary and binary solvent extraction*. Nahrain University College of Engineering Journal, 19(2), 370-384.

[54] Epelle, E. I., Otaru, A. J., Zubair, Y. O., & Okolie, J. (2017). *Improving the viscosity index of used lubricating oil by solvent extraction*. Int. Res. J. Eng. Technol, 4, 1581-1585.

[55] Ramadhan, B., & Wiyanti, D. (2018). *Treatment of waste lubricating oil by chemical and adsorption process using butanol and kaolin*. In IOP Conference Series: Materials Science and Engineering (Vol. 349, No. 1, p. 012054). IOP Publishing.

[56] Oladimeji, T. E., Sonibare, J. A., Omoleye, J. A., Adegbola, A. A., & Okagbue, H. I. (2018). *Data on the treatment of used lubricating oil from two different sources using solvent extraction and adsorption*. Data in Brief, 19, 2240-2252.

[57] Adewole, B. Z., Olojede, J. O., Owolabi, H. A., & Obisesan, O. R. (2019). *Characterization and suitability of reclaimed automotive lubricating oils reprocessed by solvent extraction technology*. Recycling, 4(3), 31.

[58] Santos, J. C. O., Almeida, R. A., Carvalho, M. W. N. C., Lima, A. E. A., & Souza, A. G. (2019). *Recycling of lubricating oils used in gasoline/alcohol engines: Thermal characterization*. Journal of Thermal Analysis and Calorimetry, 137, 1463-1470.

[59] Nour, A. H., Elamin, E. O., Nour, A. H., & Alara, O. R. (2021). *Dataset on the recycling of used engine oil through solvent extraction*. Chemical Data Collections, 31, 100598.

[60] Osman, D. I., Elsayed, A., Attia, S., & Taman, A. R. (2021). *Optimization of acidic activated conditions for natural clay and its application in waste oil bleaching*. Egyptian Journal of Chemistry, 64(11), 6787-6798.

[61] Ayeni, A. O., Tagwai, S., Dick, D. T., Agboola, O., Ayoola, A. A., Babatunde, D. E., & Oni, B. A. (2021). *A two-stage coupling process for the recovery of base oils from used lubricating oils*. In IOP Conference Series: Earth and Environmental Science (Vol. 655, No. 1, p. 012029). IOP Publishing.

[62] Dinesh, K., Kaithari, K.D., Krishnan, K.P and Al-Rivami, A. (2021). *Recycling of Used Lubricating Engine Oil by A Solvent Extraction Process*. International Journal of mechanical and production engineering research, 11(1): 151-158.

[63] Benjamin, W., Mohammed, R., & Gero, M. (2022). *Binary Solvent Pretreatment, Adsorption and Definite Characterization of the Used Engine Lubricants*. Science Open Preprints.

[64] Naife, T. M., Rashid, S. A., & Jabbar, M. F. A. (2022). *Treatment of Used lubricant Oil by Solvent Extraction*. Iraqi Journal of Chemical & Petroleum Engineering, 23(1).

[65] Decote, P. A., Negris, L., Simonassi, P., Druzian, G. T., Flores, E. M., Vicente, M. A., & Santos, M. F. (2023). *Quality analysis of oil recovered from used locomotive engine oil using ultrasound-assisted solvent extraction*. Chemical Engineering Research and Design, 197, 603-616.

[66] Olaremu, A. (2024). *Treatment and Recycling of Used Lubricating Oil in Nigeria: Solvent Extraction Approach*. SRA-Archives, 15(1), 9-17.
[67] Mu'azu, M., Abdulsalam, S., & El-Nafaty, U. A. (2024). *Optimisation of Base Oil Regeneration Using Response Surface Methodology from Spent Lubricating Oil through Binary Solvent Extraction Process*. Path of Science, 10(10), 2048-2057.