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A Comprehensive Review of Global Waste Lubricating Oil Re-Refining Technologies: Mechanisms, Performance, and Environmental Footprint

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ABSTRACT: The global demand for lubricants, driven by industrial expansion and a growing vehicle fleet, has led to a significant increase in the generation of waste lubricating oil (WLO). This waste presents a formidable environmental challenge, particularly in developing economies where indiscriminate disposal leads to severe contamination of water, soil, and air with toxic and carcinogenic compounds. In response to these pressures, the re-refining industry has emerged as a crucial component of a global circular economy, transforming this hazardous waste into a valuable resource. This article presents an in-depth comparative analysis of the diverse technologies employed globally for the re-refining of WLO. It systematically examines processes such as acid clay, hydrogenation, solvent extraction, and thermal methods, evaluating their respective mechanisms, technical performance, and environmental footprints. The analysis highlights a clear technological evolution from environmentally problematic methods, such as the acid-clay process, toward more sophisticated and sustainable approaches like hydrogenation and advanced distillation. It systematically describes their mechanisms, evaluates their performance in terms of product quality and yield, and assesses their environmental footprints. The findings and analysis demonstrate that this combined process effectively removes contaminants, producing lubricating base oil and diesel of comparable quality to commercial-grade products. This study not only reaffirms the technical viability of WLO re-refining but also underscores its vital role in achieving resource conservation, economic resilience, and environmental preservation on a global scale.

KEYWORDS: Waste Lubricating Oil, Re-refining, Hydrogenation, Solvent Extraction, Vacuum Distillation, Clay Treatment, Circular Economy, Environmental footprint, Sustainability.

INTRODUCTION

The industrial and automotive sectors are fundamentally dependent on lubricants for the smooth and efficient operation of their machinery (Kupareva et al., 2013a; Audibert, 2011). The annual global consumption of lubricating oils is approximately 35 million metric tons, with a market value exceeding $142 billion, a figure projected to grow significantly in the coming years (Statista et al., 2023). However, this high rate of consumption inevitably results in the generation of vast quantities of waste lubricating oil (WLO), estimated at around 17.5 million metric tons annually (Mohammed et al., 2013). This waste, laden with heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other toxic compounds from engine wear and degradation, poses a severe environmental and public health threat if not managed properly (Sanchez-Alvarracin et al., 2021; GEF Islands, n.d.). Historically, the disposal of WLO has been dominated by linear economic models, involving incineration or indiscriminate dumping, which has led to widespread environmental contamination (Motshumi et al., 2013; Zitte et al., 2016). In response, the global community, driven by increasing environmental awareness and the economic imperative of resource conservation, has shifted towards a circular economy model for WLO management (Saleem and Karim, 2020). The re-refining industry, which converts WLO into high-quality lubricating base oil and other valuable products, stands as a cornerstone of this paradigm shift (Motshumi et al., 2013). This process not only diverts a hazardous waste from the environment but also conserves finite crude oil resources, requiring only one-third of the energy needed to produce virgin base oil from crude oil (Speight & Exall, 2014).

This provides a comprehensive review of the primary global technologies for WLO re-refining. It delves into the mechanisms, performance, and environmental footprint of various processes, categorizing them for clarity and comparative analysis. This broad literature review is complemented by a detailed experimental case study focusing on vacuum distillation and clay treatment. This combination of a wide-ranging review with an in-depth empirical study aims to provide a holistic and authoritative perspective on the state of WLO re-refining, contributing to the body of knowledge for policymakers, industry stakeholders, and researchers seeking to advance sustainable waste management practices.

LITERATURE REVIEW: RE-REFINING TECHNOLOGIES

The evolution of re-refining technologies has been a direct response to both environmental regulations and the demand for higher-quality base oils (Kupareva et al., 2013; Dang, 1997). Early commercial processes, while effective in recovering base oil, often produced hazardous byproducts that were themselves difficult to manage. This led to the development of more sophisticated methods that prioritized environmental performance alongside product quality and economic viability (Audibert, 2011). Modern re-refining technologies can be broadly classified into several categories based on their primary mechanisms: acid-clay based, hydrogenation based, solvent extraction, filtration/adsorption, and thermal/chemical processes.

- **Acid-Clay Based Processes**

These processes represent some of the earliest commercialized methods for re-refining WLO, primarily relying on chemical and physical separation.

a. **Acid Clay (Meinken) Re-refining Process:** This was the first re-refining process to be widely commercialized in the 1960s (Oladimeji et al., 2018a). The process begins with pretreatment, typically using pre-flash or vacuum distillation, to remove water and light hydrocarbons. A significant amount of concentrated sulphuric acid (10-15 wt%) is then added to the dehydrated WLO (Kupareva et al., 2013a). This acid causes foreign compounds, such as additives and sulphides, to coagulate and form a sludge, which settles at the bottom and is subsequently separated. Following this, impurities like colloids and waxy substances are removed by filtration through clays, such as porcelain clay or aluminum silicate. The final step involves distillation to produce lubricant base oils (Udonne, 2011). While this method is relatively low-cost and simple to operate, it has severe drawbacks. It produces low-quality base oil with a yield of only 62-63% on a dry basis, which is often dark in color and has a high content of polycyclic aromatic hydrocarbons (4 to 17 times higher than virgin oil). Its major flaw is the generation of highly hazardous by-products like acid tar and oil-saturated clay, which led to its ban in most countries (Kupareva et al., 2013a). Modern multigrade engine oils are not effectively regenerated to their original quality by this technology (Oladimeji et al., 2018a).

b. **The Matthys-Garap Re-refining Process:** This process builds on the acid-clay approach but introduces additional steps for improved separation (Audibert, 2011). WLO is first settled or centrifuged at 80 °C before undergoing atmospheric distillation at 180 °C to remove water and light hydrocarbons. The residue is then subjected to vacuum distillation at 360 °C to produce various base oil cuts. The residue from this vacuum distillation is hot centrifuged to remove metal compounds and asphalt. All the oil fractions are then separately acidified at 40 °C, centrifuged to remove the acid sludge, and finally neutralized and bleached with clay (Audibert, 2011).

c. **Ecohuile (Sotulub) Re-refining Process:** The original Ecohuile process relied on vacuum distillation and acid-clay treatment after initial settling and emulsion treatment (Kupareva et al., 2013a). However, due to the environmental toxicity of acid-clay treatment, it was modified into the Sotulub process. The Sotulub process incorporates an alkaline additive, Antipoll (1-3 wt% pure sodium hydroxide), which helps to prevent corrosion and fouling of equipment. This mixture is then sent to a flash evaporator to remove water and light hydrocarbons. The dehydrated oil is heated and sent to a thin-film vacuum distillation column where asphaltic residues and heavy metal additives are separated. The distilled oil is then further treated with a small amount of Antipoll before fractionation into various base oil cuts. This process achieves a high base oil yield of 82-92% and produces base oils of acceptable quality with properties like a flash point of 216-230 °C and a viscosity index (VI) of 105-110 (Speight and Exall, 2014; Kupareva et al., 2013a).

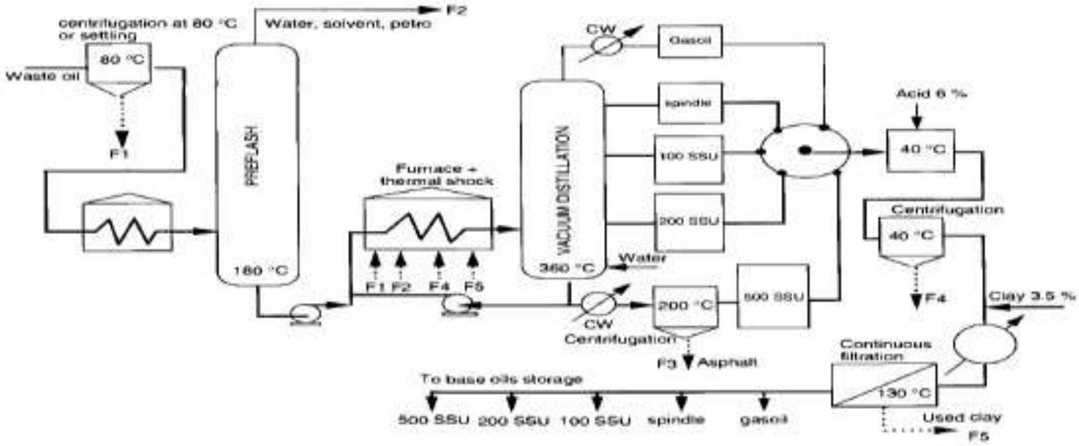

Figure 1.1: Process flow diagram of the Matthys–Garap re-refining process (Audibertt, 2011)

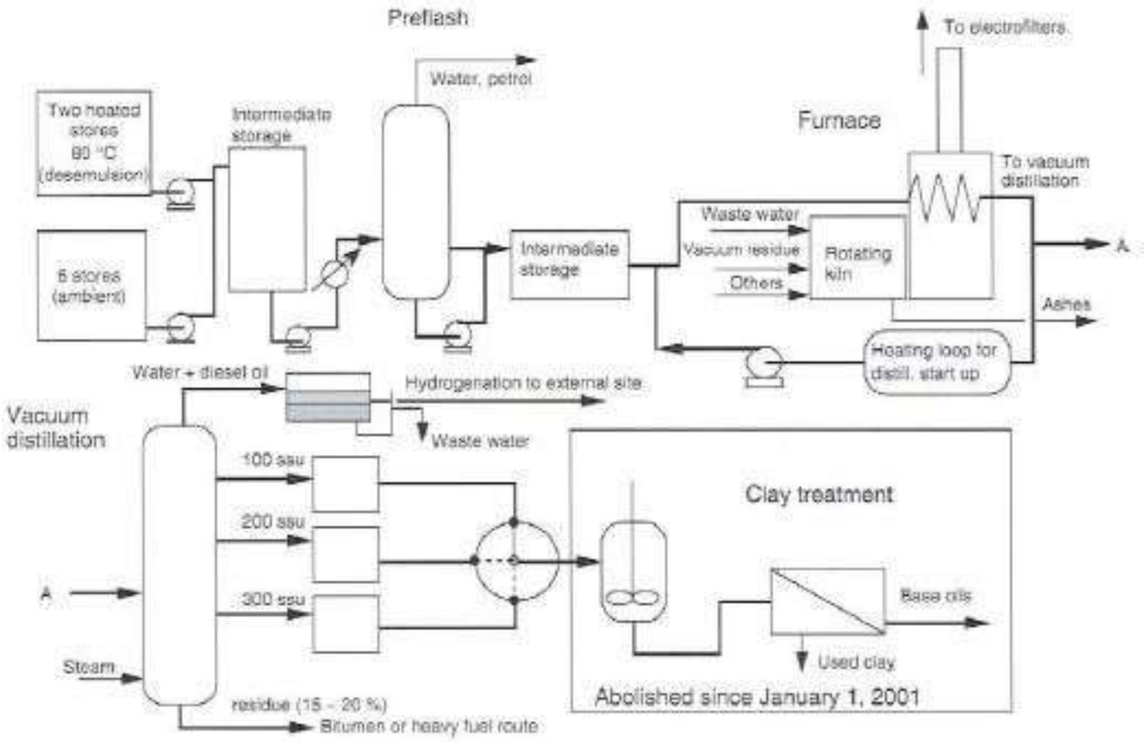

Figure 1.2: Process flow diagram of the Ecohuile waste lubricating oil re-refining process (Audibert, 2011)

- **Hydrogenation-Based Processes**

These technologies utilize hydrogen in the presence of catalysts to remove impurities and improve base oil quality, generally offering superior environmental performance and producing higher grade products (Kupareva et al., 2013a).

a. **Hylube Process:** This is an innovative "direct contact hydrogenation (DCH)" process developed by Universal Oil Products (UOP) that treats the entire WLO feedstock in a reducing hydrogen environment without any pretreatment (Kajdas, 2000b; Kupareva et al., 2013a). This approach prevents the formation of polymeric and carbonaceous compounds that cause fouling. It destroys halogenated and oxygenated compounds and involves catalytic processing of WLO into re-refined base oil stocks. The process includes a "guard" reactor with a large-pore-size catalyst to aggregate metallic contaminants, followed by a main hydrofinishing reactor that operates at 60-80 bar and 300-350 °C. This stage eliminates hetero-atoms like sulfur and nitrogen, and saturates multi-ring aromatic compounds to increase the viscosity index (Kupareva et al., 2013a). The Hylube process significantly increases the yield of high-quality product by 30% compared to other processes and eliminates the production of hazardous by-products. The heavy residue can be used as an asphalt blending component (Kajdas, 2000b). The capital cost for a 60,000 ton/year unit is estimated at $10 million, with product quality and operating costs being competitive with virgin base stock production (Kajdas, 2000b).

b. **Safety Kleen Re-refining Process:** This process combines wiped-film vacuum distillation with fixed-bed catalytic hydrotreatment (Kajdas, 2000b). It begins with an atmospheric flash drum to remove water and light solvents, followed by a vacuum column to strip fuel and heavy solvents. The vacuum distillation separates lubricating oil from heavy ends. The resulting oil cuts are then hydrotreated in stages over fixed beds of nickel-molybdenum catalyst. This step improves color, odor, and thermal stability while decreasing polynuclear aromatics and eliminating higher boiling halogenates and polar compounds (Kajdas, 2000b). The process produces base oil that meets API requirements for standard base oils, with a high viscosity index of 199 and low sulfur content (<50 μg/g) (Safety Kleen Corps, 2025). The light ends are used as fuel for the re-refinery, and aqueous by-products are treated (Kajdas, 2000b).

c. **Chemical Engineering Partners (CEP) Process:** A modification of the Mohawk re-refining process, the CEP process combines distillation, wiped film evaporation, and hydro processing (Audibert, 2011). It utilizes a chemical pretreatment with sodium hydroxide (80-170 °C) to prevent fouling and corrosion. Distillation separates water and light hydrocarbons, and high-vacuum distillation in a thin-film evaporator separates diesel fuel. The distillates then undergo hydro-purification at high temperature (315 °C) and pressure (90 bar) in a fixed-bed catalytic reactor (Kupareva et al., 2013a). This hydrofinishing step uses three reactors in series to eliminate nitrogen, oxygenated organic compounds, sulfur, and chlorine, aiming to meet API Group II base oil requirements (Speight & Exall, 2014). The process has a base oil yield of about 70% and is operational in a 60,000 tons/year plant in Hamina, Finland (Kupareva et al., 2013a).

d. **Kinetics Technology International (KTI) or Cyclon Re-refining Process:** This technology employs vacuum distillation and hydrofinishing without a dedicated pretreatment step (Oladimeji et al., 2018a). It uses atmospheric distillation to remove water and light hydrocarbons, followed by a special high-vacuum distillation unit (thin film or wiped film evaporator) that operates at temperatures not exceeding 250 °C in short bursts to minimize thermal stress and coking. The distilled oil is then mixed with hydrogen and passed through a fixed-bed catalytic reactor to remove hetero-atoms and enhance color (Kupareva et al., 2013a). The process accepts WLO contaminated with polychlorinated biphenyls (PCBs) and yields approximately 80% base oil. The residue from vacuum distillation has commercial value (Speight and Exall, 2014).

e. **Mohawk Re-refining Process:** This process combines vacuum distillation with a two reactor series hydrotreatment (guard-bed and hydrogenation reactors) (Kajdas, 2000a). It features a proprietary chemical pretreatment that precipitates contaminants, preventing fouling and extending catalyst life. The atmospheric distillation removes water and light hydrocarbons, and vacuum distillation recovers lubricating base oils. The guard-bed reactor, typically operating at 290-300 °C, removes metal contaminants (zinc, lead) that could poison the hydrotreating catalyst. The hydrogenation reactor, at a higher temperature, further improves product quality by significantly reducing sulfur, nitrogen, and halogen content (Ratiu et al., 2022). Its main drawback is the rapid deactivation of the catalyst (Kajdas, 2000a).

f. **PROP Re-refining Process:** This process integrates chemical demetallization and hydrogenation without a pre-treatment step (Dang, 1997). An aqueous solution of diammonium phosphate is blended with heated WLO to form insoluble metallic phosphates, which are then filtered out. The oil is then flashed to remove light hydrocarbons and water. Subsequently, the oil undergoes hydrogenation over a Ni/Mo catalyst after passing through a clay bed to adsorb catalyst poisons. This hydrogenation step eliminates sulfur-, nitrogen-, chlorine-, and oxygen-containing compounds, improving the base oil's color (Speight & Exall, 2014). The metallic phosphate by-product is a nonhazardous material suitable for landfill disposal (Kajdas, 2014).

g. **IFP/Snamprogetti Re-refining Technology (Selecto Propane Process):** A modification of the IFP process, this technology combines vacuum distillation and hydrogenation with a unique two-stage propane extraction (Kupareva et al., 2013a). After atmospheric distillation, the water-free WLO undergoes a first propane de-asphalting (PDA I) stage (70-95 °C) to extract dirt, sludge, additives, and polymers. The propane-containing oil is then vacuum distilled (300 °C) to separate low-viscosity base oils. The vacuum distillation residue is sent to a second propane extraction stage (PDA II) to further reduce metal content. The base oil cuts are then hydrogenated in a two-bed catalytic reactor to improve color and oxidation stability. This process produces high-quality base oil with a high yield of 74-80% (Awaja and Pavel, 2006).

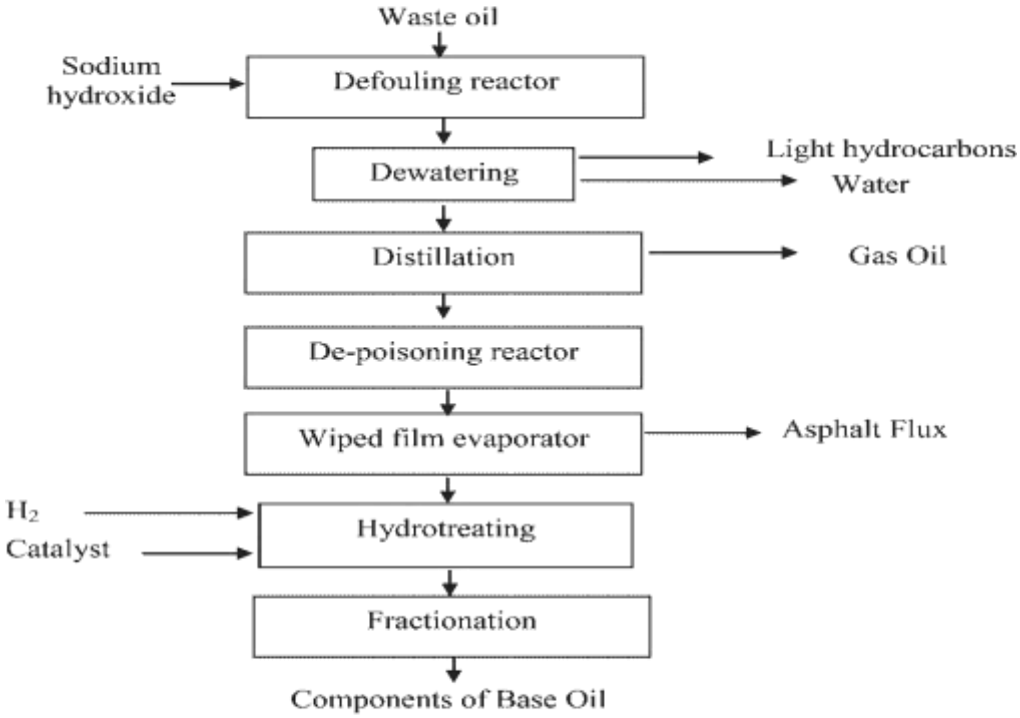

Figure 1.3: Block flow diagram of the Chemical Engineering Partners re-refining process (Kupareva et al., 2013a).

- **Solvent Extraction Processes**

These methods use specific solvents to selectively dissolve and remove undesirable components from WLO (Abdel-Jabbar et al., 2010).

a. **Mineralöl Raffinerie Dollbergen (MRD) Re-refining Process:** This is a solvent extraction process that uses N-methyl-2-pyrrolidone (NMP) as a powerful, non-toxic, low-volatility solvent with high selectivity for aromatic hydrocarbons, including PAHs (Kupareva et al., 2013a). Distillates from a vacuum distillation stage are fed into an extraction column, where NMP flows counter-currently to separate unwanted aromatic hydrocarbons and other contaminants. The raffinate (oil) and extract (solvent with impurities) phases are then sent to separate recovery sections to recover and recycle the NMP solvent. This process yields high-quality base oil at approximately 91% (Kupareva et al., 2013a).

b. **Recycled Oil Saves Energy (ROSE) Re-refining Technology:** Based on the Kerr-McGee ROSE™ process, this is a solvent de-asphalting process that uses supercritical solvent recovery (typically propane) (Hsu and Robinson, 2019). WLO is mixed with propane and charged to an asphaltene separator for phase separation. The heavier asphaltene fraction is collected, while the lighter mixture of propane and cleaner oil is sent to a de-asphalted oil (DAO) separator. Here, the DAO is collected, and supercritical propane is recovered and recycled. The primary benefit is significant capital and energy savings due to the efficient recovery of 93% of the propane solvent as a supercritical fluid, which reduces the size and complexity of the plant (Kajdas, 2014).

c. **The Lubrizol Corporation Re-refining Process:** This patented process involves immiscible solvent extraction combined with two-stage distillation (Speight and Exall, 2014). Initial vacuum distillation yields a first distillate fraction (water, light hydrocarbons, kerosene) and a lubrication oil fraction. The liquid residue can be used as a rubber or asphalt extender. The lubricating oil fraction then undergoes liquid-liquid extraction with an immiscible organic liquid (e.g., ethylene glycol) to remove soluble impurities. The lubricating oil is then distilled to remove any residual extracting agent, which is recovered and recycled. A modified version of this process eliminates the initial distillation, instead mixing the WLO feedstock with a diluent, removing insoluble impurities, and then performing liquid-liquid extraction and vacuum distillation.

d. **Texaco Incorporated Re-refining Process:** This process focuses on separating aromatic and unsaturated components from saturated components in WLO using n-methyl-2pyrrolidone as the solvent (Hsu and Robinson, 2019). WLO and NMP are contacted in a countercurrent flow in a tower (50-120 °C, 1:1 to 3:1 solvent to oil ratio), producing a solvent-refined base oil and an extract stream. The extract stream is then cooled and decanted to recover more oil, and the solvent is recovered via flash towers and recycled.

e. **The Delta Central Refining Inc. process:** This is a seven-stage process combining multistage distillation with solvent extraction using tetrahydrofurfuryl alcohol. The solvent is reported to have high selectivity, high raffinate yields, and low toxicity. The process involves a series of evaporators to remove water, light hydrocarbons, and fuel oil before the light lubricating oil fraction undergoes liquid-liquid extraction. The raffinate and extract streams are then processed for solvent recovery, yielding finished light and heavy lubricating base oil products (Speight and Exall, 2014).

f. **The Krupp Koppers Re-refining Process:** This process uses a supercritical solvent, such as ethane or propane, to separate lubricating base oil from impurities. After filtration and atmospheric distillation, the bottom stream is injected into an extraction column (20-80 °C, 50-150 bar) where the supercritical solvent extracts soluble oil components. The oil is then separated from the solvent by de-pressurizing, and the recovered solvent is recycled. The lubricating base oil fraction can then undergo hydrogenation, with an option for bleaching clay, to further improve quality.

Table 1.1: Properties of Base oil products from the MRD Solvent extraction re-refining process using NMP as solvent (Kupareva et al. 2013a)

Properties	**Base oil**		
	Light grade (KS 100)	**Medium grade (KS 150)**	**Heavy grade (KS 200)**
Density @ 15 °C kg/m^3	852 – 856	857 – 860	860 - 865
Flash point °C	>220	>230	>230
Pour point °C	-12	-9	-9
Kinematic viscosity @ 40 C mm^2/s	22 – 26	32 – 36	40 – 46
Kinematic viscosity @ 100 C mm^2/s	4.4 – 4.9	5.5 – 5.6	6.4 – 7.1
Viscosity index	108 – 112	110 – 115	110 - 115
Sulphur wt%	≤ 0.25	≤ 0.25	≤ 0.25

- **Filtration/Adsorption Based Processes**

These processes rely on physical separation using membranes or adsorbent materials like clay, often as a final finishing step (Al-Bidry & Azeez, 2020).

a. **BERC / NIPER Re-refining Process:** This technology is similar to the KTI process but includes a solvent treatment stage using a blend of 2-propanol, 1-butanol, and methyl ethyl ketone (1:2:1 ratio) to precipitate sludge and metallic additive components (Dang, 1997). This solvent extraction stage effectively eliminates coking and fouling precursors. After solvent recovery and fractional distillation, the oil undergoes either hydrofinishing or clay treatment to improve its odor and remove color (Kajdas, 2014).

b. **Regelub Re-refining Process:** Developed as a replacement for the acid-clay process, Regelub is based on ultrafiltration as a physical separation step (Audibert, 2011). It begins with centrifugation to remove water and sediments, followed by pre-flash dehydration. The dehydrated oil is heat-treated to destroy dispersing agents and precipitate diesel oil. The heat-treated oil is then centrifuged to separate oil sludge before undergoing ultrafiltration through inorganic (ceramic) membranes (250-300 °C, up to 20 bar) to separate impurities. The final base oil (raffinate) is then catalytically hydrogenated to remove soluble compounds and residual nitrogenous compounds (Audibert, 2011).

c. **The Ciora and Liu Process:** This process combines WLO filtration with clay treatment to eliminate odor and color from the filtrate (Speight and Exall, 2014). It also incorporates a system for the regeneration and reuse of the clay. Prefiltered and heated WLO is sent to a ceramic membrane filtration unit. The permeate, which may still retain color and odor, is then treated with anionic clay powder (hydrotalcite) at 70 °C. This clay can be thermally regenerated in the presence of air to restore over 80% of its adsorption capacity.

d. **Other Conceptual Ultrafiltration Membrane Re-refining Processes:** Recent research has explored the use of hydrophobic polymer membranes, such as polypropylene (PP), polyethersulphone (PES), and polyvinylidene fluoride (PVDF), for the ultrafiltration of WLO (Widodo et al., 2020). These membranes have demonstrated high effectiveness in removing ash content (90-99%), water (78-82.5%), carbon residue (52.6-65.9%), and various metals. The development of superhydrophobic membranes (water contact angle >150°) is a key area of interest, as their high resistance to wetting significantly enhances membrane performance in non-aqueous systems like WLO re-refining (Himma et al., 2019).

e. **ORYX Re-refining Process:** This process is a vacuum distillation process that uses four distillation columns (modules) in a series (UNEP, 2012). The first three modules remove diesel, water, and base oil fractions, leaving a residue of bright stock, carbon, and other heavy components. The base oil products from the second and third modules are considered intermediate products and require further treatment with activated alumina clay in the fourth module. This process segregates residues without using chemicals, coagulants, or acid, leading to a reduced quantity of non-toxic waste that can be safely disposed of (UNEP, 2012).

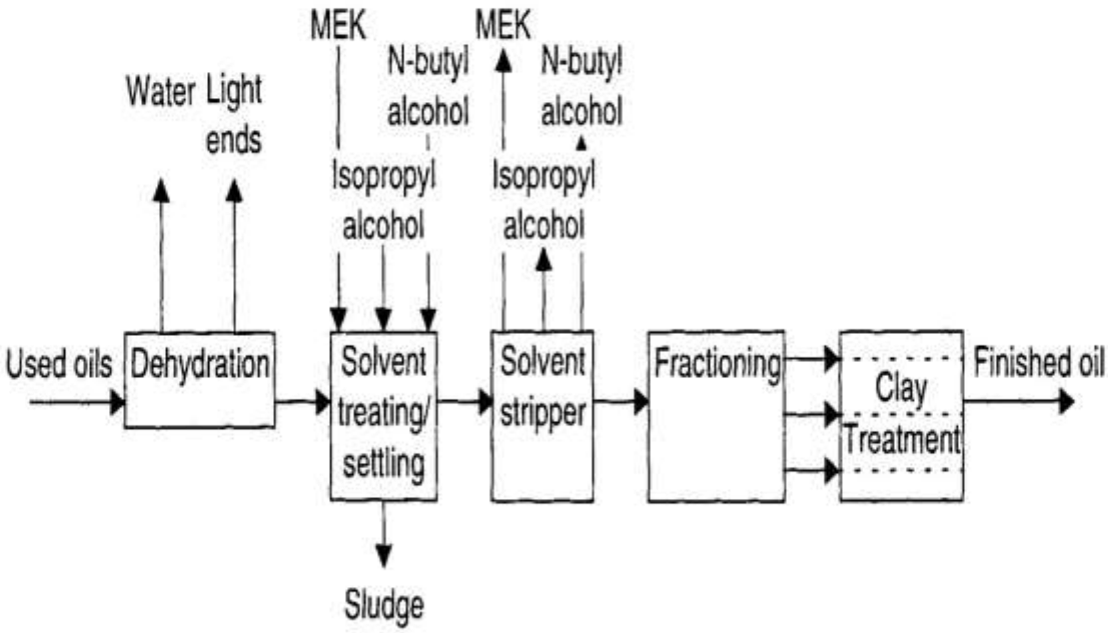

Figure 1.4: Block flow diagram of the BERC / NIPER re-refining process (Dang, 1997)

• **Thermal/Chemical Processes**

This category includes processes that use heat to crack or break down WLO components or chemical reactions for contaminant removal.

a. **Propak Thermal Cracking Process:** This process incorporates screening and dewatering stages, followed by a thermal cracking section, a separation/distillation stage, and finally, purification and stabilization (Kupareva et al., 2013a). The dehydrated WLO is heated in a fired process heater and thermal cracking section under specific pressure, temperature, and residence time conditions to convert it into gas oil boiling range hydrocarbons. The vaporized gas stream is distilled to separate naphtha from gas oil, which is then stabilized to produce diesel fuel. The Propak process allows for the production of gas oils, diesel, and re-refined base oil and is characterized by a wide range of operational and product flexibility.

b. **Degussa Process:** This re-refining process uses a sodium-based method, primarily for waste electrical insulating oils contaminated with polychlorinated biphenyls (PCBs) (UNEP, 2012). Dispersed metallic sodium is mixed with dehydrated and de-gassified waste insulating oil in a vessel. The sodium reacts with PCBs, converting them into non-toxic compounds (common salt and hydrocarbon residues), which are then removed as sludge via centrifugation. The resulting sludge, being non-toxic, can be disposed of as industrial waste. This process can re-refine waste oils with up to 7,000 ppm of PCBs to achieve a concentration lower than the detectable limit of 2 ppm (UNEP, 2012).

Advanced and Niche Re-refining Technologies

In addition to the primary categories, a variety of advanced and specialized technologies exist to address specific waste streams or to achieve particular outcomes.

- **Ultrafiltration Membranes:** These processes use polymer or ceramic membranes to physically separate contaminants from the oil at low temperatures and pressures, offering high energy efficiency. They are effective at removing metal particles, dust, and polymerization products but can be susceptible to fouling (Widodo et al., 2020; Cao et al., 2009).
- **Degussa Process:** This highly specialized chemical process uses dispersed metallic sodium to detoxify waste electrical insulating oils contaminated with polychlorinated biphenyls (PCBs), converting them into non-toxic compounds (UNEP, 2012).
- **Thermal Cracking:** Technologies like the Propak thermal cracking process convert waste oil into gas oil-boiling-range hydrocarbons. This method offers a high degree of flexibility to produce diesel-like fuels but may not be ideal for producing high-quality lubricating base oils (Kupareva et al., 2013a).

The diversity of these technologies underscores that no single re-refining method is universally superior. The optimal choice depends on a complex interplay of the waste oil feedstock's composition, the desired end product, available capital, and the regulatory environment.

Strategic Considerations for Sustainable Implementation

The long-term economic and environmental sustainability of any re-refining operation is fundamentally tied to the effective management of all output streams. A true circular economy model extends beyond the primary product to encompass the valorization of all by-products, converting them from a liability into an asset.

The Criticality of By-product Valorization

Modern re-refining technologies are designed to produce multiple valuable streams from a single feedstock. For instance, the distillation bottoms from vacuum distillation, which contain high concentrations of heavy metals, carbon, and asphaltenes, are no longer treated as a waste. These residues can be repurposed as asphalt extenders for road construction or used as a fuel source in industrial furnaces fitted with emission controls. This approach not only prevents the disposal of a hazardous material but also creates an additional revenue stream, significantly improving the economic viability of the entire process.

The Circularity of Spent Clay

The management of spent clay provides an excellent example of this circularity in practice. Used clay, a key component in many re-refining and finishing processes, is classified as a hazardous waste due to the heavy metals and residual oil it adsorbs. Historically, this was a major environmental and economic problem, with much of the spent clay being discarded in landfills. However, modern methods have focused on regenerating and reusing this material.

Regeneration processes, which typically involve solvent extraction and/or thermal treatment, serve a dual purpose. They first recover the valuable oil entrained within the clay, which can constitute a significant portion of its weight. Subsequently, these processes restore the clay's adsorption capacity, allowing it to be used multiple times before final disposal (ResearchGate, 2016). For example, the experimental process described in the provided research material details a method for draining the saturated clay and then heating it to 200-250 °C under vacuum to burn off impurities. The final inert mineral residue from this process can be repurposed as a raw material for construction, cement production, or soil improvement, thereby completely closing the loop and eliminating the need for landfilling. This strategic approach transforms a costly and hazardous waste stream into a valuable, reusable asset, making the re-refining operation more sustainable and profitable.

Implementation Strategy and Policy Recommendations for Nigeria

The Policy Vacuum and Regulatory Challenges

A key finding from the research material is the critical disconnect between the environmental and economic realities in Nigeria and the existing regulatory framework. There is currently no organized national policy for the collection, storage, or recycling of waste lubricating oil, leading to indiscriminate disposal and widespread pollution. While legislative instruments exist to combat environmental degradation, enforcement by agencies like the National Environmental Standards and Regulations Enforcement Agency (NESREA) is often weak due to a combination of political dependence on oil revenues and corruption. This policy-implementation gap is the single greatest barrier to establishing a viable re-refining industry in the country. A sustainable re-refining industry cannot thrive without a robust regulatory environment that mandates waste collection and penalizes illegal disposal.

A Phased Circular Economy Model for Nigeria

To overcome the policy-implementation gap and effectively establish a re-refining industry, a phased approach is necessary.

- **Phase 1: Regulatory and Foundational Infrastructure:** The first and most critical step is to create a comprehensive legal framework for waste oil management. This must include clear policies that designate waste lubricating oil as a hazardous material, mandate its separate collection, and hold generators accountable for its proper disposal. This will create a reliable supply chain of feedstock, which is essential for the economic viability of any re-refining plant.

- **Phase 2: Pilot and Scale-Up:** The next step is to encourage private sector investment in modular, smaller-scale re-refining plants. The advanced vacuum distillation and clay treatment process is a proven, cost-effective technology that aligns with Nigeria's technical and capital capabilities. It produces a commercially viable product (API Group I base oil) and a usable diesel by-product, providing a rapid return on investment. Crucially, this phase should incorporate the concept of a secondary circular economy loop for the management of by-products. The spent clay from the process, which contains heavy metals and entrained oil, should not be landfilled. Instead, systems should be put in place for its regeneration or its use as a raw material in other industries, such as construction.
- **Phase 3: Integration and Advanced Technology:** As the industry matures and capital becomes available, a long-term strategy should focus on transitioning to more advanced, high-quality technologies. Investing in hydrogenation-based systems would enable the production of API Group II base oils, which would allow the domestic industry to compete in higher-end markets, further reducing import dependence and increasing the value of the re-refined product (Kupareva et al., 2013a).

CONCLUSION

This report has systematically analyzed the technical, economic, and environmental profiles of various re-refining technologies, affirming that re-refining is a powerful solution to Nigeria's waste lubricating oil challenges. The vacuum distillation and clay treatment process stands out as a robust and economically viable starting point for a developing economy. Its ability to produce a high-quality base oil and a diesel by-product, while minimizing hazardous waste, presents a clear path toward sustainable industrialization. However, the success of this model hinges on a strong regulatory framework and institutional commitment to a circular economy. By transforming waste oil from a pollutant into a national asset, Nigeria can not only protect its environment and public health but also foster economic growth, create jobs, and reduce its overreliance on foreign imports. The path forward is clear: a phased approach that starts with sound policy, leverages proven technology, and continuously seeks innovative ways to close the loop on every waste stream.

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