Indian Journal of Chemical Technology
Vol. 32, November 2025, pp. 755-765
DOI: 10.56042/ijct.v32i6.17045

Refining of used engine oil by solvent extraction and adsorption processes: A circular economy strategy

Dawit Tessema Ebissa[1, 2]*, Haileamlak Getachew[3], Eshetu Getahun[1,3]* & Zenamarkos Bantie[3]

[1] Bahir Dar Energy Center, Bahir Dar Institute of Technology, Bahir Dar University, Po. Box 26, Bahir Dar, Ethiopia

[2]Pre-engineering and Sciences, Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, Po. Box 1037, Bahir Dar, Ethiopia

[3]Chemical and Food Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Po. Box 26, Bahir Dar, Ethiopia

*E-mail: awwce2005@gmail.com (DTE); eshetu201384@gmail.com (EG)

Received 10 February 2025; accepted 23 October 2025

To address the issues related to lubricating oil used in vehicles, present study is aimed to investigate the characterization of waste engine oil and its treatment using solvent extraction and adsorption methods. The motor oil sample used has been treated with different solvents and solvent ratios to analyze the effect of solvent type and oil-solvent ratio on sludge removal, density, and ash content. The results showed that methanol-based treatment at a 1:3 oil-solvent ratio gave the best-refined oil, with a maximum sludge removal of 54% and a significantly lower density (0.874 g/ml) and ash content (0.54%). Additionally, the study employed adsorption as a further purification method, and the results indicated that an adsorbent dosage of 2.5 g per 50 mL of solvent-extracted oil at a temperature of 60°C gave the best-refined oil, with a 99% removal of metals as contaminants. The waste and treated engine oil have been characterized using various parameters, including density, viscosity, flash point, ash content, water content, and metal contents. The results indicated that the treated oil had comparable quality to the virgin oil, with a density of 0.871 g/mL, flash point of 210°C, and ash content of <0.1%. The study's findings suggest that the solvent extraction and adsorption methods can be effective in removing contaminants from used engine oil, producing a refined oil of comparable quality to virgin oil. This study significantly impacts Ethiopia's environmental pollution reduction and energy conservation.

Keywords: Adsorption, Engine oil, Phenolic compounds, Recycling potential, Refining of used engine oil, Solvent extraction

Introduction

Used engine oil, a polluting substance, is essential for modern machinery and equipment. It reduces wear and friction, serves as fuel, eliminates heat, maintains cleanliness, inhibits corrosion, and increases efficiency[1]. A significant amount of used engine oil from various sources is disposed of as hazardous waste in the environment. Disposing of used oil in lakes, rivers, and seas leads to several environmental issues; it contaminates the water and endangers freshwater and marine life[2]. Sustainable management of used engine oil is essential for environmental conservation and resource conservation, promoting sustainability through solvent extraction and adsorption processes[3]. A circular economy reduces waste and maximizes resource efficiency, exemplified by refining used engine oil through solvent extraction and adsorption processes, transforming waste into reusable products[4]. Solvent extraction is a method used to separate and recover various components of used engine oil. In this process, a solvent such as propane or butane is used to dissolve the oil, allowing for the separation of base oil from contaminants such as additives, heavy metals, and other impurities. The solvent can then be evaporated, leaving behind the extracted base oil, which can be further refined for reuse[5]. Adsorption is another essential step in the refining of used engine oil. Adsorbents such as activated carbon or clay are utilized to remove any remaining impurities or contaminants in the oil. These adsorbents have a high surface area and can effectively trap pollutants, enhancing the quality of the recovered base oil. The adsorption process plays a crucial role in ensuring that the refined oil meets the required specifications for reuse[6]. The refining of used engine oil through solvent extraction and adsorption processes offers numerous benefits. Firstly, it helps to reduce the environmental impact of used oil by preventing pollution and minimizing the need for new oil resources. Additionally, the recovered base oil can be reprocessed and used in various applications, including lubricants, fuels, and other industrial products. This not only conserves resources but also contributes to cost savings and energy efficiency[7]. Engine oil contains contaminants and components from engine wear, including unsaturation, phenolic, aldehyde acidic chemicals, metal particles, sulfur and barium-containing compounds, water, dirt, burned carbon, and ash, which must be separated and eliminated before reuse[2,8].

Depending on the use, lubricants can be categorized as automotive, industrial, process, or marine oils. The percentage for the automotive sector was 57% in 2016[1]. Lubricating oil is primarily used for three purposes in automobile engines: (i) lubricating metal components; (ii) cooling the combustion cycle; and (iii) removing heavy metals[9]. The complicated aging process of lubricating oil involves the co-occurrence of additive depletion and base oil degradation. Oxidative degradation, water, ethylene glycol, and soot pollution, as well as metal attrition, are the primary causes of lubricating oil degradation[8]. As a result, fresh lubricating oil is used to replace the old one to enhance performance. As a result, over 50% of fresh lubricating oil ends up as waste because it contains unwanted, poisonous, and environmentally dangerous compounds that could hurt the environment and human health[10]. The estimated value of the global lubricant market in 2017 was 35.7 million tons. Asia-Pacific holds the largest share of 43% of the worldwide market and is experiencing the fastest growth in lubricant consumption. With 6.8 million tons of lubricating oil utilized annually, Europe accounts for 19% of global lubricant consumption, while Africa accounts for roughly 6%[1]. It is estimated that Ethiopia disposes of more than 19,950,360 L of motor oil each year from automobile engines. A massive amount of renewable energy must be produced due to rising fuel consumption and depleting fossil fuel sources. Since waste lubricating oil (WLO) is an organic waste with a high heating value, it can be used to generate energy from waste[11]. The industry is focusing on sustainability principles, reducing emissions, and preserving resources. Public interest in lubricant production and recovery is increasing, necessitating waste management and renewable energy generation to address environmental, public health, and industrial issues[12].

WLO-based alternative energy production addresses environmental issues and energy crises by reducing dependency on fossil fuels, increasing net worth, and creating job opportunities. Engine oils, used in developing nations for dust management, weed control, and emergency lubrication, harm the environment and can cause negative human side effects[13]. Recycling is crucial for conserving the environment and maximizing resource use. Common WLO treatment technologies include acid-clay adsorption and solvent extraction, which reduce waste and enhance the reusable potential of once-purchased resources[14]. The integrated solvent extraction technique is the optimal method for refining used engine motor oil, involving sedimentation, dehydration, solvent reaction, vacuum distillation, bentonite clay adsorption, and filtration[15]. Ethiopia lacks accessible used oil management techniques and lacks knowledge about environmental effects. As urbanization and businesses emerge, waste streams are created, necessitating proper management of hazardous lubricating oil, a crucial waste from various development sectors [16]. This research explores the use of affordable, eco-friendly re-refining procedures for expensive lubricating oils. It focuses on the characterization of waste and refined engine oil, highlighting the potential of solvent extraction and adsorption processes for sustainable waste management and resource efficiency.

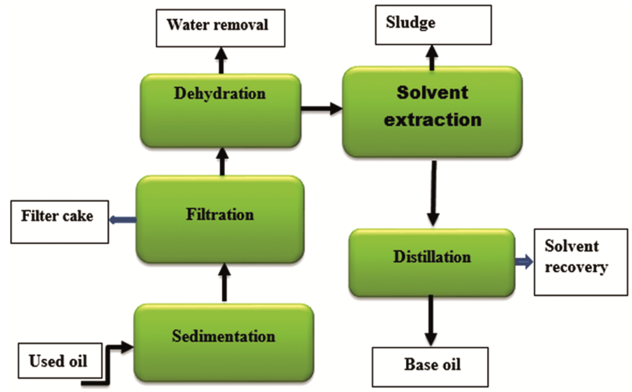

Fig. 1 — Flowchart for experimental procedure

Experimental Section

Samples of used engine oil were collected from a reputable garage in Bahir Dar City, Ethiopia, after thousands of kilometers in use. The sample consists of various types of used lubricating oils from various vehicles. Analytical grade chemicals like organic solvents (ethanol and methanol). The brewer's spent grain (BSG) was collected from Dashen Brewery Company, Ethiopia for the preparation of the activated carbon. There were numerous experiments done to treat and filter the contaminants out of the spent lubricating oil. The detailed flow sheet and the experimental procedure are shown in Fig. 1.

The used oil was allowed to sediment for a day in a separator funnel so that different types of solid wastes to be discarded at the bottom of the funnel. Then decantation process was followed to separate the sediment/solid waste from the oil. The used engine oil was filtered to remove impurities such as metal chips, sand, dust, particles, micro impurities that are contained in the waste motor oil. This was done using a funnel with a filter cloth placed in it, and then a vacuum pump was connected to the filtering flask to which the funnel was fixed with the aid of a rubber stopper. Finally, the filter cake was separated at the top. Water becomes part of used oil due to poor collection systems in workshops even sometimes this used oil is kept in open drums in which rainwater could also be mixed. For dehydration, water is heated up to 105°C so that water is evaporated. Here, solvent extraction takes place. Organic solvents methanol and ethanol were used. In addition, the blending of these organic solvents with different ratios have been analyzed too as another solvent type (blending ratio of methanol: ethanol; 1:1, 1:2, and 2:1). The solvents were selected according to their efficiency to form hydrogen bonds. (Alcohols have higher capacity to form hydrogen bond says Burrel's classification).

By preparing flasks of size 250 mL for each oil-to-solvent ratio (1:1,1:3,1:5) and two solvent types (methanol and ethanol) plus the blending or composite of the methanol : ethanol (1:1,1:2 and 2:1) organic solvents mixing was put in a mixing shaker at a speed of 150 rpm. Then the waste engine oil and solvent mixture was left to settle in the separation flask for 96 h. The degraded additives, metals, and other contaminants present in the oil fraction were observed settling at the bottom, and the oil fraction and solvent mixture layer was at the top. Finally, the distillation method was followed after the mixture of oil and solvent at the top was decanted in a flask so that the solvent would be recovered. The mixture of each solvent and oil was distilled to recover the solvent. At the boiling point of methanol (64.7°C) and ethanol (78°C), the distillation process was performed and the condensed solvent was collected by beakers. After separating the oil and recovering the solvents, the yield of the product was calculated in addition the sludge removal was also calculated.

A UV-spectrophotometer was used to obtain the response (% removal of metals) for the treated engine oil. The percentage removal of impurities (metals) was determined for the treated engine oil using the equation below.

$$\% \text{ removal} = \frac{P_{untreated} - P_{treated}}{P_{untreated}} \times 100$$

Where; $P_{untreated}$ and $P_{treated}$ are the absorbance of untreated and treated oil.

Characterization of used motor oil

Used motor oil characterization is an important part of the re-refining process. It provides information about the condition and composition of the used oil. It also tells us how the magnitude and composition are different when comparing with refined and virgin oil.

Density, viscosity (ASTM D445 method), Flashpoint (ASTM D92 method), ash content (ASTM D482), metal content (ASTM D 4628-2) were determined as per the standard procedures. The metal content of the waste and refined engine oil analysis was performed by atomic absorption spectrometry using a fast sequential atomic absorption spectrometer. Firstly, the used engine oil samples were heated to 60°C and stirred in order to ensure homogeneity of the sample. Finally, record each metal's absorbance at a specific maximum wavelength.

Calcium determination

1000 ppm stock solution was prepared and from each standard stock solution 100, 300, 500 and 700 ppm working standard solution with a blank of distilled water were also prepared. Finally, the absorbance was recorded at 575 nm.

Working standard preparation applies a formula: $C_1V_1=C_2V_2$;

Where; C_1 is concentration of the stock solution (1000 ppm), V_1 is volume of stock solution needed to prepare the standard, C_2 concentration of working solutions (100, 300, 500 and 700 ppm) and V_2 is the target volume of the working solution needed for absorbance reading.

Iron determination

After preparing 1000 ppm stock solution, 100, 300, 500 and 700 ppm of solution were taken in labeled test tubes, and hydroxytriazine was added to each test tube and another test tube for blank standard with a test tube. Finally, the mark was filled with distilled water and read absorbance at 410 nm.

Lead determination

100,300,500 and 700 ppm working standards were prepared and taken into a test tube from the stock solution of Pb^{2+}(1000ppm) and a blank standard of distilled water. Reading was taken at 520 nm and absorbance was recorded.

Magnesium determination

from the stock solution of Mg^{2+}(1000 ppm), a working solution of 100, 300, 500 and 700 ppm with EBT (Erichrome black tea) with ammonia buffer for the standard solution with a blank standard of EBT in ammonia buffer and read absorbance at 535 nm.

Cadmium determination

A stock solution of 1000 ppm was prepared and 100, 300, 500 and 700 ppm of working solution was prepared from the stock with a blank standard of distilled water, to read absorbance at 517 nm. Fourier Transform Infrared (FT-IR) spectrometry was utilized to determine the functional groups of the waste engine oil. The experiment consists of two factors: type of solvent (each solvent type and the composite of solvents at different ratios) and solvent-to-oil ratio dosage. The experiment was conducted in a multilevel categorical design (MLCD) for refining of used motor oil samples. Both used oil to solvent ratio and solvent type are varied in three and two levels, respectively. Each run was repeated to ensure precision.

Results and Discussion

Water content

As shown in the Table 1, the water content in the used engine oil (0.98%) was much higher than the refined oil, this may be due to the engine's low temperature, such as at startup and during short-trip operations in low ambient temperature, which causes the water vapour to condense (turn into a liquid) on cylinder walls and enter the crankcase, where it leads to sludge. In addition, the reason behind the availability of water in an engine may; as a result of absorbing moisture from air since oil is hygroscopic, as a result of combustion since fuel combustion creates water which could enter the lubricating oil through worn rings and free water may enter during oil change. So, the relatively low amount of water content (<0.1%) recorded after the refining process can be evidence for the removal of the waste engine's water during the dehydration and pretreatment processes.

Table 1 — Characterization of the waste and treated/extracted engine oil

Properties	Used engine oil sample	Treated engine oil
Density(g/mL)	0.923	0.874
Viscosity @ 40 °C (CST)	148.26	58.4
Viscosity @ 100°C (CST)	26.82	9.8
Ash content (%)	2.42	0.54
Water content (%)	0.98	<0.1
Flashpoint(°C)	160	201
Metal contents(ppm)		
Fe	268	39.8
Ca	167	29.5
Pb	17.5	8.3
Mg	14	7.8
Cd	0.95	0.2

Ash content

The total amount of incombustible material present in an engine oil which is also called ash content was also analyzed as a one of characterizing properties of the engine oil. The ash content recorded in the waste engine oil was relatively very high (2.42%), which is an indication of contamination of the oil with minerals. On the other hand, the refined oil indicates a significant reduction of the ash content (0.54%), due to the removal of impurities during the refining process.

Flash point

Another common characterizing property of engine oil is flash point. The data revealed that the low flash point recorded for the used engine oil (160°C) is a reliable indicator which indicates that the oil has become contaminated with volatile products like gasoline and other impurities. Also, this value indicates the oxidation oil would result information of volatile components which leads to decrease the flash point. While refining, there was a significant increment of the flash point to 201°C which indicates the removal of volatile and other impurities. Initially, it is known that industrially produced base oils are treated with additives to increase their flash point this is to minimize their flammability and hazardous causing effects in the high temperature of the engine. So, a higher flash point is an indication of good lubricating oil.

Viscosity

The waste engine oil showed a high viscosity (148.26 CST @ 40°C and 26.82 CST@ 100°C) value which indicates the oil was degraded or/and oxidized due to the presence of various contaminants (Table 1).

Table 2 — Experimental results of selected responses

Std	Run	Factor 1 A: oil-solvent ratio	Factor 2 B solvent type	Response 1 Sludge removal (%)	Response 2 Density (g/mL)	Response 3 Ash content (%)
24	1	1:5	Met-eth (1:2)	42	0.885	0.61
19	2	1:3	Met-eth (2:1)	47.5	0.883	0.61
16	3	1:1	Methanol	49	0.875	0.66
30	4	1:5	meth-eth (2:1)	48	0.882	0.6
26	5	1:3	met-eth (1:1)	44.5	0.886	0.63
14	6	1:3	met-eth (2:1)	48	0.883	0.61
9	7	1:5	Met-eth (1:2)	42	0.885	0.61
1	8	1:1	Methanol	48	0.875	0.65
10	9	1:1	Met-eth (1:1)	41	0.886	0.63
12	10	1:5	Met-eth (1:1)	45	0.885	0.59
8	11	1:3	Met-eth (1:2)	41	0.886	0.64
15	12	1:5	Met-eth (2:1)	48.5	0.882	0.6
4	13	1:1	Ethanol	35	0.889	0.7
17	14	1:3	Methanol	54	0.874	0.58
21	15	1:5	Ethanol	40	0.888	0.63
19	16	1:1	Ethanol	36	0.889	0.71
27	17	1:5	met-eth (1:1)	45.5	0.885	0.6
5	18	1:3	Ethanol	39.5	0.887	0.63
6	19	1:5	Ethanol	40	0.887	0.62
22	20	1:1	met-eth (1:2)	37	0.866	0.65
20	21	1:3	Ethanol	39.8	0.888	0.63
18	22	1:5	Methanol	54	0.874	0.54
7	23	1:1	Met-eth (1:2)	36.5	0.886	0.65
25	24	1:1	Met-eth (1:1)	41	0.886	0.63
11	25	1:3	Met-eth (1:1)	44.5	0.885	0.63
23	26	1:3	Met-eth (1:2)	41	0.886	0.64
3	27	1:5	Methanol	54	0.874	0.55
13	28	1:1	Met-eth (2:1)	45	0.884	0.62
2	29	1:3	Methanol	54	0.874	0.59
28	30	1:1	Met-eth (2:1)	48.5	0.884	0.62

These contaminants are the oxidized and polymerized products that had been suspended and/or dissolved in the used engine oil. In contrast, the viscosity (58.4 CST @40°C and 9.8 CST @100°C) value of refined engine oil was lower compared with waste engine oil due to the elimination of these oxidized and polymerized contaminants, and the oil was recycled and turned to a comparable extent of its source. On the other hand, if there was an increment of viscosity while refining, the contaminant would be fuel as fuel contamination causes a decrement in viscosity. So from the waste and refined oil viscosity values, it is possible to decide that the oxidized and polymerized products were the main causes of contamination rather than fuel. This result is in agreement with the previous studies[17].

Density

Table 2 shows the density amount of the waste engine oil to be higher than the refined engine oil. This is because of the higher amount of aromatic compounds available in waste motor oil as contaminants. In addition the increasing amount of solids in the waste engine oil causes the rising amount of density. It has been studied that a one percent weight availability of solids in used oil could increase the density by 0.007[Rf. 18]. The used oil density which initially had a value of 0.923 g/mL was recorded to decrease (0.874 g/mL) just after solvent extraction treatment. This was because of the elimination of products like oxidation products, metals, and contaminations, which caused the high density of the oil. The selected responses that have basic determination factors on the quality of the refined

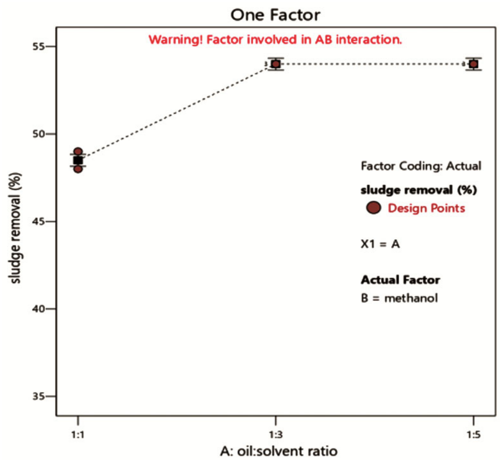

Fig. 2 — Effect of oil: solvent ratio on sludge removal

engine oil were sludge removal, density, ash content, and viscosity. These responses were selected based on their being significant characteristics for oil properties and ease of determination.

Effect of solvent to oil ratio on sludge removal (%)

As shown in Fig. 2, the solvent-to-oil ratio increases the sludge removal also increases. This is because as the solvent proportion increases, the medium mutual solubility of the oil in the solvent increases. The higher percentage of sludge removal means good efficiency of the re-refining oil process. The highest sludge removal recorded was at methanol 1:3 and 1:5 (54%) from this result, it is important to notice that increasing the solvent ratio (from 1:3 to 1:5) may not have an effect if it has already achieved its optimal point, which means increasing solvent above this point will not have an effect other than solvent loss (economical loss). These findings are in agreement with the previous studies[19].

Effect of Solvent type on sludge removal

It is known that the extraction process works based on solubility efficiency and/or the dielectric constant. The dielectric constant value of methanol is 33.64 and ethanol is 26.47 @293k)[20]. Methanol-based (as a single solvent) treated base oil gave the best sludge removal (54%) result compared to ethanol and other composite solvents. In addition, a methanol-based blended solvent (48.5%) gave better sludge removal than a single solvent, ethanol. As illustrated in Fig. 3, blending ethanol with a higher ratio of methanol (met-eth/2:1 ratio) will give better sludge removal and good quality base oil than single solvent ethanol. This is due to the good characteristics of methanol, which have better solubility.

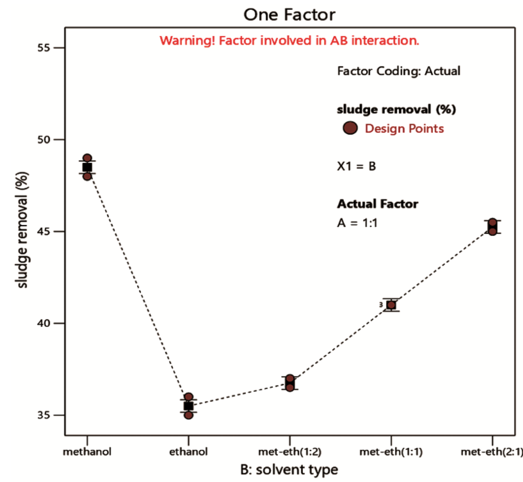

Fig. 3 — Effect of solvent types on sludge removal

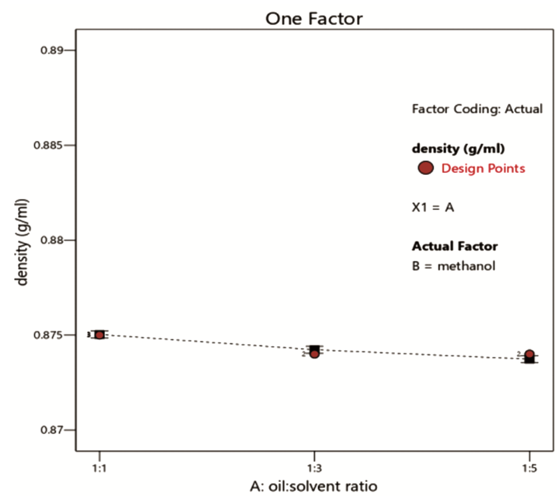

Fig. 4 — Effect of oil: solvent ratio on density

Effect of oil-solvent ratio on density

The density of the used oil was higher than that of the treated oil as contaminants contribute negatively to the oil to be dense. Refining makes the dense oil to be less dense after eliminating those heavy metals and other impurities. While seeing the effect of different solvent amounts/ratios on the same solvent type the effect was not that significant. Even if there were some variations it is difficult to conclude about the significant effect of solvent amounts on density. Fig. 4 shows that, density variations for methanol extracted oil while increasing the solvent amount from (1:1 to 1:5) the difference was just only 0.002 which is too low to say ratio affects density. The reason behind this is the initial amounts of solvents were just enough to settle impurities which made the density of the oil to be maximum.

Effect of solvent type on density

As shown in Fig. 5, while comparing the solvent types on the effect they had on density decrement, each solvent was seen to decrease the waste engine oil's density with different intensities. Methanol-based extracted oil had a higher density decrement than that of ethanol and composite solvents. Refined oil by ethanol had a relatively higher density of 0.883 g/mL while methanol-based refined oil had an average density of 0.874 g/mL, which implies that good quality oil was extracted on the methanol-based solvent extraction method. This has a strong relation with the sludge removal efficiencies of the solvents. Because more sludge removal implies dense impurity removal.

Effect of solvent type and solvent amount on ash content

Figs 6 and 7 illustrate that ash content significantly decreased for each type of solvent. The total amount of incombustible material/ash present in waste motor oil was very high (2.42%), indicating the oil contains minerals as contaminants. On the other hand, the refined oil indicates a significant reduction of the ash content (0.54%), due to the removal of impurities during the refining process. While comparing the solvent types, there was an observed difference between solvents because the lowest ash content recorded was at methanol (0.54%), while the highest ash content recorded was at ethanol. Generally, here, the amount of solvent has a great effect on the removal of incombustible materials because, as anyone can see from the graph, there is an inverse relation between solvent amount/ratio and ash content, keeping in mind that methanol, with the highest sludge removal efficiency, gave the least ash content.

FT-IR analysis

The surface characteristics in terms of functional groups of waste, treated, and virgin engine oil, in the

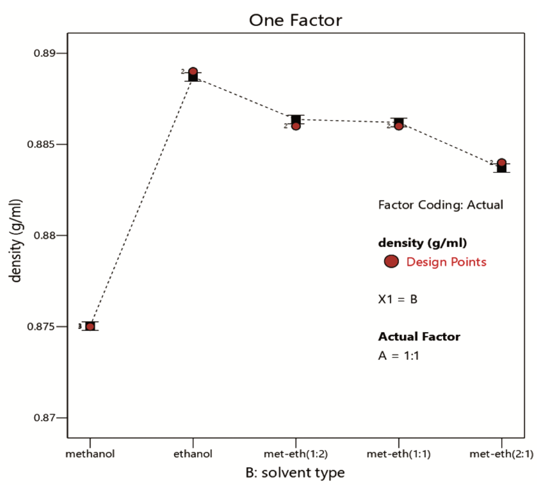

Fig. 5 — Effect of solvent type on density

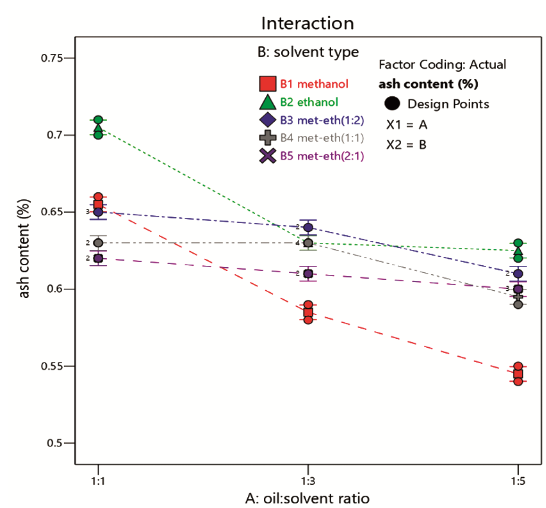

Fig. 7 — Effect of solvent type and solvent oil ratio interaction on ash content

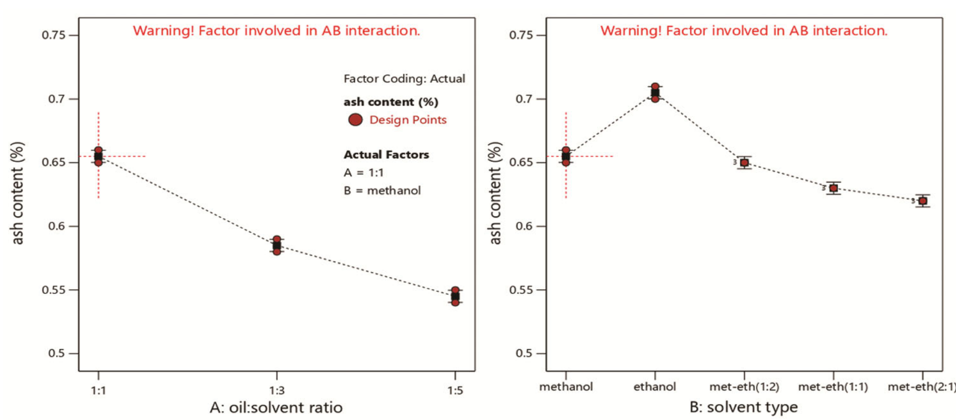

Fig. 6 — Effect of A: oil: solvent ratio and B: solvent type on the ash content of the refined oil

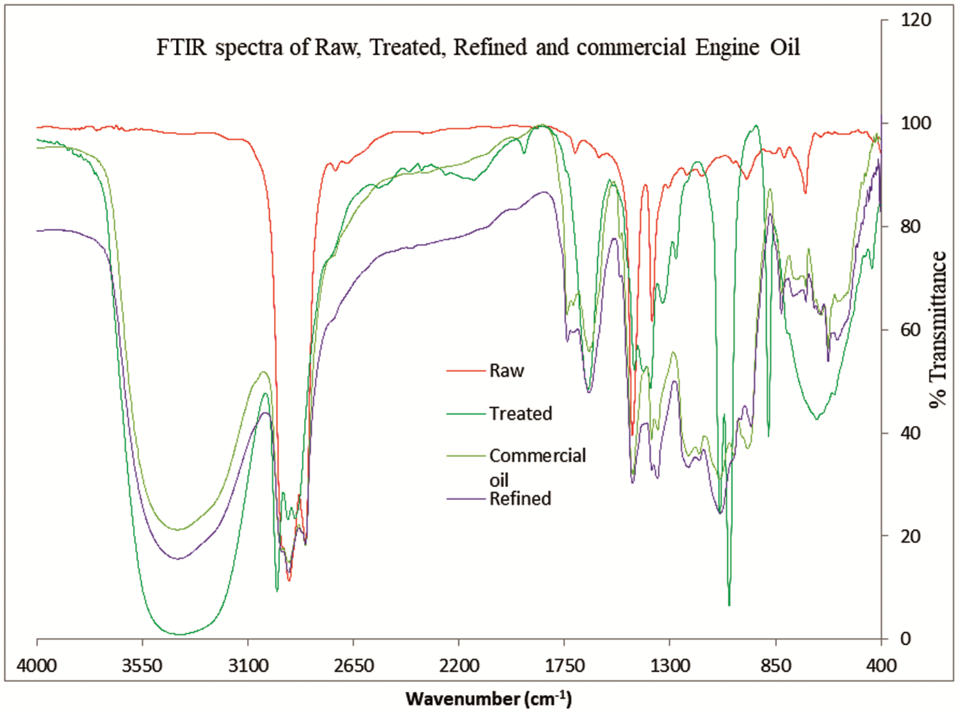

Fig. 8 — The FT-IR result of the raw (waste), treated (solvent extraction), refined (after adsorption), and commercial (virgin) engine oil

range of 4000–400 cm^{-1}, are presented in Fig. 8. The characteristic surface absorption peaks of all the analyzed samples at around 3371-3468 (O-H stretching), 2845 and 2939 (C–H stretching vibrations in aliphatic chains), 1452 (C–H asymmetric deformation in CH_2 and CH_3), 1373 (C–H symmetric deformation in CH_3 vibrations), 1157 (C-O stretching), and 728 (bending vibration of long-chain methylene ($(CH_2)n$) are almost similar, indicates the basic structures of oils remains unchanged through interactions, except for slight shifts/changes from their positions and the intensity of peaks. These slight position shifts can be related to the involvement of surface properties of oil impurities in waste engine oil. An additional important indicator in the analysis of FT-IR was the intensity of peaks or the bending shape of the analyzed samples. Thus, the refined engine oil peak intensity was maximum. This shows that the surface of the oil was relatively free from impurities due to refining/ treatment processes, and hence, the infrared light was transmitted without any disturbance[20].

Effect of adsorption on the %removal of metals

Adsorption had a significant effect on the removal of impurities from initially treated engine oil (with solvent extraction). From Table 3, it is clear that treating the engine oil with adsorbent gives better quality oil that is almost free from impurities of metals as compared to the initially treated engine oil. Those results of the adsorption process on metal concentrations are in agreement with the previous studies[21].

Table 3 — Metal contents of treated engine oil

Metals (ppm)	Engine oil treated with solvent extraction	Engine oil after the adsorption process (99% removal)
Fe	39.8	0.4
Ca	29.5	0.3
Pb	8.3	0.1
Mg	7.8	0.1
Cd	0.2	Nil

Effect of selected factors of adsorption on %removal of impurities

Effect of temperature

From Table 4 it can be observed that increasing the temperature of the adsorption process had a significant effect on the % removal of impurities. Fig. 9 also illustrates that increasing the temperature from 30 to 40°C and from 40 to 60°C shows an increment of %removal of impurity. This is because the decrease in engine oil viscosity, led to faster movement of impurities to the active site of the adsorbent. This is in agreement with previous findings[22].

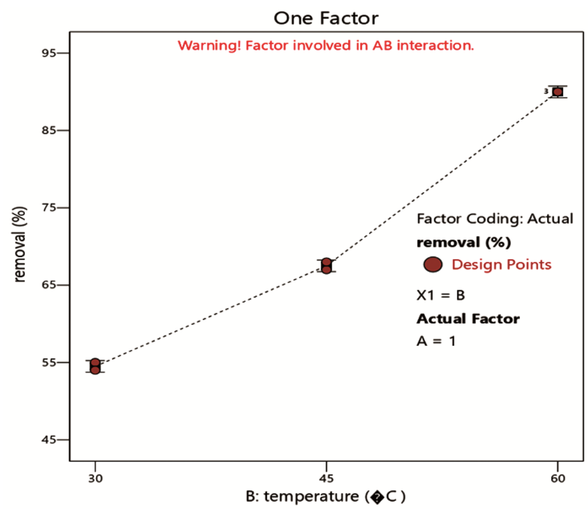

Fig. 9 — Effect of temperature on % removal of impurities

Table 4 — Experimental results of adsorbent-treated engine oil

Std	Run	Factor-1 A: adsorbent dosage (g)	Factor-2 B: temperature (°C)	Response 1 % removal
3	1	5	30	65
12	2	5	30	63
16	3	1	60	90
9	4	5	60	98
17	5	2.5	60	98
14	6	2.5	45	81
15	7	5	45	82
13	8	1	45	68
8	9	2.5	60	97
10	10	1	30	54
5	11	2.5	45	81
11	12	2.5	30	65
7	13	1	60	90
4	14	1	45	67
1	15	1	30	55
2	16	2.5	30	65
18	17	5	60	99
6	18	5	45	82

Effect of adsorbent dosage

From Fig. 10, it is clear that the optimum removal of impurities was recorded at an adsorbent dosage (99%) of 2.5 g; increasing the adsorbent dosage to 5 g did not affect the elimination of impurities. This may be as a result of over-crowded adsorbent, which led to the overlapping of their active sites. At that dosage, aggregation of the adsorbent may led to the repulsion of the binding sites. The same is true for adsorbents and impurities.

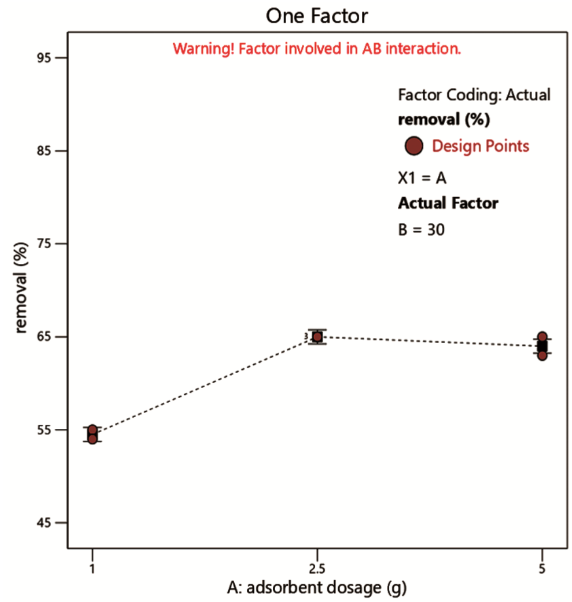

Fig. 10 — Effect of adsorbent dosage on % removal of impurities

Statistical analysis of the adsorption process

Table 5 shows the statistical analysis for the adsorption-based treatment process, ANOVA, and model fitting results from the experimental data. It can be observed that both factors, adsorbent dosage ($P<0.0001$) and temperature ($P<0.0001$), had a significant effect on the selected response, % removal of impurities, which is considered the P value as less than 0.05 for experimental factors to be influentially significant on the selected response.

Comparison of treated and used oil with virgin engine oil

The previous discussion was based on the factors and parameters that affected the treated oil of the two treatment processes (solvent extraction and adsorption) In this section comparison was made between the treated oil (based on solvent extraction and adsorption), virgin (commercial sold) and the used (waste) engine oils. Table 6 shows how the characterized properties varied. The density of the used oil (0.923 g/mL) was much higher than the treated oil (both treatment methods, i.e., solvent extraction and adsorption, 0.874 and 0.871 g/mL, respectively) and the virgin oil (0.888 g/mL). This was due to the high amount of solids in the used engine oil, responsible for the enhancing the density. The two treatment methods have approximately restored the density of the oil to a comparable extent of the virgin oil. This was because of the elimination of products like oxidation products, metals, and contaminants, which caused the oil's density to

Table 5 — Response - % removal ANOVA for selected factorial model

Source	Sum of squares	Df	Mean square	F-value	P-value	Remark
Model	3993.11	8	499.14	1123.06	<0.0001	Significant
A-adsorbent dosage	455.44	2	227.72	512.37	<0.0001	
B-temperature	3510.11	2	1755.06	3948.87	<0.0001	
AB interaction	27.56	4	6.89	15.50	0.0005	
Pure error	4.00	9	0.4444			
Cor total	3997.11	17				

Table 6 — Comparison of the engine oils

Characterized property	Used engine oil	Refined oil with solvent extraction	Treated oil after adsorption	Virgin oil
Density	0.923	0.874	0.871	0.888
Flashpoint (°C)	160	201	210	236
Viscosity @40°C	148.26	58.4	52	98.7
Viscosity @100°C	26.82	9.8	12.4	13.4
Ash content (%)	2.42	0.54	<0.1	<0.05
Water content (%)	0.98	<0.1	Nil	-
Metal contents(ppm)				
Fe	268	39.8	0.4	
Ca	167	29.5	0.3	
Pb	17.5	8.3	0.1	
Mg	14	7.8	0.1	
Cd	0.95	0.2	Nil	

become higher. The flash point of the used engine oil recorded (160°C) was much lower than the two methods-based treated oil (i.e., solvent extraction and adsorption, 201 and 210°C, respectively) and the virgin oil (236°C). This was because of the breakdown that had been added to improve the flash point of the oil during combustion and oxidation at high temperatures in an engine. So, after refining, there was an increment in the flash point, which indicates good quality base oil production because a higher flash point is an indication of good quality oil. The higher the flash point, the less flammable the oil will be during the activity of oils at high temperatures. The availability of additives made the virgin oil's flash point much higher than the used and treated oil.

The metals, as a result of contamination and degradation, were eliminated in both treatment methods. The adsorption process gave almost zero amount of metal, like the virgin engine oil. In addition, other characterizing properties like ash content and water content were seen to decrease in a way that of the virgin oil.

Conclusion

The refining process significantly improves the properties of used and treated engine oil, making it comparable to virgin oil. Solvent extraction-based treated engine oil was analyzed for different parameters, i.e., oil:solvent ratio and solvent type, on selected responses (sludge removal, density, and ash content). These factors (solvent amount and type) of the solvent extraction method showed a significant effect on the sludge removal, density, and ash content. The maximum amount of sludge removal (54%) was recorded on a 1:3 oil-solvent ratio with methanol solvent. This implies that increasing the solvent amount has a significant effect on the sludge removal with methanol solvent because of its higher solubility. A relatively less amount of density (0.874 g/mL) was recorded at the methanol-based extracted oil, which shows the high relationship between the sludge removal and density because the high amount of sludge removal means the elimination of solids and impurities, causing the raised amount of density of the base oil. In addition, the amount of solvent had a great effect on the removal of incombustible materials. There was an inverse relation between solvent amount and ash content, keeping in mind that methanol, with the highest sludge removal efficiency, gave less ash content. So, from the solvents used, including the composite mixtures of solvents in different ratios, the methanol-based treatment method was selected as the best to give good quality oil in terms of the parameters used to analyze the quality of the base oil. The adsorption process was another treatment method used to see if there was a significant effect on further purification of the solvent-extraction-treated engine oil. To study this adsorbent dosage and temperature were used as factors of the treatment process on the percent removal of impurities as a response to the experiment. Both temperature and adsorbent dosage of the adsorption process showed a significant effect on % removal of metals as contaminants. The higher % removal of metals (99%) was recorded at an adsorbent dosage of 2.5g per 50 ml of solvent-extracted oil with a temperature of 60°C. Generally, it can be drawn from the experiment that methanol solvent-based treatment at a 1:3 oil-solvent ratio gave the best refined oil for the solvent extraction method. An adsorbent dosage of 2.5 g of adsorbent per 50 mL of solvent extraction base oil at a temperature of 60°C gave the best-refined oil.

Conflict of interest

The authors declare no conflict of interest.

References

1 Pinheiro C T, Quina M J & Gando-Ferreira L M, Management of waste lubricant oil in Europe: A circular economy approach, *Crit Rev Environ Sci Technol*, 51 (2021) 2015.

2 Wagh K, Halmare R & Suryawanshi M, Non edible vegetable oils as an alternative lubricants in automotive sector, 2 (2017) 60.

3 Dan-Asabe B & Nwokeocha H, Environmental impact of used automobile engine oil on some soil properties and review of remediation techniques, *Niger Corros Assoc Conf*, 1 (2019) 60.

4 Aithal S & Aithal P S, Importance of circular economy for resource optimization in various industry sectors-A review based opportunity analysis, *Int J Appl Eng Manag Lett*, 7 (2023) 191.

5 Khan A H, Batool N & Aziz A, Recovery of base oil from used oil through solvent extraction followed by adsorption: A Review, *Environ Prot Res*, 3 (2023) 319.

6 Wathi A F D, Dewi S S, El-Ridlo N K, Wijayanti S W, Masbukhin F A A & Bikharudin A, Adsorption of lubricant waste by porous materials: A review, *Walisongo J Chem*, 6 (2023) 38.

7 Kwao-Boateng E, Anokye-Poku T, Agyemang A N P & Fokuo M K, Re-refining used engine oil in ghana using solvent extraction and acid-clay treatment, *Int J Chem Eng*, 2022 (2022) 6344409.

8 Mishra A, Siddiqi H, Kumari U, Behera I D, Mukherjee S & Meikap B C, Pyrolysis of waste lubricating oil/waste motor oil to generate high-grade fuel oil: A comprehensive review, *Renew Sustain Energy Rev*, 150 (2021) 111446.

9 Macián V, Tormos B, Ruiz S & Miró G, Low viscosity engine oils: Study of wear effects and oil key parameters in a heavy duty engine fleet test, *Tribol Int*, 94 (2016) 240.

10 Mishra A, Kumari U, Turlapati V Y, Siddiqi H & Meikap B C, Extensive thermogravimetric and thermo-kinetic study of waste motor oil based on iso-conversional methods, *Energy Convers Manag*, 221 (2020) 113194.

11 Kipkorir D, Nturanabo F, Tewo R, Rutto H & Enweremadu C, Properties of waste-distilled engine oil and biodiesel ternary blends, *Heliyon*, 7 (2021) e07858.

12 Emam E A & Shoaib A M, Re-refining of used lube oil, i- by solvent extraction and vacuum distillation followed by hydrotreating, *Pet Coal*, 55 (2013) 179.

13 Nwachukwu A, Review and assessment of mechanic village potentials for small scale used engine oil recycling business, *Afr J Environ Sci Technol*, 6 (2012) 464.

14 Izza H, Abdessalam S B, Bouida M & Haddad A, Recycling of used motor oil as an alternative method for production feedstock for the conversion processes, *Pet Sci Technol*, 36 (2018) 1511.

15 Sánchez-Alvarracín C, Criollo-Bravo J, Albuja-Arias D, García-Ávila F & Raúl-Pelaez-Samaniego M, Characterization of used lubricant oil in a latin-american medium-size city and analysis of options for its regeneration. *Recycling*, 6 (2021) 1.

16 Mekonnen G B, dos-Muchangos L S, Ito L & Tokai A, Analyzing key drivers for a sustainable waste management system in Ethiopia: An interpretive structural modeling approach, *Environ Challenges*, 8 (2022) 100556.

17 Hamawand I, Yusaf T & Rafat S, Recycling of waste engine oils using a new washing agent, *Energies*, 6 (2013) 1023.

18 Hubauer T, Roshchin M, Fabio-Ceschini G & Avdovic A, A diagnostic corrective action system based on deep learning and natural language processing, *Future Gas Turbine Technol*, (2016) 1.

19 Mohammed A S, Yakong V N, Twumasi E, Apuswin A R, Ameyaw C, Atuga A A & Cudjoe F K, Exploring the factors influencing home delivery: A cross sectional study among rural residents in tamale metropolis, *Asian J Med Heal*, 21 (2023) 1.

20 Mohsen S M, Yaseen A A, Ammar A M & Mohammad A A, Quality characteristics improvement of low-phenylalanine toast bread, *Int J Food Sci Technol*, 45 (2010) 2042.

21 Riyanto, Ramadhan B & Wiyanti D, Treatment of waste lubricating oil by chemical and adsorption process using butanol and kaolin, *IOP Conf Ser Mater Sci Eng*, 349 (2018) 012054.

22 Ani I J, Akpan U G, Hameed B H & Okafor J O, Treatment of spent engine oil (spent SAE W50) via solvent extraction-adsorption process for the production of transfer oil: Physico-chemical properties of the adsorbents, *Sci Afr*, 20 (2023) e01617.