BIOREMEDIATION OF REFINERY OIL SLUDGE WITH FOOD WASTE DIGESTATE AS FEEDSTOCK

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UNIVERSITI SAINS MALAYSIA

2025

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by

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Thesis submitted in fulfilment of the requirements
for the degree of
Master of Science

February 2025

ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious, the Most Merciful.

First and foremost, Alhamdulillah and all praise be to Allah SWT for His infinite blessings, guidance and strength throughout my journey in completing my Master's degree at Universiti Sains Malaysia (USM). Without His mercy and endless help, this achievement would not have been possible. Through every challenge, every difficult, and every moment of uncertainty, He provided me with patience, wisdom, and resilience to persevere. I am eternally grateful for the opportunity granted to me to embark on this academic pursuit and to successfully complete this journey.

I would like to extend my deepest and heartfelt gratitude to my supervisor Prof. Madya Ts. Dr. Mohamad Anuar Kamaruddin, for his unwavering support, invaluable guidance and continuous encouragement throughout the course of my research. His insightful feedback, constructive criticism, and steadfast belief in my potential have played a crucial role in shaping my work and strengthening my academic abilities. His mentorship has been an inspiration and I am sincerely thankful for his dedication and commitment to my success.

I also wish to express my appreciation to the staff of the School of Industrial Technology for their assistance in preparing the necessary apparatus, providing access to laboratory equipment, and offering guidance in conducting my experiments has been instrumental in the successful execution of my research. Their expertise and willingness to help have significantly contributed to the smooth progress of my work, and for that, I am truly grateful.

My deepest gratitude goes to my beloved parents, whose unconditional love, sacrifices, and unwavering support have been the foundation of my journey. Their prayers, encouragement, and constant belief in me have been my greatest source of motivation. Without their endless patience and guidance, I would not have reached this milestone. To my family members who have supported me in every possible way, thank you for being my pillar of strength and for always reminding me of the importance of perseverance and faith.

To my friends and colleagues who have been part of this journey, I sincerely appreciate your encouragement, advice and companionship throughout the ups and downs of my academic journey. Your kindness, motivation, and shared experiences have made this path more meaningful, and I am thankful for the camaraderie and inspiration you have provided along the way.

"Last but not least, I want to thank me. I want to thank me for believing in me. I want to thank me for doing all this hard work. I want to thank me for having no days off. I want to thank me for never quitting. I want to thank me for always being a giver and try to give more than I receive. I want to thank me for trying to do more right than wrong. I want to thank me for just being me at all times. I want to thank me because I have made it".

This journey has been one of dedication, perseverance, and self-discovery, and I am proud of the person I have become through it all. With immense gratitude, I dedicate this thesis to all who have been part of this journey. Your support has been my greatest asset, and for that, I will always be thankful.

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LIST OF SYMBOLS

C	Carbon
Cl^-	Chloride
CO^2	Carbon Dioxide
CO	Carbon Monoxide
H	Hydrogen
N	Nitrogen
Na^+	Sodium Chloride
NSO	Nitrogen Sulphur Oxygen
NH_4^+	Ammonium
NH_4^+-N	Ammonium Nitrogen
NO_3^- -N	Nitrate Nitrogen
Na_2SO_4	Anhydrous Sodium Sulphate
O	Oxygen
O^3	Ozone
PO_4^{3-}	Phosphate

LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
DOE	Department of Environment
DOSH	Department of Occupational Safety and Health
DEFRA	Department of Environment, Food and Rural Affair
EPA	Environmental Protection Agency
FW	Food Waste
FWD	Food Waste Digestate
GHG	Greenhouse Gas
MHLG	Ministry of Housing and Local Government
PHC	Petroleum Hydrocarbon Contaminant
PAH	Polycyclic Aromatic Hydrocarbons
POP	Persistent Organic Pollutants
RCRA	Resource Conservation and Recovery Act
SDG	Sustainability Development Goals
SW	Scheduled Waste
SWCorp	Solid Waste Management and Public Cleansing Corporation
TPH	Total Petroleum Hydrocarbon
UNEP	United Nations Environment Program
USEPA	United State Environmental Protection Agency
VOC	Volatile Organic Compounds
WHO	World Health Organization

BIOREMEDIASI ENAP CEMAR MINYAK DENGAN PENCERNAAN SISA MAKANAN SEBAGAI BAHAN SUAPAN

ABSTRAK

Kajian ini adalah untuk menilai potensi bioremediasi penghadaman sisa makanan (FWD) untuk merawat enap cemar minyak penapisan (OS) untuk menangani cabaran kepada alam sekitar dan pengurusan sisa. Enap cemar minyak penapisan (OS) ialah hasil penapisan petroleum yang menimbulkan risiko kepada alam sekitar disebabkan oleh hidrokarbon kompleks dan bahan pencemar yang berterusan. Pendekatan kaedah rawatan enapcemar minyak petroleum terkini mempunyai kelemahan asas dari segi perbelanjaan operasi, keberkesanan, dan menghasilkan bahan pencemar sekunder. Sisa makanan (FW) adalah krisis global kerana ia dilupuskan melalui pembakaran dan pelupusan yang menghasilkan pencemaran gas rumah hijau (GHG), pelepasan metana daripada penguraian tapak pelupusan, dan pencemaran air yang menjejaskan isu sosial, alam sekitar dan ekonomi. Kajian ini bertujuan untuk menyiasat potensi menggunakan FWD sebagai sumber berharga bersama dengan OS dengan mengenal pasti morfologi mikrob dalam FWD, menilai keberkesanan dalam meningkatkan kadar degradasi jumlah hidrokarbon petroleum (TPH), dan mengkaji potensinya sebagai pindaan tanah melalui ujian percambahan biji benih. Pengenalpastian mikrob menggunakan sampel FWD melalui kaedah pewarnaan Gram. Degradasi untuk eksperimen TPH telah dijalankan di bawah keadaan makmal menggunakan ujian skala kelompok dan kadar degradasi TPH dikaji menggunakan kaedah analisis gravimetrik. pH sampel diselaraskan kepada 7, dan keadaan sampel ditetapkan pada 150 rpm, 37°C selama 1,3,5,9 dan 11 hari di dalam inkubator shaker berputar. Ujian percambahan biji benih dijalankan menggunakan 6 biji *Vigna radiata*

L. (kacang hijau) dalam setiap pasu dengan 150 g tanah asli selama 21 hari. Hasil pemerhatian mikrob melalui mikroskop menunjukkan kehadiran Gram-positif *Bacillus sp*. Analisis gravimetrik menunjukkan bahawa pada hari 1, nisbah 1:3 mempunyai 39.07% pengurangan TPH manakala kumpulan kawalan dan 1:1 mempunyai 35.71% dan 33.26%. Pada hari ke-11, nisbah 1:3 mempunyai kadar degradasi yang lebih tinggi dengan 59.15% degradasi berbanding kumpulan kawalan dan nisbah 1:1 dengan 43.47% dan 53.11%. Nisbah FWD yang lebih tinggi menghasilkan kadar degradasi TPH yang lebih tinggi. Ujian percambahan biji benih menunjukkan pada hari 1 keadaan kawalan dan nisbah 1:1 tiada percambahan biji benih manakala nisbah 1:3 mempunyai 3 (50%) percambahan biji benih. Pada 21 hari eksperimen, kumpulan kawalan dan nisbah 1:1 mempunyai 3 (50%) dan 4 (67%) percambahan biji manakala 1:3 mempunyai 6 (100%) percambahan biji benih. Ini mencadangkan bahawa fitotoksisiti menjejaskan kumpulan kawalan (tiada FWD) yang melambatkan kadar percambahan dengan ketara. Selain itu, daun tertinggi diperhatikan dalam nisbah 1:3 mencecah 24.8 cm berbanding 20.3 cm dan 22.8 cm dalam kumpulan kawalan dan nisbah 1:1. FWD yang lebih tinggi memberi kesan positif terhadap biji benih yang bercambah dan daun yang lebih tinggi berbanding kumpulan kawalan dan nisbah 1:1.

BIOREMEDIATION OF REFINERY OIL SLUDGE WITH FOOD WASTE DIGESTATE AS FEEDSTOCK

ABSTRACT

This study was to assess the bioremediation potential of food waste digestate (FWD) for treating refinery oil sludge (OS), addressing significant environmental and waste management challenges. OS is a byproduct of petroleum refining poses an environmental risk due to its complex hydrocarbon and persistent pollutants. Recent petroleum oil sludge treatment methods approach possesses fundamental drawbacks in terms of operating expenses, effectiveness, and produce secondary pollutants. Food waste (FW) is a global crisis as it is disposed of through incineration and landfills that produce greenhouse gas (GHG) pollution, methane emission from landfill decomposition, and water pollution affecting social, environmental, and economic issues. This study aims to investigate the potential of using FWD as valuable resources for co-digestion with OS by identifying the microbial morphology in FWD, assessing the effectiveness in enhancing the Total Petroleum Hydrocarbon (TPH) degradation rates, and examining its potential as a soil amendment via seed germination test. The microbial identification for FWD using the Gram-staining method. The degradation for TPH experiments was conducted under laboratory conditions using a batch scale test and TPH degradation rates were studied using gravimetric analysis method. The sample pH was adjusted to 7, and the sample condition was set at 150 rpm, 37ºC for 1,3,5,9 and 11 days in a rotary shaker incubator. A seed germination test was conducted using 6 seeds of *Vigna radiata L.* (mung bean) in each pot with 150g of natural soil for 21 days. The result of microbial observation through microscopy shows the presence of Gram-positive *Bacillus sp*. The gravimetric analysis shows that on day

1, the 1:3 ratio had 39.07% of TPH degradation while the control group and 1:1 had 35.71% and 33.26%. On day 11, the 1:3 ratio had a higher degradation rate with 59.15% degradation compared to the control group and the 1:1 ratio with 43.47% and 53.11%. The higher ratio of FWD results in a higher TPH degradation rate. The seed germination test shows that on day 1 the control condition and 1:1 ratio had no seed germination while the 1:3 ratio had 3 (50%) seed germination. At 21 days of experiments, the control group and 1:1 ratio had 3 (50%) and 4 (67%) of seed germination while 1:3 had 6 (100%) seed gemination. This suggested that the phytotoxicity affected the control group (no FWD) which significantly delayed the germination rates. In addition, the highest leaf was observed in a 1:3 ratio reaching 24.8 cm compared to 20.3 cm and 22.8 cm in the control group and a 1:1 ratio. The higher FWD had a positive effect on seeds germinated and taller leaf compared to the control group and 1:1 ratio.

CHAPTER 1

INTRODUCTION

1.1 Research background

Petroleum oil sludge is a byproduct of refining crude oil (Thong et al., 2021). Globally, 5 tons of oil sludge is produced from 1000 tons of crude oil (Teng et al., 2021). Malaysia produced 584 thousand barrels daily in oil refinery throughput and 25.5 million tonnes of oil production in 2022, the fourth largest oil production in the Asia Pacific placing the country behind China, India, and Indonesia (Energy Institute, 2023). PETRONAS is Malaysia's primary oil and gas corporation for global energy with 24 oil and gas discoveries, with 20 in Malaysia and four internationally. It generated an overall output per day of 2,431 thousand barrels of oil. In 2022, PETRONAS produced 144,620 tonnes of toxic waste, rising to 19,736 tonnes from 124,884 tonnes in 2021. The waste was produced from the production of tank cleaning, sludge from wastewater treatment plants, discarded catalysts, and used oils. The volume of waste produced increases mainly from scheduled maintenance and tank cleaning operations. The total volume of waste recycled and recovered was 73,643 tonnes of which 63,133 tonnes were linked to the production activity (PETRONAS, 2023).

The petroleum refining process consists of heavy metals, a complicated mixture of hydrocarbons and various pollutants (Khatatbeh et al., 2020; Niu et al., 2022; Sabour et al., 2022; Singh et al, 2020; Tao et al, 2018). The production of oil sludge waste has a significant volume during various industrial activities of oil treatment including exploration, mining, delivering, storing, and refining (Hu et al., 2015; Zhao et al., 2019). Total petroleum hydrocarbon (TPH) encompasses a range of hydrocarbon mixtures generated through the petroleum process, including gasoline, diesel, kerosene, lubrication oil, and grease (Adedeji et al., 2022). Recent petroleum oil sludge treatment methods in Malaysia primarily involve a mix of mechanical, chemical, and biological treatments such as oil recovery, solvent extraction, bioremediation, incineration, solidification, and thermal processes are being increasingly used to manage sludge effectively while minimizing its environmental impact. Each of these approaches possesses fundamental drawbacks in terms of operating expenses, effectiveness, development of secondary pollutants, and the duration of remediation (Zhang et al., 2017).

Food waste is a global crisis that currently shows no signs of declining, resulting in environmental, economic, and social issues (UNEP, 2024). Food waste generation becomes higher simultaneously with both the economy and the population. (Makkawi et al, 2021; Wu et al., 2020). Based on UNEP Food Waste Index Report 2024, Malaysia ranks fourth in Southeast Asia in terms of household food waste per capita. The report reveals that Malaysian households generate an average of 81kg of food waste per capita annually with 2 754 808 tonnes, placing the country behind Laos, Thailand, and Cambodia (UNEP, 2024). It has been expected that the volume of food waste in households will increase from 17% of the calories that were purchased in 2013 to 26% in the year 2050 (Lopez et al., 2021). The National Bureau of Statistics of China projects that by 2025, the food waste generated in Asia might reach 4.16 billion tonnes.

In Malaysia, food waste has been related to the increased urbanization that contributed to waste management concerns (Luhar et al., 2022; Seng et al., 2021). The National Solid Waste Management Department reported in 2022 that 142 operational landfills and 174 closed due to the maximum landfill capacity (MHLG, 2022). According to solid waste composition carried out by Solid Waste Management and

Public Cleansing Corporation (SWCorp), the most significant amount of solid waste in 2022 was produced by food waste, with 30.6% out of the overall composition, followed by plastics 21.9%, and paper 15.3%. The data indicates the worldwide waste composition, with 44% from food or organic waste (Brahme et al., 2023). Malaysia's solid waste management system mainly relies upon landfill as the primary disposal method, with 80% utilization (Chen et al., 2021; Siddiqua et al., 2022). The treatment of food waste is complicated due to the high moisture content, complex composition, and organic content (Sharma et al., 2022).

Anaerobic digestion (AD) generates digestate from organic feedstock without oxygen (US EPA; Peng et al., 2019). Food waste, animal dung, domestic waste, and sewage are used as feedstock to produce digestate (Gielnik et al., 2020). Food waste digestate (FWD) has higher nutrients than other digestates (Opatokun et al., 2015). It is known that hydrocarbon remediation could increase soil nutrient values using food waste digestate, as it contains low metal and metalloid contents, as well as high nitrogen, phosphorus, and potassium contents (Peng et al., 2019). Moreover, AD treatment is a suitable approach for waste management concerning economic sustainability (Xiao et al., 2022). Researchers suggested that using digestate from the AD method as cost-effective method for treating oil sludges and used to convert oil sludge into a valuable product (Castro et al., 2023; Ghaleb et al., 2021; Janajreh et al., 2020; Lee et al., 2022; Obileke et al., 2022; Yang et al., 2020) also improve the soil properties (Cheong et al., 2020; Lu et al., 2021; Connor et al., 2021).

The advantages of being involved in the synergistic interactions between the constituents of food waste digestate and petroleum oil sludge. The union of nutrient-rich digestate and the recalcitrant oil sludge potentially activates dormant microbial communities, engendering a microbial consortium equipped to combat even the most recalcitrant hydrocarbons (Gielnik et al., 2021; Roy et al., 2018). The digestate's capacity to reduce the processes that pollutants can restrict microbial activity can improve the remediation process (Oghoje et al., 2021; Selvaraj et al., 2022; Song et al., 2021). By utilizing food waste digestate as a soil amendment, two significant waste streams of petroleum oil sludge and food waste are synergistically transformed into resources. This decreases the challenge of landfills and exemplifies the transition from a linear "take-make-dispose" approach to a regenerative and sustainable one (Peng & Pivato, 2019). Recycling the food waste digestate into renewable products has great potential for a wide range of ecological uses as a biofertilizer, solid biofuel, and carbon-based material (Alberto, 2022).

1.2 Problem statement

The petroleum sectors are a vital part of modern society and the most predominant energy resource in the world. Oil sludge contains petroleum hydrocarbons (PHCs) such as aliphatic, asphaltenes, saturated hydrocarbons, and aromatic hydrocarbons (Ma et al., 2021). Oil sludge that is not properly managed will contaminate the soil, water, and air affecting the balance of precious ecosystems and posing a threat to human health due to the possibility of contaminants migrating into food sources (Qabil, 2022; Honda et., 2020; Jagaba et al., 2022; Khatatbeh et al., 2020; Koolivand et al., 2022; McGowan et al., 2017). The safe disposal of these residues was the main challenge facing refineries and petrochemical industries since their fate and improper treatment may have serious consequences for the environment and may pose a risk to public health (Almansoory et al., 2019; Cerqueira et al., 2014; Rodriguez et al., 2019).

These wastes must be managed and disposed of properly to avoid the contamination of both surface and groundwater, ambient air, risk of fires, explosions, food contamination, and depletion of habitats for plants (Islam, 2015). The discharge of petroleum through spilling leaking, and other ways of discharge frequently leads to the pollution of both groundwater and soil, particularly in situations involving greater scales (Xia et al., 2014). Various physical, chemical, or physicochemical treatment methods have been applied and introduced to treat and minimize mineral oil sludge pollution (Johnson et al., 2022), yet the results exhibit further treatment is required. It could be mainly due to its complexity and the stability of its chemical structure, high operational cost, and incomplete treatment generates secondary pollution which requires proper management (Varjani, 2017). Bioremediation is a cost-effective method that uses bacterial species to reduce the presence of petroleum contaminants (Patel et al., 2020). Researchers have done several studies on the bioremediation of oil sludge with digestate from animal manure (Oghoje et al., 2021; Onwuka et al., 2019), sewage sludge (Gielnik et al., 2021), and yard waste (Choudhury et al., 2023).

The study on the bioremediation of refinery oil sludge with food waste digestate has the potential to provide an economical, and eco-friendly approach to waste management. This approach addresses the environmental concern of oil sludge while promoting a green economy by developing food waste into a valuable resource (Bayat et al., 2021; Bedoić et al., 2020; Pascual et al., 2018). Using food waste digestate in the bioremediation process, the amount of organic waste that needs to be disposed of in landfills is reduced, thus mitigating landfill overuse and reducing methane pollution (El Achkar et al., 2022; Castro et al., 2018). Investigating the combination of food waste digestate and refinery oil sludge opens up new avenues for research in microbial ecology, waste valorization, and greener technologies that can be scaled to industrial applications significantly reducing the ecological footprint of both waste management processes (Khazaal & Ismail, 2021; Poorsoleiman et al., 2021; Sarkar et al., 2020). This study corresponds with global sustainability development goals (SDG) aimed to reduce waste, recycle valuable resources, and reduce environment pollution, making it highly relevant to modern environmental challenges.

1.3 Research Objectives

This study aims to investigate the potential of using food waste digestate for bioremediation of refinery oil sludge with a focus on effectiveness for the co-digestion with food waste digestate on hydrocarbon degradation rates from refinery oil sludge via seed germination test. The research is structured with three primary objectives firstly to identify microbial morphology of food waste digestate through the gram staining method. This will provide insight into the types of microorganisms involved in the degradation process. Secondly, to determine the effectiveness of food waste digestate in enhancing the Total Petroleum Hydrocarbon (TPH) degradation of refinery oil sludge (OS) with food waste digestate (FWD). This analysis will quantify the reduction of TPH levels. Finally, to assess the potential of food waste digestate (FWD) as feedstock through seed germination test assay, which will evaluate the impact on plant growth.

1.4 Scope of Study

The scopes of this research are listed below:

1. The research is carried out in Environmental Laboratory, USM
2. Refinery oil sludge (OS) sample is obtained from the petroleum industry sector and food waste digestate (FWD) sample from E-idaman Jitra, Kedah.
3. The parameters selected to be tested for characterization of oil sludge and food waste digestate are pH, moisture content, and total solid residue.
4. Microbial identification of food waste digestate using gram staining method.
5. Total petroleum hydrocarbon (TPH) degradation using gravimetric determination with different incubation days and the ratio of FWD.
6. Seed germination using mung bean seed.

1.5 Thesis Outline

Chapter one outlines an introduction to the research topic, providing crucial background information and objectives.

Chapter two outlines a review of the literature concerning petroleum oil sludge, anaerobic digestion, food waste digestate, and bioremediation techniques.

Chapter three outlines the comprehensive methodology of the study with an introduction that sets the stage for research objectives. The first section details the sample collection for refinery oil sludge and food waste digestate. The characteristics of physio-chemical properties for both samples were examined for pH, moisture content, and total solid residues (TSR). Then methodology focuses on microbial morphology using the Gram-staining method for food waste digestate, detailing the preparation of culture media, serial dilution, and plating method. Continues on batch scale test for determination of TPH and lastly seed germination test was conducted.

Chapter four outlines the research findings and a discussion of the results. These findings related to the study objectives for microbial morphology, TPH degradation, and germination test assay.

Chapter five outlines the conclusion and recommendations. From the results obtained, the conclusion from the objectives can be decided whether it is achieved or not. The recommendations are about the suggestions that can be made to improve this study and to continue this study to the next level.

CHAPTER 2

LITERATURE REVIEW

2.1 Source of petroleum oil sludge

Oil sludge produced by the petroleum industry piles up in tanks from desalters, refinery processes, treatment facilities, and transmission pipes (Atagana, 2015; Hui et al., 2020; Jerez et al., 2021). In the petroleum industry, both the upstream and downstream produce large amounts of sludge oil. Upstream operation consists of the extraction of crude oil, transportation, and storage, whereas downstream operation involves refining crude oil. The oil waste is classified as either simple oil or sludge based on the ratio of water to solids in the oil matrix (Al-Futaisi et al., 2007; Hu et al., 2013; Hui et al., 2020).

The upstream process included drilling mud residues, slope oil from oil wells, and tank bottom sediments (Japper-Jaafar et al., 2018; O'Rourke & Connolly, 2003). The downstream processes of oil sludge include slope oil emulsion solids, heat exchange package cleaning sludge, and oil–water separators (Hui et al., 2020; Islam, 2015; Teng et al., 2021). Sediments from rail cars, trucks, and storage tanks can also contribute to the downstream process. Oil sludge is formed when crude oil is temporarily stored in storage tanks and breaks down into petroleum hydrocarbons. Petroleum sludge is mixed with PHCs, solid particles, and water in storage tank (Ayotamuno et al., 2007; Hassanzadeh et al., 2018; Hui et al., 2020).

Petroleum industries have developed several innovative approaches to reducing maintenance and corrosion costs as well as environmental impacts associated with sludge remediation by separating paraffin waxes and slop oil from crude oil during storage and pipeline transfer (Jagaba et al., 2022). Oil sludge is a complicated combination containing water, diverse petroleum hydrocarbon showing certain levels of degradability, and mineral substances present in a variety of concentrations (Gielnik et al., 2019).

2.1.1 Characteristics of petroleum oil sludge

Petroleum oil sludge typically appearing as a black semi-solid cake and it is a viscous combination of sediments, water, oil, sand, clay, mineral, and high concentrations of hydrocarbons (Hui et al., 2020; Koolivand et al., 2022; Mandal et al., 2014; Rondon et al., 2023; Wang et al., 2010). The primary components of petroleum oil sludge are oil, grease and various toxic metallic and organic compounds such as benzene, toluene, xylenes and phenolics alongside small amounts of non-acidic species such as ketones, esters and amides (Almahbashi et al., 2021; Kankia et al., 2021). Researcher have been identified over 17,000 distinct of chemical compound within crude oil (Salehi et al., 2022; Svinterikos et al., 2019; Varjani & Upasani, 2019).

The composition of varies by source but generally contains 82% - 85% carbon, 10%-14% hydrogen, 0.01% - 7% sulphur, 0.02% - 2% nitrogen and 0.1% - 1% oxygen (Stepanova et al., 2022). Light oils tend to have a more pronounced impact on plants compare to heavy oils (Stepanova et al., 2022). While the lighter fractions of petroleum hydrocarbon (PHCs) are rapidly broken down by microbial activity, the heavier fraction that contaminate soil are more resistant to degradation posing significant harm to ecosystems and living organisms (Ite & Ibok, 2019). These mixture remains in the environment due to its elevated of hydrocarbon content, significant viscosity, challenges dehydration properties, and pronounced emulsification tendencies (Ramirez et al., 2019; Su et al., 2021). It is defined by low fixed carbon content, high moisture content levels and minimal volatile components (Noor et al., 2021). Compared to oil and water, oil sludge has lower sediment content but consists immunotoxin and carcinogenic materials (Al-Mahbashi et al., 2022; Kankia et al., 2021).

The US Environmental Protection Agency has been designated oil sludge as a priority of environmental pollutant due to its toxic, mutagenic, and carcinogenic characteristics which enforces stringent regulations regarding its release into the environment (Zhao et al., 2019). Oil sludge has a pH of 5.2 to 7.5, and chemical composition depending on the source of crude oil, processing scheme, and equipment used in the refinement process. It has been found that oil sludge contains a TPH ranging 5% - 86.2% by mass, often in the range of 15% - 50%, whereas the proportions of water and solids are between 30% - 85% and 5% - 46%, respectively (Kralova et al., 2011; Liu et al., 2012). The composition of PHCs found in oil sludge can be divided into four categories: aliphatics, aromatics, nitrogen sulfur oxygen (NSO) containing compounds, and asphaltenes (Kebede et al., 2021). The basic components are solids, water, and hydrocarbons, including metallic chemical elements and PAH, which are toxic, mutagenic, and carcinogenic (Zhao et al., 2020). Table 2.1 presents the proximate and ultimate analysis of petroleum industry in different country. Table 2.2 presents the heavy metal present in different petroleum oil sludge.

Table 2.1 Proximate and ultimate analysis of petroleum industry in different country

Country	**Sludge type**	**Proximate analysis on dry basis**				**Ultimate analysis on dry basis**					**Reference**
		Moisture content (wt%)	**Ash content (wt%)**	**Volatile matter (wt%)**	**Fixed carbon (wt%)**	**C**	**H**	**N**	**S**	**O**	
Malaysia	Petroleum sludge	15.7	52.0	93.2	6.8	20.9	2.7	1.4	0.1	6.0	(Aeslina et al., 2017)
	Petroleum sludge	79.0	5.0	5.5	11.0	51.4	7.3	3.3	2.2	36.0	(Ali et al., 2019)
Indonesia	Petroleum sludge	6.1	71.3	20.0	3.6	14.6	2.1	0.1	0.6	2.4	(Permadi et al., 2017)
Iran	Petroleum sludge	27.8	72.1	15.6	1.8	7.3	1.2	0.4	0.5	18.6	(Koolivand et al., 2022)
United Arab Emirates	Petroleum sludge	3.6	67.4	26.5	2.5	55.7	4.3	1.2	9.4	29.4	(Mazzoni et al., 2020)
China	Refinery oil sludge	69.0	13.0	18.0	1.2	65.0	8.4	0.4	2.0	10.5	(Zhao et al., 2021)
	Tank oil sludge	47.0	23.00	52.0	3.0	23.5	3.0	0.2	1.2	2.4	(Gong et al., 2018)
	Petroleum sludge	83.6	28.	62.9	8.2	36.3	4.4	1.4	1.3	27.8	(Alhadj et al., 2015)
India	Petroleum refinery sludge	23.3	2.4	66.1	9.2	57.0	7.0	2.0	3.2	35.0	(Singh et al., 2020)
	Petroleum sludge	21.4	4.0	63.0	12.0	50.4	7.1	1.7	3.5	37.4	(Singh et al., 2021)
Japan	Oil sludge	25.5	50.0	39.3	10.6	21.8	2.9	0.4	8.5	16.4	(Cheng et al., 2016)
Algeria	Petroleum sludge	9.0	1.8	90.0	-	78.0	13.1	-	-	8.0	(Bellahcene et al., 2021)

Table 2.2 Heavy metal present in different petroleum oil sludge

Metal concentration in the oil sludge (mg/kg)															Reference
Cd	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Mg**	**Al**	**Ba**	**Co**	**Na**	**Zn**	**K**	**Others**	
-	162	121	4300	2594	1311	3609	-	3600	9200	-	-	1591	4321	Ti - 2646 Si - 106 P - 3385 Sr - 877	(Hu et al., 2017)
0.72	26	75	10770	184	-	89	1614	43180	-	23	489	192	368	Ni – 442 As – 3 Hg – 1 Be – 3775 Ca - 1272	(Behera et al., 2020)
-	-	-	2100	-	-	-	2300	7300	-	-	3006	-	500	Ca - 5400	(Gong, Wang, et al., 2018)
0.06	45.39	12.92	150.47	-	34.93	2.68	-	-	-	1.34	3.13	34.70	-	Ca - 49.51 As - 2.24	(Zhao et al., 2018)
5	5	14	2780	-	23	-	178	144	-	-	410	168	572	Ca - 8600 As - 11	(Nejad et al., 2020)
-	2.94	-	211.35	-	18.05	1.16	-	-	-	-	-	60.74	-	-	(Paul et al., 2022)
-	-	107.00	30.4-817.00	25.5-69.00	54	34.41	1460.56	3213	1111.17	-	61.90	-	-	Ti - 57.17	(Aziz et al., 2020)

12.58	47.52	32.84	-	-	-	124.39	-	-	-	-	-	79.21	-	Hg - 0.02 As - 15.45	(Ke et al., 2021)
-	-	67	4462	-	21	71	1290	1019	-	-	14298	202	629	Si - 2062 Ca - 2614	(Hentati et al., 2022)
-	0.60	1.10	300	-	0.80	94.50	19.20	24.14	0.20	-	59.40	22.40	-	Ca - 85.9 Ti - 1.1 Ag - 0.2 Si - 89.5	(Alves et al., 2019)
44.40	119.90	4420.46	4033.58	398.06	56.01	132.70	-	273.02	110.38	-	-	12248.70	-	Ti - 0.13 Sn - 58.65 Ag - 6.18 Se - 0.14 Li - 49.92 Sr - 43.33 Hg - 3.49 As - 4.96	(Panova et al., 2018)
0.0004	0.01-59.00	0.11	5.16	0.08-82.00	0.05	0.01-0.86	0.48-89.00	3.75	2.58	0.01-64.00	1.24	0.12-85.00	1.37	Sr - 0.478 Ti - 0.13-13 Mo - 0.006	(Kariminezhad & Elektorowicz, 2018)
22.64	70.69	537.09	5923.10	96.50	37.61	122.40	2.79	1134.55	30.08	-	-	-	-	Ti - 57.81 Sn - 2.95	(Ahmad, 2017)

2.1.2 Treatments of oil sludge

Over the years, a multitude of techniques have been utilized in the pursuit of recycling, oil recovery, the elimination of toxic substances, and the restoration of contaminated sludge, particularly in the field of sludge dewatering (Eskander et al., 2013), solvent extraction (Naggar et al., 2010), thermochemical treatment (Q. Song et al., 2019), incineration (Sankaran et al., 1998), stabilization/ solidification (Caldwell et al., 1990; Conner et , 2010), oxidation treatment (Ferrarese et al., 2008), bioremediation (Koolivand et al., 2022), and phytoremediation (Sharma, 2021), compositing/ bio piles (Mukjang et al., 2022), and bio-slurry treatment (Mansur et al., 2016). Each of these approaches have fundamental drawbacks in terms of operating expenses, effectiveness, development of secondary pollutants, and the duration of remediation (Zhang et al., 2017).

Tables 2.3 provide a comprehensive overview of each of the treatments and removal approaches from other papers with emphasis on their specific production condition, efficiency, treatment time, expenses, positive effects, and restrictions for petroleum oil sludge. The field of oil recovery and sludge disposal has established with a variety of technologies, and some were implemented on a large-scale treatment system. A variety of strategies present for the recovery and handling of petroleum waste involve solvent extraction, centrifugation, freeze/thaw, sludge pyrolysis, ultrasonic, thermal cleaning, stabilization/solidification (S/S), incineration, oxidation, and bioremediation.

Stabilization/solidification is the method that binder used to reduce the risk of pollution to the atmosphere. Stabilization is implemented by adding chemicals to minimize the moisture level, mobility, and toxicity levels. Solidification is minimising the contaminants by enhance the mechanical durability that generate a monolithic solid product. The end-product of the process can be used to the construction materials (Johnson et al., 2022).

Incineration usually used as alternative of treatment for the disposal of petroleum sludge. Incineration is treatment that used combustion process to minimise the volume and toxicity. Bioremediation used microorganisms into the treatment through enhancing the rate of bacteria's breakdown of petroleum hydrocarbons. Over the past studies (Johnson et al., 2022; Wang et al., 2021) indicated that freeze/thaw method had succeeded of restoration of oil sludge. The freeze/thaw technique involves a demulsification process that occurs during freezing, causing internal disruption as the oil gradually solidifies. During the thawing phase, the oil particles merge leading to the separation of oil and water due to gravitational process. This method has shown effectiveness in colder climate, however in warmer regions additional costs are necessary to sustain the required temperature (Hu et al., 2015; Johnson & Affam, 2022).

A more effective treatment can be used by combined other treatment into one. For example, the ultrasonic combined with freeze/thaw treatment to treat oil recovery performance (Zhang et al., 2012). Solidification/stabilization technique and Fenton's oxidation approach are capable of being used together to assist in mitigating the elimination of oily sludge in a more effective manner (Adhami et al., 2021). The inclusion of biosurfactants in froth flotation and bioremediation could further increase the effectiveness (Karlapudi et al., 2018). Furthermore, a lot of research has mostly concentrated on the extraction of oil sludge has been directed towards achieving optimal elimination PAH. It is important to note that the leftovers that cannot be recovered can have more persistent and harmful substances, hence posing challenges in terms of their disposal. However, there is limited information on the combined application of these methods. Hence, it is imperative to conduct additional analysis on both the environmental and economic aspects of the converged method of oil recovery and sludge disposal.

PETRONAS has partnered with TiME MARINE Services Sdn Bhd to develop an innovative technology that utilizes biodegradable chemicals and mechanical processes to efficiently recover hydrocarbons, water and solids from oil sludge. In 2022, PETRONAS collaborated with the Shimizu Institute of Technology with funding from Japan Cooperation Center for Petroleum and Sustainable Energy (JCCP) to launch a pilot project exploring the use of carbonization technology for treating hazardous waste and oil sludge from refining process. The Phase 1 pilot test conducted on oil sludge samples was completed in December 2022 with preliminary results indicating an oil recovery rate of 99.6% to 99.9% and a weight reduction of 84% to 97% across all samples. Phase 2 pilot testing is planned in 2023, utilising 500 kg kiln capacity (PETRONAS, 2022).

In most cases, a specific technological system is incapable of fulfilling the diverse recycling and removal demands associated with various oil sludge wastes. Certain methods exhibit significant potential in relation to energy recovery and/or the remediation of irrecoverable wastes. However, the financial implications, encompassing both capital and operating expenses tend to be too expensive. Additionally, the practicability of implementing these strategies on a broad scale may present challenges. Alternative treatment methods, especially land treatment and composting, exhibit significant potential and cost-effectiveness for large-scale treatment. However, it is worth noting that these methods may involve an extensive microorganism degrading cycle. The decision on oil sludge remediation strategies will need to be based on the specific characteristics of the sludge, processing ability, expenses, regulatory requirements for disposal, and time limitations.

Table 2.3 Summary of various technologies oil recovery and disposal method for oil sludge

Oil recovery method				
Methods	**Process**	**Advantages**	**Limitations**	**Reference**
Solvent extraction	Extract specific components from a mixture using a solvent such as filtration and distillation	• Low energy consumption • High processing efficiency • Easy to operate • High oil recovery rate	• Less recovery • Low efficiency for large scale operation • High variability • Complexity	(Naggar et al., 2010; Panova et al., 2018)
Centrifugation	Separate water or solids from the oil phase.	• Low energy consumption • Low space usage and low cost • High separation efficiency • Effective at dewatering sludge oil	• Generate noise and vibrations • Less efficient for the separation of oil and water • Require specialized equipment and regular maintenance	(Silva et al., 2012; Jafarinejad, 2017)
Freeze/ thaw	Via demulsification process	• Simple, effective, suitable for cold zone	• Not effective for desorption • Low sludge settleability	(Hu et al., 2015; Johnson & Affam, 2022)
Sludge pyrolysis	Thermal decomposition via heating at 500 to 1000 °C	• Good operational efficiency • Highest oil extraction rates	• High equipment operating and maintenance cost • High energy consumption	(Bellahcene et al., 2021; Wang et al., 2021)

		• Minimal potential for secondary pollution	• Low extraction	
Ultrasonic	High-frequency sound waves that produce mechanical vibrations and cavitation in liquids.	• An extensive variety of applications • Good operational efficacy • Environmentally friendly	• High energy input • Condition difficult to control	(Gao et al., 2015; Luo et al., 2020; Zhao et al., 2017)
Thermochemical cleaning	Using heat and chemical reactions to break down, remove, or transform to reduce the volume, toxicity, and environmental impact.	• Low cost • High reliability • Easy to operate • Easy to scale up	• Insufficient process density • Heavy viscous sludge can be difficult	(Jafarinejad, 2017; Ramirez & Collins, 2018)

Disposal method

Methods	**Process**	**Advantages**	**Limitation**	**Reference**
Stabilization/ Solidification	Adding additives to make the contaminants into least soluble, mobile, or toxic	• Simple and fast degradation process • Low cost, widely available • Easy to handle	• Larger amount of chemical reagents • Higher concentration of petroleum hydrocarbon	(Asim et al., 2021; Gong et al., 2018; Islam, 2015; Johnson & Affam, 2022)

			• Retention relies on physical entrapment • High operating and maintenance cost	
Incineration	Controlled combustion at high temperatures to make the waste less bulky and toxic	• Established technology • High processing efficiency • Larger processing capacity • Suitable for low quality sludge	• High capital and operating costs • Emission of secondary pollutants • Lack of societal acceptability	(Gong et al., 2018; Jafarinejad, 2017; Sankaran et al., 1998)
Oxidation	Addition of oxygen to the molecules in the sludge oil, resulting in the breakdown of various organic compounds into simpler molecules	• Rapid decomposition • Unaffected by external interference • No secondary contamination	• Required larger amount of chemical reagents • Expensive operational and maintenance cost • Not recycle resources	(Hu et al., 2013; Jafarinejad, 2017)
Bioremediation	Using microorganisms such as bacteria, fungi, and other organisms, to degrade, transform, or remove contaminants into less harmful substances	• Low energy consumption • Eco-friendly • Targeted degradation • Simple operation procedure • Cost effectiveness	• Minimal operational efficacy • Prolonged time frame for treatment • Required larger space • Impacted by environmental constraints • Inconsistent results	(Ahmad, 2017; Liu et al., 2022; Zhang et al., 2019)

2.1.3 Toxicity of oil sludge

Oil sludge is potentially dangerous to the surrounding owing to presence of high toxic level, making its improper disposal a major concern. The physical and chemical characteristics of soils can be altered by oil sludge entering the terrestrial environment, leading to morphological changes in the soil (Collin et al., 2022; Robertson et al., 2007; Salimnezhad et al., 2021). When in contact with oil sludge-contaminated soil, plants may suffer from nutrient deficiencies, limited growth, and mortality (Al-Mutairi et al., 2008; Jabbar et al., 2022; Khan et al., 2018; Kuppusamy et al., 2017). Oil sludge components have a high viscosity and can be fixed in porous soil, adsorbed onto mineral constituent surfaces, or form a continuous layer on other surfaces (Gaur et al., 2022; Wang et al., 2018). Consequently, there is a reduction in hygroscopic moisture in soils, as well as in hydraulic conductivity and water retention capacity (Khan et al., 2018; Popoola et al., 2021; Suleimanov et al., 2005). High molecular weight and degradation products can remain near the soil surface, forming hydrophobic crusts that reduce water availability and limit water flow in the soil (Gaur et al., 2022; Tang et al., 2012). As a result of the presence of petroleum sludge, soil chemical and physical properties can also be affected, resulting in morphological changes and destruction of the soil (Haroni et al., 2019; Kuppusamy et al., 2017).

When oil sludge is disposed of in the environment, it can cause a variety of toxic effects in the environment that are caused by PHCs and heavy metals (Sinha et al., 2020). Heavy metals are cumulatively hazardous and pose a particular hazard. PHC are the most concerning because of their genotoxic effects on human health and organisms (Patel et al., 2020; Robertson et al., 2007). As a result of PHC accumulation in oil sludge, they might migrate into soil profile and water that connects to aquatic habitat, posing risks to the reduction of fish diversity and abundance in aquatic ecosystems

(Honda et al., 2020; Wake, 2005). The presence of PHCs could cause a decrease in soil enzyme activity such as hydrogenase and invertase and toxic effects to the soil (Koolivand et al., 2022; Suleimanov et al., 2005). The removal of oil sludge from lagoons lined with cement and bricks still results in odor problems and fire hazards (Bhattacharyya et al., 2003). It has also been noted that refinery oily sludge disposed in lagoons or landfills can have a significant impact on atmospheric VOC (Suganya et al., 2019). Consequently, communities and workers are more likely to suffer from health problems. Numerous laws have been enacted around the world to deal with, store, and dispose of petroleum sludge due to its potential dangers, such as the RCRA (Alengebawy et al., 2021; Hu et al., 2013; Ibrahim et al., 2021; Khatatbeh et al., 2020). The inadequate management and inappropriate disposal of petroleum sludge can have serious consequences affecting the ecosystem, human well-being, aquatic ecosystems, and the quality of soil (Cheng et al., 2018; Saleh et al., 2020).

2.1.4 Regulations

Oil sludge has been categorizing as hazardous waste and become a significant issue in both developed and developing countries, including Malaysia (Ibrahim et al., 2021). It is mandatory under Malaysia's Environmental Quality (Scheduled Wastes) Regulations 2005 (EQA, 1974) that waste oil has been listed as code SW 310, also known as petroleum sludge to be appropriately treated. According to the USEPA also has classified that oil sludge as a hazardous organic compound (USEPA, 2005). Table 2.4 shows the regulation and legislation of petroleum oil sludge based on country.

Table 2.4 Regulation and legislation of petroleum oil sludge based on country

Country	Regulation and Legislation	Year
United State	Resource Conservation and Recovery Act (RCRA)	1976
	United States Environmental Protection Agency (US EPA) published a final rule (57 FR 37194, 37252)	1992
Malaysia	Environmental Quality Act Regulation, under the First Schedule of the Environmental Quality (Scheduled Wastes) Regulations, (SW 310)	2005
China	National Catalogue of Hazardous Wastes, No. HW08, Ministry of Environmental Protection	2007
Australia	Environmental Protection (Industrial Waste Resource) Regulations 2009	2009
Thailand	Hazardous Substance Act B.E. 2535 (1992)	1992
Vietnam	Law on Environmental Protection (2020)	2020
UK	The Waste (Circular Economy) (Amendment) Regulations 2020	2020
Norway	The regulations relating to Petroleum Product Storing for Emergency Purposes (RPP) and the 2011 Act on Business and Industry Preparedness	2011
Mozambique	Decree no.34/2015 approves the Regulation of Petroleum Operations	2015

2.2 Food waste (FW)

Food waste is the residues of leftover food and the inedible pieces of food disposed through manufacturing, processing, retailing, and consumption (Devi et al., 2023; Rajesh et al., 2020). Researcher indicates that 6.8% of the world's pollutants come from food waste (Mahmudul et al., 2022) and leads to water scarcity using 250 billion litter of water per year (Muhirwa et al., 2023). The anticipated economic and population growth in Asian countries over the next 25 years will lead to an increase in the generation of food waste. By 2025, urban areas are expected to produce 138 million more tonnes of food waste compared to the amount generated in 2005. In Asian countries, FW productions is predicted to increase with 278 to 416 million tonnes yearly from 2005 to 2025 (Paritosh et al., 2017).

The primary challenge of food waste is insufficient infrastructure and legislation (Cecilia et al., 2019). The inefficient of FW disposal effect the surrounding by produce the greenhouse gas (GHG) pollutions (Usmani et al., 2021), methane emission from landfill decomposition (Mahmudul et al., 2022) and water pollution (Cerar et al., 2022). FW is disposed through incineration and landfills effecting the social, environmental, and economic issues (Palansooriya et al., 2023). During the FW combustion, dioxins are formed due to the high nutrient and moisture content in FW affect the human health and environment (Palansooriya et al., 2023). Landfills, incineration, and recycling are methods for the treatment and disposal of household waste (Wong, 2022). In China, municipal solid waste (MSW) is predominantly managed via incineration and landfill, yielding a treatment rate over 90% (Jin et al., 2021).

Household food waste's higher moisture content generates more contaminants through both the transportation and disposal stages, even though sanitary landfills are typically cost-effective (Zhang et al., 2019). While for incineration method is not an