RECOVERED SPENT ENGINE OIL TREATMENT BY USING SILICA GEL FILTRATION TECHNIQUE

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by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF SYMBOLS

gm	Gram
mL	milliliter
cP	centipoise
μm	micron
g/cm^3	gram per cubic centimetre
SiO_2	silicon dioxide
Pa.s	pascal-second
mPa.s	millipascal-second
^oC	degree celsius
cSt	Centistokes
cm^{-1}	Per centimeter

LIST OF ABBREVIATIONS

2D	Two Dimension
3D	Three Dimension
AFM	Atomic-force microscopy
ASTM	American Society for Testing and Materials
ATR	Attenuated Total Reflectance
CAGR	Compound Annual Growth Rate
DCH	Direct Contact Hydrogenation
DSC	Differential Scanning Calorimetry
EO	Engine Oil
EVs	Electric Vehicles
FT-IR	Fourier Transform Infrared Spectroscopy
FEO	Filtered Engine Oil
H_2S	Hydrogen Sulphide
KTI	Kinetic Technology International
MAP	Microwave Assisted Pyrolysis
MEK	Methyl Ethyl Ketone
MOFs	Metal Organic Frameworks
MPP	Microwave Pyrolysis Process
PAH	Polycyclic Aromatic Hydrocarbon
PAN	Polyacrylonitrile
PCB	Polychlorinated Biphenyls
PE	Polyethylene
PES	Polyethersulfone
PGF	Polyvinylidene Fluoride-Glass Fiber
PP	Polypropylene
PP	Pyrolysis Process
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene Fluoride
REO	Raw Spent Engine Oil
SEM	Scanning Electron Microscope
SEO	Spent Engine Oil

SG FEO	Silica Gel Filtered Engine Oil
SiO_2	Silicon dioxide
SW	Scheduled Waste Management
TGA	Thermogravimetric Analysis
UEO	Used Engine Oil
VD	Vacuum Distillation
WEO	Waste Engine Oil

RAWATAN MINYAK ENJIN DIPEROLEH TERPAKAI DENGAN MENGGUNAKAN TEKNIK PENAPIS GEL SILIKA

ABSTRAK

Mengitar semula minyak enjin terpakai adalah penting untuk menyokong kelestarian alam sekitar, ekonomi dan kesihatan yang mampan untuk mengelak daripada pelupusan yang tidak wajar. Penyelidikan ini menerokai keberkesanan penggunaan kain penapis ultrahalus dan gel silika semasa penapisan minyak enjin terpakai. Keadaan eksperimen yang mempengaruhi pH, ketumpatan, kelikatan dan rupa warna ialah jisim gel silika dan isipadu untuk minyak enjin yang telah digunakan. Minyak enjin terpakai dicirikan dari segi ciri fizikal dan kimia termasuk SEM, AFM, FTIR dan DSC. Pendekatan satu faktor pada satu masa (OFAAT) telah digunakan untuk mengawal pembolehubah tertentu manakala pembolehubah lain dipelbagaikan semasa ksperimen. Keputusan telah menunjukkan bahawa kejelasan visual, ketumpatan, pH, kelikatan dan komposisi kimia minyak telah dipertingkatkan dengan penggunaan kain penapis ultrahalus. Pemboleh ubah yang dikaji berkesan meenyingkirkan bahan zarahan, bahan cemar, dan kekotoran, menghasilkan warna minyak yang lebih cerah, mengurangkan ketumpatan, meningkatkan pH dan mengurangkan kelikatan minyak enjin yang ditapis (FEO). Analisis SEM bagi kain penapis sebelum dan selepas penapisan mendedahkan pengumpulan bahan cemar yang banyak, menunjukkan keberkesanan kain dalam memerangkap bendasing. Minyak enjin yang ditapis yang dibantu dengan gel silika (SG FEO) menunjukkan peningkatan yang lebih besar, termasuk warna yang lebih cerah, ketumpatan yang lebih rendah (0.77 g/cm^3), pH lebih hampir kepada minyak enjin segar (6.694), dan kelikatan berkurangan (32.3 cSt), menjajarkan ia rapat dengan sifat minyak enjin segar. Analisis

FT-IR menunjukkan pengurangan ketara sebatian berasid dan aromatik, menunjukkan penyingkiran bahan cemar yang berkesan. Analisis DSC mendedahkan takat lebur yang lebih rendah untuk SG FEO, setanding dengan minyak enjin baru, mengesahkan sifat terma yang lebih baik selepas penapisan. SEM dan analisis topografi gel silika sebelum dan selepas penapisan menyerlahkan peranan mereka dalam menyerap bahan cemar, dibuktikan dengan peningkatan kekasaran permukaan dan kehadiran hidrokarbon dan sebatian aromatik pada permukaan gel silika selepas penapisan. Penemuan ini membuktikan keupayaan teknik penapisan termaju dalam meningkatkan kualiti dan kebolehkitar semula minyak enjin terpakai, yang berpotensi membawa kepada prestasi enjin yang lebih baik, mengurangkan haus dan meningkatkan kelestarian alam sekitar.

RECOVERED SPENT ENGINE OIL TREATMENT BY USING SILICA GEL FILTRATION TECHNIQUE

ABSTRACT

Recycling spent engine oil is essential for supporting sustainable environmental, economic, and health concerns arising from improper disposal. This research explores the effectiveness of using ultrafine filter cloth and silica gels during filtration of spent engine oil under ambient temperature. The experimental conditions influencing the pH, density, viscosity and color appearance were mass of silica gels and working volume for the spent engine oil. The spent engine oil were characterized in terms of physical and chemical characteristics including SEM, AFM, FTIR and DSC. One factor at a time approach (OFAAT) was adopted to control certain variables while other variables were varied during the experimental work. Results have shown that oil's visual clarity, density, pH, viscosity, and chemical composition were improved by the use of ultrafine filter cloth. They effectively removed particulate matter, contaminants, and impurities, resulting in a lighter color, reduced density, increased pH, and decreased viscosity of the filtered engine oil (FEO). SEM analysis of the filter cloth pre- and post-filtration revealed substantial accumulation of contaminants, demonstrating the cloth's efficacy in trapping impurities. The filtered engine oil assisted with silica gels (SG FEO) exhibited greater improvements, including a further lightened color, lower density (0.77 g/cm^3), pH closer to fresh engine oil (6.694), and reduced viscosity (32.3 cSt), aligning it closely with the properties of fresh engine oil. FT-IR analysis showed the significant reduction of acidic and aromatic compounds, indicating effective removal of contaminants. DSC analysis revealed a lower melting point for SG FEO, comparable to fresh engine oil,

confirming the improved thermal properties post-filtration. SEM and topographical analysis of the silica gels pre- and post-filtration highlighted their role in absorbing contaminants, evidenced by increased surface roughness and the presence of hydrocarbons and aromatic compounds on the silica gel surfaces post-filtration. These findings proven the the ability of advanced filtration techniques in enhancing the quality and recyclability of spent engine oil, potentially leading to better engine performance, reduced wear, and improved environmental sustainability.

CHAPTER 1

INTRODUCTION

1.1 Background Information

According to Malaysian Automotive Association (MMA), the trend of owning vehicles in Malaysia are in the increasing trend. In year 2023, there were 799,731 vehicles have been registered for individual and commercial purposes. Meanwhile, as the number of registered vehicles on the road increasing, it lead to increasing number for engine market in Malaysia. For the record, the engine market which had a volume of 447.91 million litres in 2021, is anticipated to grow at a CAGR of 3.58 percent to 534.03 million litres by 2026 as per data by commercial and industries database website, Statista (2024). Statistic Department of Malaysia (2024) has reported that the automotive industry was the largest end-user category in Malaysia among all segments due to the higher amount of engines used in automobiles as compared to industrial uses. Engine oils are the most popular product category in Malaysia because of the wide range of engine sizes found in vehicles, lorries, and buses, as well as their frequent oil changes.

The market for gearbox and gear oils is projected to increase at a healthy rate due to the use of automated gearbox vehicles and a rebound in industrial activities. Global engine oil production is led by countries with large automotive and industrial sectors, such as the United States, China, and Germany. In Asia, engine oil production is particularly robust, with China, India, and Japan being major producers due to their extensive automotive manufacturing and maintenance industries. Narrowing down to Malaysia, the country has a growing engine oil production sector, supported by its well-developed automotive industry and strategic location in Southeast Asia, which facilitates both local consumption and export opportunities in the region. According to Statisa (2024), Malaysia produced over 144.67 thousand metric tonnes of engine oil in 2022 as shown in Figure 1.1 (Statisa, 2024). Over the years, the nation's engine oil production has fluctuated. Table 1.1 list down the segments for engine oil in Malaysia.

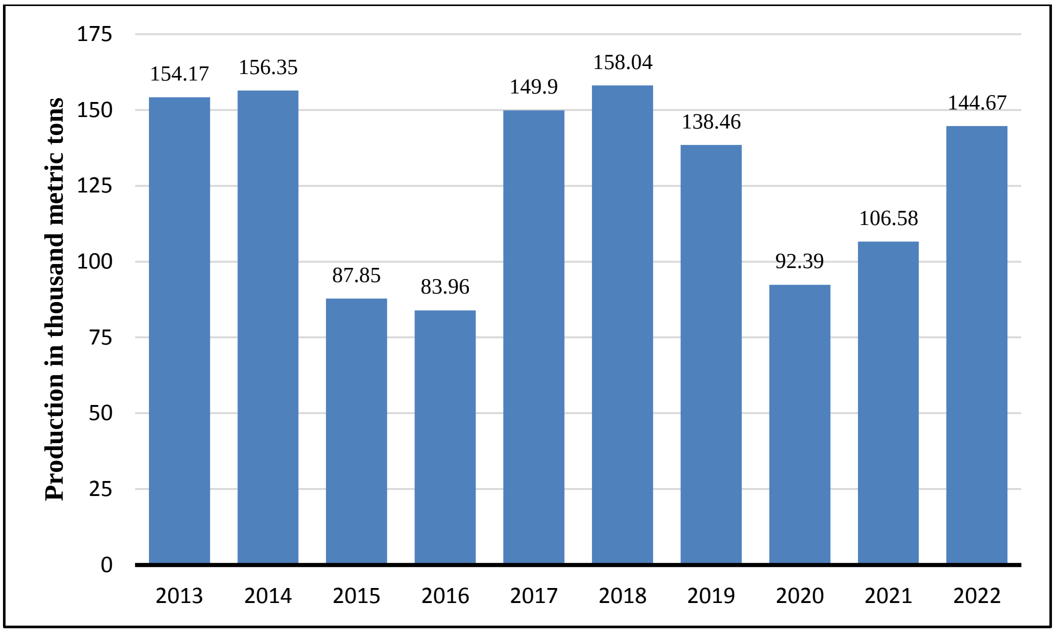

Figure 1. 1 Statistic on Engine Oil Consumption in Malaysia (Source: Statista 2024)

Table 1. 1 Segment of Engine Oils in Malaysia (Source: Mordor Intelligence, 2023)

Type of User	**Segment**
By end user	Automotive
	Heavy equipment
	Metallurgy & metalworking
	Power generation
	Other end user industries
By product type	Engine oils
	Greases
	Hydraulic fluids
	Metalworking fluids
	Transmission & gear oils
	Other product type

The top five companies account for 81.80% of the Malaysian Engines Market, which is fairly consolidated. There are BP PLC (Castrol), Chevron Corporation, PETRONAS Engines International, Royal Dutch Shell Plc, and Total Energies are the leading companies in this market. Although they are more expensive, the growth in the number of passenger vehicles on the road and the quickly rising need for high-performing engines are what are driving the automotive engines market in Malaysia. According to Ken Analysis, the demand for passenger vehicles has increased in recent years as a result of rising income levels, particularly in metropolitan areas, and a movement in consumer preference towards pricey synthetic and semi-synthetic engines (Ken, 2023).

The number of passenger automobiles on the road has increased significantly, primarily as a result of people choosing to commute privately instead of using public transportation. In Malaysia, a passenger automobile makes 2,300 km and a motorbike does 1,800 km in a month, respectively. Due to the concentration of automobiles in these areas, Kuala Lumpur, Penang, Perak, Selangor, and Johor are key regional hubs in Malaysia. The automotive engines industry would also be supported by the Malaysian government's National Automotive Policy which tends to focus on strengthening the capabilities of the domestic automotive industry and creating a mechanism to promote investments to ramp up the domestic production which will result in the increased demand for automotive engines.

1.2 Engine Oil and Spent Oil Composition

A broad range of products with hundreds of different base chemicals and additives are together referred to as engine oils. Although both synthetic and plant-based engine engines are employed, crude oil distillate fractions are the most widely used. A typical engine oil is made up with 80% base oil and 20% additives as shown in the figure 1.2. Engine oil is made up of 80–90% petroleum hydrocarbon distillate and 10–20% additives that give the oil particular qualities. The characteristics of the paraffinic or naphthenic chemicals that typically make up the petroleum hydrocarbon distillate are listed in Table 1.2.

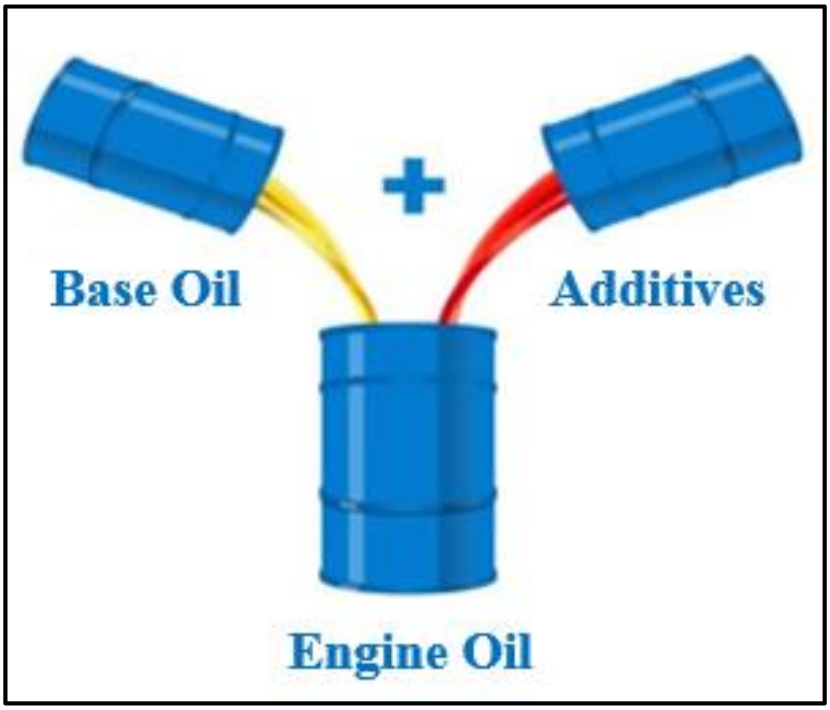

Figure 1. 2 A typical Engine Oil Composition (Source: Bharat Petroleum)

Table 1. 2 Properties of Paraffinic and Naphthenic Oils

No.	**Property**	**Paraffinic Oil**	**Naphthenic OIl**
1.	Chemical structure	Long carbon chains	Multiple carbon rings
2.	Resistance to oxidation[a]	High	Medium
3.	Pour point[b]	High	Low
4.	Viscosity[c]	High	Low
5.	Volatility[d]	Low	High
6.	Specific gracity[e]	Low	High

[*a]Measure of stability/chemical breakdown, [b]Lowest temperature at which oil will pour, [c]Resistance to flow/shear, [d]Property of transition to vapor state, [e]Density related to water.

Engine oil exposure can occur through both direct contact with the material and contact with ambient media containing the oil. Direct skin contact with the liquid oil is the main environmental exposure route. Inhaling oil mists produced during machine engine use is the main method of exposure at work. An exposure standard has been determined because occupational exposure to oil mists is sufficiently concerning (Sullivan, 2005). Engine oil can be exposed secondarily through contact with environmental media. These include cutaneous contact with contaminated soil, accidental consumption, and dust particle inhalation. Exposure to engine oil can happen through ingesting and skin contact with contaminated water when it leaks into the water. Under use conditions of heat, friction, and, if appropriate, exposure to internal combustion engine exhaust gases, unused engine oil changes. In comparison to unused oils, used engine oil and crankcase oil often include higher levels of polynuclear aromatic hydrocarbons. Although used oils are not discussed in detail in this article, they would be thought to be more harmful due to the increasing presence of poisonous components.

According to the guideline for Standard and Specification of Recovered Waste Oil in Malaysia published by the Department of Environment Malaysia, waste oil may contain physical and chemical contaminants that, when inhaled, ingested, or in touch with the skin, can cause a range of illnesses and disorders in people and other living things. The leading pollutants in waste oil are displayed in Table 1.3 below.

Table 1. 3 Principal Contaminants in Waste Oil (Source: Standard and Specification of Recovered Waste Oil in Malaysia, DOE)

Metals and snorganics	**Chlorinated hydrocarbons**	**Other organics**
Aluminium	Dichlorodifluoromethane	Benzene
Antimony	Trichlorodifluoromethane	Toluene
Arsenic	1,1,1-Trichloroethane	Xylenes
Barium	Trichloroethylene	Benza(a)anthracene
Cadmium	Tetrachloroethylene	Benzo(a)pyrene
Calcium	Total chlorine	Naphthalene
Chromium	Polychlorinated biphenyls	Other PAHs
Cobalt		
Copper		
Lead		
Magnesium		
Manganese		
Mercury		
Nickel		
Phosphorus		
Silicon		
Sulphur		
Zinc		

Waste oil that has been treated by facilities for recovery and complies with the requirements for recovered waste oil as listed in Table 1.4 can be regarded as non-scheduled waste. Even when waste oil has been processed, it is still classified as scheduled waste if it does not meet the requirements for recovered waste oil.

Table 1. 4 Recovered Spent Oil Requirement by DOE Malaysia

No.	**Parameters/constituents**	**Allowable level**
1.	Arsenic	5 ppm maximum
2.	Cadmium	2 ppm maximum
3.	Chromium	10 ppm maximum
4.	Lead	100 ppm maximum
5.	Total Halogen (as chlorine)	1000 ppm maximum
6.	Flash point	37.7 °C or higher
7.	Appearance	The recovered waste oil must have a clear and bright appearance
	Poly-aromatic hydrocarbons	
1.	Benzo(a)pyrene	10 mg/ 1 kg oil (10 ppm) maximum
2.	Dibenz(ah)anthracene	10 mg/ 1kg oil (10 ppm) maximum
3.	Benz(a)anthracene	100 mg/ 1 kg oil (100 ppm) maximum
4.	Benzo(b) fluoranthene	100 mg/ 1 kg oil (100 ppm) maximum
5.	Chrysene	100 mg/ 1kg oil (100 ppm) maximum
6.	Indeno(123-cd)pyrene	100 mg/ 1 kg oil (100 ppm) maximum

1.3 Spent Engine Oil Management in Malaysia

One of the waste streams included in the Environmental Quality (Scheduled Wastes) Regulations 2005 is waste oil. Despite being a waste, waste oil has economic worth, which encourages the construction of recovery plants to turn it into completed goods like fuel oil, lubrication oil, hydraulic oil, base oil, and other products. A Department of Environment operating licence is required for the recovery or processing of waste oil. In Malaysia, waste oil is classified as scheduled wastes under the First Schedule of the Environmental Quality (Scheduled Wastes) Regulations 2005, with the following codes and descriptions as in the Table 1.5.

Table 1. 5 Waste Oil Classification

No.	**Scheduled waste codes**	**Description**
1.	SW305	Spent engine oil
2	SW306	Spent hydraulic oil
3.	SW307	Spent mineral oil- water emulsion
4.	SW308	Oil tanker sludges
5.	SW309	Oil – water mixture such as ballast water
6.	SW310	Sludge from mineral oil storage tank
7.	SW311	Waste oil or oily sludges
8.	SW312	Oily residue from automotive workshop, service station oil or grease interceptor
9.	SW314	Oil or sludge from oil refinery or petrochemical plant

According to the Environmental Quality (Scheduled Wastes) Regulations 2005, waste oil must be managed properly. Waste oil recovery facilities with Department of Environment licences can recover waste oil that still has a marketable value. Waste oil that has been collected, recycled, or reconstituted but does not adhere to the established standards and specifications is still categorised as scheduled waste. During routine use, the oil may become contaminated with pollutants like dirt, extremely fine metallic scrapings from engine erosion, water or chemicals, etc. Additionally, when engine oil is used in internal combustion engines, a lot of contaminants are produced in the oil owing to oxidation or thermal degradation.

1.4 Mechanisms of Spent Engine Oil Recovery using Vaporization Filtration

The spent oil product's purity, recover viscosity, and flash point are all improved during the recovery process by the purification step, which involves the removal of water, gases, contaminants, and volatile substances from the spent oil. The following steps are part of the purifying process:

i. Primary filtration
ii. Vaporisation
iii. Secondary filtration
iv. Tertiary filtration

Vacuum oil filtration is one of the most acceptable methods in purifying spent engine oil. Under the influence of the internal and external pressure differences, the spent lubricating oil enters the main filter during the filtering process, where the large impurity particles in the oil are filtered out. After being heated by a vacuum oil purifier with multiple stages of infrared radiation, the oil enters the vacuum separator. The film is created in the vacuum separator after the mist has first formed, increasing the contact surface there by a factor of hundreds. Under the circumstances of fast pumping speed, high vacuum, and big surface, the moisture in the transformer oil is quickly vaporised and expelled from the vacuum system.

The condenser first cools and dehumidifies the water vapour that is released from the upper half of the vacuum separator, after which it enters the cooler to be cooled once more, and the condensed water is then released into the water storage tank. After being twice dehumidified and condensed, the gas is eventually released into the air using a vacuum pump. The oil transfer pump raises the dry oil in the vacuum separator from negative pressure to positive pressure after vacuum vaporisation and dehydration, and after fine filtration, it is expelled through the oil outlet to finish the transformer oil filtration process. A typical equipment for spent engine oil recovery is shown in the Figure 1.3.

Figure 1. 3 A Typical Set up of Spent Engine Oil Recovery

Centrifuging, coalescing, and vacuum distillation are the three main techniques for cleaning or recovering lubricating oils that are generally used in process facilities and utilities. The majority of free water can be eliminated by centrifuging and coalescing, however these processes are unable to separate emulsified water, dissolved water, light hydrocarbons, or dangerous gases like Hydrogen Sulphide (H_2S). Centrifuging involves separating the components with different specific gravities—water with a high specific gravity and oil with a low specific gravity. For a certain lubricating oil specific gravity, the configuration of the centrifuge bowl must be such that the overflow port is precisely at the level where there is no carryover of water into the reclaimed oil or loss of centrifuged oil into the free water being extracted. A typical engine oil composition is shown in Table 1.6.

Table 1. 6 A Typical Composition of Engine Oil (Vouitsis et al., 2007).

Property/element	**Low Sulphur Oil**	**High Sulphur Oil**
Base/stock	Synthetic	Mineral
Viscosity grade	0W-40	15W-40
KV100 (cSt)	12.8	14.94
KV40 (cSt)	74.48	105.94
Viscosity Index	174	148
Barium (Ba)	0.066 ± 0.002	0.067 ± 0.002
Cadmium (Cd)	0.01 ± 0.001	0.32 ± 0.03
Cobalt (Co)	NA	NA
Chromium (Cr)	3.9 ± 0.1	1.76 ± 0.1
Copper (Cu)	0.062 ± 0.002	0.063 ± 0.002
Iron (Fe)	19 ± 0.3	13.5 ± 0.1
Manganese (Mn)	0.41 ± 0.001	0.035 ± 0.01
Nickel (Ni)	2.72 ± 0.1	1.3444 ± 0.05
Phosphorus (P)	605 ± 40	883 ± 45
Antimony (Sb)	0 ± < 0.4	0 ±<0.4
Selenium (Se)	0 ±<0.1	0 ±<0.1
Silicon (Si)	0 ±<0.1	0 ±<0.1
Strontium (Sr)	0.54 ± 0.05	0.072 ± 0.004
Calcium (Ca)	1540	NA
Zinc (%)	662±	NA
Sulphur (%)	0.176	0.889
Color	1.0 (Pale yellow)	2.5 (Yellowish)

1.5 Problem Statement

Lubricant oil plays a crucial role in reducing friction and wear in engines and machinery, ensuring smooth and efficient operation. However, after prolonged use, engine oil becomes contaminated and degraded, transforming into spent engine oil. Improper disposal of spent engine oil can lead to significant ecological damage and health risks. Waste oils are considered more hazardous to health and the environment than virgin base oils due to the presence of degraded additives, contaminants, and by-products of oil degradation. Spent engine oil contains impurities that affect its physical and chemical properties, including increased viscosity, altered density, degraded pH levels, and changes in color appearance due to oxidation, contamination, and breakdown of additives.

In order to minimize environmental contamination and conserve natural resources, spent engine oil should be collected and recycled. However, certain properties of spent engine oil, such as viscosity, density, pH, and color appearance, present significant challenges to simple recycling techniques like vacuum vaporization. Oxidation or contamination may cause the oil to become more viscous, while changes in density and pH may affect the oil's performance and suitability for reuse. Additionally, the darkening of the oil’s color indicates contamination and degradation, which are difficult to reverse through conventional filtration methods alone.

To address these challenges, this research explores the use of ultrafine filter cloth and silica gels as advanced filtration mechanisms during the recovery process. Ultrafine filter cloth can physically remove fine particulate contaminants, while silica gels, with their highly porous and adsorptive properties, have the potential to target specific impurities that affect the chemical characteristics of spent oil. This study will evaluate the effectiveness of these filtration mechanisms by analyzing the impact of the filtration process on the pH, density, viscosity, and color appearance of recovered oil. The goal is to improve the quality of recycled oil and ensure its viability for reuse, while also reducing environmental hazards associated with improper disposal of spent oil.

1.6 Research Objectives

This research aims to explore the utilization of filtration of spent engine oil towards the characteristics of the recovered spent engine oil. The specific objectives of the work are as follows:

- To characterize the raw spent engine oil in terms of physical and chemical properties before and after pretreatment filtration step.
- To investigate the effectiveness of ultrafine filter cloth and silica gels filtration under ambient temperature for pH, density, viscosity and color appearance.
- To assess the morphological and functional properties of filter cloth and silica gels before and after filtration.

1.7 Scope of Works

The scope of work for this research will cover the following:

i. The spent engine oil will be taken from automovitve servicing workshop discarding spent engine oil.
ii. The spent engine oil will be subjected to gravitational and vacuum condition with the aid of negative pressure diaphragm pump.
iii. The physical and characterization of spent engine oil will be evaluated based on its pH, density, viscosity and color apperaance
iv. The chemical characteristics of the spent oil that will be evaluated for the study are FTIR. Meanwhile, AFM, DSC and SEM will be assessed on the ultrafine filter cloth and silica gels before and after filtration.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Waste management is critical, yet challenging, as many wastes are difficult to recycle, leading to extensive landfilling globally. Hazardous waste disposal contributes to pollution and greenhouse gas emissions without recovering toxic components (Zahir Hussain, Santhoshkumar, and Ramanathan 2020). With the modern society's reliance on cars, the demand for lubricants, particularly engine oil, has surged. The automotive industry's rapid growth in the last decade has boosted demand for engine oil, which accounted for 57% of global production by 2016 (Patel and Shadangi 2020). The increase in vehicle numbers has generated around 20 billion tons of spent engine oil (SEO), posing environmental concerns due to ineffective treatment (Pinheiro, Quina, and Gando-Ferreira 2021, Yang *et al.* 2021). About 95% of SEO is either incinerated or disposed of in landfills and wastewater streams (Makwana *et al.* 2020, Zgheib and Takache 2021).

According to recent studies, the global used engine oil recycling market was valued at USD 2268.3 million in 2023, projected to reach USD 3414.4 million by 2030, with a CAGR of 6.0% (Information 2023). Figure 2.1 presents the publication trends over the past 23 years, highlighting the emergence of studies focusing on waste engine oil recycling. A prominent feature of Figure 2.1 is the steady rise in the number of publications over time. Notably, there is a substantial increase in relevance observed from 2006 to 2023. The analysis of the database indicates the enduring importance and growing interest in the recycling of waste engine oil, indicating that it continues to be a central and expanding area of research.

Engine oil, the primary petroleum fraction, serves a critical role in vehicles and machines, reducing friction between moving parts and facilitating smooth operation (Osman, Attia, and Taman 2018). It performs three functions of heat transfer, friction reduction, and corrosion resistance in automotive engines, essential for lubrication and cooling (Mishra et al. 2020). Engine oil lubricants comprise approx. half the lubricant market, extending the lifespan of moving parts under varying conditions (Nour *et al.* 2021). Despite its importance, decreasing fossil fuel sources, increasing demand, and environmental hazards associated with waste engine oil (WEO) disposal have drawn attention (Li *et al*. 2020). WEO consists of base oil containing hydrocarbons and chemical additives, loses its properties over time due to friction, temperature, and contamination, reducing its volume by 50% (Zzeyani et al. 2019). Used oil, resulting from impurities like dirt, metal scrapings, and thermal degradation, requires replacement as its quality deteriorates (Gaur *et al*. 2023, Rammohan 2016). Improper disposal of used engine oil causes pollution, whereas valuable products and be produced if properly recovered and recycled (Yash 2015). Therefore, responsible handling and disposal are crucial for environmental sustainability.

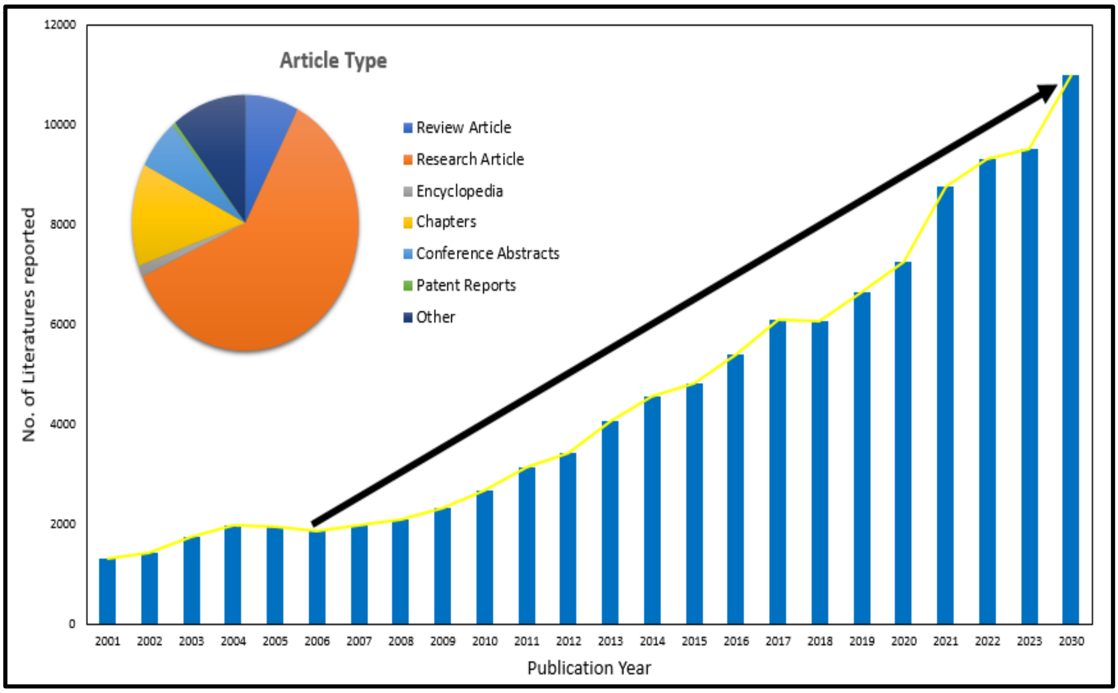

Figure 2. 1 Number of scientific studies in the last twenty years about recycling of waste engine oil. Search conducted through Science Direct database on 16 march 2024 and forecasted for upto 2030.

Additives in base oil enhancing the oil's performance. These additives include antioxidants, anti-wear, thickeners, anti-foam, detergents, corrosion protection, dispersants, and high pressure additives (Gunawan *et al.*, 2019; Mohammed et al., 2013; Yash, 2015). They introduce or enhance specific properties, such as oxidation resistance and friction reduction. However, used oil contains contaminants like heavy metals (lead, cadmium, arsenic, chromium, nickel), sulfur, toluene, benzene, chlorinated paraffins, chlorinated solvents, polychlorinated biphenyls (PCBs), and polyaromatic hydrocarbons (PAHs), posing environmental and health risks (Anufriev *et al.*, 2019; Gaur *et al.*, 2023; Peng *et al.*, 2018; Ramirez *et al.*, 2019; Zahir Hussain *et al.*, 2020). These contaminants can originate from additive degradation, wear debris, and external pollutants (Kheireddine *et al.*, 2013; Sadeek *et al.*, 2014). Due to its hazardous components, waste engine oil (WEO) can contaminate water sources, soil, and air if improperly disposed of (Yadav & Saravanan, 2015). Figure 2.2 illustrates the journey of engine oil, spanning from its initial state of being unused to its eventual fate of either disposal or recycling. Despite impurities, much of the base oil in waste oil remains unexhausted, preserved by the stability of heavy compounds (Patel & Shadangi, 2020). Therefore, rigorous processing is essential before considering reuse or recycling.

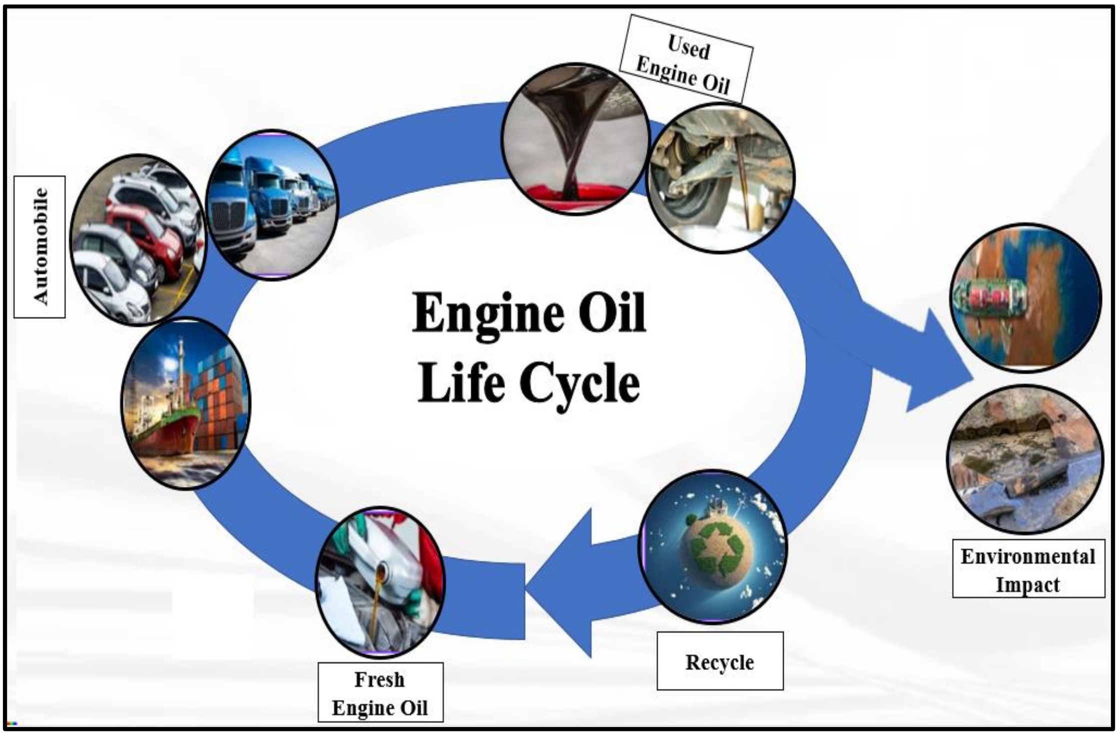

Figure 2. 2 Schematic drawing of Life cycle of engine oil from unused state to either recycled or disposal.

2.1.1 Environmental impact of spent engine oil

Improper disposal of waste, including hazardous waste like spent engine oil, poses significant threats to social, economic, and environmental sustainability (Tekin *et al.*, 2019). Various materials, including discarded tires, used automotive engine oil, and residue from automobile shredders, primarily from vehicles, contribute to this waste stream (Korchak *et al.*; Lam & Chase, 2012; Patel & Shadangi, 2020). They require proper handling due to their hazardous nature, emphasizing environmental considerations (Widodo *et al.*, 2020). The significant volume of waste engine oils has economic and environmental impacts, costing millions to manufacture and posing high pollution risks when improperly disposed of. Discharging waste engine oils into water, land, or burning them as low-grade fuel can lead to severe pollution problems, releasing harmful pollutants into the environment. Therefore, appropriate handling and disposal procedures are crucial to mitigate these risks and promote environmental sustainability.

Spent engine oil is a hazardous substance that poses significant threats to both the environment and human health if not properly managed and disposed. It contains a cocktail of metals and heavy polycyclic aromatic hydrocarbons, resulting from incomplete combustion and the wear process of engine components. These compounds have been linked to chronic hazards such as carcinogenicity and mutagenicity, potentially leading to increased cancer risk, bone marrow damage, and liver or kidney disease, upon prolonged exposure (Goyal *et al.*, 2022; McLoone *et al.*, 2021). This contamination not only harms animal populations by adhering to their fins, feathers, and hair but also disrupts ecosystems as affected animals are forced to migrate to other areas. Additionally, the insolubility, persistence, and slow degradation of engine oil further compound its environmental danger, ensuring that contaminated water sources remain hazardous for extended periods (Ossai *et al.*, 2020). Moreover, modern engine oil additives only serve to heighten its toxicity in the environment. Thus, the proximity of polycyclic aromatic hydrocarbons, heavy metals and polychlorinated biphenyls in used engine oil presents a grave threat to ecological balance and human well-being.

2.1.2 Importance of recycling spent engine oil

In this mentioned context, recycling, reuse, energy recovery, and proper disposal is must (Pinheiro *et al.*, 2021). Spent engine oil poses significant environmental risks, with just one gallon capable of contaminating a million gallons of groundwater. Even small concentrations of 50–100 ppm in sewage treatment plants can disrupt the water treatment process (Adelowo *et al.*, 2006; Klamerus-Iwan *et al.*, 2015). The recycling of spent engine oil (SEO) may offer a cost-effective alternative to incineration. Incineration and chemical treatment, while common methods for disposing of , incur high operation costs and carbon dioxide emissions due to the energy-intensive equipment required. Consequently, about 55% of worldwide SEO is directly dumped into landfills or waterways, treating it as municipal solid waste due to lower processing costs (Sam *et al.*, 2020). Used engine oil, a byproduct of vehicle servicing, contributes millions of liters of waste annually (Afreen Nissar *et al.*, 2022; Patel & Shadangi, 2020). Proper treatment of SEO is necessary to mitigate health and environmental risks. Untreated burning and inappropriate disposal elevate pollution levels, despite the potential value of waste oil from an energy conservation perspective (Hamawand *et al.*, 2013). Therefore, recycling is crucial to maintaining environmental cleanliness. The characteristics and environmental impacts of waste engine oil, as well as the significance of recycling this material is illustrated in Figure 2.3.

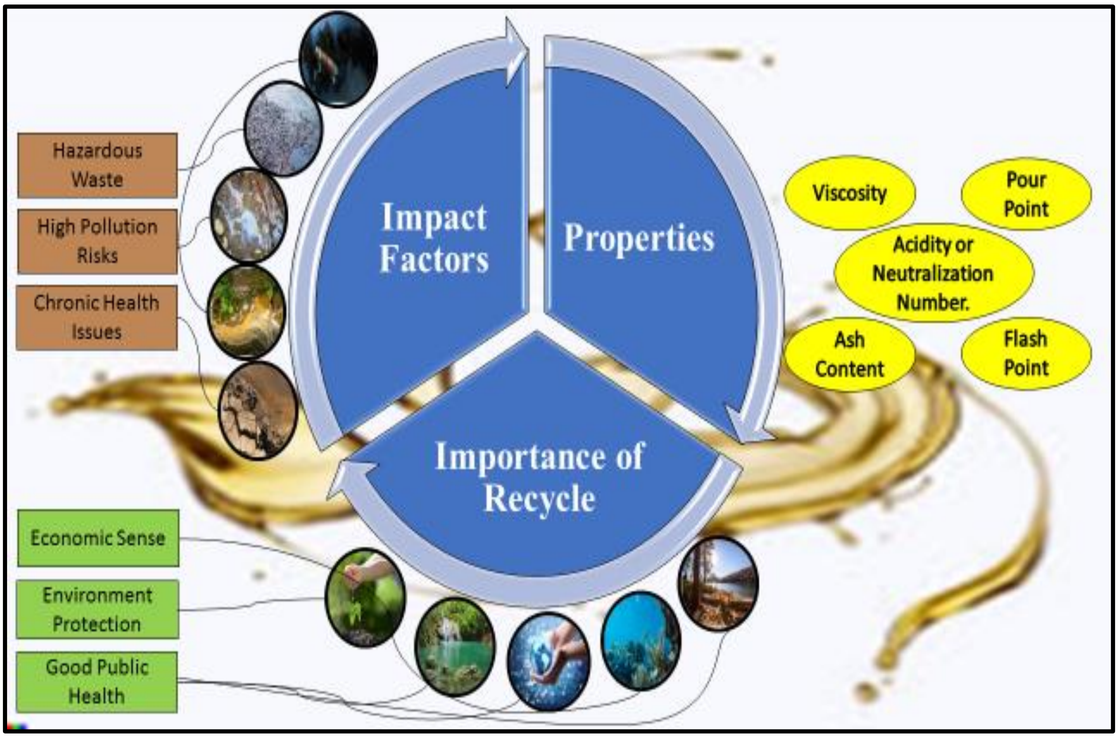

Figure 2. 3 Properties and Environmental Impact of SEO, and Importance of Recycling.

Several reviews have examined the recycling processes and environmental impacts of waste lubricating and other oils. However, a comprehensive review focusing specifically on the challenges in traditional engine oil recycling and recent advancements in engine oil recycling technology remains notably absent. Therefore, the objective of this review is to provide a comprehensive examination of engine oil recycling, encompassing both the challenges associated with traditional methods and recent advancements in recycling technology. This review aims to stimulate research on advanced SEO recycling techniques and generate innovative ideas for harnessing environmental impact, improving fuel and lubricant quality, and implementing circular economy approaches in refining operations, while discussing the ecological and economic benefits of employing these technologies. By addressing emerging technologies and potential obstacles, this review aims to provide a comprehensive understanding of the current landscape of waste engine oil recycling and pave the way for future advancements in the field.

2.2 Overview of Engine Oil Recycling Process

Engine oil recycling is crucial for environmental sustainability and resource conservation, especially considering the damage caused by used engine oil when dumped into the water streams, land, and sewers (Al-Khafaji *et al.*, 2018). Recycling involves collecting used oil, pre-treatment, and re-refining. Additives may be blended with the recycled oil to enhance its performance characteristics, and quality control measures are implemented throughout the process to ensure compliance with regulatory standards (Hussain *et al.*, 2024). The detailed SEO recycling process, as depicted in the Figure 2.4, encompasses the entire journey from the extraction and collection of used engine oil to its recycling, and finally, the assessment of its environmental impact postrecycling. Engine oil recycling is guided by fundamental principles aimed at minimizing waste, conserving resources, and preventing environmental pollution (Pinheiro et al., 2021). These principles drive the entire process, starting from collection to reprocessing and reuse. Oil recycling supports sustainability and resilience by preventing pollution, saving energy, generating economic benefits, and embracing the principles of a circular economy. By keeping valuable materials in circulation, it contributes to a more sustainable and resilient environment. Public awareness and education initiatives play a vital role in promoting responsible oil management practices and increasing participation in recycling efforts. Through these principles, oil recycling contributes to environmental sustainability and resource efficiency, making it an integral part of sustainable development strategies.

Figure 2. 4 Schematic illustration of stages in waste engine oil recycling, pictures adapted from (C. Liu & Wang, 2021; Sun *et al.*, 2021; Zulqarnain *et al.*, 2021).

2.2.1 Historical Development in Recycling Processes

The growing attention towards recycling SEO is primarily driven by escalating environmental concerns stemming from increased pollution and the imperative to natural resources conservation. In some technologically advanced countries, as much as 50% of waste engine oils are sourced from recycled ones. In areas such as the European Union, the production of refined base oils from used engine oil accounts for only 13% of the total required base oils (Zimmermann & Jepsen, 2018). Exploring the historical development of waste engine oil recycling techniques is crucial to gaining insights into addressing environmental concerns and improving resource efficiency over time. Table 2.1 showcases the chronological evolution of waste engine oil recycling techniques. These advancements highlight the evolving landscape of waste engine oil recycling, with efforts directed towards maximizing resource recovery and minimizing environmental impact.