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Experimental Validation of Vacuum Distillation and Clay Treatment for Waste Engine Oil Re-refining: Process Optimization and Product Characterization

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Abstract | **Original Research Article**

Driven by the dual imperatives of environmental sustainability and economic self-sufficiency, the research addresses the critical challenge of WEO management in developing economies like Nigeria. A laboratory-scale, batch-operated vacuum distillation unit was fabricated using accessible engineering principles. The experimental process involved atmospheric dehydration, vacuum distillation for separating diesel and lubricating oil fractions, and a final polishing step with thermally activated Attapulgite clay. The produced oils were rigorously characterized and compared against virgin lubricating oil and commercial diesel using standard ASTM methods, EDXRF, and FT-IR spectroscopy. The results demonstrate that this two-step process effectively removes a broad spectrum of contaminants; including water, light hydrocarbons, wear metals, and oxidation products. The re-refined base oil exhibited physicochemical properties, such as viscosity index (93.4), flash point (209°C), and total acid number (0.4 mg KOH/g), that are on par with virgin base oil and meet industry-specific quality standards. A high-quality diesel by-product was also recovered, with properties comparable to commercial diesel, enhancing the economic viability of the process. The findings confirm that vacuum distillation coupled with clay treatment is a technically effective and environmentally sound method for WEO re-refining, providing a pragmatic, scalable, and economically attractive solution for sustainable waste management in regions facing a lack of advanced refining infrastructure.

Keywords: Waste engine oil, re-refining, vacuum distillation, clay treatment, process optimization, product characterization, circular economy, waste management.

INTRODUCTION

Lubricating oils are indispensable for the smooth and efficient operation of machinery across diverse industrial and automotive sector. With an annual global consumption of approximately 35 million metric tons, the lubricant market is a colossal industry, valued at over $142 billion and projected to grow significantly. This robust demand, however, is coupled with the inevitable generation of vast quantities of waste lubricating oil (WLO), estimated at around 17.5 million metric tons annually (Mohammed *et al.*, 2013).

However, the lifecycle of a lubricant is finite. During use, lubricating oil undergoes degradation, and approximately 50% of it is consumed, leaving the other half as waste lubricating oil (WLO). This translates to a staggering 17.5 million metric tons of waste oil generated globally each year. WLO is a complex, hazardous mixture composed of degraded base oil, metallic wear particles, water, sludge, and additives. Its improper disposal poses a severe environmental threat, as it can pollute ground and surface water, contaminate soil, and introduce toxic and carcinogenic heavy metals (such as lead, cadmium, and chromium) into ecosystems. A single liter of WLO can contaminate up to 250,000 liters of water (Saleem and Karim, 2019). The uncontrolled combustion of WLO also releases metallic contaminants into the atmosphere, further exacerbating pollution.

In Nigeria, a developing economy undergoing rapid industrial and urban expansion, the challenge of WLO is particularly acute. The country's lubricant market is estimated to reach 695.80 million liters by 2030, with a corresponding generation of approximately

287.465 million liters of WLO in 2025 (Mohammed *et al.,* 2013; Umejei, 2018). Despite this significant volume, Nigeria lacks an organized WLO collection and recycling system and currently has no operational commercial re-refining plants. The country's five refineries have an epileptic operational history, leading to an over-reliance on imported virgin base oil and additives to meet domestic demand. This situation creates a critical dual challenge: a severe environmental pollution problem stemming from the indiscriminate dumping of WLO and a significant economic burden due to capital flight for virgin oil imports. The absence of local re-refining capacity is not just an environmental failure but a missed opportunity for economic growth and the creation of a circular economy in the country (Udonne, 2011; Oguche *et al.*, 2022).

A key contribution of this work is its focus on a re-refining technology that is both effective and accessible. The use of vacuum distillation and clay treatment, as opposed to more complex and capital-intensive methods like hydrotreating, provides a practical model for a developing economy. This approach, which can be implemented with a lower initial investment, offers a vital bridge from the current state of unmanaged waste to a more structured and sustainable industrial solution (Kupareva *et al.,* 2013). This pragmatic approach is essential for scaling up waste management practices in regions where financial constraints and technical capacity pose significant barriers to adopting advanced, high-cost technologies (Audibert, 2011).

LITERATURE REVIEW: RE-REFINING MECHANISMS

Lubricants are typically composed of a base oil and various performance-enhancing additives (Speight and Exall, 2014; Kupareva *et al.*, 2013a). The base oil accounts for over 80% of the mixture, with mineral oils being the most common type, though synthetic oils are also widely used. Additives such as viscosity index improvers, antioxidants, detergents, and dispersants are crucial for meeting high-performance standards, but they degrade or are consumed during the lubricant's service life.

The degradation of lubricating oil during its use is a complex process influenced by factors such as heat, contamination, and exposure to air. Key degradation mechanisms include:

a. **Oxidation:** A reaction with oxygen that produces acidic compounds, sludge, and varnish, leading to an increase in oil viscosity and a loss of anti-foam properties.
b. **Thermal Degradation:** The breakdown of hydrocarbon molecules at high temperatures, causing light hydrocarbons to vaporize or decompose (Mekonnen and Ababa, 2014).
c. **Additive Depletion:** The consumption of additives, such as antioxidants and detergents, reduces the oil's ability to protect the engine and maintain cleanliness.
d. **Contamination:** The introduction of foreign compounds such as water, metallic particles from engine wear, and carbon soot significantly accelerates the oil's degradation.

The consequence of these degradation processes is the accumulation of various contaminants and by-products in the oil, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and organic acids, making it unsuitable for further use and a hazard to the environment (SanchezAlvarracin *et al.*, 2021). This accumulation is reflected in a change in the oil's chemical signature, which can be detected through analytical methods. The degradation processes lead to a marked increase in the oil's total acid number (TAN) and a reduction in its total base number (TBN), alongside the presence of heavy metals, which will be further discussed in the results section of this report (Jurny *et al.*, 2023; Hasch, 2019).

Overview of Waste Lubricating Oil Re-refining Technologies

Various technologies have been developed over the years for the re-refining of WLO, each with its own set of advantages and disadvantages (Motshumi *et al.*, 2013; Kupareva *et al.*, 2013a). These technologies can be broadly categorized by their primary separation and finishing mechanisms.

a. **Acid-Clay Process:** An early and relatively low-cost method that uses concentrated sulfuric acid to remove impurities, followed by clay for filtration. While simple and having a low capital cost, this process is now largely banned due to the generation of highly hazardous acid tar sludge, which is difficult and expensive to dispose of environmentally. Modern lubricants with complex additive packages have also rendered this method less effective.
b. **Vacuum Distillation:** This is a core re-refining step that separates the base oil fraction from lighter components and heavier residues based on their boiling points under reduced pressure (Audibert, 2011; Motshumi *et al.*, 2013). By lowering the boiling point, vacuum distillation prevents the thermal cracking of the oil that would occur at atmospheric pressure. This process is highly effective for bulk separation and is a fundamental component of many modern re-refining technologies, including the Safety Kleen, STP, and Vaxon processes.
c. **Hydrotreating:** Considered one of the most advanced technologies, hydrotreating involves a catalytic hydrogenation process at high temperature (280–370°C) and pressure (3–8MPa). This method effectively removes a wide range of impurities, including sulfur, nitrogen, and oxygen, while saturating unsaturated compounds (Kupareva *et al.*, 2013a). It is

capable of producing very high-quality base oils that meet API Group II and Group III specifications. However, the main drawbacks are the high initial capital investment, operational complexity, and the need for a reliable hydrogen supply.

d. **Solvent Extraction:** This method uses a solvent (e.g., N-methylpyrrolidone (NMP) or propane) to dissolve and separate desirable base oil molecules from undesirable contaminants like PAHs, oxidized compounds, and heavy metals (Speight and Exall, 2014. The process operates under milder conditions than hydrotreating and has a lower capital cost. However, its effectiveness in removing sulfur and nitrogen is limited, and the energy required for solvent recovery can be high.

e. **Emerging Technologies:** Newer approaches such as membrane filtration, specifically organic solvent nanofiltration (OSN), are being researched for their potential to separate contaminants with high efficiency and significantly lower energy consumption. These pressure-driven, heatless processes could potentially reduce energy consumption by up to 90% compared to traditional thermal separation methods.

Mechanism of Vacuum Distillation and Clay Treatment

Mechanism of Vacuum Distillation:

Vacuum distillation is a core physical separation process in WLO re-refining. Its primary function is to separate the various components of WLO, including diesel-like fuel and base oil fractions, at temperatures below the threshold for thermal cracking and degradation (Treese *et al.*, 2015). This is achieved by conducting the distillation under pressures significantly lower than atmospheric pressure.

The principle behind this process is rooted in the Clausius-Clapeyron relation, which dictates that the boiling point of a substance decreases dramatically as pressure is reduced (Koutsoyannis, 2012). By applying a vacuum, the constituents of the WLO vaporize at much lower temperatures, typically below 350 °C, which is the temperature at which oil molecules begin to break down and form coke (Kandasamy *et al.*, 2025). This low-temperature operation is crucial for preserving the chemical integrity of the base oil molecules and ensuring a high-quality final product.

In practice, the process begins after the initial dehydration and de-fueling stages, which are typically performed at atmospheric pressure to remove water and light hydrocarbons. The preheated WLO is then fed into a vacuum distillation column. Here, it vaporizes under high vacuum conditions. The resulting vapor rises, condensing at different temperature zones to be collected as various base oil fractions. The heavier residue, which contains impurities and asphaltic components, is collected at the bottom of the column and can be repurposed for other industrial applications, such as bitumen production (Treese *et al.*, 2015). This process is thermodynamically efficient and vital for separating hydrocarbons based on their boiling points without causing molecular degradation (Al-Muslim & Dincer, 2005).

Mechanism of Clay Treatment:

Following distillation, the re-refined oil often retains trace amounts of color- and odor-forming compounds, as well as some residual metals and oxidation products that were not fully removed (Al-Bidry & Azeez, 2020; Emam, 2018). The clay treatment, or clay finishing, step addresses these remaining impurities through the mechanism of adsorption (Alaqarbeh, 2021; Emam, 2018). Clay minerals, such as bentonite and attapulgite, are inexpensive and abundant natural resources known for their unique properties, including a high surface area, layered structure, and excellent adsorption capacity.

The adsorption process can be either physical (physisorption) or chemical (chemisorption). In the case of WLO, physical adsorption occurs as weak van der Waals forces cause dark-colored compounds to adhere to the clay's surface (Emam, 2018). Chemical adsorption involves the formation of stronger bonds, either ionic or covalent, between the clay's active sites and impurities like heavy metals, sulfur, or acidic compounds. This process effectively performs several functions simultaneously:

a. **Bleaching:** It removes color- and odor-causing compounds through physisorption, restoring the oil's appearance to a state comparable to virgin oil without altering its fundamental chemical properties (Saleem and Karim, 2020).

b. **Demetallization:** Activated clays have a strong capacity to adsorb heavy metals like lead, zinc, and iron, significantly reducing their concentration in the oil. This is a critical step for producing high-quality base oils that meet international specifications (Emam, 2018).

c. **Corrosion Reduction:** By removing acidic components and reducing the Total Acid Number (TAN), clay treatment helps to prevent corrosive wear in engines and extend the life of the final lubricant product (Emam, 2018).

d. **Desulphurization:** Clays can also adsorb sulfur compounds from petroleum derivatives, contributing to the production of cleaner, more environmentally friendly fuels (Al-Bidry and Azeez, 2020).

The combination of vacuum distillation and clay treatment provides a robust, two-stage approach: physical separation of oil fractions at low temperatures, followed by chemical adsorption of the remaining impurities. This synergistic process results in a high-

quality final product that is technically and economically competitive with virgin base oil.

METHODOLOGY

Materials and Equipment

The materials used for this study included 30 liters of waste diesel engine lubricating oil (SAE 40) from a heavy-duty electromotive diesel (EMD) engine that had operated for 1,500 hours, a sample of new virgin SAE 40 Monograde lubricating oil, and Ultra Clear™ 30/60 (thermally activated Attapulgite) clay. For analytical purposes, various pure-grade chemical reagents were used (Oduola and Okwonna 2016).

The key equipment employed for the re-refining process and sample characterization included:

a. A fabricated Vacuum Distillation Unit.
b. A Shimadzu FT-IR Spectrophotometer 8400S for functional group analysis.
c. A Xenemetrix ED XRF Spectrometer Genus IF for elemental composition.
d. An Oswalt Viscometer for kinematic viscosity.
e. A BIOBASE Closed-Cup Flash Point Tester BK-FP261.
f. An Aniline point tester.
g. A HANNA pH meter 9813-6.
h. An Oxidation stability tester.
i. A BIOBASE Carbon residue tester.
j. A Hydrometer for specific gravity.
k. A Colorimeter for color measurement.
l. A BIOBASE Ash content tester (Muffle Furnace) TP-508.

Fabrication of the Vacuum Distillation Unit

A batch vacuum distillation unit was fabricated for this experiment. The main components were constructed from modified domestic gas cylinders and carbon steel pipes.

a. Vacuum Distillation Drum: A 12.5 kg gas cylinder was modified to serve as the distillation drum, with a 4-inch vapor/liquid outlet and a 2-inch residue drain. It was fitted with threaded sockets for a 10.5 kW electric immersion heater and monitoring gauges for temperature and pressure.

b. Vacuum Drum: A 2.5 kg gas cylinder was repurposed as a vacuum drum, connected to the condenser and fitted with a compressor suction line and a vacuum pressure gauge.

c. Heat Exchanger (Condenser): A shell-and-tube heat exchanger was fabricated from an 8inch carbon steel pipe (shell) and a ½-inch pipe (tube), designed for water cooling.

d. Packed Column: A 4-inch pipe with a concentric reducer and a perforated grid plate was fabricated to support packing materials.

e. Product Receiver Drum: A 2.5 kg gas cylinder was modified to collect re-refined products, with inlet, outlet, and vacuum lines.

f. Compressor: A 1.5 HP air conditioning compressor was used to generate and maintain the vacuum condition by removing non-condensable vapors.

This setup was purposefully designed to be a low-cost, modular system that showcases the feasibility of a grassroots engineering approach to a complex industrial problem. The use of standard, off-the-shelf components and repurposed materials underscores the practicality of scaling this technology in resource-constrained environments, making it a viable option for smallto-medium-scale enterprises or pilot projects.

Experimental Procedure: Re-refining Process Stages

The re-refining process was conducted in five distinct stages, following a systematic approach to feedstock preparation, distillation, and final product polishing (Kajdas, 2014).

1. **WLO Feedstock Preparation:** A 30-liter sample of WLO was allowed to settle for 72 hours to separate any free water. The oil was then filtered through a 26 µm mesh filter to remove solid impurities and debris. A 20-liter portion of the filtered oil was then transferred into the distillation drum (Audibert, 2011).
2. **Dehydration and De-fueling:** The oil in the distillation drum was heated to 130°C under atmospheric pressure. This step vaporized and removed any emulsified water and light hydrocarbon contaminants, such as diesel or gasoline, that were present in the WLO (Audibert, 2011; Kajdas, 2014; Kupareva *et al.*, 2013a).
3. **Diesel Recovery:** The pressure in the system was then reduced to a vacuum of -0.07 MPa using the compressor. The temperature was gradually increased from 200°C to 280°C, and the vaporized diesel fraction was condensed and collected in the receiver drum.
4. **Lubricating Base Oil Recovery:** The remaining oil was further heated to a temperature range of 300°C to 330°C, while the vacuum pressure was maintained at a mean of -0.043 MPa. Under these conditions, the lubricating base oil fraction was vaporized, condensed, and collected.
5. **Clay Treatment:** The recovered lubricating base oil was heated to 40°C in a water bath. A 500 ml sample of this oil was then filtered through a packed bed containing 500 g of thermally activated Attapulgite clay. This final polishing step was performed to remove residual color, odor, and trace impurities. The same clay treatment procedure was applied to the recovered diesel by-product.

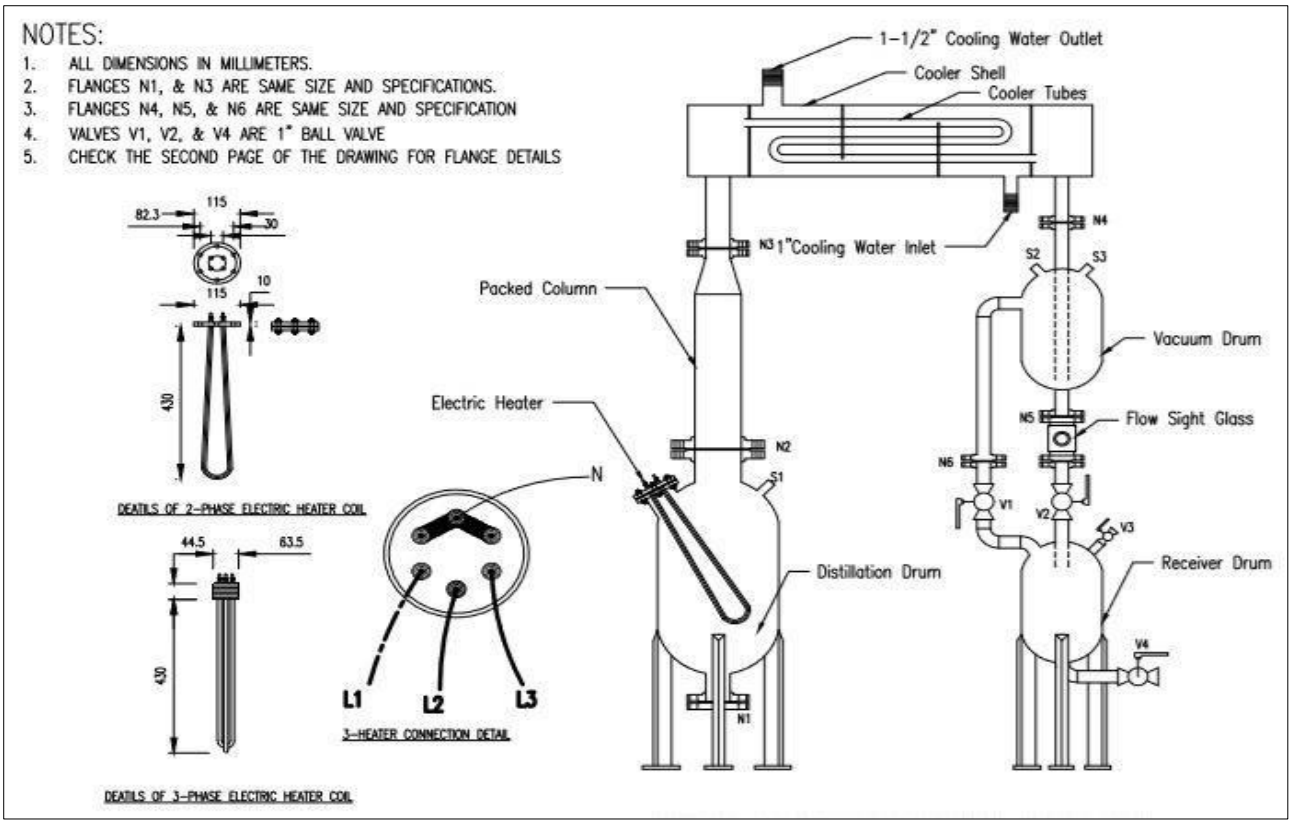

Figure 1.1: General arrangement schematic of fabricated vacuum distillation unit

Figure 1.2: Fully set up vacuum distillation unit

Characterization and Analysis: Oil Samples

The quality of the raw materials and final products was assessed through a series of physicochemical and instrumental analyses based on industry standards, primarily from the American Society for Testing and Materials (ASTM). All oil samples: W01 (waste oil), V01 (virgin oil), RRBO-01 (re-refined base oil), CRBO-01 (clay-treated base oil), UD-01 (untreated diesel), CTD-01 (clay-treated diesel), and SD-01 (standard diesel), underwent characterization using American Society for Testing and Materials (ASTM) International standards. Physicochemical properties, spectroscopic analysis (FT-IR), and elemental analysis (ED-XRF) were all performed.

a. **Physicochemical Properties:** Standard tests were performed to determine specific gravity (ASTM D1298), kinematic viscosity at 40°C and 100°C (ASTM D445), viscosity index (ASTM D2270), flash point (ASTM D93), pour point and cloud point (ASTM D2500), sulphated ash content (ASTM D874), water content (ASTM D6304), total acid number (TAN) and total base number (TBN) (ASTM D974), and carbon residue (ASTM D189).

b. **Elemental Analysis:** A Xenemetrix EDXRF Spectrometer (Genus IF) was used to perform non-destructive, quantitative elemental analysis of the oil samples, allowing for the determination of sulfur content (ASTM D4294) and the concentration of various metals (ASTM D7751).

c. **Spectroscopic Analysis:** Fourier Transform Infrared (FT-IR) spectroscopy with a Shimadzu FT-IR Spectrophotometer 8400S (ASTM E2412) was employed to identify the functional groups of hydrocarbons and detect the presence of degradation products, providing a molecular-level view of the changes in oil composition.

d. **Color Analysis:** A colorimeter was used to measure the color of the samples according to ASTM D-1500, which is an important indicator of the oil's quality and degree of refinement.

RESULTS AND ANALYSIS

Product Yield and Process Optimization

The two-stage distillation process successfully fractionated the WLO feedstock. As shown in Table 1.1, 1.2, & 1.3 the initial atmospheric distillation yielded 680 ml of water and light fuels from a 20,000 ml WLO sample, representing a 3.4% yield. The subsequent vacuum distillation, from a feedstock volume of 19,320 ml, produced 2,306 ml of lubricating base oil (69% yield) and 612 ml of diesel by-product (18% yield). The total distilled fraction was 3,349 ml, and the overall yield of lubricating base oil before clay treatment was 69% of the vacuum distillation feedstock.

Table 1.1: Product yield after atmospheric distillation process

S/N	Component	Initial Volume (ml)	Final Volume (ml)	Yield (%)
1	Waste engine oil	20,000	19,320	
2	Water and light fuels	-	680	3.4
	Total	20,000	20,000	

Table 1.2: Product yield after vacuum distillation process

S/N	Component	Initial Vol (ml)	Final Vol (ml)	Yield (%)
1	Waste engine oil	19,320	-	
2	Diesel/light end	-	612	18
3	Base oil	-	2,306	69
4	Losses	-	431	13
5	**Total**	**19,320**	**3,349**	**100**
6	**Bottom residue**	**-**	**15,971**	

Table 1.3: Product yield after clay treatment

S/N	Component	Initial Vol (ml)	Final Vol (ml)	Yield (%)
1	Base oil	2,306	2,136	64
2	Loss due to clay treatment	-	170	5
3	Vacuum Distillates	3349		

The process parameters were found to have a direct influence on the distillation outcome. As the temperature in the distillation drum was increased, the pressure also rose, which necessitated the use of the vacuum pump to lower the boiling points of the fractions. By operating under a vacuum, the distillation temperature for the base oil was kept below 330°C, well below the thermal cracking threshold of 350°C, thereby preventing product degradation and the formation of undesirable coke (Kandasamy *et al.*, 2025). The use of vacuum pressure not only reduces the overall energy consumption of the process but also allows for a more efficient separation of the various hydrocarbon fractions. This finding confirms that a high vacuum pressure is a critical factor for successful distillation, enabling the

production of high-quality products at lower temperatures.

Characterization and Comparison of Re-refined Lubricating Base Oil, Waste Lubricating Oil, and Virgin Lubricating Oil

The physicochemical and elemental analyses provide a comprehensive understanding of the changes in oil properties during the re-refining process.

a. **Appearance and Color:** The WLO was a dark, opaque fluid with a high ASTM color index of 8.0, indicating the presence of oxidation products, sludge, and soot (Udonne *et al.*, 2016; Jurny *et al.*, 2023; Kamal *et al.*, 2009). Vacuum distillation alone partially improved the color to an index of 6.8 (RRBO-01), but the subsequent clay treatment was crucial, reducing the color index to 4.2 (CRBO-01), making it very similar in appearance to the light brown virgin oil (V01) with an index of 4.0. This observation confirms that while distillation is effective at removing bulk contaminants, the clay finishing step is essential for polishing the product to an acceptable commercial standard.

b. **Viscosity and Viscosity Index (VI):** WLO exhibited a lower kinematic viscosity (119 mm^2/s at 40°C) and a significantly lower VI (80) compared to the virgin oil (214 mm^2/s at 40°C). This reduction in viscosity and VI in the WLO is a direct consequence of thermal degradation and additive depletion during service. The re-refining process was highly effective in restoring these properties, with the final clay-treated product (CRBO-01) achieving a VI of 93.4, which falls squarely within the API Group I base oil specification of 80-120. This result compares favorably with other studies (Abdulkareem *et al.*, 2014; Udonne *et al.*, 2016).

c. **Flash Point:** The WLO had a dangerously low flash point of 156°C, a clear sign of contamination by volatile, lighter fuel fractions that were not fully combusted in the engine (Hamad *et al.*, 2005; Saleem and Karim, 2020). The vacuum distillation process effectively removed these volatile components, raising the flash point to 207°C (RRBO-01) and 209°C (CRBO-01) after clay treatment. This value is well within the acceptable range for re-refined base oils (190–230°C) and is crucial for ensuring product safety and stability (Abdulkareem *et al.*, 2014; Bobde *et al.*, 2019).

d. **Total Acid Number (TAN) and pH:** The WLO was highly acidic, with a TAN of 5.6 mg KOH/g and a pH of 5.6, due to the formation of acidic compounds from oxidation reactions (Hasch, 2019; Boadu *et al.*, 2019b; Jurny *et al.*, 2023). The re-refining process drastically reduced this acidity. Vacuum distillation lowered the TAN to 0.9 mg KOH/g and increased the pH to 7.1. The clay treatment further polished the oil, resulting in a final TAN of 0.4 mg KOH/g and a pH of 7.3 for CRBO-01, which is directly comparable to the virgin oil's values (TAN 0.43, pH 7.8). This demonstrates the excellent synergistic effect of the twostep process in neutralizing the oil.

e. **Sulphated Ash and Carbon Residue:** The WLO had a very high sulphated ash content of 4.96% and a carbon residue of 8.66%. These values are indicative of the accumulation of metallic wear particles, dirt, and coke-forming precursors from degraded additives (Shihab *et al.*, 2019). The distillation process, which separates the volatile hydrocarbons from the non-volatile residue, was highly effective, reducing the ash content to 1.18% and the carbon residue to 1.89%. The final clay treatment step further reduced these to 0.52% and 1.58%, respectively. The lower values in the re-refined oil suggest a reduced tendency for carbonaceous deposits to form in an engine, making it a suitable base stock for lubricant blending.

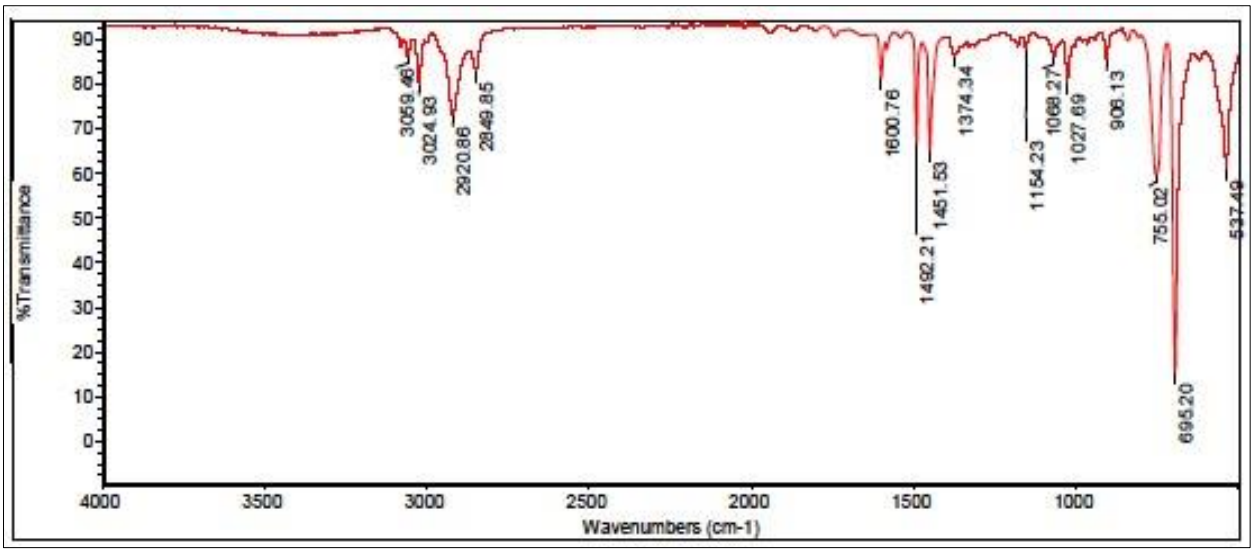

Figure 1.2: FT-IR spectroscopy of sample V01

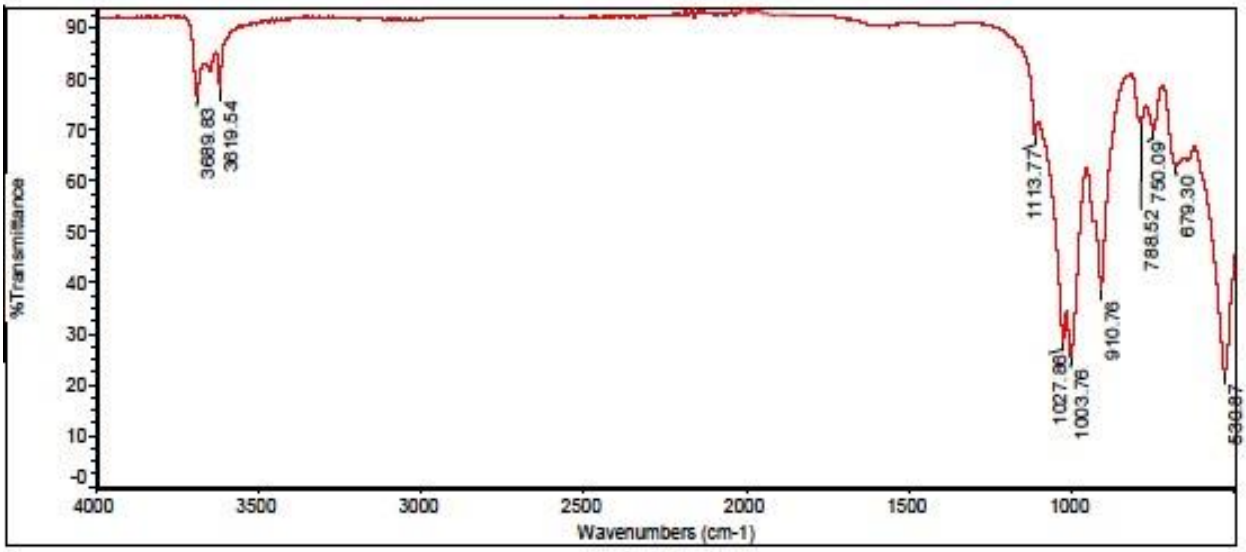

Figure 1.3: FT-IR spectroscopy of sample RRBO-01

Characterization of the Diesel By-product

A significant advantage of this re-refining process is the ability to recover a marketable diesel byproduct, which enhances the overall economic viability of the operation. As seen in Table 1, the untreated diesel (UD-01) produced from the vacuum distillation had a dark color and a high total acid number (TAN) of 1.8 mg KOH/g. However, after a simple clay treatment, the diesel's properties were substantially improved, with the color becoming light brown, the specific gravity moving closer to that of commercial diesel, and the TAN reducing to 0.6 mg KOH/g. This final TAN value is comparable to the maximum allowable value for standard diesel and is indicative of a fuel that will cause minimal corrosive wear in a fuel system (Demirbas *et al.,* 2015). The FT-IR analysis further confirmed that the clay-treated diesel (CTD-01) had a chemical composition similar to that of commercial diesel (CD-01) (Okopi *et al.,* 2024). This demonstrates that the re-refining process not only produces a high-quality base oil but also generates a valuable secondary product that can be used for the plant's own energy needs or sold commercially.

Limitations and Recommendations for Future Work

The experimental setup, while effective for validation, presented several limitations that should be addressed for commercial scale-up. These included an inability to achieve a perfect vacuum, difficulty with real-time reaction rate monitoring, an assumption that all impurities were similar, and the use of a temperature gun for monitoring. The following recommendations are proposed to address these limitations:

- **Improved Vacuum System:** Modify the system from a fixed-speed to a variable-speed compressor for enhanced pressure regulation.

- **Continuous Operation:** Convert the batch process to a continuous one for higher throughput and efficiency.
- **Residue Utilization:** Conduct studies on the residue from the process to determine its suitability for other industrial applications, such as bitumen production.
- **Advanced Characterization:** Implement advanced analytical techniques, such as Gas Chromatography-Mass Spectrometry (GC-MS), for a more detailed understanding of the oil's molecular composition.

CONCLUSION

This experimental case study on vacuum distillation and clay treatment reaffirms the effectiveness and viability of this combined approach as a sound method for re-refining waste lubricating oil. The findings demonstrate that this process is highly effective in removing a broad range of contaminants, including water, light hydrocarbons, metals, and oxidation products. The final re-refined base oil and diesel by-product exhibited physicochemical properties and elemental compositions that were comparable to their commercial-grade counterparts, confirming their suitability for reuse.

This research contributes to the body of knowledge by providing a detailed empirical validation of vacuum distillation and clay treatment as a viable and environmentally sound re-refining method. By embracing these technologies, developing economies can not only mitigate critical environmental challenges associated with WLO disposal but also achieve significant economic and social benefits, including reduced import dependence, enhanced energy security, job creation, and alignment with global sustainable development goals. This study serves as a foundational template for future research and commercial endeavors in WLO re-refining, paving the way for a more sustainable and economically resilient industrial landscape in Nigeria and beyond.

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