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A Comprehensive Review on Chemical Treatment Methods for Used Lubricant Oils

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Abstract: This research explores the chemical processing of used lubricant oil (ULO) with the aim of improving its recyclability and mitigating its environmental footprint by utilizing an optimized solvent extraction technique. ULO, extensively used in automotive and industrial sectors, deteriorates over time due to oxidation, contamination, and the buildup of harmful elements such as heavy metals (including lead, zinc, copper), sulfur compounds, and various additives. These impurities compromise the oil's functionality, rendering it unsuitable for reuse unless properly treated. Hence, efficient chemical treatment is crucial to restore its lubricating qualities and enable environmentally responsible recycling.

The study assesses multiple chemical treatment methods, such as solvent extraction, acid-base treatments, adsorption, and hydrocracking. The primary focus is on solvent extraction employing a ternary solvent mixture made up of 1-butanol, isopropyl alcohol (IPA), and either methyl ethyl ketone (MEK) or methyl isobutyl ketone (MIBK). Two solvent formulations were tested: (i) MEK-based (comprising 25% MEK, 25% IPA, and 50% 1-butanol) and (ii) MIBK-based (consisting of 25% MIBK, 25% IPA, and 50% 1-butanol), with solvent-to-ULO ratios of 1:1.5 and 1:2.5. Experiments conducted at laboratory scale investigated how solvent composition, solvent-to-oil ratio, and temperature affected oil recovery efficiency and contaminant removal. Findings indicated that the MEK-based solvent system (50% 1-butanol, 25% IPA, 25% MEK) achieved superior sludge separation and contaminant elimination, with optimal performance at a solvent-to-oil ratio of 3:1 and an extraction temperature of 25°C. Post- extraction, the ULO underwent further refinement via vacuum distillation. The entire re-refining process was simulated for a capacity of 2200 kg/h using Aspen Plus™, modeling four pseudo-components (saturates, monoaromatics, diaromatics, and polyaromatics) and applying the non-random two-liquid (NRTL) and universal quasi- chemical activity coefficient (UNIQUAC) models for liquid–liquid equilibrium (LLE). The simulation outcomes closely matched experimental data, validating the solvent mixture's efficacy. Additional analysis of the sludge composition revealed that oil recovery and contaminant removal rates were strongly dependent on the proportion of 1-butanol in the solvent blend. The study concluded that the concentrations of MEK and IPA should each remain below 25%, while maintaining 1-butanol at 50% as the most effective solvent base.

This investigation presents an optimized chemical treatment process that enhances the recyclability of ULO, reduces its environmental impact, and supports sustainable waste management. The results provide a promising approach to advancing the re-refining industry by minimizing waste and maximizing oil recovery through solvent extraction combined with vacuum distillation.

Keywords: Lubricant Oil, Purification, Chemical treatment

1. Introduction

Lubricating oil consists of a complex blend of thick, viscous hydrocarbon compounds. One of its defining characteristics is its high boiling point, typically exceeding 400°C, which sets it apart from other crude oil fractions [01], with molecular weight ranging from 250-100 [02]. The primary functions of lubricating oil include reducing friction, preventing corrosion, facilitating heat transfer, and acting as a medium to suspend contaminants [03].

Used lubricant oil (ULO) is generated by machines, vehicles, and industrial equipment as part of regular operation. It contains a variety of contaminants such as metals (e.g., zinc, copper), carbon particles, sulfur compounds, and additives that degrade its quality. Without proper treatment, ULO poses a significant environmental threat, contributing to soil and water pollution when improperly disposed of. However, with effective chemical treatment, these oils can be rejuvenated for reuse, reducing reliance on virgin oils and minimizing environmental impacts.

ULO is one of the most significant waste streams in the automotive and industrial sectors. The management of ULO is critical because improper disposal leads to soil contamination, water pollution, and air pollution. As ULO contains valuable base oils, its recycling has become an essential practice in many industries to conserve resources and reduce environmental harm. Used motor oil is classified as a hazardous substance due to its harmful effects on both the environment and human health, primarily because it contains various contaminants such as heavy metals, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) [04]. Without proper disposal or treatment methods, waste motor oil is often irresponsibly released into the soil or water bodies, including drainage systems, posing serious environmental risks [05]. However, used lubricating oils (ULOs) also represent a valuable resource, as their recycling can reduce the reliance on imported petroleum products and contribute positively to environmental protection [06].

With growing environmental regulations and economic concerns, there is an increasing emphasis on regenerating and reusing used lubricating oil. The regeneration of base oil from spent lubricants involves applying physical and chemical techniques to recover oil suitable for reuse in producing new lubricants. Conventional regeneration methods include solvent extraction, hydro-treatment, and acid-clay treatment [7]. Chemical processing methods play a crucial role in purifying and restoring the quality of these used oils. Numerous studies have indicated that combining solvent extraction with adsorption offers a more effective and efficient approach for recycling used lubricating oils. This review highlights the solvent extraction technique and explores how various process parameters influence its overall effectiveness [8]. This study utilizes three different composite solvent mixtures comprising 2-propanol, 1-butanol, and MEK. These mixtures were initially examined on a laboratory scale for their effectiveness in treating used oil. The selection of solvents and their ternary ratios was guided by findings from previous literature [09]; [10]; [11]. The primary aim of this study is to identify the most effective combination of solvents and determine the optimal operating parameters for the extraction unit. Choosing the right solvent is crucial for designing a cost-efficient extraction process. This selection typically relies on laboratory testing prior to initiating the design or selection of the extraction equipment. Accordingly, this investigation will examine how various factors—including solvent type and composition, the ratio of solvent to oil, and operating temperature—affect both the efficiency of oil recovery and the physicochemical characteristics of the extracted oil.

Subsequently, the entire re-refining process will be modeled using Aspen Plus™ software. Simulation results for the extraction unit, based on variations in solvent properties and process conditions, will be evaluated against experimental data. Additionally, the simulated composition of the oil residue (sludge) will be analyzed to understand how different solvents and their concentrations influence contaminant removal and oil retention. In the final phase, a financial analysis assessing profit and loss will be conducted to determine the feasibility and economic viability of implementing the process on an industrial scale.

2. Literature Survey

Used lubricating oil—also known as waste oil or used engine oil—is any type of lubricant originally refined from crude oil or synthetic materials that has become contaminated through use [12]. As it is utilized, the oil accumulates various physical and chemical impurities, which diminish its effectiveness. Over time, exposure to demanding operational conditions leads to the deterioration of both the base oil and the additive components. Key contributors to this degradation include oxidation, thermal stress, incompatible gases, entrapped air, moisture, and accidental mixing with other fluids [13]. Additionally, the depletion of additives accelerates the decline in oil quality. As a result, the degraded oil becomes unsuitable for reuse, containing substances such as metal particles, ash, varnish, sludge, soot, gel-like structures, carbon deposits, water, and potentially harmful polycyclic aromatic hydrocarbons [14].

Used lubricating oils (ULOs) is to be considered hazardous waste which pose a significant threat to both the environmental and human health, as they contain toxic substances like heavy metals, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) [15]. If there is an improper management and haphazard disposal of used lube oils are done it will lead us to have an adverse effect on the environment [16]. Among the various factors influencing the environmental quality, the release of various heavy metals has impacted millions of individuals due to their toxic effects, making it one of the most significant environmental issues globally [17]. Heavy metals are known for their persistence in the environment, their ability to bioaccumulate, and their potential to interfere with metabolic activities and essential organs in both humans and animals [18]. Although trace amounts of these metals are vital for the normal biological processes in plants and animals, their toxicity and environmental impact largely depend on the chemical or physical changes they undergo [19].

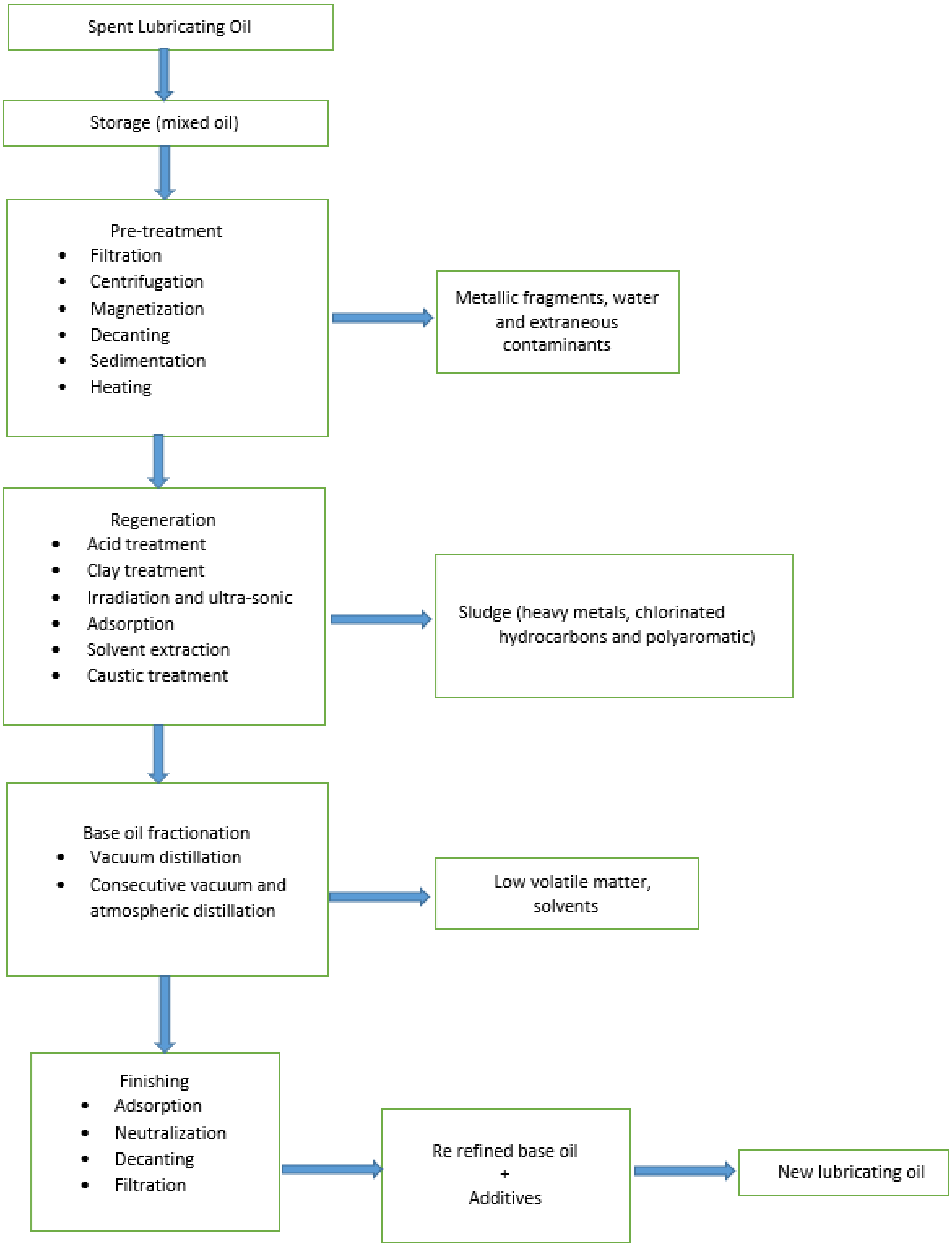
Figure 2.1 Typical Recycling Process Cycle

Used Lubricating Oil (ULO) can be recycled and repurposed as an alternative fuel for various engine types and furnaces, or utilized as a key ingredient in road paving asphalt, as illustrated in Figure 2.1. Among the options available, the re-refining process is considered the most favorable in terms of energy efficiency, cost-effectiveness, and environmental impact [20]. Re-refining involves eliminating all impurities to reclaim the base oil for reuse as lubricating oil. Traditional contaminant removal methods applied on an industrial scale often involve hazardous substances like sulfuric acid or require expensive techniques such as vacuum distillation. Chemical treatment methods are among the most effective ways to purify ULO and restore it to a usable form. These treatments include solvent extraction, acid-base neutralization, adsorption, and advanced techniques like vacuum distillation and hydrocracking. Each method varies in efficiency, cost, and environmental impact, requiring a thorough evaluation to identify the best approach for industrial-scale application [21]. The oldest method for treating used motor oils involves an acid process followed by clay treatment. This approach can yield high-quality base oil at a relatively low cost, but it carries significant environmental hazards. Another technique for recycling used motor oils is membrane technology, which utilizes hollow fiber membranes made from materials such as polyethersulfone, polyvinylidene fluoride, and polyacrylonitrile [22].

Solvent extraction is also used as an alternative treatment method for used oil. The ideal solvent should exhibit high solubility for the base oil while showing minimal affinity for additive and contaminants [23]. Vacuum distillation are applied to separate asphaltic substances, additives, and degradation products through the base oil. However, this process operates at elevated temperatures exceeding 300 Celsius and has been found impractical due to issues like coking and fouling of the processing equipment. An alternative to vacuum distillation is the use of liquid–liquid solvent extraction prior to distillation, which effectively separates asphalt and additives from the used lubricating oil. [24].

Numerous studies have explored for re-refining of used oils through the process of solvent extraction techniques [25]; [26]. Supercritical fluids such as propane and ethane have been utilized as extraction solvents for recycling used motor oils, though they tend to produce relatively low yields ranging between 72% and 80% (Rincón et al., 2003). Reis et al. [10] reported that ketones and alcohols serve as the most effective solvents for extraction because they are miscible with the base oil, yet simultaneously induce flocculation of certain additives and carbonaceous materials via an antisolvent mechanism. The efficiency of sludge separation is strongly influenced by the difference in solubility between the solvent and polyisobutylene, a viscosity-enhancing additive. Aremu et al. (2015) [27] demonstrated that a ternary solvent mixture comprising 25% 2-propanol, 25% butanone, and 50% 1-butanol effectively reduces contaminants in the oil while facilitating good sludge separation. Their findings suggested that systems rich in 2-propanol result in high ash reduction but poorer sludge separation, whereas butanone-dominant systems provide better sludge separation but tend to re-dissolve contaminants. To balance ash removal and oil recovery, an equal ratio of 2-propanol and butanone was utilized, with 1-butanol serving as the primary solvent [28].

Several study have addressed the simulation of extraction processes using vacuum distillates as the primary feedstock [29]; [30]. The simulation of such extraction systems is particularly challenging due to the large number of components contained within lubricating oil. Accurately replicating the equilibrium behavior during extraction requires the use of an appropriate thermodynamic model. Additionally, it is essential to clearly define the number, composition, and properties of the components considered in the system's description. Commonly, petroleum product components are characterized using distillation curve data; however, this approach is not well suited for extraction processes, since the chemical makeup of the oil and solvents has a far greater impact than boiling points alone. To estimate the liquid-liquid equilibrium (LLE) of furfural/lubricating oil systems, [30] applied a model that correlates pseudo-component properties—such as specific gravity, density, refractive index, and sulfur content—with NRTL parameters and the oil's average boiling temperature. This approach has demonstrated strong accuracy across different lubricating oil fractions, requiring only the average boiling temperature and three physical properties as input experimental data.



2.1 Solvent extraction process

Solvent extraction is a widely studied technique for re-refining spent lubricating oil, aiming at base oil recovery and impurity removal. The process involves mixing spent oil with a suitable solvent to extract base oil while flocculating contaminants. Various researchers have investigated different process parameters, including solvent type, solvent-to-oil ratio, extraction time, and temperature. Sterpu et al. (2012) found that a4:1 solvent-to-oil ratio using a composite solvent yielded a 92% oil recovery and a 49% reduction in ash. Similarly, Mohammed et al. (2013) combined solvent extraction with adsorption, demonstrating that 1-butanol was most effective in sludge removal, while acid-activated clay improved product quality. Studies by Diphare et al. (2013) and Kamal and Khan (2009) highlighted the importance of optimal solvent ratios to maximize oil recovery while minimizing sludge formation.

Several researchers have examined the effectiveness of different solvents and extraction conditions in maximizing base oil regeneration. Yang et al. (2013) used butanol and monoethanolamine (MEA) to optimize the regeneration process, establishing that a refining temperature of 30°C, 20-minute mixing time, and a 5:1 solvent-to-oil ratio provided the best results. Abro et al. (2013) compared single and composite solvent extraction methods, concluding that composite solvents such as butanol, propane, and butanone provided superior iron contamination reduction but at higher costs. Emam and Shoaib (2013) observed that using methyl ethyl ketone at a 5:1 solvent-to-oil ratio and a 24-hour settling time resulted in the highest quality base oil with an 84% saturation composition. Kannan et al. (2014) confirmed that regenerated base oil met SAE standards, supporting its viability for reuse in engines.

Further advancements in solvent extraction technology emphasize optimization techniques and comparative analyses of solvents. Aremu et al. (2015) and Araromi et al. (2016) found that 1-butanol consistently achieved the highest sludge removal efficiency. Ani et al. (2015) reinforced earlier findings by demonstrating that increasing the solvent-to-oil ratio from 3:1 to 5:1 significantly improved yield while controlling ash content. Abdulaziz and Mahmood (2016) explored extraction-distillation methods, confirming that 1-butanol achieved the highest oil recovery (93.7%) at optimal conditions of 4:1 solvent-to-oil ratio and 40°C extraction temperature. These studies collectively establish solvent extraction as a viable method for regenerating spent lubricating oil, with ongoing refinements in process parameters enhancing efficiency and sustainability.

3. Methodology

1. Sample Collection and Preparation:
   - Collect used lubricant oil samples from automotive and industrial sources.
   - Pre-treat samples to remove large particulate matter and water content.
2. Solvent Extraction Process:
   - Prepare two solvent mixtures:
     - MEK-based system (25% MEK, 25% IPA, 50% 1-butanol)
     - MIBK-based system (25% MIBK, 25% IPA, 50% 1-butanol)
   - Conduct experiments at solvent-to-oil ratios of 1:1.5 and 1:2.5.
   - Vary extraction temperatures to determine optimal conditions for sludge separation and contaminant removal.
3. Vacuum Distillation:
   - Subject extracted oil to vacuum distillation to further remove impurities and enhance oil purity.
4. Process Simulation and Analysis:
   - Utilize Aspen Plus™ for process modeling and validation.
   - Employ pseudo-components (saturates, monoaromatics, diaromatics, and polyaromatics) to represent ULO composition.
   - Use NRTL and UNIQUAC models to simulate liquid-liquid equilibrium.
5. Performance Evaluation:
   - Analyze oil recovery efficiency and contaminant removal percentage.
   - Characterize sludge composition and assess its environmental impact.
   - Compare experimental results with simulation outcomes to validate findings.

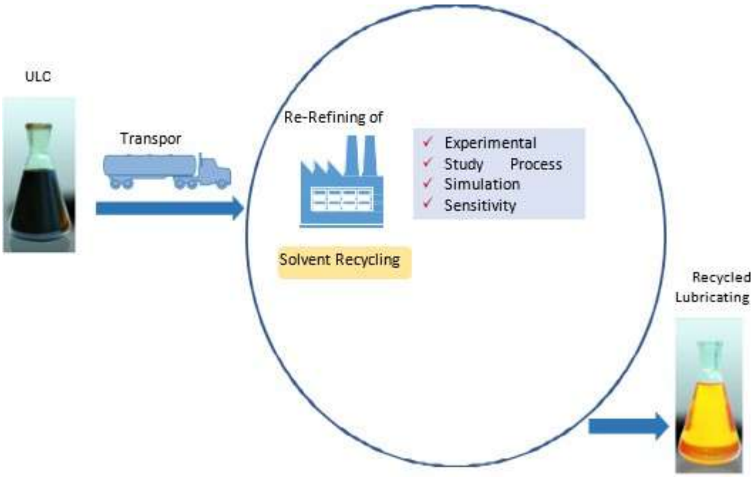


Figure 3.1- Pictorial Flow diagram

3.1 Scenarios Overview

The study involves two solvent-based extraction scenarios aimed at optimizing the removal of unwanted organic compounds from the used lubricating oil (ULO). Each scenario utilizes a different solvent combination and varying solvent to ULO flow ratios.

Scenario 1 (MEK-Based Extraction)

- Solvent Combination: Methyl Ethyl Ketone (MEK), Isopropyl Alcohol (IPA), and N- Butanol.
- Purpose: MEK is a strong polar solvent that helps in separating unwanted heavy components in the ULO. IPA and N-Butanol aid in solubility and phase separation.
- Variations: The process is tested at two different solvent-to-ULO ratios 1:1.5 and 1:2.5 to assess the impact of solvent quantity on extraction efficiency.

Scenario 2 (MIBK-Based Extraction)

- Solvent Combination: Methyl Isobutyl Ketone (MIBK), Isopropyl Alcohol (IPA), and N-Butanol.
- Purpose: MIBK is a moderately polar solvent that provides a different selectivity compared to MEK. It is used to test its effectiveness in removing impurities from ULO with the support of IPA and N-Butanol.
- Variations: Similar to Scenario 1, the process is evaluated at solvent-to-ULO ratios of 1:1.5 and 1:2.5 to study the effect of solvent concentration.

Table 3.1 : Refined Table of Solvent Combinations and Ratios

Scenario	**Solvent Combination**	**MEK (%)**	**MIBK (%)**	**IPA (%)**	**N-Butanol (%)**	**Solvent: ULO Flow Ratio**
Case 1	MEK-Based	25%	-	25%	50%	1:1.5
Case 2	MEK-Based	25%	-	25%	50%	1:2.5
Case 3	MIBK-Based	-	25%	25%	50%	1:1.5
Case 4	MIBK-Based	-	25%	25%	50%	1:2.5

Table 3.2 : Chemical Composition Used in Each Scenario

Component Code	**Chemical Name**	**Molecular Formula**
H2O	Water	H2O
C6H14	1-Hexanol	C6H14O-1
C20H42	N-Eicosane	C20H42
1:3:5-01	1,3,5-Trinitrobenzene	C6H3N3O6
N-BUT-01	N-Butylbenzene	C10H14-1
DIPRO-01	Dipropyl Phthalate	C14H18O4
BENZO-01	Benzo[b]naphtho[2,1-d]thiophene	C16H10S
ISOPR-01	Isopropyl Alcohol	C3H8O-2
N-BUT-02	N-Butanol	C4H10O-1
Scenario 1 Solvent	Methyl Ethyl Ketone (MEK)	C4H8O-3
Scenario 2 Solvent	Methyl Isobutyl Ketone (MIBK)	C6H12O-2

Both scenarios use a consistent composition of base chemicals, with the only difference being the ketone solvent used (MEK vs. MIBK).

- MEK-based extraction (Scenario 1) is expected to provide better phase separation and impurity removal due to its strong polar nature.
- MIBK-based extraction (Scenario 2) is designed to test a less polar alternative, which may have different selectivity and efficiency in dissolving impurities.
- The two different solvent-to-ULO ratios (1:1.5 and 1:2.5) allow analysis of the impact of solvent volume on extraction performance.

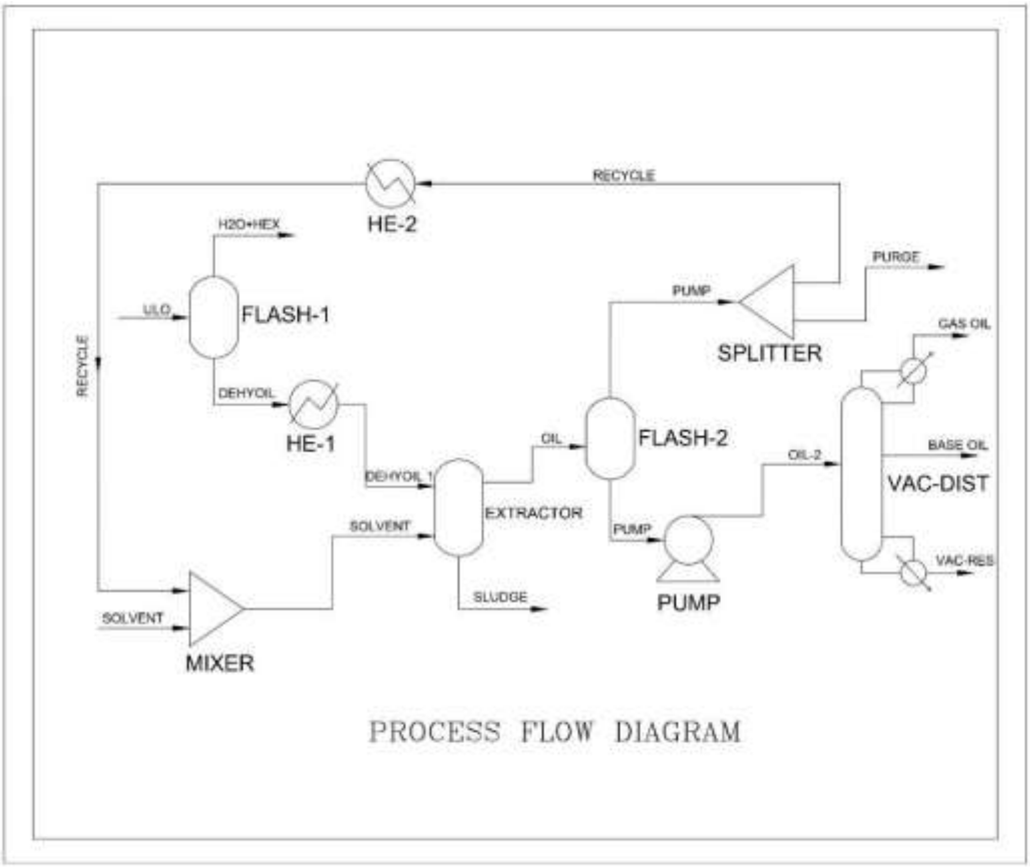


Figure 3.2 Process Flow diagram

4. Results

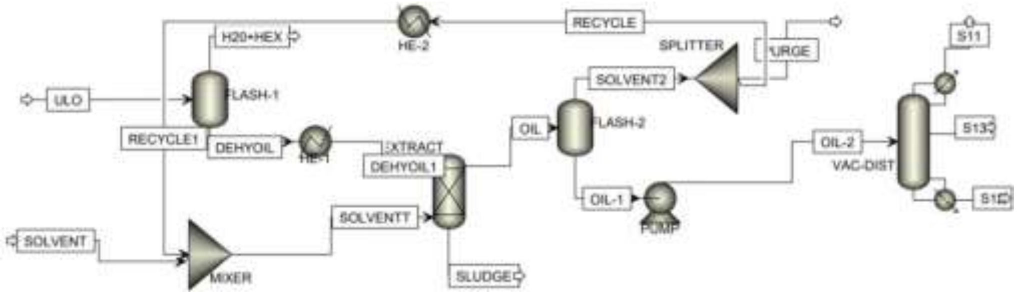


Figure 4.1 Aspen Plus Schematic

The flash drum operates at an outlet temperature of 132°C and a pressure of 1 bar, with a vapor fraction of 0.258. This indicates that approximately 25.8% of the incoming liquid stream undergoes phase separation into vapor while the rest remains as liquid. ULO flow will kept constant while the solvent flow will be changing based on the combination. Water and dissolved water which are present in the ULO will be removed in flash 1 vessel with temperature and pressure difference.

The first cooler reduces the temperature of the liquid stream from FLASH-1 from 132°C to 60°C while maintaining a pressure of 1 bar. This cooling process does not cause a phase change, but it requires the removal of 21,699.37 cal/sec of heat energy. The mixer combines the cooled DEHYOIL stream (60°C) with a solvent stream (25°C) to form a homogeneous mixture. The separation efficiency is dictated by solubility and temperature gradients across the extractor stages. The extractor operates in two stages, with the top stage at 127.99°C and the bottom stage at 147.97°C. The purpose of this unit is to separate oil from the solvent. Then the bottom stream will be sent to flash 2 where the fresh and recycled solvents will be mixed with ULO. The second flash drum is used to separate solvent vapours from the extracted oil. Operating at 150°C and 1 bar, this unit has a vapor fraction of 0.913, meaning that approximately 91.3% of the total feed stream is converted into vapor, while the remaining portion remains as liquid. 91% of the feed stream is converted into vapor while the other will be in liquid stream. Solvents which come from top of the flash 2 vessel will be sent into splitter where the purge and the recycled streams will be separated. It will be maintained the stream of fresh solvents and recycled will kept same. The cooler condenses the recycled solvent by lowering its temperature from 150°C to 60°C.

Vacuum distillation tower operates at different temperature ranges. Top stream operates at 21c where the bottom will be at 225c. Heavy components from flash 2 will be sent into vacuum distillation tower where the components will be separated under vacuum. The vacuum distillation column operates at a reduced pressure (top stage: 0.05 bar, bottom stage: 0.08 bar) to facilitate separation at lower temperatures. The specified reflux ratio is 40, with a distillate flow rate of 20 kg/hr.

Table 4.1 Aspen Plus Schematic

Stream Name	H20+HEX	RECYCLE	S11	S13	S12	SLUDGE	SOLVENT	SOLVENT2	SOLVENTT	ULO	PURGE
Description											
From	FLASH-1	SPLITTER	VAC-DIST	VAC-DIST	VAC-DIST	EXTRACT		FLASH-2	MIXER		SPLITTER
To		HE-2					MIXER	SPLITTER	EXTRACT	FLASH-1	
Phase	Vapor Phase	Vapor Phase	Vapor Phase	Liquid Phase	Liquid Phase	Liquid Phase	Liquid Phase	Vapor Phase		Liquid Phase	Vapor Phase
Temperature	132	150	21.39482548	51.73545898	225.9966065	147.9746188	25	150	26.79296655	25	150
Pressure	1	1	0.05	0.08	0.04	1	1	1	0.04	1	1
Molar Vapor Fraction	1	1	1	0	0	0	0	1	0.568008097	0	1
Molar Liquid Fraction	0	0	0	1	1	1	1	0	0.431991903	1	0
Molar Solid Fraction	0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	-53529.01406	-57642.67506	-60865.11022	-89078.973	-93966.94799	-66923.94167	-73460.19057	-57642.67506	-66910.22289	-78212.91332	-57642.67506
Mass Density	0.000868472	0.002105329	0.000137855	0.677793809	0.79901535	0.665443027	0.804112615	0.002105329	0.000201788	0.818763901	0.002105329
1st solvent 1.15											
Average MW	28.97861892	72.54224298	67.35509601	274.6047565	218.6887356	71.46763047	70.11211	72.54224298	71.3268534	164.8762805	72.54224298
Mole Flows	3.452729078	47.04257048	0.296933732	0.170008785	8.459512085	0.989069234	47.06747522	94.08514095	94.11005549	13.34333837	47.04257048
H2O	3.094107682	0.50392298	0.004126918	6.90507E-09	0.00017821	0.005342075	0	1.00784596	0.503922923	3.607677929	0.50392298
C6H14	0.12736888	0.521899113	0.000145866	3.50022E-05	0.098831899	0.005542078	0	1.043798225	0.521898716	0.753823236	0.521899113
C20H42	0.001295752	0.053778621	4.23887E-08	0.149162857	4.751258082	0.001059417	0	0.107557241	0.053778829	4.956554551	0.053778621
1:3:5-01	0.000500206	0.021360582	4.99636E-11	0.015041942	0.979432339	0.000325734	0	0.042721164	0.021360668	1.016660718	0.021360582
N-BUT-01	0.229201722	1.731395658	0.000580715	0.000502034	0.704305936	0.018423428	0	3.462791316	1.731393915	2.68441124	1.731395658
DIPRO-01	0.000240343	0.009047164	2.21074E-09	0.003957116	0.272150745	0.000123473	0	0.018094327	0.009047118	0.285518889	0.009047164
BENZO-01	1.4493E-05	0.000546316	2.48678E-11	0.001091773	0.037029634	9.59783E-06	0	0.001092633	0.000546318	0.038691812	0.000546316
ISOPR-01	0	11.27296773	0.107743374	1.04352E-05	0.144255279	0.241900273	11.7668688	22.54593545	23.03984481	0	11.27296773
N-BUT-02	0	21.76153032	0.032687691	0.000185386	1.263777281	0.475564817	23.53373761	43.52306064	45.29527582	0	21.76153032
METHY-01	0	11.166122	0.151649122	2.22318E-05	0.208292679	0.240778343	11.7668688	22.33224399	22.93298637	0	11.166122
1st solvent 1.25											
Average MW	28.97861892	71.93202839	67.6345119	274.0866739	221.3409134	71.23333538	70.11211	71.93202839	71.02421555	164.8762805	71.93202839
Mole Flows	3.452729078	78.81677249	0.295707021	0.328511564	7.906355243	0.989061917	78.44579203	157.633545	157.2625714	13.34333837	78.81677249
H2O	3.094107682	0.507839172	0.002367977	8.73168E-09	9.78839E-05	0.003265206	0	1.015678344	0.507839173	3.607677929	0.507839172
C6H14	0.12736888	0.562231798	9.05453E-05	4.95585E-05	0.060458894	0.003623494	0	1.124463596	0.562231717	0.753823236	0.562231798
C20H42	0.001295752	0.092980912	5.01721E-08	0.285329089	4.575630924	0.001317316	0	0.185961825	0.092980986	4.956554551	0.092980912
1:3:5-01	0.000500206	0.037412999	4.69198E-11	0.031540036	0.946822253	0.000385348	0	0.074825998	0.037413075	1.016660718	0.037412999
N-BUT-01	0.229201722	1.983057798	0.00038696	0.000755117	0.458192463	0.012816846	0	3.966115597	1.983057353	2.68441124	1.983057798
DIPRO-01	0.000240343	0.015564568	2.26619E-09	0.0082326	0.26134133	0.000139966	0	0.031129135	0.015564472	0.285518889	0.015564568
BENZO-01	1.4493E-05	0.000959224	2.45174E-11	0.002115209	0.035591136	1.17483E-05	0	0.001918447	0.000959225	0.038691812	0.000959224
ISOPR-01	0	19.12479763	0.107225062	2.27038E-05	0.136144381	0.243260958	19.61144801	38.24959526	38.73624833	0	19.12479763
N-BUT-02	0	37.47218534	0.033075468	0.000418884	1.235581432	0.48163983	39.22289602	74.94437069	76.69508599	0	37.47218534
METHY-01	0	19.01974305	0.152560955	4.83581E-05	0.196494546	0.242601205	19.61144801	38.0394861	38.63119111	0	19.01974305
2nd solvent 1.15											
Average MW	28.97861892	79.10332616	75.1522794	273.9068188	205.7524315	94.14385882	77.12555	79.10332616	77.50396761	164.8762805	79.10332616
Mole Flows	3.452729078	10.12346663	0.266126327	0.308760335	4.860208994	37.11989542	42.78737721	20.24693325	52.91131503	13.34333837	10.12346663
H2O	3.094107682	0.16815293	0.004051445	6.60348E-09	5.22761E-05	0.341309185	0	0.336305859	0.168148526	3.607677929	0.16815293
C6H14	0.12736888	0.155952988	0.000401152	0.000101405	0.083898273	0.386102768	0	0.311905976	0.155955172	0.753823236	0.155952988
C20H42	0.001295752	0.010441782	2.45757E-08	0.268606234	2.37433667	2.301873629	0	0.020883564	0.010442379	4.956554551	0.010441782
1:3:5-01	0.000500206	0.00397222	1.66002E-10	0.028592843	0.510428637	0.473167075	0	0.00794444	0.003972448	1.016660718	0.00397222
N-BUT-01	0.229201722	0.474977015	0.00110829	0.001340755	0.548354251	1.429442479	0	0.949954029	0.474989985	2.68441124	0.474977015
DIPRO-01	0.000240343	0.001729115	2.94919E-09	0.007495841	0.14283877	0.133214928	0	0.003458231	0.001729212	0.285518889	0.001729115
BENZO-01	1.4493E-05	0.000101966	4.34036E-11	0.001960046	0.018635814	0.017979493	0	0.000203931	0.000101972	0.038691812	0.000101966
ISOPR-01	0	2.453794708	0.112954258	1.03304E-05	0.043048864	8.087157687	10.6968443	4.907589417	13.15076054	0	2.453794708
N-BUT-02	0	4.615141113	0.070499728	0.000351975	0.713464849	15.99447409	21.3936886	9.230282226	26.00907247	0	4.615141113
METHY-01	0	2.239202789	0.077111425	0.000300899	0.425150589	7.955174079	10.6968443	4.478405578	12.93614233	0	2.239202789
2nd solvent 1.25											
Average MW	28.97861892	78.56887183	73.17360193	269.8295326	205.1041928	80.52790437	77.12555	78.56887183	77.84481854	164.8762805	78.56887183
Mole Flows	3.452729078	70.84214931	0.273322615	1.053653609	8.044691473	0.98906516	71.31229534	141.6842986	142.1544222	13.34333837	70.84214931
H2O	3.094107682	0.506070448	0.002938171	4.29458E-08	8.61274E-05	0.004475539	0	1.012140897	0.506070531	3.607677929	0.506070448
C6H14	0.12736888	0.548786804	0.000192296	0.000407703	0.072075387	0.00499205	0	1.097573608	0.548786656	0.753823236	0.548786804
C20H42	0.001295752	0.077232501	3.92134E-08	0.856854764	4.010756786	0.010413769	0	0.154465002	0.077232668	4.956554551	0.077232501
1:3:5-01	0.000500206	0.030231648	2.31625E-10	0.141065652	0.842629451	0.00223367	0	0.060463296	0.030231655	1.016660718	0.030231648
N-BUT-01	0.229201722	1.898069693	0.000697771	0.006094894	0.532505127	0.017841491	0	3.796139386	1.898068925	2.68441124	1.898069693
DIPRO-01	0.000240343	0.012801387	4.34031E-09	0.037001226	0.234819342	0.000656501	0	0.025602774	0.012801321	0.285518889	0.012801387
BENZO-01	1.4493E-05	0.000776753	6.42848E-11	0.006513925	0.031304164	8.24687E-05	0	0.001553507	0.000776753	0.038691812	0.000776753
ISOPR-01	0	17.31800525	0.140945212	0.000130785	0.129338649	0.239656089	17.82807384	34.6360105	35.14608122	0	17.31800525
N-BUT-02	0	33.7769353	0.058071061	0.002954565	1.344740776	0.47345429	35.65614767	67.55387059	69.43309069	0	33.7769353
METHY-01	0	16.67323953	0.070478059	0.002630052	0.846435665	0.235259294	17.82807384	33.34647906	34.50128177	0	16.67323953

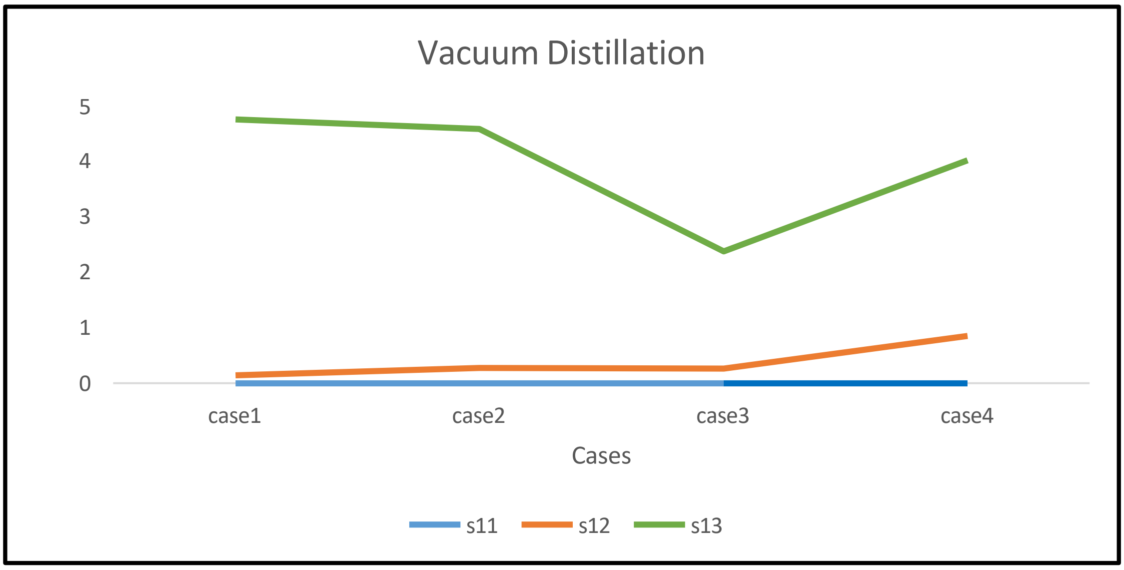


Figure 4.2 Vacuum distillation

The graph represents the mole flow output from three streams (S11, S12, and S13) of a vacuum distillation column under four different cases. The X-axis represents the four operating cases, while the Y-axis represents the mole flow rate of the three output streams.

- S11 (Blue Line): Likely represents the lightest fraction (overhead or top product).
- S13 (Green Line): Likely represents the middle fraction (side stream).
- S12 (Orange Line): Likely represents the heaviest fraction (bottom residue).

Key Observations from the Data Variation in S13 (Middle Product)

- S12 shows a downward trend from Case 1 to Case 3 but increases again in Case 4.
- This suggests that operating conditions (pressure, temperature, or feed composition) influenced the separation efficiency.
- A dip in Case 3 indicates possible operational inefficiencies, such as poor vapor- liquid equilibrium or entrainment issues.

S11 (Top Product) Remains Nearly Constant

- The mole flow of S11 (lightest fraction) remains almost stable across all four cases.
- This implies that the light-end separation is consistent, possibly due to stable column top pressure and vacuum conditions.

Gradual Increase in S12 (Bottom Product)

- The heaviest fraction (S12, bottom product) increases slightly across cases, with the highest value in Case 4.
- This suggests a higher fraction of heavy hydrocarbons retained in the bottom stream, potentially due to:
  - Higher reboiler duty leading to heavier cuts.
  - Reduced vacuum efficiency, causing less fractionation.

- Feed composition changes, introducing heavier compounds.

Possible Reasons for the Observed Trends Impact of Vacuum Level Changes:

- If vacuum pressure varies between cases, it shifts boiling points, affecting how much material exits through each stream.
- A higher vacuum level (lower pressure) would shift more molecules to the top and middle fractions, reducing bottom residue.
- A lower vacuum level (higher pressure) retains more heavy compounds in S12, as seen in Case 4.

Reboiler Duty Adjustments:

- Increasing reboiler duty (heat input) causes more heavy components to vaporize, increasing middle (S13) or top (S11) product flow.
- A decrease in Case 3 may indicate a temporary reduction in reboiler duty or inefficient heat transfer.

Feed Composition Influence:

- If the feedstock in different cases has varying amounts of light and heavy hydrocarbons, the distribution across streams changes.
- Case 4 may have a higher proportion of heavy hydrocarbons, leading to a rise in S12 (bottom fraction).

The Aspen HYSYS simulation results indicate variability in the product distribution due to changes in vacuum pressure, reboiler duty, and feed composition. The middle fraction (S13) showed fluctuations, likely due to vacuum variations or separation inefficiencies, while the bottom product (S12) increased over cases, possibly due to heavier feed or lower vacuum efficiency.

5. Conclusion

The study successfully demonstrated an optimized solvent extraction process for enhancing the recyclability of used lubricant oil (ULO). Through a series of controlled experiments and process simulations, it was evident that both the MEK-based and MIBK-based solvent systems effectively removed contaminants such as heavy metals, sulfur compounds, and oxidation by-products. Among the tested solvent compositions, the MEK-based system exhibited superior phase separation and impurity removal due to its strong polar nature, resulting in higher oil recovery efficiency.

The integration of vacuum distillation as a post-extraction refinement step further improved the quality of the reclaimed oil. This method effectively eliminated residual contaminants and optimized the final oil composition, ensuring it met industry standards for reuse. Process validation using Aspen Plus™ simulations provided reliable predictive modeling, confirming the scalability and efficiency of the proposed methodology.

Key findings from the results highlight that optimal solvent-to-oil ratios and extraction temperatures play a crucial role in maximizing recovery efficiency while minimizing energy consumption. The study also confirmed that solvent recycling within the system reduces waste generation, making the process more sustainable and cost-effective. Furthermore, the analysis of sludge composition emphasized the environmental benefits of proper disposal and potential resource recovery from by-products.

Among the extraction scenarios analyzed, the MEK-based solvent extraction (Scenario 1) at a solvent-to-oil ratio of 1:2.5 yielded the best overall performance.

1. **Higher Impurity Removal:** MEK demonstrated stronger polar interactions, effectively removing heavy contaminants, including sulfur compounds and oxidation by-products. This resulted in a cleaner, more refined oil output.
2. **Improved Phase Separation:** The MEK-based system allowed for clearer separation between the oil phase and sludge, ensuring higher oil recovery efficiency. In contrast, the MIBK-based system exhibited less distinct separation, leading to slightly lower recovery efficiency.
3. **Higher Oil Recovery Efficiency:** The MEK-based system at a 1:2.5 ratio maximized oil recovery while maintaining process efficiency.
4. **Better Compatibility with Vacuum Distillation:** The MEK-extracted oil responded more effectively to vacuum distillation, further enhancing final oil purity, while the MIBK-based extractions required additional processing to reach similar quality.

The MEK-based extraction (Scenario 1) at a 1:2.5 ratio provided the best results, ensuring higher oil recovery, superior contaminant removal, and efficient process scalability.

The research contributes to sustainable waste management by providing an improved and optimized approach to ULO recycling. The combination of solvent extraction and vacuum distillation presents a viable solution for reducing hazardous waste, promoting resource conservation, and advancing the circular economy in lubricant oil re-refining. Future studies can focus on further refining solvent compositions and exploring additional purification techniques to enhance process efficiency and economic feasibility.

REFERENCE

1. Abro, R., Chen, X., Harijan, K., Dhakan, Z. A., and Ammar, M. (2013). A Comparative Study of Recycling of Used Engine Oil Using Extraction by Composite Solvent, Single Solvent, and Acid Treatment Methods. ISRN Chemical Engineering, 2013(i),1-5. https://doi.org/10.1155/2013/952589
2. Abdel-Jabbar, M, N.; Zubaidy,A.H.E.; and Mehrvar,M. (2010). Waste Lubricating Oil Treatment by Adsorption Process Using Different Adsorbents. International Journal of Chemical and Biological Engineering, Vol.3 (2), pp.70- 73
3. Kannan, S. C., Kumar, M. K., Hussain, S. M., and Priya, D. N. (2014). Studies on Reuse of Re-Refined Used Automotive Lubricating Oil. In Research Journal of Engineering Sciences, 3(6). www.isca.me
4. Kanokkantapong V, Kiatkittipong W, Panyapinyopol B et al (2009) Used lubricating oil management options based on life cycle thinking. Resour Conserv Recycl 53:294–299. https ://doi. org/10.1016/j.resconrec.2009.01.002
5. Hamad A, Al-Zubaidy E, Fayed ME (2005) Used lubricating oil recy cling using hydrocarbon solvents. J Environ Manag 74:153–159. https://doi.org/10.1016/j.jenvman.2004.09.002
6. Totten GE, Bruce RW (eds) (2006) Handbook of lubrication and tribol ogy, 2nd edn. CRC Press, Boca Raton, FL
7. Tabassi, D., Harbi, S., Louati, I., and Hamrouni, B. (2017). Response surface methodology for optimization of phenol adsorption by activated carbon: Isotherm and kinetics study. Indian Journal of Chemical Technology, 24(3), 239–255.
8. Sánchez-Alvarracín, C., Criollo-Bravo, J., Albuja-Arias, D., García-Ávila, F., and Pelaez-Samaniego, M. (2021). Characterization of Used Lubricant Oil in a Latin-American Medium-Size City and Analysis of Options for Its Regeneration. Recycling, 6(1), 10. https://doi.org/10.3390/recycling6010010
9. Whisman ML, Reynold JW, Goetzinger JE, Cotton FO (1978) Re refining makes quality oils. Hydrocarb Process 141–145
10. Dos Reis MA, Jeronimo MS (1988) Waste lubricating oil rerefining by extraction-flocculation. 1. A scientific basis to design efficient sol vents. Ind Eng Chem Res 27:1222–1228. https ://doi.org/10.1021/ ie00079a023
11. Alves dos Reis M, Jeronimo MS (1990) Waste lubricating oil rerefin ing by extraction-flocculation. 2. A method to formulate efficient composite solvents. Ind Eng Chem Res 29:432–436. https ://doi. org/10.1021/ie00099a019

12. Speight, J. G., and Exall, D. I. (2014). Refining used lubricating oils (1st ed.). CRC Press, Taylor and Francis Group. https://doi.org/10.1201/b16745
13. Santos, J. C. O., Almeida, R. A., Carvalho, M. W. N. C., Lima, A. E. A., and Souza, A. G. (2019). Recycling of lubricating oils used in gasoline / alcohol engines Thermal characterization. Journal of Thermal Analysis and Calorimetry, 2. https://doi.org/10.1007/s10973-018-7976-2
14. Udonne, J.D, A comparative study of recycling of used lubrication oils using clay and three acids as a method of recycling journal of International Archive of Applied Sciences and Technology 93from 2011, 1-7
15. Boadu KO, Joel OF, Essumang DK, Evbuomwan BO (2019) A review of methods for removal of contaminants in used lubricating oil. Chem Sci Int J. https://doi.org/10.9734/CSJI/2019/v26i430101

16. Lam, S. S., Liew, R. K., Cheng, C. K., Rasit, N., Ooi, C. K., Ma, N. L., Chase,
H. A. (2018). Pyrolysis production of fruit peel biochar for potential use in treatment of palm oil mill effluent. Journal of Environmental Management, 213, 400–408.
17. Lam, S. S., Liew, R. K., Jusoh, A., Chong, C. T., Ani, F. N., and Chase, H. A. (2016). Progress in waste oil to sustainable energy, with emphasis on pyrolysis techniques. Renewable and Sustainable Energy Reviews, 53, 741–753.
18. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., and Sutton, D. J. (2012). Molecular, clinical and environmental toxicicology Volume 3:Vol.101, pp. 133- 164
19. Jiménez-Castañeda, M. E., and Medina, D. I. (2017). Use of surfactant-modified zeolites and clays for the removal of heavy metals fromwater. Water (Switzerland)MDPI AG, 9(4).
20. Jafari AJ, Hassanpour M (2015) Analysis and comparison of used lubricants, regenerative technologies in the world. Resour Conserv Recycl 103:179–191. https ://doi.org/10.1016/j.resco nrec.2015.07.026
21. Josiah, P. N., and Ikiensikimama, S. S. (2010). The Effect of Desludging and Adsorption Ratios on the Recovery of Low Pour Fuel Oil (LPFO) from Spent Engine Oil. Chemical Engineering Research Bulletin, 14(1), 25–28.
22. Cao Y, Yan F, Li J et al (2009) Used lubricating oil recycling using a membrane filtration: analysis of efficiency, structural and composing. Desalin Water Treat 11:73–80. https ://doi. org/10.5004/dwt.2009.845
23. Akpen, G.D., Aho, M. I., and Mamwan, M. H. (2018). Equilibrium and kinetics of colour adsorption from textile wastewater by a novel adsorbent. Global Journal of Pure and Applied Sciences, 24(1), 61.
24. Akpen, Gabriel Delian, and Leton, T. (2014). Adsorption characteristics of mango (magnifera indica) seed shell activated carbon for removing phenol from wastewater. Journal of Applied Science and Technology, 19(1–2), 37-42– 42.
25. Abu-Elella, R., Ossman, M. E., Farouq, R., and Abd-Elfatah, M. (2015). Used Motor Oil Treatment: Turning Waste Oil Into Valuable Products. Ijcbs, 7,pp. 57–67.
26. Hussein, H. Q., and Abdulkarim, A. L. (2016). Investigation of Binary Solvents Performance for Regeneration of Iraqi 15W- 40 Waste Lubricant. Iraqi Journal of Chemical and Petroleum Engineering, 17(4), 83–94.
27. Aremu, O., Olurotimi, D., and Olatunji, O. (2015). Regeneration of Used Lubricating Engine Oil By Solvent Extraction Process. International Journal of Energy and Environmental Research, 3(1), 1–12.
28. Udonne, J.D, A comparative study of recycling of used lubrication oils using clay and three acids as a method of recycling journal of International Archive of Applied Sciences and Technology 93from 2011, 1-7
29. Botas JA, Moreno J, Espada JJ et al (2017) Recycling of used lubri cating oil: evaluation of environmental and energy performance by LCA. Resour Conserv Recycl 125:315–323. https://doi. org/10.1016/j.resconrec.2017.07.010
30. Coto B, van Grieken R, Peña JL, Espada JJ (2006b) A generalized model to predict the liquid–liquid equilibrium in the systems furfural+lubricating oils. Chem Eng Sci 61:8028–8039. https :// doi.org/10.1016/j.ces.2006.09.037