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Original Research Paper

Efficient Reclamation of Base Oils from Spent Lubricants Using Novel Ternary Solvent Combinations

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ABSTRACT

To address the environmental hazards of improper disposal of used engine oils and reduce reliance on fossil resources, this study investigates a novel approach for recovering base oils from spent lubricants using two innovative ternary solvent systems. System (a) comprised acetonitrile (35 vol.%), xylene (40 vol.%), and n-heptane (25 vol.%), while system (b) included dimethyl sulfoxide (35 vol.%), toluene (40 vol.%), and n-hexane (25 vol.%). A series of laboratory-scale extractions were performed under varying solvent-to-oil ratios (1:1 to 6:1 wt./wt.), temperatures (60–90°C), and mixing durations (15–60 min), with constant stirring at 500 rpm. The extracted oils were bleached using hydrogen peroxide (5–15% v/v) and activated bentonite (1–5 g/100 mL). System (a) exhibited superior performance, achieving a maximum base oil recovery of 86.6% at 70°C, 6:1 ratio, and 60 minutes, compared to 74.4% for system (b) at 80°C under the same conditions. The use of tailored ternary solvent systems combining polar and non-polar components highlights a novel and efficient approach to oil regeneration. Beyond high recovery yields, this method offers clear environmental advantages and industrial scalability, supporting sustainable waste oil management.

INTRODUCTION

Lubricating oil is a critical fluid widely used in automotive and industrial machinery due to its essential functions in reducing friction, dissipating heat, and protecting moving mechanical components. In internal combustion engines, lubricating oil facilitates heat transfer and minimizes wear between engine parts (Zhou et al. 2019). The base oil, which constitutes the primary component of lubricants, is typically derived from petroleum refining or synthesized through chemical processes to produce synthetic variants (Kajdas. 2000).

Over time, lubricating oil undergoes degradation as it accumulates a variety of contaminants, including metallic particles (e.g., iron, copper, lead, and zinc), oxidation products, water, soot, combustion residues, sulfur compounds, and ash (Armioni et al. 2024). To enhance performance and extend oil service life, various additives are incorporated, such as antioxidants, pour point depressants, corrosion inhibitors, and detergents (Han. 2024). However, during operation, both internal engine wear and external environmental exposure contribute to the deterioration of oil quality (Adewole et al. 2019).

The improper disposal of used lubricating oils poses serious environmental risks, including soil and water contamination. Moreover, the increasing demand for lubricants and declining availability of crude oil resources have intensified the need for sustainable oil regeneration technologies. Recycling used lubricating oils not only reduces environmental impact but also offers economic benefits by recovering valuable base oils for reuse (Sadeek et al. 2014).

Various methods have been developed for the re-refining of waste lubricants, including acid/clay treatment, vacuum distillation, adsorption, and solvent extraction (Mustapha et al. 2021). Among these, solvent extraction has emerged as a particularly

promising approach due to its ability to selectively remove polar impurities, additives, and degradation products while preserving the base oil. An ideal solvent system ensures high miscibility with the oil and efficient separation of contaminants (El Din et al. 1987).

Previous studies have explored both binary and ternary solvent systems to enhance extraction efficiency. For example, Benjamin et al. (2022) demonstrated the effectiveness of a methanol/n-hexane mixture, achieving a recovery rate of 95.7% with significant improvement in oil quality. Mu'azu et al. (2024) used a hexane–methyl ethyl ketone system and optimized process conditions using statistical methods, obtaining a recovery of 77.2%. Olaremu (2024) investigated ternary solvent systems involving toluene, 1-butanol, and alcohols, showing that such systems can yield re-refined oil with properties com-parable to virgin lubricants. Similar findings were reported by Osman et al. (2021) and Adewole et al. (2019), who highlighted the importance of solvent selection and post-treatment in achieving acceptable physicochemical properties. However, most studies either focused on binary mixtures or conventional ternary systems without exploring the full potential of novel sol-vent combinations that may offer improved separation efficiency, lower toxicity, and reduced cost.

Despite the promising advances in solvent-based oil regeneration, there remains a notable gap in optimizing ternary solvent systems for both technical efficiency and economic feasibility. Previous studies often used traditional or partially optimized combinations, with limited exploration into novel solvents or synergistic solvent interactions. The novelty of this study lies in the design and evaluation of previously untested ternary solvent combinations, selected based on polarity, solubility parameters, and compatibility with degradation compounds. Unlike earlier research, this work systematically integrates extraction with oxidative and adsorptive post-treatments, providing a holistic, scalable, and environmentally sustainable process for waste oil re-refining.

2. MATERIALS AND METHODS

2.1. Materials

The spent lubricating oils were gathered from various automobile service stations, each representing different operational conditions. A Base oil sample (Stock 60), obtained from the Daurah Refinery in Iraq, was employed as a reference standard for evaluating the regenerated oil's quality. All physicochemical properties of both the base oil and the used lubricating oils were analysed at the Research Centre of Chemical and Petrochemical Laboratories, affiliated with the Iraqi Ministry of Industry. These properties are suitably illustrated in Table 1. On the other hand, the solvents used for the extraction process included acetonitrile, xylene, dimethyl sulfoxide (DMSO), n-hexane, and toluene, all of which were procured from Loba Chemie (India), in addition to n-heptane, which was obtained from J.T. Baker. It is worth mentioning that all these solvents are analytical grade with 99% purity.

Table 1. Specifications for both base oil and used lubricating oil

Properties	Used lubricating oil	Base oil (Stock 60)
Specific gravity	0.89	0.82
Pour point oC	-43	-12
Flash point oC	211	231
Kinematic Viscosity at 100 oC, cst	6.8	8.1
Total acid number (TAN) mg/g.	9.69	3.37
Ash wt.%	0.52	0
Carbon Res. wt.%	1.1	0.04
Color	Too dark	2

2.2. Extraction Experiments

Figure 1 illustrates the scientific methodology applied in the treatment of spent oil. The following provides a detailed explanation of each step involved in the process.

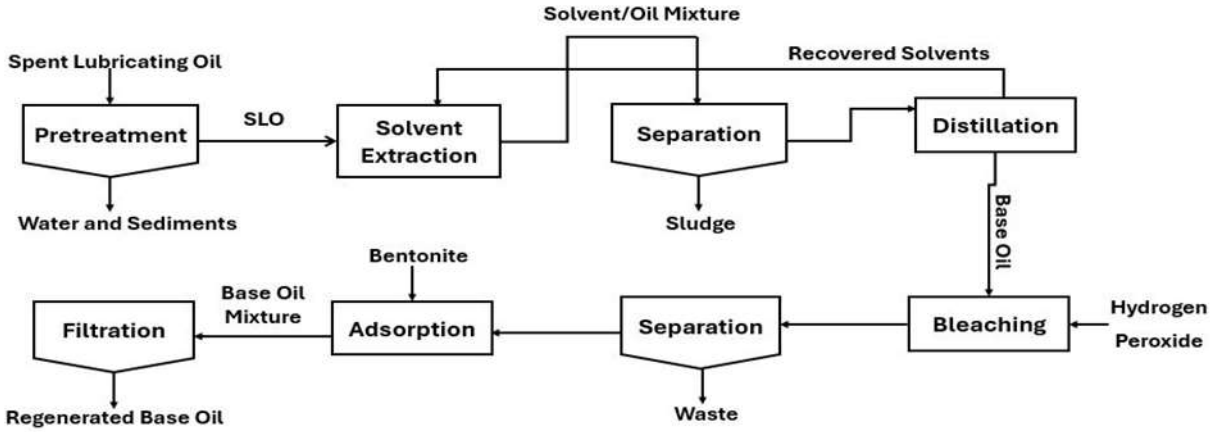

Fig. 1. Process Diagram for the Regeneration of Used Lubricating Oil by Solvent Extraction and Distillation Methods.

2.2.1. Pretreatment

The pretreatment of the spent lubricant feedstock was carried out in two sequential steps: filtration and dehydration, with the purpose of removing solid contaminants and residual water, respectively, prior to solvent extraction.

1-Filtration:

This step was performed to eliminate suspended solid impurities such as dust, metal particles, and degraded additives. The filtration setup consisted of a Büchner funnel fitted with a 0.55 µm ceramic micro-filter connected to a 1000 mL conical flask. A vacuum pressure pump (Model V-I120, 230V/50–60 Hz, 1/4 HP) was used to apply suction and expedite the fil-tration process.

2-Dehydration (Water Removal):

After filtration, the oil was subjected to a dehydration process, which refers specifically to the removal of residual moisture or water content in the spent lubricant. This was done to avoid water interference during the subsequent solvent extraction step. The filtered oil was placed in a 1000 mL glass beaker and heated to 120 °C on a hot plate equipped with a magnetic stirrer (Model SH-4) to ensure uniform heating. A thermometer was used to monitor the temperature throughout the process. The operation was conducted inside a ventilated vacuum hood room to minimize odor emission and mitigate potential health and safety risks associated with heating spent lubricants. The endpoint of dehydration was determined by the ab-sence of visible water bubbles and the stabilization of the oil's appearance.

2.2.2. Solvent Extraction

A laboratory-scale batch extraction unit, which consist of was utilized to conduct the extraction stage of used oil treatment. Two solvent systems were formulated and examined: Solvent Mixture A, consisting of 35% acetonitrile, 40% xylene, and 25% n-heptane; and Solvent Mixture B, composed of 35% dimethyl sulfoxide (DMSO), 40% toluene, and 25% n-hexane. The experimental parameters included varying solvent-to-oil ratios (1:1, 2:1, 4:1, and 6:1) (wt. /wt.), extraction temperatures (60, 70, 80, and 90 °C), and contact times (15, 30, 45, and 60 minutes), while maintaining a constant stirring speed of 500 rpm.

After mixing, the system was allowed to settle under static conditions for 24 hours to facilitate phase separation, following established methodologies reported in the literature (Osman et al. 2018, Abdulaziz & Mahmood. 2016). Upon reaching equi-librium, the two phases were separated using a separating funnel. The extraction process led to the formation of an upper phase containing the treated oil and solvent, and a lower phase rich in contaminants, precipitates, and sediments. The upper layer was subjected to filtration and solvent evaporation to isolate the recovered base oil.

The impact of solvent type and operating conditions on the physicochemical properties of the treated oil was thoroughly in-vestigated, providing insight into the efficiency and selectivity of the solvent extraction process for used oil regeneration.

2.2.3. Solvent Recovery

The extracted phase, consisting of a mixture of solvents and base oil, was subjected to solvent recovery using a rotary vacuum evaporator, as illustrated in Fig. 2. The separation process was conducted under a vacuum pressure of 100 mbar, with the oil bath maintained at 100 °C and a rotation speed of 150 rpm. During this process, the recovered solvent was collected in a 500 mL conical flask, while the purified base oil remained in the round-bottom flask.

Fig. 2. Rotary Evaporator System.

2.3 Bleaching

2.3.1. Hydrogen Peroxide

Hydrogen peroxide (30% w/w) was utilized in varying volume ratios of 5%, 10%, and 15% (v/v) relative to the recovered oil. The treatment was carried out by placing the recovered oil in a 150 mL beaker immersed in a water bath maintained at 65 °C. The hydrogen peroxide was then added, and the mixture was agitated at a constant speed of 500 rpm for 60 minutes. Following the reaction, the samples were centrifuged at 15,000 rpm for 30 minutes to facilitate the removal of oxidized compounds and heavy impurities.

2.3.2. Bentonite Clay

Dry, clean bentonite was activated using diluted sulfuric acid at a ratio of 1:10 (w/w), following procedures established in previous studies (Abu-Elella et al. 2015, Aziz et al. 2011, Bhattacharyya et al. 2014). The activated clay was added to the recovered oil at concentrations ranging from 1 to 5 g per 100 mL. The mixture was stirred at a constant speed of 500 rpm and heated to 90 °C for 1 hour to ensure effective contact and adsorption. After the treatment, the pH was neutralized by washing the mixture several times with distilled water. The spent clay was then separated from the base oil using vacuum filtration.

2.4. Analysis of samples

2.4.1. Specific gravity

The specific gravity of used lubricating oils and the final extracted base oil was determined in accordance with standard test methods ASTM D1298-12 (ASTM International. 2012)conforming to specification E 100 or ISO 649-1and uncertainty ±0.001. An increase in specific gravity is generally associated with a higher aromatic content in the oil. Accordingly, used engine oil exhibits elevated specific gravity values due to the presence of vari-ous contaminants and degradation products.

2.4.2. Pour point

The pour point of both the used lubricating oils and the extracted base oil was measured using an automatic pour point tester (Model CAPP-I, Germany). The procedure followed the standard method ASTM D97-04 (ASTM International, 2017) and also complied with ISO 3016:2019, which define the pour point as the lowest temperature at which the sample shows any visible movement, indicating that the fluid can no longer flow under specified test conditions. The instrument was regularly calibrated using certified reference materials traceable to international standards, in accordance with the manufacturer's recommendations and ISO/IEC 17025 guidelines. The measurement uncertainty for the pour point determination was estimated to be ±0.43 °C.

2.4.3. A kinematic viscosity

The kinematic viscosity of both the used lubricating oils and the extracted base oil was measured using a continuous sensing viscometer (Model SVM3001, Germany). The measurement followed the standard method ASTM D445-04 (ASTM International, 2017), and also complied with ISO 3104:2020, which specifies the procedure for determining the kinematic viscosity of petroleum products. Kinematic viscosity is defined as the ratio of dynamic viscosity to fluid density, and it is an important

indicator of how the oil flows under specific temperature conditions. The results were compared with the standard specifications provided by Dura Refinery to evaluate the quality of the recovered base oil. The instrument was calibrated regularly using certified reference oils that are traceable to international standards. Calibration procedures followed both the manufacturer's instructions and the guidelines of ISO/IEC 17025 to ensure reliable and accurate measurements.The measurement uncertainty for the viscosity test was estimated to be ±0.03 cSt, based on instrument precision and repeated measurements.

2.4.4. Total acid number

The total acid number (TAN) of both the used lubricating oils and the extracted base oil was measured using a laboratory titration instrument (Model AT-500N, Germany). The analysis was conducted in accordance with the standard test method ASTM D664-24 (ASTM International, 2024), and was also compliant with the international standard ISO 6619:2009, which outlines the procedure for determining the acidity of petroleum products using potentiometric titration. TAN is a key indicator of oil degradation, as it reflects the presence of acidic compounds resulting from oxidation and chemical breakdown. Higher TAN values indicate increased acidity, which is typically associated with the formation of corrosive by-products and signal the need for oil replacement. The measured TAN values were compared against the reference specifications provided by Dura Refinery to assess the condition and quality of the recovered base oil. The titration instrument was routinely calibrated using certified reference solutions traceable to international standards. Calibration procedures followed both the manufacturer's recommendations and ISO/IEC 17025 guidelines to ensure measurement accuracy and reliability. The measurement uncertainty associated with the TAN determination was estimated to be ±0.04 mg KOH/g, based on repeatability studies and instrument performance data.

2.4.5. The flash point

The flash point of both the used lubricating oil and the extracted base oil was measured using the Cleveland open cup method with an automatic tester (Model P/N 135402, Germany), in accordance with ASTM D92 (Montemayor et al., 2002). The procedure also complies with the international standard ISO 2592:2017, which specifies the determination of flash and fire points of petroleum products using the Cleveland open cup apparatus.The flash point is defined as the lowest temperature at which the vapor above a liquid ignites upon application of a test flame. It serves as a key parameter for evaluating the flammability and volatility of oils, and is critical in assessing the thermal safety and storage stability of petroleum-based products.The instrument was calibrated routinely using certified reference materials traceable to international standards, following both the manufacturer's instructions and the requirements of ISO/IEC 17025 to ensure measurement reliability.The measurement uncertainty for flash point determination was estimated to be ±0.21 °C, based on equipment specifications and validation through repeated measurements.

2.4.6. Ash content

The ash content of both the used lubricating oils and the extracted base oil was measured using a high-temperature furnace (Petro-test model M110, Germany). The test followed the standard method ASTM D482-03 (ASTM International, 2010) and the international standard ISO 6245:1999, which both describe how to determine ash in petroleum products.Ash content shows how much solid residue remains after burning the oil, which helps assess if the oil is suitable for certain uses. The results were compared to the specifications from Dura Refinery to check the quality of the recovered base oil.The furnace was calibrated regularly with certified reference materials, following both the manufacturer's instructions and ISO/IEC 17025 standards to ensure reliable results.The uncertainty of the ash content measurement was estimated to be ±0.01 wt.% based on repeated tests and instrument performance.

2.4.7. carbon residue

The carbon residue of both the used lubricating oils and the extracted base oil was determined using a laboratory oven (model K27190, USA) equipped with a lower chamber. The test was performed according to the standard method ASTM D189-01 (ASTM International, 2017). This method measures the amount of heavy, non-volatile materials that remain as residue when the oil is heated to high temperatures, serving as an indicator of oil stability and contamination.The procedure also complies with the international standard ISO 10370:2017, which specifies the determination of carbon residue in petroleum products using a similar method.The oven was regularly calibrated using certified reference materials, following manufacturer guidelines and ISO/IEC 17025 standards to ensure accuracy and reliability of measurements.The measurement uncertainty for the carbon residue test was estimated to be ±0.1 wt.%, based on instrument precision and repeatability tests.

2.4.8. Color measurement

The color of both the used lubricating oils and the final extracted base oil was measured using a PFX 995/950 pigment meter (Petro-test, Germany). The test followed the standard method ASTM D1500-24 (ASTM International, 2024), which is the approved procedure for determining the color of transparent or semi-transparent petroleum products.This procedure also complies with the international standard ISO 2049:2020, which describes methods for color determination in petroleum products.The measured color values were compared with the reference specifications provided by Dura Refinery to evaluate the

level of oil degradation. Color measurement serves as an important indicator of oil quality and the efficiency of treatment and recovery processes.The instrument was regularly calibrated using certified reference standards, following the manufacturer's instructions and ISO/IEC 17025 guidelines to ensure accurate and reliable results.The measurement uncertainty associated with the color determination was estimated to be ±0.1 ASTM color units, based on repeatability and instrument specifications.

3. RESULTS OR RESULTS AND DISCUSSIONS

3.1. Properties of used, treated, and stock 60 lubricating oil

In this study, two different solvent mixtures, referred to as Mixture A and Mixture B, comprising both polar and non-polar solvents, were used to regenerate used lubricating oil. The selection of solvents was based on their polarity and solubility properties. Non-polar solvents effectively dissolve base oil components while facilitating the precipitation of contaminants such as sludge and varnish. In contrast, polar solvents enhance the coagulation and removal of polar degradation products due to their high dielectric constant and solubility index.

This behavior is in line with the classical principle of "like dissolves like", which states that solvents tend to dissolve solutes with similar polarity (Hildebrand & Scott, 1950). Non-polar solvents like n-heptane and xylene are chemically compatible with hydrocarbon-based base oils, promoting selective solubilization. Polar solvents such as acetonitrile and DMSO, on the other hand, interact more efficiently with oxidized or polar degradation compounds, enhancing their separation from the bulk oil. The synergistic effect of combining both polar and non-polar solvents contributes to the selective removal of contaminants while preserving the base oil fractions.

Additionally, the efficiency of the solvent mixtures can also be interpreted through the lens of molecular diffusion theory. According to Fick's Law, the concentration gradient between the spent oil and solvent phases drives mass transfer, which is further accelerated by increased temperature and agitation. This enhances the extraction of both low and high polarity contaminants (Cussler, 2009). The improvement observed with Mixture A may also be attributed to its broader solubility parameter range, allowing better compatibility with the diverse chemical nature of contaminants present in used oil (Marcus, 1997).

The physical and chemical properties of the used, treated, and fresh (Stock 60) lubricating oils are summarized in Table 2. The used oil exhibited a noticeable deterioration in key properties due to oxidation, thermal degradation, and contamination with fuel and water. Specifically, the flash point and pour point were significantly reduced, indicating the presence of volatile compounds and suspended matter. Additionally, the specific gravity and carbon residue increased as a result of oxidation and contamination, consistent with findings by Olaremu (2024).

The kinematic viscosity of the used oil decreased, primarily due to the breakdown of viscosity modifiers, dilution with fuel, and additive depletion. A significant increase in total acid number (TAN) was also observed, reflecting the formation of acidic oxidation products, which is an important indicator of oil degradation.

Upon treatment with the solvent mixtures, especially Mixture A, the regenerated oil demonstrated remarkable improvement in all assessed properties. The specific gravity decreased from 0.89 in the used oil to 0.81, approaching the value of fresh oil (0.82 g/cm³). The pour point improved by 4 °C in the oil treated with Mixture A compared to that treated with Mixture B, indicating enhanced removal of waxes and polar impurities. The flash point increased substantially after regeneration, reflecting the successful elimination of volatile contaminants.

The kinematic viscosity was restored to levels comparable with fresh oil, suggesting effective removal of oxidized and decomposed compounds. Carbon residue and ash content decreased significantly, confirming the effective separation of carbonaceous materials and inorganic additives. The TAN was reduced to values near those of the fresh oil, indicating improved chemical stability.

Overall, Solvent Mixture An Outperformed Mixture B, delivering oil properties closest to those of the fresh base stock. This superior performance is attributed to the optimized combination of polar and non-polar solvents, providing enhanced solubility and diffusion capacity across a broad range of degradation products. These findings are consistent with prior work by Akpoveta et al. (2024), who highlighted the critical role of

Table 2. Physical and chemical parameters of utilized and refined oils derived from the extraction technique employing a solvent mixture (A, B) and base oil (Stock 60)

Properties	Used lubricating oil	A	B	Base oil (Stock 60)	standard deviation
Specific gravity	0.89	0.81	0.83	0.82	±0.002
Pour point °C	-43	-15	-19	-12	±1.5
Flash point °C	211	228	232	231	±3.4
Kinematic Viscosity at 100 °C, cst	6.8	8.2	7.8	8.1	±0.07
Total acid number (TAN) mg/g.	9.69	3.56	3.1	3.37	±0.1
Ash wt.%	0.52	0	0	0	±0.002
Carbon Res. wt.%	1.1	0.29	0.25	0.04	±0.06

3.2. Impact of extraction temperature and solvent to oil ratio on extraction

The influence of extraction temperature at different solvent-to-oil ratios on oil recovery efficiency was systematically investigated for both solvent mixtures A and B. The results are clearly illustrated in Figures 3 and 4, which depict the percentage of oil recovered at varying solvent-to-oil ratios under different extraction temperatures. All experiments were conducted at a fixed extraction time of 30 minutes.

A positive relation was observed between the solvent-to-oil ratio and the recovery efficiency for both oil and solvent. As the solvent-to-oil ratio increased, the recovery percentage improved correspondingly. This enhancement can be attributed to the reduction in solvent saturation with base oil components at higher solvent volumes, allowing for more effective solubilization of the oil constituents. In other words, increasing the amount of solvent promotes selective dissolution of the base oil by minimizing solute-solvent saturation effects.

Furthermore, the optimal extraction temperatures differed slightly between the two solvent systems. For Mixture A, the highest oil recovery was achieved at 70°C, whereas for Mixture B, the optimum temperature was 80°C. This variation can be explained by the differences in the physicochemical behaviour of the two solvent systems, including solvent volatility, polarity balance, and interaction with the oil matrix. At these respective temperatures, a favorable viscosity range of the oil was achieved, enhancing mass transfer, solute diffusion, and solubility. Additionally, these conditions likely promoted better phase equilibrium between the solvent components and the oil, thereby facilitating more efficient extraction. Error bars corresponding to ±5% of the measured recovery values were included in the graph to reflect the experimental variability. This margin accounts for potential deviations due to measurement uncertainties and ensures better representation of data reliability.

Overall, the results confirm that both the solvent-to-oil ratio and the extraction temperature play critical roles in optimizing oil recovery. Proper tuning of these parameters is essential for maximizing the efficiency of the solvent extraction process in used oil regeneration. The above results are entirely consistent with another research (Khan et al. 2023, Altaee et al. 2022).

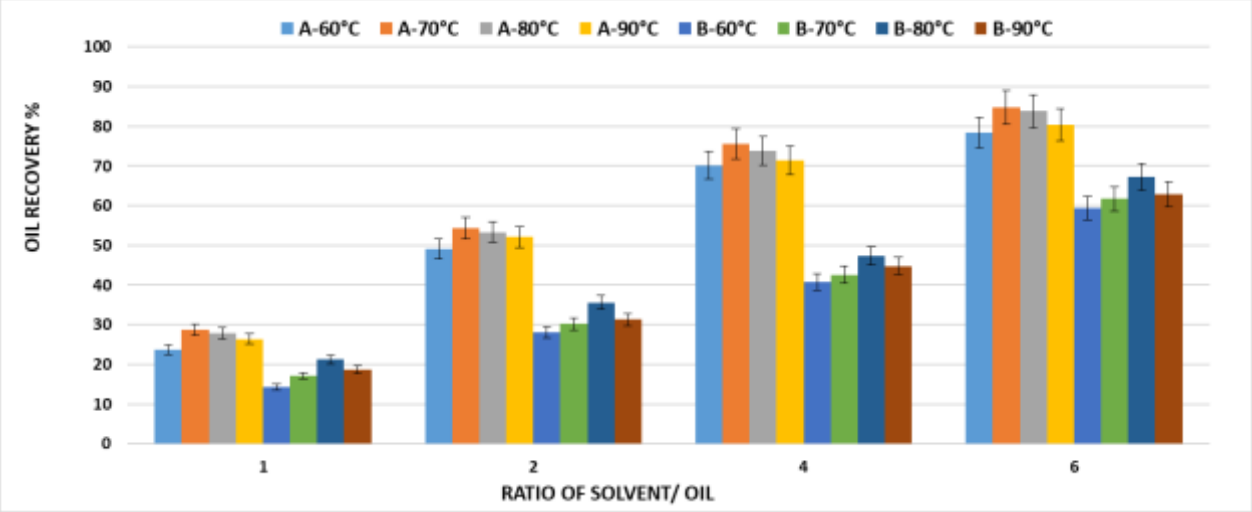

Fig. 3. The effect of solvent/used oil ratio on percent oil recovery at different extraction temperatures for solvent mixture A and B.

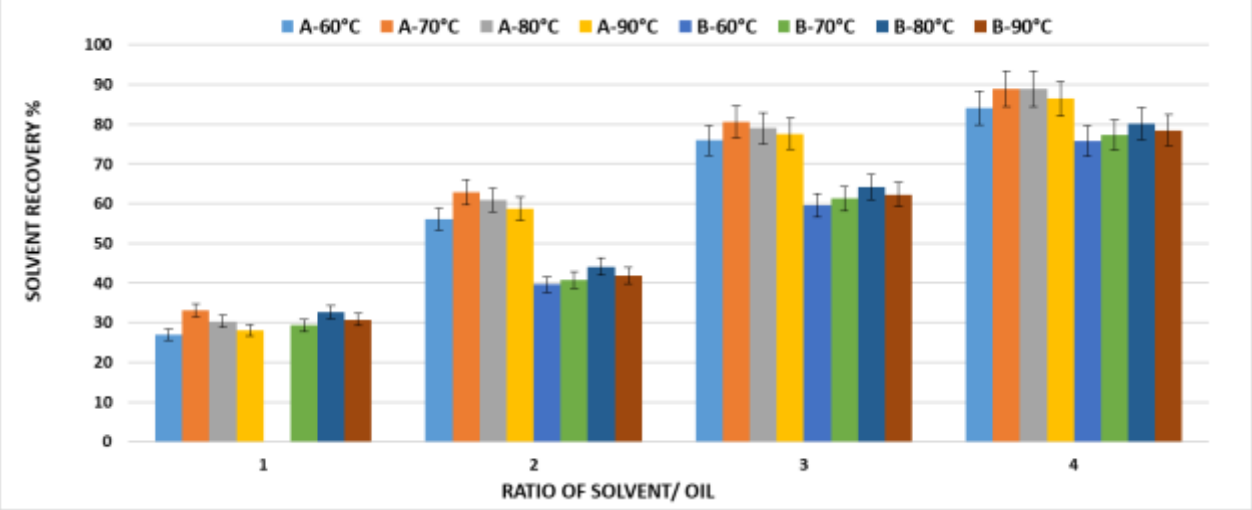

Fig. 4. The effect of solvent/used oil ratio on percent solvent recovery at different extraction temperatures for solvent mixture A and B.

3.3. Impact of mixing time and solvent to oil ratio on extraction

The impact of mixing time at varying solvent-to-oil ratios on oil recovery efficiency was systematically evaluated for two solvent systems, Mixture A and Mixture B. The experimental outcomes are comprehensively illustrated in Figures 5 to 6, which represent the percentage of oil recovered as a function of solvent-to-oil ratios across different mixing durations. All extractions were performed under controlled thermal conditions of 70 °C for Mixture A and 80 °C for Mixture B.

The results demonstrated a clear trend of increasing oil recovery efficiency with extended mixing times for both solvent mixtures. Notably, the maximum recovery was achieved at a mixing duration of 60 minutes, indicating that prolonged contact time significantly enhances solvent diffusion and facilitates the attainment of solubility equilibrium. This equilibrium state appears critical in maximizing the mass transfer of oil into the solvent phase prior to reaching saturation limits.

These findings suggest that the extraction process is governed predominantly by diffusion kinetics in the early stages, transitioning into a solubility-driven equilibrium process at extended durations. The enhanced recovery at longer mixing times may be attributed to improved molecular interaction between the oil and solvent molecules, allowing more complete phase contact and solute transfer. Furthermore, the effect of solvent-to-oil ratio is also evident, as higher ratios provided a greater driving force for mass transfer, particularly when combined with optimal mixing time. Error bars corresponding to ±5% of the measured recovery values were included in the graph to reflect the experimental variability. This margin accounts for potential deviations due to measurement uncertainties and ensures better representation of data reliability.

Overall, the observed trend indicates that both parameters solvent-to-oil ratio and mixing time play synergistic roles in enhancing oil recovery. The solvent ratio primarily influences the capacity for solubilization, while mixing time controls the kinetics of diffusion and phase contact. The diminishing incremental gains in oil recovery at longer times and higher solvent ratios imply that the system gradually approaches a thermodynamic equilibrium state, beyond which further improvements are minimal. These results are in full agreement with those of other workers (Alemu et al. 2025, Hussein et al. 2014).

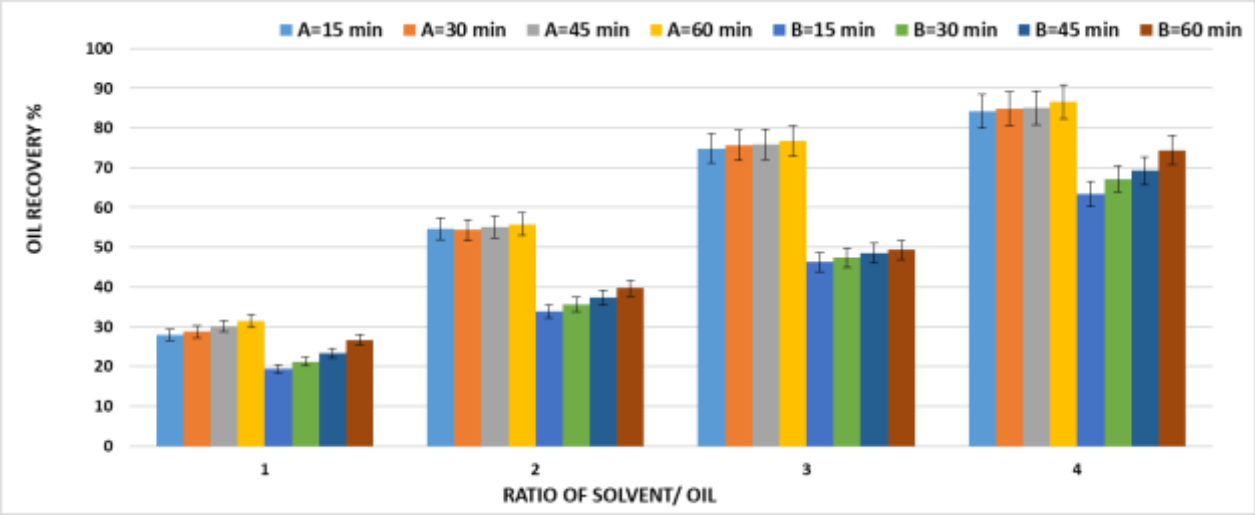

Fig. 5. The effect of solvent/used oil ratio on percent oil recovery at different mixing times for solvent mixture A and B.

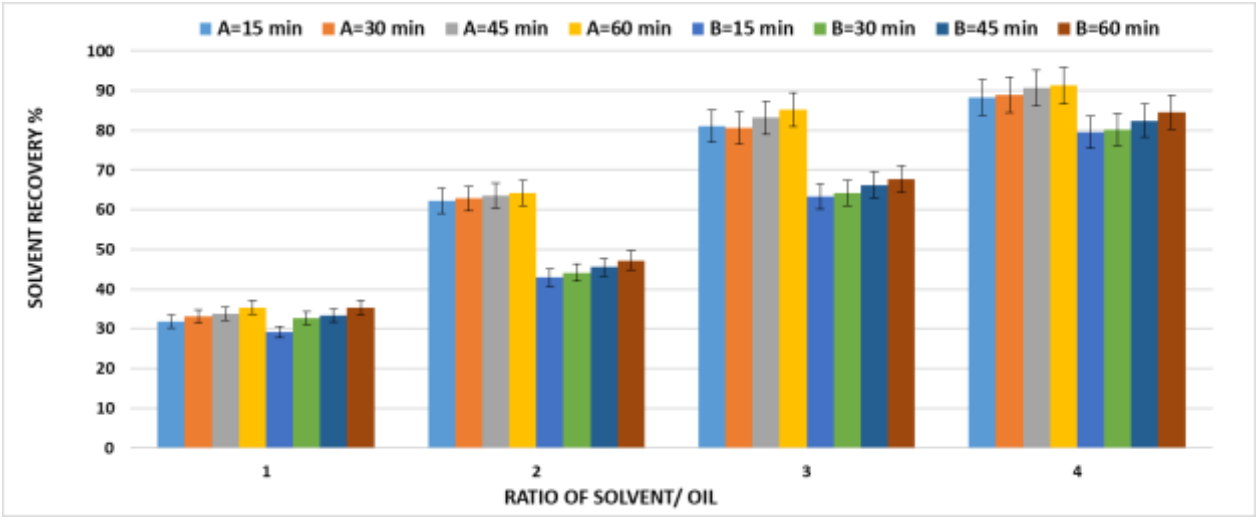

Fig. 6. The effect of solvent/used oil ratio on percent solvent recovery at different mixing times for solvent mixture A and B.

3.4. Bleaching

The oil recovered from Mixture A under optimal extraction conditions namely, 70 °C, 60 minutes of mixing time, and a solvent-to-oil ratio of 6:1 was subjected to a bleaching treatment to improve its visual and chemical quality. The bleaching process was carried out using a sequential treatment involving hydrogen peroxide (H_2O_2) oxidation followed by adsorption with activated bentonite clay. The effectiveness of this treatment was evaluated by measuring the color number of the final product, as illustrated in Figure 7. This figure presents the relationship between the amount of activated bentonite clay and the concentration of hydrogen peroxide (H_2O_2) on the color number of the recovered oil after bleaching. The results clearly demonstrate that increasing both the concentration of hydrogen peroxide and the dosage of bentonite clay leads to a significant and consistent reduction in the color number of the treated oil.

At a fixed clay dosage, increasing H_2O_2 concentration from 5% to 15% resulted in a marked improvement in bleaching efficiency. For example, at a clay weight of 3 g/100 mL oil, the color number decreased from approximately 6.4 (at 5% H_2O_2) to 3.2 (at 15% H_2O_2). This effect can be attributed to the higher oxidative potential of H_2O_2 at elevated concentrations, which enhances the breakdown of chromophoric organic compounds through oxidative cleavage of double bonds and aromatic structures.

Simultaneously, increasing the weight of bentonite clay from 1 to 5 g at constant H_2O_2 concentrations also led to a gradual decline in color number, albeit with diminishing returns beyond 3 – 4 g. This trend reflects the high adsorption capacity of bentonite, which becomes progressively saturated with degradation by-products and residual pigments. The plateauing behavior at higher clay doses may suggest the attainment of near-maximum adsorption efficiency.

Notably, the lowest color number almost 2.8 was achieved with a combination of 15% H_2O_2 and 5 g of clay per 100 mL of oil, indicating a synergistic effect between oxidative degradation and subsequent adsorption these results are in complete agreement with those of other workers (Osazuwa et al. 2024). This confirms that the sequential mechanism, initial chemical oxidation followed by physical adsorption, is significantly more effective than using either agent in isolation. Figure 8 demonstrates the photo picture of spent lubricant, finally treated base oil and standard base oil (stock 60) from Dura Refinery.

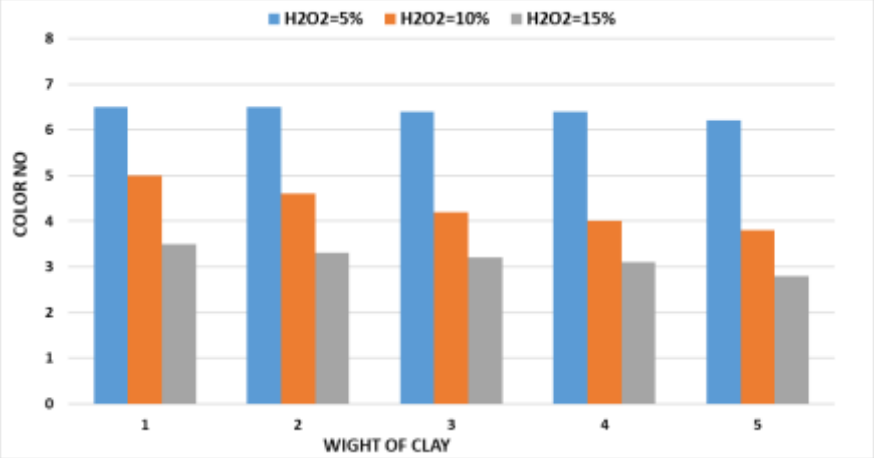

Figure 7: Effect of hydrogen peroxide on the color number of different weights of activated bentonite clay.

Figure 8: (A) spent oil, (B) Recovered base oil after bleaching, (C) Stock 60

4. CONCLUSIONS

This study has demonstrated the technical feasibility of using a ternary solvent extraction system for the regeneration of used lubricating oil, with results indicating strong potential for industrial application. The regenerated oil exhibited physicochemical properties closely resembling those of virgin oil, confirming the process's effectiveness in restoring oil quality for potential reuse. Critically, the use of Solvent Mixture A—a blend of acetonitrile, xylene, and n-heptane—under optimized operational parameters yielded notably higher recovery and purification efficiency compared to previously reported methods. The process achieved an oil recovery yield improvement of approximately 86.6% over comparable solvent systems highlighting the superior performance of this ternary combination.

Furthermore, the incorporation of a post-extraction treatment—combining hydrogen peroxide bleaching with bentonite clay adsorption—proved highly effective in removing residual color bodies and polar contaminants. This dual-stage treatment significantly enhanced both the aesthetic and chemical quality of the regenerated oil, supporting its reuse in demanding lubrication applications. Beyond technical performance, the feasibility of employing ternary solvent systems also involves key practical considerations such as solvent cost, recyclability, and safety. Common solvents like xylene, toluene, and light alkanes are low-cost and readily available, supporting economic viability for large-scale applications. Although solvents such as acetonitrile and DMSO are relatively more expensive, their high recovery efficiency through distillation offsets long-term operational costs. Notably, all solvents used in the systems are recyclable, contributing to environmental sustainability and reducing the need for fresh inputs over multiple cycles.

However, safety considerations must not be overlooked. Several solvents are flammable and pose health risks, necessitating strict safety protocols, including proper storage, ventilation, and use of personal protective equipment (PPE). With adequate controls, these risks can be effectively managed in industrial environments. While the current results validate the technical viability of the method, its broader value lies in its potential for cost-effective deployment in industrial-scale recycling operations. The process can be adapted to operate under modified conditions—such as reduced solvent-to-oil ratios or lower processing temperatures—to optimize performance while addressing economic and environmental constraints. These findings establish a solid foundation for pilot-scale implementation and further optimization toward sustainable waste oil management solutions.

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