ENVIRONMENTAL IMPACTS AND ENERGY CONSUMPTION OF WASTE LUBRICANT OIL RECOVERY SYSTEM BY LIFE CYCLE ASSESSMENT

NADZIRAH BT MUHAMAD DAUT

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by

NADZIRAH BT MUHAMAD DAUT

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ANOVA	Analysis of variance
AP	Acidification Potential
ASTM	American society for testing and materials
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
cSt	centistokes
DOE	Department of environment
EP	Eutrophication potential
EPA	Environmental Protection Agency
FE	Freshwater ecotoxicity
FEU	Freshwater eutrophication
FPMF	Fine particulate matter formation
FRS	Fossil resource scarcity
GW	Global warming
GWP	Global warming potential
HCT	Human carcinogenic toxicity
HNT	Human non-carcinogenic toxicity
IR	Ionizing radiation
ISO	International organisation of standardisation
kg	kilogram
kWh	kilowatt per hour
L	litre

LCA	Life cycle Assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use
ME	Marine ecotoxicity
ME	Marine eutrophication
MRS	Mineral resource scarcity
MS	Material safety
NO_x	Nitrogen oxides
OFHH	Ozone formation (human health)
OFTE	Ozone formation (terrestrial ecosystem)
OLD	Ozone layer depletion
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
SO_2	Sulfur dioxide
SOD	Stratospheric ozone depletion
SO_x	Sulfur oxides
SW	Schedule waste
TA	Terrestrial acidification
TE	Terrestrial ecotoxicity
VOCs	Volatile organic compounds
WCHH	Water consumption (human health)
WEO	Waste engine oil

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IMPAK ALAM SEKITAR DAN PENGGUNAAN TENAGA SISTEM PEROLEHAN SISA MINYAK PELINCIR MELALUI PENILAIAN KITAR HIDUP

ABSTRAK

Proses perolehan sisa minyak pelincir boleh memberi kesan kepada alam sekitar yang ketara disebabkan oleh input bahan dan tenaga, yang boleh dinilai melalui Penilaian Kitaran Hayat (LCA). Walau bagaimanapun, penyelidikan dalam bidang ini adalah terhad. Kajian ini menangani jurang tersebut dengan menganalisis secara kuantitatif kesan alam sekitar dan penggunaan tenaga bagi tiga kategori minyak buangan: SW 305 (Sisa Minyak Pelincir), SW 306 (Sisa Minyak Hidraulik) dan SW 307 (Sisa Emulsi Air Minyak Mineral). Kajian ini menggunakan data operasi daripada kemudahan perolehan sisa minyak di Seberang Perai, Pulau Pinang, meliputi Januari hingga Jun 2023. Menggunakan kaedah ReCiPe 2016 dalam OpenLCA, kesan alam sekitar terhadap kesihatan manusia, kualiti ekosistem dan ketersediaan sumber dinilai untuk 13,000 L bagi setiap sisa minyak. Pencirian menunjukkan variasi ketara antara minyak buangan SW 306 dan SW 305 mempunyai sifat yang lebih konsisten, memudahkan proses perolehan yang stabil, manakala SW 307 memerlukan rawatan khusus kerana kandungan air yang lebih tinggi, kelikatan yang lebih rendah dan ketumpatan yang lebih tinggi. Dari segi kesan kesihatan manusia, SW 305 secara amnya mempunyai kesan yang lebih tinggi, kecuali ketoksikan bukan karsinogenik manusia (HNT), dimana SW 306 lebih tinggi. SW 307 secara konsisten menunjukkan impak yang paling rendah, menjadikannya paling tidak berbahaya untuk kesihatan manusia. Berkenaan kualiti ekosistem, SW 305 mempunyai kesan yang lebih tinggi dalam kebanyakan kategori, kecuali dalam

ekotoksisiti daratan (TE) dan eutrofikasi air tawar (FE), di mana SW 306 lebih berbahaya. SW 307 menunjukkan impak yang paling rendah, menunjukkan ia adalah yang paling tidak berbahaya kepada alam sekitar. Bagi ketersediaan sumber, SW 305 mempunyai impak tertinggi dalam kekurangan sumber fosil (FRS) dan kekurangan sumber mineral (MRS), yang menekankan keperluan untuk amalan yang lebih mampan. SW 306 mempunyai kesan sederhana terhadap kekurangan sumber mineral tetapi tiada data tentang kekurangan sumber fosil. SW 307 secara konsisten mempunyai kesan paling rendah, mencadangkan ia adalah pilihan paling mampan untuk mengurangkan kekurangan sumber fosil (FRS) dan sumber mineral (MRS). Walau bagaimanapun, analisis penggunaan tenaga mendedahkan bahawa SW 307 memerlukan tenaga paling banyak untuk perolehan, dengan penggunaan tenaga yang ketara juga dikaitkan dengan pengangkutan sisa minyak, menggunakan 7,722 L diesel setiap bulan sepanjang 23,400 km. Penemuan ini menekankan keperluan untuk mengoptimumkan proses perolehan dan logistik untuk mengurangkan kesan alam sekitar dan meningkatkan kecekapan tenaga dalam pengurusan sisa minyak pelincir.

ENVIRONMENTAL IMPACTS AND ENERGY CONSUMPTION OF WASTE LUBRICANT OIL RECOVERY SYSTEM BY LIFE CYCLE ASSESSMENT

ABSTRACT

The waste lubricant oil recovery process can have significant environmental impacts due to material and energy inputs, which can be evaluated through Life Cycle Assessment (LCA). However, research in this area is limited. This study addressed the gap by quantitatively analyzing the environment impacts and energy consumption of three waste oil categories: SW 305 (Spent Lubricating Oil), SW 306 (Spent Hydraulic Oil) and SW 307 (Spent Mineral Oil-Water Emulsion). The study utilized operational data from a waste oil recovery facility in Seberang Perai, Pulau Pinang, covering January to June 2023. Using the ReCiPe 2016 method in OpenLCA, the environmental impacts on human health, ecosystem quality, and resource availability were assessed for 13,000 liters of each waste oil. Characterization revealed significant variations among the waste oils. SW 306 and SW 305 had more consistent properties, facilitating stable recovery process, while SW 307 required specialized treatment due to higher water content, lower viscosity, and higher density. In terms of human health impacts, SW 305 generally had higher impacts, except for human non-carcinogenic toxicity (HNT), where SW 306 was higher. SW 307 consistently showed the lowest impacts, making it the least harmful for human health. Regarding ecosystem quality, SW 305 had higher impacts in most categories, except for terrestrial ecotoxicity (TE) and freshwater eutrophication (FE), where SW 306 was more harmful. SW 307 again showed the lowest impacts, indicating it was the least harmful to the environment. For resource availability, SW

305 had the highest impacts in both fossil (FRS) and mineral resource scarcity (MRS), highlighting the need for more sustainable practices. SW 306 had a moderate impact on mineral resource scarcity (MRS) but no data on fossil resource scarcity (FRS), requiring fewer resources than SW 305. SW 307 consistently had the lowest impacts, suggesting it is the most sustainable choice for reducing fossil and mineral resource depletion. However, energy consumption analysis revealed that SW 307 required the most energy for recovery, with significant energy consumption also attributed to the transportation of waste oil, consuming 7,722 L of diesel monthly over 23,400 km. These findings emphasize the need to optimize recovery processes and logistics to reduce environmental impacts energy efficiency in waste lubricant oil management.

CHAPTER 1

INTRODUCTION

1.1 Research Background

“Waste lubricant oil” refers to a petroleum-based substance that has been rendered unfit for its intended purpose by the introduction of impurities or deterioration of its original properties as a result of its use or management. It is also referred to “waste oil”, “used oil” or “spent oil” that has been previously utilised or is not fit for its intended function. It is used to describe oil that has been polluted with compounds that may or may not pose a risk to health or the environment (Anisuzzaman et al., 2021). Commonly produced waste oils include: engine oil; hydraulic oil; transmission fluid diesel fuel; gas oil; kerosene; turbine oil; aviation fuel and; marine oil. If any oil is contaminated with hazardous waste, it is considered a hazardous waste and must be managed according to hazardous waste management guidelines. Waste oils necessitate appropriate recycling, recovery or disposal to prevent the creation of an environmental issue. The proper and efficient management of waste oil can be divided into three primary categories: storage, collection, and recovery.

Waste oil treatment and disposal practices can have a big impact on the environment. Waste oil can pollute soil and water sources if it is thrown on the ground or into bodies of water. Ecosystems, aquatic life, and drinking water supplies may all be negatively impacted by this contamination. Without adequate emission control, burning waste oil can emit dangerous chemicals into the atmosphere. These contaminants can negatively impact both human health and the environment while also contributing to air pollution and smog production (Vineet K. and Sattar H., 2010). It is anticipated that waste oil treatment technologies will reduce hazardous contaminants to a safe level, thereby enabling the handling and use of treated oils without posing excessive risks. The primary objective of management techniques is to reduce the hazards associated with waste oil throughout its entire lifecycle. The complexity, process end products, environmental benefits, and financial constraints of used oil management options are highly variable. Landfilling, discarding, and open burning are the least preferred methods of disposal. The most preferable management strategy is the complete recycling of waste oil into base oil. This approach is in close alignment with the circular economy principles, as it results in significant energy savings and a decrease in environmental impact.

Almost all waste oil pollution has the potential to be safely recycled, thereby reducing environmental pollution and preserving a valuable non-renewable resource (Panicker et al., 2010). Waste oil can be reprocessed into fuel oil, refined into base lubricant, or used as feedstock for a variety of processes that generate petroleum-based products or other economically valuable products after being properly treated to eradicate pollutants (Abu-Elella et al., 2015).

Waste oil recovery is considered a best practice due to its substantial reduction in environmental impact. Again, only licenced operators are permitted to conduct this procedure in compliance with the regulations. Waste oil recovery refers to the procedure of extracting and reusing substances from used oil. After collecting waste oil, which is then transported to a laboratory for analysis to determine whether or not it can be reused, it is appropriately treated to recover any fuels, lubricants, or metals that may be present in the mixture. Waste oil, for instance, can be treated and refined for use in steam rising boilers and the bitumen industry.

In Malaysia, waste oil is one of the waste streams prescribed under the Environmental Quality (Scheduled Wastes) Regulations 2005. Although it is a waste, it has economic value, thus, it promotes the setting up of recovery plants to process the waste oil into finished products such as fuel oil, lubrication oil, hydraulic oil, base oil and etc. The recovery or processing of waste oil requires an operating licence from the Department of Environment. Waste oil in Malaysia is categorised as scheduled wastes according to the Environmental Quality (Scheduled Wastes) Regulations 2005. It is listed in the First Schedule with a description code of SW 3 along with specific codes and descriptions as follows:

a) SW 305 – Spent lubricating oil
b) SW 306 – Spent hydraulic oil
c) SW 307 – Spent mineral oil-water emulsion
d) SW 308 – Oil tanker sludges
e) SW 309 – Oil-water mixture such as ballast water
f) SW 310 – Sludge from mineral oil storage tank
g) SW 311 – Waste oil or oily sludges
h) SW 312 – Oily residue from automotive workshop, service station oil or grease interceptor
i) SW 314 – Oil or sludge from oil refinery or petrochemical plant

Proper management of waste oil is necessary in accordance with the Environmental Quality (Scheduled Wastes) Regulations 2005. Waste oil with remaining economic value can be reclaimed by licenced waste oil recovery facilities approved by the Department of Environment. In order to comprehensively evaluate the environmental effects of waste oil, it is imperative to quantify these impacts using a Life Cycle Assessment (LCA). Life Cycle Assessment (LCA) is a thorough approach that assesses the environmental impacts linked to every phase of a product's lifespan, starting from extraction and ending with disposal. In the context of waste oil management, LCA can help identify the most significant environmental impacts, such as air and water pollution, soil contamination, and greenhouse gas emissions, which may arise during the collection, transportation, processing, and disposal of waste oil. These impacts may occur during the several stages of waste oil management, such as collection, transportation, processing, and disposal.

The reliability of Life Cycle Assessment in waste oil management lies in its systematic approach to assessing environmental issues. By considering the full life cycle of waste oil, LCA can provide a more accurate and holistic view of the environmental trade-offs involved in different waste oil management strategies. For instance, it can compare the environmental benefits and drawbacks of reclaiming waste oil versus disposing of it through incineration or landfilling. However, the accuracy of LCA results depends on the quality of the data used and the assumptions made during the assessment. Therefore, to enhance the reliability of LCA in waste oil management, it is crucial to use up-to-date, region-specific data and to apply standardized methodologies.

When performing an LCA for waste oil, it is necessary to take into account certain crucial elements and feed them into the LCA analysis or modelling program. The factors encompassed in this context are inventory data, system boundaries, impact categories, geographical and temporal data, and life cycle impact assessment (LCIA) approaches. Further discussion on these aspects can be found in Chapter 2.

1.2 Problem Statement

In the manufacturing industry, various types of machinery are employs, such as engines, pumps, compressors, conveyors, and gears. These machines require petroleum-based oils to reduce friction, minimize wear and tear, dissipate heat, and prevent corrosion. As the manufacturing industry focuses on sustainable practices, petroleum-based oil usage and disposal also come under scrutiny. Additionally, the development of eco-friendly petroleum-based oils and initiatives promoting recycling and re-refining of waste oils contribute to a more sustainable manufacturing industry (Dudak et al., 2021).

Waste oil is oil that has been used but can no longer properly fulfil its original function due to contamination or degradation (Anisuzzaman et al., 2021). Because of its potential to harm the environment and human health if not managed properly, this oil is considered hazardous waste. There are many methods including recycling, recovery or disposal in the management and treatment of waste oils. Waste oil recovery is often regarded as the optimal approach for managing waste oil due to its numerous environmental and reputational benefits. Waste recovery technology contributes to sustainable development by promoting resource efficiency, reducing waste generation, preventing pollution, and mitigating climate change (Utsey et al., 2013). However, during the recovery process, waste oil requires material and energy inputs that contribute to adverse environmental impacts. The treatment of waste oils using waste recovery systems utilizes energy mainly from fossil fuels, resulting in greenhouse gas emissions and carbon dioxide emissions (Yu et al., 2023). There is a need to assess the environmental impacts of waste oil recovery systems to identify solutions for improving environmental performance in the industry. Thus, it can be seen that the waste oil issues and their environmental impacts are intimately connected to sustainability (Shahbaz et al., 2023). Environmental impacts and energy consumption can be evaluated by using LCA approach. Life Cycle Assessment (LCA) is a technique use to assess the environmental impact of a product, process, or system throughout its entire life cycle, from the extraction of raw materials to disposal. LCA consider various environmental factors such as energy use, resource consumption, emissions, and waste generation. Many researchers have studied life cycle assessment of waste management (Dudak et al., 2021).

The existing body of research on waste oil recovery system has been constrained, especially in terms of technical analysis that takes into account environmental impacts and energy consumption. Previous studies have primarily focused on the efficiency of the process and the techniques employed, neglecting the evaluation of environmental impact and energy consumption across various categories of waste oil. Thus, this study seeks to fill this gap by concentrating on the environmental impacts and energy consumption of waste oil recovery system, utilizing a quantitative Life Cycle Assessment (LCA) model grounded in actual operational data. This study presented a quantitative model to analyst the contribution of subsystem from the perspective of environmental impact and energy consumption. The assessment model filled the gap in the quantitative assessment of waste oil recovery system by integrating environmental impact analysis and energy consumption from its subsystems into the whole system. It can be used not only for analyzing the energy consumption and environmental impacts of different categories of waste lubricant oil, but also for identifying the main factors that influence energy consumption and environmental impact. Thus, it could provide a reference for the development, selection, and optimization of an environment-friendly waste oil recovery technology.

1.3 Research Questions

This study embarks to answer the following specific research questions:

i. What are the differences of physical properties and chemical compositions of the waste oils SW 305, SW 306 and SW 307?

ii. How the waste oils SW 305, SW 306 and SW 307 impacted the environment?

iii. How the recovery process of waste oils SW 305, SW 306 and SW 307 influenced the energy consumption?

1.4 Research Objectives

The specific objectives are going to be attained as the following:

i. To characterize physical properties and chemical compositions of different of waste oils categories.

ii. To evaluate the environmental impacts of recovery process based on different waste oil categories through life cycle assessment.

iii. To analyze energy consumption of recovery process based on different waste oil categories.

1.5 Scope of Research

The research delves into the environmental impacts and energy consumption analysis of waste oils recovery, focusing on three specific categories of waste oil as designated in the First Schedule of the Environmental Quality (Scheduled Waste) Regulations, 2005. These wastes are generated with SW 3 Code with a description of wastes containing principally organic constituents which may contain metals and inorganic materials. The code categories are:

- SW 305: Spent Lubricating Oil
- SW 306: Spent Hydraulic Oil
- SW 307: Spent Mineral Oil-Water Emulsion

SW 305 and SW 306 were sourced from industrial machinery and automobile workshops as well as manufacturing industry within Seberang Perai Industrial Zone, Pulau Pinang. In contrast, SW 307 originates from the petrochemical industry. The research utilized actual operating data between January to June 2023 obtained from a waste recovery processing facility located in Seberang Perai, Pulau Pinang. The operational data includes the types of waste oil and volume of each waste oil as well as transportation details.

A detailed characterization of these waste oils was conducted, considering both physical and chemical parameters to provide a comprehensive understanding of the material handling and processing challenges. By identifying and quantifying the different characteristics, this study provided a thorough understanding of the nature and variability of the waste oils being processed. The characterization covered eight (8) physical parameters and fifteen (15) chemical parameters.

To assess environmental impacts and energy consumption, the study employed the life cycle assessment (LCA) approach, using OpenLCA which evaluates the effects on human health, ecosystem quality, and resource availability. The LCA was conducted by defining goal and scope, life cycle inventory (LCI), life cycle inventory analysis (LCIA) and interpretation of results. A thorough analysis by taking into considerations several factors such as inventory data, system boundaries, impact categories, geographical and temporal data was performed. In the LCIA analysis, ReCiPe 2016 methodology, which is a robust framework that quantifies the environmental pressures associated with product systems, both during use and post-use phases. It includes assessing the potential impacts on human health, ecosystem quality and resource availability. Physical properties, chemical characteristic, energy input, transportation details were inputted in the process flow of the LCA analysis of each waste oil by using 13,000 L of volume. Besides, this study also focused on analyzing the energy requirements of the recovery processes for the three different waste oil categories. It involved measuring and comparing the energy consumption across recovery process and waste oil types. The analysis helped to identify the most energy-efficient methods and provide recommendations for optimizing energy use in the recovery process.

For a more granular analysis of environmental impacts and energy consumption, the waste oil recovery system was segmented into four key sub-units.

- Primary filtration process: Primary filtration for waste oil recovery typically involves separating large particles and debris from the oil whereby the waste oils in the storage tank are pumped into a primary filtration system which is equipped with composite 0.02 mm millipore structure fabric filter material to filter off bigger particles such as metals, glass, etc. from the oils. This process is crucial for removing contaminants that could damage equipment or hinder further recovery process.
- Vacuum vaporization process: This process can be used to remove the contaminants by heating the waste oil under reduced pressure, causing the contaminants to vaporize and separate from the oil, enhancing the quality of the recovered oil and reducing the volume of waste.
- Secondary filtration process: After vacuum vaporization process, the waste oil is then pumped into a secondary filtration system similar to the primary filtration system with 0.02 mm composite millipore structure material filter will be used in order filter or removes any impurities still present in the waste oils.
- Tertiary filtration process: The final stage of the recovery process involves tertiary filtration whereby the treated oil finally passes through another fine filter of 0.005 mm metal filter material with a high performance efficiency for the removal of residual impurities.

1.6 Significance of Research

By comprehensively evaluating the environmental impacts and energy consumption associated with waste oil recovery practices, this study aims to illuminate the sustainability of these processes. Utilizing a Life Cycle Assessment (LCA) approach, the research measures the ecological footprint of each stage in the waste oil recovery system, from collection and processing to the final disposal or reuse of by-products. This methodical analysis helps in pinpointing critical areas that require improvements and could significantly benefit from technological advancements or revised operational strategies.

Moreover, the study is set to explore and recommend recovery technologies and strategies that not only optimize resource recovery but also minimize environmental degradation. Emphasizing the selection of eco-friendly and energy-efficient technologies, the findings will offer pivotal baseline data that stakeholders can use to make informed decisions. This data encompasses detailed assessments of pollutant emissions, energy use, and resource depletion, providing a comprehensive overview of the environmental impacts associated with current waste oil recovery practices.

The findings from this study could serve as a cornerstone for policy makers and industry leaders, guiding the development of regulations and practices that foster more sustainable waste management systems. By demonstrating the potential environmental and energy consumption benefits of optimized waste oil recovery strategies, this research could influence broader industry practices and encourage the adoption of greener technologies. Through a robust evaluation, the study aspires to contribute significantly to the body of knowledge on sustainable waste management, offering a clear pathway towards more environmentally responsible practices in the sector.

1.7 Thesis Structure

The thesis presents a total of five (5) chapters. In Chapter 1, the general idea of the thesis is described, which covered the research background, problem statement, research question, research objectives, research scope, and also included significance of research. In Chapter 2, a detailed review of scientific literature is discussed to ascertain the state of knowledge gathered from prior studies and potential ideas and limitation of existing studies related to waste oils, waste oils recovery process, environmental impacts and energy consumption as well as life cycle assessment (LCA).

Chapter 3 explains the details scientific methods that were used in the thesis. The research was conducted to achieve the main aim to investigate energy consumption and environmental impacts of waste oils recovery with three main objectives comprising of several stages and steps, as illustrated in the flow chart of Figure 3.1. In general, this study involved data collection, characterization of physical and chemical properties of waste oils, energy consumption analysis and environmental impact analysis. In analyzing energy consumption and environmental impact, life cycle assessment approach was used. Each data set was analyzed based on descriptive analysis, one-way analysis of variance (ANOVA) was also used in a few relevant sections pertaining to the physical properties.

In Chapter 4, the results and discussion of Objectives 1, 2 and 3 are presented. In Objective 1, the physical properties and chemical composition of three different waste oils in terms of SW 305, SW 306 and SW 307 were characterized based. In Objective 2, the environmental impacts of SW 305, SW 306 and SW 307 were evaluated based on human health, ecosystem quality and resource availability using both midpoint and endpoint assessment. In Objective 3, energy consumption in terms of electricity consumption and diesel consumption involving the recovery process of the waste oils were analyzed. Finally, Chapter 5 presents the conclusions based on each objective. Recommendations for future research are also highlighted in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Waste Oils

Waste oil originating from transportation, construction, and industrial activities, includes lubricating oils such as motor and transmission oils and industrial varieties like hydraulic oils. Collected from diverse sources, this oil is centralized at authorized treatment, storage, and disposal facilities. In the U.S., approximately 1 billion gallons of waste oil are collected annually. This collection is managed through three primary methods: 14% is re-refined, 11% is transformed into space heating fuel, and the remaining 75% is repurposed as fuel oil for industrial consumption (Pinheiro et al., 2021). This comprehensive management strategy extends to waste mineral oil, showcasing a broad approach to waste oil management that emphasizes recycling and repurposing to mitigate ecological and health impacts while meeting the energy demands of various sectors. Compared to low-sulfur crude-based heavy fuel oils, Waste oils contain significantly higher levels of heavy metals, sulfur, phosphorus, and total halogens (Nelyubov et al., 2023). Their typically lower quality as a fuel, waste oil is necessitates blending with other fuels to reduce pollutant concentrations to acceptable levels, meeting both equipment specifications and current emission standards (Kiran et al., 2023). This blending process is predicated on the assumption that the combustion of mixed fuel maintains consistent emissions over time. From a life-cycle analysis perspective, the dilution does not alter the total emissions per unit of waste oil consumed, underscoring the importance of sustainable management practices in addressing environmental and health concerns.

In general, scheduled waste (SW), SW 305, SW 306, and SW 307 were served as lubricating, hydraulic, and mineral oils respectively, that are foundational to the efficient operation and longevity of machinery across various sectors (Pabsetti et al., 2023). SW 305 excels in creating protective microfilms to reduce wear, SW 306 ensures the seamless transmission of power in hydraulic systems, and SW 307 lubricates while minimizing friction and protecting against corrosion in mechanical systems. Each oil is engineered with a focus on balancing operational efficacy with environmental sustainability. They share a commitment to possessing critical physicochemical properties such as optimal viscosity, stability across temperatures, and appropriate safety margins through defined melting and flash points. Formulated primarily from base oils and enhanced with eco-friendly additives, these oils exceed 85% of their composition, aiming to bolster performance while adhering to strict biodegradability standards (Nowak et al., 2019). As waste oils, SW 305, SW 306, and SW 307 underscore the imperative for responsible management to ensure mechanical efficiency and environmental safety, highlighting the ongoing challenge of aligning industrial needs with ecological stewardship.

The environmental challenges posed by waste oils extend far beyond localized pollution, affecting global soil and water quality, and consequently, the health of entire ecosystems (Ikhajiagbe et al., 2020). When these oil are improperly managed, it releases harmful contaminants that degrade natural habitats, reduce biodiversity, and pose significant risks to aquatic life. This global issue necessitates urgent and effective waste oil management strategies that encompass not only the protection of natural habitats but also aim to preserve the delicate balance of ecosystems (Mamaghani et al., 2022). Subsequently, the public health implications of these environmental degradations become increasingly apparent. Contaminants from waste oils can seep into drinking water sources and enter the human food chain, significantly elevating the risk for a range of health issues, including cancer and respiratory conditions (Singh et al., 2023). This intricate connection between environmental harm and public health challenges underscores the critical need for comprehensive regulatory measures and the advancement of pollution control technologies (Adeola et al., 2021). A unified approach to manage waste oils sustainably is imperative, integrating efforts to protect both environmental and human health. By acknowledging and addressing the interconnected nature of these challenges, more effective strategies can be developed for managing waste oils, ultimately leading to a healthier planet and populace. This approach calls for a concerted global effort, requiring innovation, cooperation, and a steadfast commitment to sustainable practices.

Transitioning to resource conservation, the recycling and repurposing of waste oils present a pivotal opportunity for reducing reliance on virgin oil production, thereby conserving precious natural resources (Shakir et al, 2023a). This approach not only minimizes environmental impact but also supports the principles of a circular economy, where materials are kept in use for as long as possible, extracting maximum value before recovery and regeneration (Osra et al., 2024). Following this, the role of legislative and policy frameworks becomes evident. Effective legislation and robust policy mechanisms are crucial in setting standards and guidelines for the sustainable management of waste oils. By fostering an environment where sustainable practices are incentivized and non-compliance is penalized, governments and regulatory bodies can significantly contribute to the preservation of ecosystems, protection of public health, and promotion of economic stability (Islam et al., 2021). This highlights the necessity for a concerted effort to enhance legal frameworks that support sustainable oil management practices, aligning with global sustainability objectives.

Emphasizing the imperative for sustainable practices in managing waste oils, it becomes crucial to explore the advancement of biodegradable alternatives and the enhancement of recycling technologies. This evolution towards sustainability not only mitigates the adverse environmental and health impacts associated with conventional oil disposal methods but also aligns with the global shift towards greener and more eco-friendly practices. The exploration and adoption of biodegradable oils can significantly reduce pollution, conserve biodiversity, and protect ecosystems (Hamidon et al., 2022). Furthermore, investing in state-of-the-art recycling technologies enhances the efficiency of oil recovery processes, promoting the reuse of valuable resources and contributing to the circular economy (Shakir et al., 2023b). This shift requires a collaborative effort among industry stakeholders, policymakers, and the scientific community to drive innovation, develop regulatory frameworks, and implement best practices that prioritize both environmental integrity and economic viability (Zgheib et al., 2021). By focusing on these sustainable practices, it can ensure a more environmentally responsible approach to waste oil management, fostering a healthier planet for future generations.

2.2 Waste Oil Management, Recovery and Treatment Technologies

Waste oil treatment technologies are expected to reduce hazardous contaminants below a safe level to allow treated oils to be handled and used without excessive risks. The priority in management techniques is to minimise the risks associated with waste oil during all stages of its lifecycle. Used oil management options vary widely in their complexity, process end products, environmental benefits and financial constraints. The least preferred option is disposal such as landfilling, dumping and open burning. The complete recycling of used oil into base oil is considered the most preferred management method. This method closely aligns with circular economy principles, with overall energy savings and reductions in environmental impacts.

Almost every waste oil pollution has the potential to be recycled safely, reducing environmental pollution, and preserving a valuable non-renewable resource (Panicker et al., 2010). Waste oil can be properly treated to eliminate pollutants and then refined again into base lubricant, reprocessed into fuel oil, or utilised as feedstock for various processes that result in the production of petroleum-based products or other economically valuable products (Abu-Elella et al., 2015).

Aside from that, properly managed waste oil management is useful for industries that recycle it as lubricant for different types of equipment since it may still be used for lubrication in other ways (Riyanto et al., 2018). In addition to reducing waste disposal to the environment, the removal of contaminants allows for the potential of recycling waste oil (Widodo et al., 2020). Effective collection and treatment methods are crucial for managing waste oils due to their high concentration of hazardous substances, which pose significant risks to both the environment and public health (Botas et al., 2017). Proper collection and treatment procedures are crucial for the efficient management of waste oils to reduce hazards to the environment and public health.

Recovering waste has several benefits, such as reduced hazards, increased energy savings, and a decreased of an impact on the environment (Anisuzzaman et al., 2021). Fundamentally, it is critical to reduce environmental effects, promote sustainability, and turn waste into profitable value-added products in the oil and gas sector (Shahbaz et al., 2023). The resultant waste is a hazardous waste that needs to be properly disposed of and treated to reduce the risk of contaminating the air, water, or land (Pinheiro et al., 2018). Significant concentrations of heavy metals, such as zinc, calcium, barium, lead, and magnesium, are found in waste engine oil (WEO) and may be harmful to all living things, including humans and entire ecosystems (Jwaida et al., 2024).

One of the major production pollutants, waste oil requires an effective strategy for treatment and operation (Yang et al., 2021). Improper recycling and disposal of waste oil from automotive and stationary engines has caused land pollution and contaminated potable groundwater (Prabakaran, 2021). The established treatment technique of a study from Liu et al. (2018) decreases contamination of the soil layer and water basins, promotes the restoration of natural ensembles, stops their degradation, and addresses the significant environmental issue of getting rid of waste containing hydrocarbons.

The practices and outcomes of waste oil recovery processes in Malaysia and globally are subject to significant variation, which is influenced by regional regulations and technologies advancements. It is estimated that approximately 3.8 billion barrels of waste lubricant fluids are commercially collected annually on a global scale. Approximately 27% of this quantity is re-refined into base inventories for reprocessing, primarily through process such as regeneration and recycling (Nisar et al., 2023). The demand for lubricating oils and as a result, waste oil recovery is driven by the Asia-Pacific region, which includes countries such as China and India, due to its large population and industrial base (Mannu & Garroni, 2021).

The Environmental Quality (Scheduled Wastes) Regulations 2005 govern the recovery and recycling of residual oil in Malaysia. In Malaysia, the waste oil recovery sector is expanding, with numerous facilities that specialize in the re-refining of used lubricating oils to satisfy local demand. These processes not only reduce the requirements for fresh oil but also minimize environmental pollution by assuring the appropriate disposal and recycling of waste oils (Nisar et al., 2023). Malaysia is a critical component of the Asia-Pacific region's overall waste management strategy, and these statistics underscore the significance of waste oil recovery as a method of conserving resources and reducing environmental impacts.

In overall, recovering waste oil provides several advantages, such as lowering risks, conserving energy, and reducing the negative effects on the environment, emphasising the significance of sustainability in the oil and gas industry. Waste oil must be properly disposed of and treated to avoid contaminating the air, water, or land especially if toxic heavy metals are present. Reducing soil and water pollution, restoring natural ecosystems, and resolving the environmental issues related to the disposal of hydrocarbon waste all depend on efficient treatment techniques, including those that have been the subject of recent studies. Table 2.1 summarises the existing studies related to waste oil management, recovery and treatment.

Table 2.1 Summary of waste oil management, recovery, and treatment based on the existing studies

Description	References
Contaminants in waste oils include particles, oil, dirt, dust, carbon residue, metals, and products of incomplete combustion.	Oladimeji et al. (2018), Wang et al. (2022), Li et al. (2019), Wang et al. (2017), Liu et al. (2019), Ouyang & Zhang (2019), Moses et al. (2023), Li et al. (2020).
Waste oil pollution can be recycled safely, reducing environmental pollution, and preserving non-renewable resources.	Panicker et al. (2010), Abu-Elella et al. (2015), Riyanto et al. (2018), Widodo et al. (2020), Anisuzzaman et al. (2021), Shahbaz et al. (2023), Pinheiro et al. (2018), Prabakaran (2021), Liu et al. (2018)
Proper treatment of waste oil can eliminate pollutants and allow for recycling into base lubricant, fuel oil, or other valuable products.	Abu-Elella et al. (2015), Wang et al. (2022), Li et al. (2019), Oladimeji et al. (2018), Wang et al. (2017), Liu et al. (2019), Ouyang & Zhang (2019), Moses et al. (2023).
Effective collection and treatment methods are crucial due to the high concentration of hazardous substances in used lubricating oils.	Botas et al. (2017) Anisuzzaman et al. (2021), Shahbaz et al. (2023), Jwaida et al. (2024), Yang et al. (2021)

Table 2.1 Continue

Description	References
Waste oils can be recycled for use as lubricants or processed to generate high-energy fuels.	Panicker et al. (2010), Riyanto et al. (2018), Widodo et al. (2020), Wang et al. (2022), Li et al. (2019), B. Wang et al. (2017), Liu et al. (2019), Ouyang & Zhang (2019), Liu et al. (2018)
Environmental regulations and standards play a crucial role in waste oil management.	Zali et al. (2015a), Aja et al. (2016), Rosli et al. (2024).

2.2.1 Innovative Recycling Technologies

Innovative recycling technologies are at the forefront of enhancing the sustainability of oil management practices. These technologies aim to improve both the efficiency and effectiveness of oil recycling processes, significantly reducing the environmental impact associated with spent oil. For example, advanced filtration and purification systems allow for the removal of a broader range of contaminants, making recycled oil nearly indistinguishable from virgin oil in terms of quality (Liu et al., 2022). Thermal and chemical treatment processes have also been developed to break down complex hydrocarbons more effectively, further reducing the environmental footprint of recycling operations (Lu et al., 2021). Moreover, innovations in catalytic conversion enable the transformation of spent oil into valuable chemicals and fuels, opening new pathways for repurposing and reducing reliance on fossil fuel extraction (Alabdullah et al., 2021). These technological advancements not only contribute to environmental protection but also enhance the economic viability of recycling spent oil, promoting a shift towards more sustainable industrial practices.

2.2.2 Repurposing Strategies

Repurposing strategies for spent oils are pivotal in advancing environmental sustainability, offering a creative approach to transforming potential pollutants into valuable commodities. These methods focus on converting spent oils into biofuels, a sustainable alternative to fossil fuels which can significantly reduce greenhouse gas emissions (Su et al., 2022). Additionally, through advanced refining techniques, spent oils are processed into high-quality lubricants, suitable for various mechanical and industrial applications, thereby extending the lifecycle of the original oil products. Moreover, spent oils serve as raw materials in the manufacturing of different industrial products, contributing to a reduction in the demand for virgin resources. These repurposing efforts are integral to the principles of a circular economy, where waste is minimized, and resources are utilized efficiently and sustainably (Shakir et al., 2020). By embracing such strategies, industries can not only mitigate environmental impact but also uncover new economic opportunities, reinforcing the viability of sustainable practices.

2.2.3 Waste Oil Recovery

Waste oil recovery is considered a best practice due to its substantial reduction in environmental impact. Again, only licenced operators are permitted to conduct this procedure in compliance with the regulations. Waste oil recovery refers to the procedure of extracting and reusing substances from used oil. After collecting waste oil, which is then transported to a laboratory for analysis to determine whether or not it can be reused, it is appropriately treated to recover any fuels, lubricants, or metals that may be present in the mixture. Waste oil, for instance, can be treated and refined for use in steam rising boilers and the bitumen industry.

Waste oil recovery is often regarded as the optimal approach for managing waste oil due to its numerous environmental and reputational benefits:

- Recovery of waste oil prevents its reintroduction into the surrounding ecosystem, hence mitigating any damage.
- The carbon emissions associated with recovered oil are far less than those of crude oil.
- A novel upcycled product has been fabricated.
- Each unit of reclaimed oil represents a unit that does not need to be extracted from the earth. Organizations that are observed to retrieve discarded oil gain advantages in terms of improved public opinions.
- It is crucial to bear in mind that waste oil is a perilous product that presents a danger to both persons and the environment. Failing to handle it properly could result in violating rules.

2.2.4 Development of Biodegradable Oils

The development of biodegradable oils represents a significant stride toward environmental sustainability, focusing on creating products that can decompose naturally without leaving a harmful footprint. Research and development efforts in this area are increasingly concentrated on bio-based oils, derived from renewable resources such as plant and animal fats (Hamidon et al., 2022). These oils are designed to break down through natural processes, significantly reducing the risk of