



## ECOLOGICAL AND HEALTH EFFECTS OF SPENT OILS TOWARD ENVIRONMENTAL SUSTAINABILITY

MOHAMMAD ALIFF SHAKIR<sup>1</sup>, NADZIRAH MUHAMAD DAUT<sup>1</sup>, ROHAYATI MOHD ISA<sup>2</sup>, SUMARNI MANSUR<sup>3</sup>, MOHAMAD ANUAR KAMARUDDIN<sup>1</sup> AND MARDIANA IDAYU AHMAD<sup>1,4\*</sup>

<sup>1</sup>Environmental Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800 Gelugor, Pulau Pinang, Malaysia. <sup>2</sup>Faculty of Education, Universiti Islam Melaka, Batu 28, Kuala Sungai Baru, 78200, Melaka, Malaysia. <sup>3</sup>Bioresource Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800 Gelugor, Pulau Pinang, Malaysia. <sup>4</sup>Renewable Biomass Transformation Cluster, School of Industrial Technology, Universiti Sains Malaysia, 11800 Gelugor, Pulau Pinang, Malaysia.

\*Corresponding author: [mardianaidayu@usm.my](mailto:mardianaidayu@usm.my)

### ARTICLE INFO

#### Article History:

Received: 14 May 2024

Revised: 4 July 2024

Accepted: 29 July 2024

Published: 15 March 2026

#### Keywords:

Spent oil, health, pollution, toxicity, sustainability.

### ABSTRACT

The utilisation of lubricating oils such as SW 305, hydraulic oils like SW 306, and mineral oils represented by SW 307 is widespread in the realms of industrial machinery, automotive applications and forestry. The environmental release of these petroleum-based oils poses significant risks to ecosystems and human health, challenging the adequacy of existing biodegradability regulations, highlighting concerns even in the face of Malaysian mandates aimed at managing such pollutants. This review focuses on the environmental and health effects of spent oils from these lubricants, highlighting the urgent need for progress in making oils biodegradable and less harmful in Malaysia. Through a detailed examination of current testing methods and regulatory frameworks, it becomes evident that there is a compelling need for enhanced standards and innovative, cost-effective solutions for oil management. The review advocates for a paradigm shift towards the development and adoption of fully biodegradable oils, underpinned by robust regulatory support and the integration of sustainable practices in oil management. By doing so, it calls for immediate, actionable measures to safeguard environmental integrity and public health, promoting a sustainable future through improved management of spent oils.

© UMT Press

### Introduction

Spent 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 centralised at authorised Treatment, Storage, and Disposal Facilities (TSDF). In the United States, approximately 1 billion gallons of spent oil is 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 for spent oil collection extends to spent mineral oil, showcasing a broad approach to management that emphasises recycling and repurposing to mitigate ecological and health impacts while meeting the energy demands of various sectors. To illustrate the multifaceted process of spent oil management, Figure 1 provides a visual representation of the journey from collection to recycling.

Compared with low-sulfur, crude-based heavy fuel oils, spent oils contain significantly higher levels of heavy metals, sulfur,

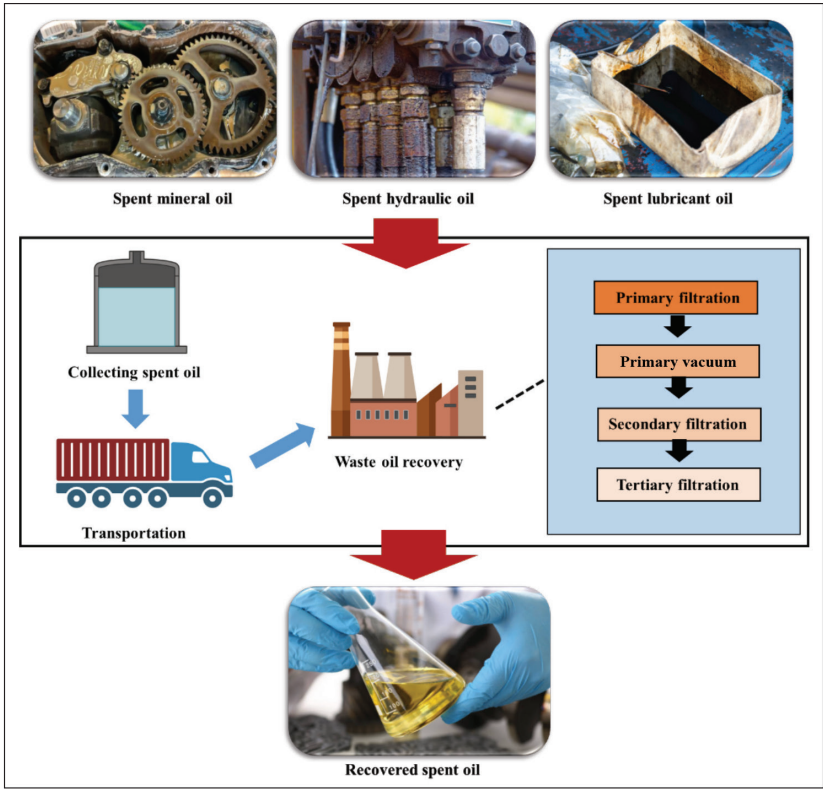


Figure 1: Overview of spent oil recovery process workflow

phosphorus, and total halogens (Nelyubov *et al.*, 2023). Their typically lower quality as a fuel, necessitates blending spent oil 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.

A study by Atmanli *et al.* (2020) demonstrated that incorporating up to 20% spent oil into blended fuel can reduce overall fuel consumption by as much as 10%. Typically, blended fuel consists of a mixture of spent oil and conventional fuels such as diesel or biodiesel. From a life-cycle analysis perspective, the dilution does not alter the total emissions per unit of spent oil consumed, underscoring the importance of sustainable management practices in addressing environmental and health concerns.

In general, spent oil is categorised as Scheduled Waste (SW) under the First Schedule of the Environmental Quality Regulation 2005 because it includes chemical and physical contaminants that could potentially harm living things. SW 305, SW 306, and SW 307 serve 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 minimising friction and protects against corrosion in mechanical systems. Each oil is engineered with a focus on balancing operational efficacy with environmental sustainability. They share a commitment to possess 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).

In Malaysia, the annual generation of spent oil includes approximately 176,910.62 metric tons of SW305 (lubricating oil), 8,611.06 metric tons of SW306 (hydraulic oil), and 171,056.62 metric tons of SW307 (mineral oil). This highlights the urgent need for sustainable management practices to mitigate the associated environmental and health risks (DOE, 2022). As spent 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 spent oils extend far beyond localised pollution, affecting global soil and water quality, and consequently, the health of entire ecosystems (Ikhajiagbe *et al.*, 2020). When these oils are improperly managed, they release harmful contaminants that degrade natural habitats, reduce biodiversity, and pose significant risks to aquatic life. This global issue necessitates urgent and effective spent 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 spent 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.*, 2020). 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 managing spent 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 spent 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. In light of the escalating environmental and public health issues associated with spent oil management, the scientific community has responded with a growing body of research and literature.

The graph in Figure 2 shows the upward trend in the number of scientific publications over the years. The substantial surge in the number of articles devoted to spent oil management over the past two decades is a clear indication of the keen interest of the global scientific community in this subject. In the pie chart, research articles constitute the largest segment with 1,756 publications, accounting for approximately 70%, followed by review articles with 362 publications, representing about 15%. This highlights the significant focus on detailed research and comprehensive reviews in the field.

Expanding on the discussion of the economic implications, it is crucial to recognise that the management of spent oils encompasses more than just the direct costs of clean-up and healthcare. It also involves the broader economic impact of lost productivity, potential legal liabilities, and the depletion of natural resources, which could otherwise contribute to sustainable economic development (Sarkar *et al.*, 2023).

Furthermore, addressing the loss of biodiversity due to spent oil pollution reveals a complex web of ecological consequences. The decline in species diversity and ecosystem services such as pollination, water purification, and disease control can have profound long-term

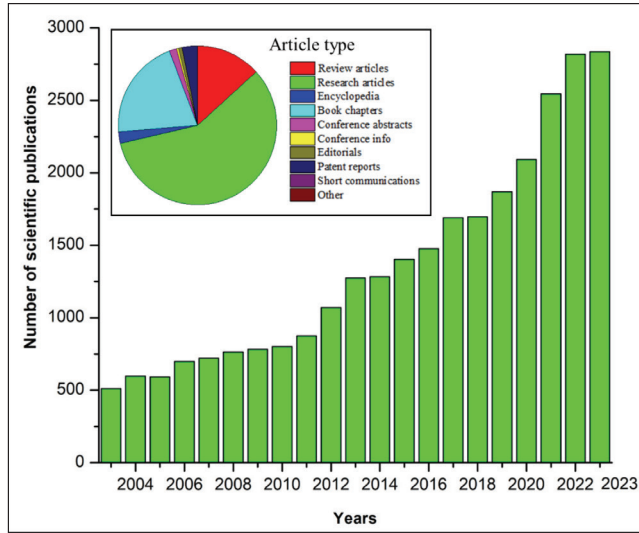


Figure 2: Accelerated number of publications about spent oil management in the past two decades

effects on global food security, livelihoods, and the resilience of communities to environmental changes (Shakir *et al.*, 2023). These intertwined economic and ecological challenges underscore the urgent need for integrated, sustainable management strategies for spent oils that align with broader environmental conservation and economic stability goals.

Transitioning to resource conservation, the recycling and repurposing of spent 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 minimises 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 spent oils. By fostering an environment, where sustainable practices are incentivised and non-compliance is penalised, 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.

Emphasising the imperative for sustainable practices in managing spent 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 prioritise both environmental integrity and economic viability (Zgheib *et al.*, 2021). Focusing on these sustainable practices can ensure a more environmentally responsible approach to spent oil management, fostering a healthier planet for future generations.

This review aims to consolidate current knowledge on the ecological and health effects of spent oils, evaluate the effectiveness of existing management practices, and explore innovative approaches for enhancing sustainability. Through a comprehensive analysis of literature and case studies, the article highlights the urgent need for integrated strategies that encompass environmental protection, resource conservation, and policy reform. By drawing attention to these critical areas, the review seeks to inform future research, guide policy development and inspire the adoption of best practices in spent oil management, ultimately contributing to the achievement of global sustainability objectives.

### Environmental and Health Impacts of Spent Oils

Spent oils degrade soil quality by reducing fertility, which in turn negatively impacts agricultural productivity and ecosystem health. These oils seep into the ground, disrupting the delicate balance of microbial communities essential for nutrient cycling and soil structure maintenance. As shown in Table 1, the presence of heavy metals and hydrocarbons in spent oils further exacerbates soil toxicity, posing a threat to plant life and underground water sources (Ikhajiagbe & Ogwu, 2020). Addressing soil contamination requires comprehensive strategies to prevent oil spillage and promote bioremediation techniques that can restore soil health. This statement aligns well with a study by Hoang *et al.* (2021), which stated that bioremediation is an alternative green solution for rehabilitating hydrocarbon-contaminated soil and water.

Table 1: Principal contaminant in spent oil (DOE, 2010)

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

Also, fly ash is an effective choice for both adsorption and oil regeneration since it exhibits efficient spent oil adsorption, like activated clay (Ouyang *et al.*, 2019). Technically, fly ash contains porous structures and active sites that enhance its ability to adsorb oil contaminants from soil. These pores and active sites trap oil molecules, reducing their concentration in the environment. The adsorbed oil on fly ash can be recovered through thermal desorption or solvent extraction methods. Thermal desorption involves heating the fly ash to volatilise the adsorbed oil, which can then be condensed and collected. Solvent extraction involves using a solvent to dissolve and extract the adsorbed oil from the fly ash, which can then be separated and purified.

Thus, while the immediate focus on soil contamination highlights the need for remedial actions to restore terrestrial health, it also brings to light the inevitable journey of these pollutants beyond the soil, reaching into the very water bodies that sustain life. This movement from land to water underscores the pervasive threat posed by spent oils, necessitating a broadened scope of environmental vigilance. As these contaminants make their way from contaminated soils into rivers, lakes, and oceans, the environmental concern broadens to encompass water pollution.

The leakage of spent oils into water bodies constitutes a major environmental concern as they affect both freshwater and marine ecosystems. These pollutants can create oil slicks on water surfaces, blocking sunlight, and impairing the photosynthetic ability of aquatic plants (Silva *et al.*, 2022). Moreover, the solubilised toxic components of spent oils can contaminate drinking water sources, posing serious health risks to human populations. Mitigating water pollution necessitates stringent regulations on oil disposal and the development of efficient oil recovery and treatment technologies.

On the other hand, spent oils can have a detrimental effect on vegetation affected by oil spillage, leading to the suffocation of plant roots and a decrease in plant growth. The toxic substances contained within spent oils such as

Polycyclic Aromatic Hydrocarbons (PAHs) can accumulate in the soil, leading to long-term damage to plant health and reduced biodiversity in affected areas (Xu *et al.*, 2021; Kariyawasam *et al.*, 2022). Previous studies highlight that PAHs, which persist in soils and show a strong affinity for accumulation in living organisms can significantly impact microbial activity, growth of plants, and invertebrates (Ukalska *et al.*, 2020). These effects are further influenced by the physical, chemical, and biological properties of soil, which play a crucial role in the availability and persistence of these hydrocarbons.

Technically, the concentration of PAHs in virgin oil is relatively low, however, this may increase with long-term use. When it turns into spent oil, the concentration can rise by a factor of up to 180. It has been reported that the level of specific PAHs such as Benzo(a)pyrene can be as high as 0.266 mg/kg in new virgin oil, but spent oil can increase up to 216 mg/kg which is 1,000 times higher (Cvengroš *et al.*, 2017). Therefore, efforts to protect vegetation must focus on preventing oil spills and promoting the use of less harmful substances in machinery and equipment. As shown in Figure 3, the detrimental impact of spent oils on vegetation, marked by the suffocation of plant roots and accumulation of PAHs, not only disrupts plant life but also serves as a dire warning for the broader ecosystem.

As vegetation suffers, wildlife too faces imminent threats. The degradation of natural habitats due to oil spillage creates a ripple effect, leading to poisoning, skin irritation, and reproductive harm in animals reliant on these environments. Birds and mammals that come into contact with oil-contaminated environments may suffer from impaired insulation and buoyancy, leading to hypothermia or drowning (Akpan, 2022). Protecting wildlife from the threats posed by spent oils requires habitat conservation efforts and rapid response strategies to contain and clean up oil spills.

The consequences of spent oils extend beyond the natural world, impacting wildlife through loss of insulation and buoyancy, and

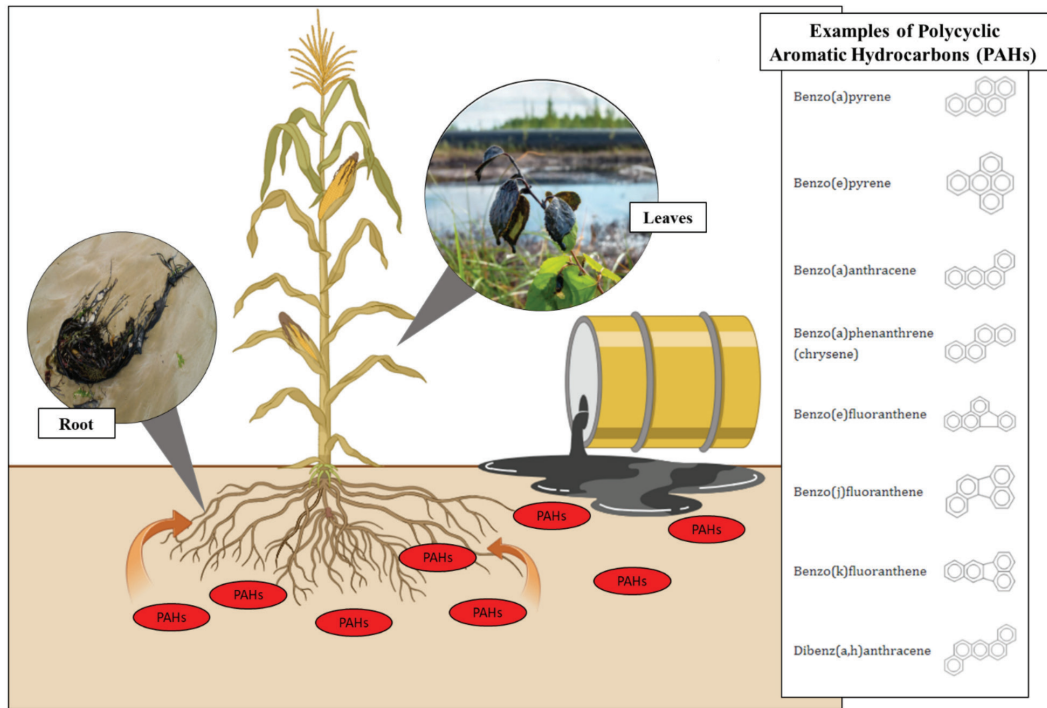


Figure 3: Soil contamination by PAHs from spent oils and effect on plant

mirror a broader environmental health crisis that directly affects human communities. This chain of adversity underscores a significant concern for human health, particularly for those in close contact with or managing these pollutants. The exposure to contaminated environments links directly to increased risks of respiratory problems, skin disorders and potential carcinogenic effects in humans, emphasising the need for comprehensive protective measures and safety protocols (Mamaghani *et al.*, 2022). Workers in industries that handle or dispose of spent oils are at particular risk, underscoring the need for protective measures and strict adherence to safety protocols. Public health initiatives should focus on minimising exposure to spent oils and promoting awareness of their potential health impacts. Figure 4 shows the extensive environmental and health impacts of spent oil contamination on animal, plant, and human health.

Transitioning from human health risks, the discussion expands into the broader implications of spent oil contamination, highlighting ecosystem disruption. This shift emphasises how the consequences of pollution extend beyond immediate health concerns to affect the intricate web of life that sustains ecosystems. Such disruption underlines the need for an integrated approach to environmental stewardship, blending pollution control with efforts to conserve and restore natural habitats. The cumulative effects of spent oil contamination across different environmental media can lead to widespread ecosystem disruption (Barron *et al.*, 2020; Johnson *et al.*, 2021). This disruption not only affects individual species but also the complex interactions within ecosystems, leading to a decline in ecological resilience and functionality. Addressing ecosystem disruption necessitates a holistic approach to environmental management, integrating pollution control with conservation and restoration efforts.

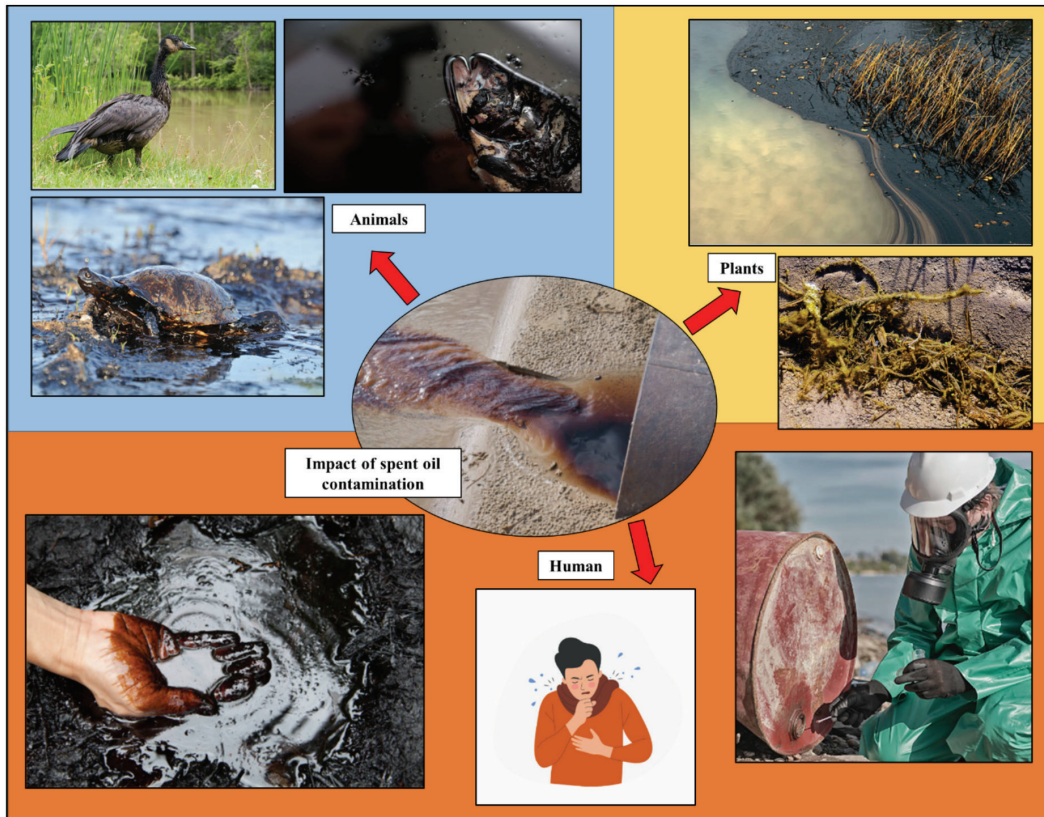


Figure 4: Impact of spent oil contamination on animals, plants, and human health

Last but not least, the substantial costs associated with cleaning contaminated environments and addressing health issues related to spent oil exposure underscore the critical importance of preventive measures (Oliveira *et al.*, 2021). By improving oil management practices and fostering research into sustainable alternatives, societies can alleviate the financial strain imposed by spent oil pollution, demonstrating the profound link between environmental health and economic well-being. Investing in preventive strategies and sustainable research is crucial to protect our natural world and ensure societal welfare, demonstrating a comprehensive approach to address the economic burdens associated with spent oil pollution.

### Current Legal Regulations and Standards for Recovered Spent Oil

#### *Overview of the Malaysian Standard and Specification for Recovered Spent oil*

Strategic environmental management and public health protection can be witnessed in Malaysia through the stringent regulation of recovered spent oil. Recognising the potential environmental and health risks posed by the improper handling of spent oil, the Malaysian government has established a guideline in 2009. This guideline outlines the standard and specifications for recovered spent oil aimed at addressing the physical and chemical impurities present in spent oil that can pose risks to living organisms, leading to its classification as scheduled waste under the First Schedule of the Environment Quality Regulation 2005.

The establishment of a comprehensive regulatory framework mandates that facilities recovering or processing spent oil are required to obtain an operational license from the Department of Environment (DOE) under the Ministry of Natural Resources, Environment and Climate Change (Lokman *et al.*, 2021). This requirement not only emphasises the dedication by the government to provide sustainable waste management but also ensures that recovered spent oil is treated and repurposed responsibly. Therefore, central to the regulation is the specification of standards for spent oil recovery, particularly concerning the permissible levels of hazardous contaminants. By setting strict limits on the presence of metals, chlorinated hydrocarbons, and other organic pollutants, the guidelines aim to minimise the environmental and health risks associated with spent oil usage (Mehr *et al.*, 2020; Wu *et al.*, 2021). These standards facilitate the transformation of spent oil into valuable commodities such as fuel and lubricating oils while safeguarding ecosystems and human health.

Furthermore, the framework clearly delineates the categorisation of spent oil based

on its processing outcomes. Spent oil processed by recovery facilities and meeting the specified standards and specifications for recovered spent oil, as detailed in Table 2 is classified as non-scheduled waste. Conversely, processed spent oil that fails to meet these criteria remains categorised as Scheduled Waste (SW). This distinction underscores the importance of adhering to established standards in the treatment and repurposing of spent oil, ensuring that only environmentally safe products are reintroduced into the market.

Testing methods for these contaminants are outlined in Table 3, relying on established protocols to accurately assess the safety and quality of recovered spent oil. These procedures ensure compliance with the specified standards, verifying that the oil is free from harmful levels of substances like arsenic, lead, and benzene. The emphasis on thorough testing reflects a commitment to maintaining high environmental and safety standards.

Moreover, the guidelines stipulate that recovered spent oil must meet certain physical criteria, including a clear and bright appearance and a minimum flash point, to be considered safe

Table 2: Standard and specification of recovered spent oil (DOE, 2010)

Parameters/Constituents	Allowable Level
Arsenic	5 ppm maximum
Cadmium	2 ppm maximum
Chromium	10 ppm maximum
Lead	100 ppm maximum
Total halogen (as chlorine)	1,000 ppm maximum
Flash point	37.7°C or higher
Appearance	Must be clear and bright
Poly-aromatic Hydrocarbons	
Benzo(a)pyrene	10 mg/1 kg oil (10 ppm) maximum
Dibenz(ah)anthracene	10 mg/1 kg oil (10 ppm) maximum
Benz(a)anthracene	100 mg/1 kg oil (100 ppm) maximum
Benzo(b)fluoranthene	100 mg/1 kg oil (100 ppm) maximum
Benzo(k)fluoranthene	100 mg/1 kg oil (100 ppm) maximum
Chrysene	100 mg/1 kg oil (100 ppm) maximum
Indeno(123-cd) pyrene	100 mg/1 kg oil (100 ppm) maximum

Table 3: Method of testing (DOE, 2010)

Parameters/Constituents	Allowable Level
Arsenic	Any established method
Cadmium	Any established method
Chromium	Any established method
Lead	Any established method
Total halogen (as chlorine)	ASTM D 5384/EPA 9075
Flash point	MS 686
Appearance	In house method (Visual)
Poly-aromatic Hydrocarbons	
Benzo(a)pyrene	EPA SW-846 Method 8270C
Dibenz(ah)anthracene	EPA SW-846 Method 8270C
Benz(a)anthracene	EPA SW-846 Method 8270C
Benzo(b)fluoranthene	EPA SW-846 Method 8270C
Benzo(k)fluoranthene	EPA SW-846 Method 8270C
Chrysene	EPA SW-846 Method 8270C
Indeno(123-cd) pyrene	EPA SW-846 Method 8270C

for further use. This focus on the physical and chemical properties of recovered oil underscores the holistic approach taken by Malaysian authorities to manage spent oil effectively. By integrating strict regulatory measures with detailed testing and specification standards, Malaysia is at the forefront of promoting sustainable spent oil management practices that benefit both the economy and the environment.

**Implications of the Standards on Environmental and Health Safety**

The standards for recovered spent oil have profound implications for both environmental and health safety. By setting strict limits on hazardous contaminants, these standards play a crucial role in reducing pollution. This not only helps in preserving soil and water quality but also protects diverse ecosystems from the adverse effects of toxic substances. Moreover, these regulatory measures safeguard public health by minimising exposure to harmful chemicals, which can arise from improper spent oil management. The emphasis on maintaining low levels of pollutants ensures that communities are

shielded from potential health risks associated with exposure to toxic spent oil components.

The adoption of these standards also promotes sustainable practices within the industry, encouraging the development and use of cleaner technologies for spent oil recovery and processing (Li *et al.*, 2021). This shift towards sustainability enhances the value of spent oil as a resource, making it safer for recycling and reuse in various applications. Compliance with these standards necessitates rigorous monitoring and enforcement mechanisms, which are essential for ensuring that spent oil management practices meet the required safety criteria (Ruzouq *et al.*, 2020). This oversight encourages continuous improvement in environmental and health safety measures, driving innovation in waste management technologies and processes. Overall, the implications of these standards are far-reaching, fostering a safer, more sustainable approach to spent oil management. By prioritising environmental protection and public health, these regulations not only mitigate the risks associated with spent oil but also contribute to the broader goals of ecological preservation and sustainable development.

## Review of Biodegradability and Toxicity Standards

Biodegradability tests for spent oils are crucial for assessing their environmental impact, defining the speed and completeness with which these substances decompose naturally. These tests aim to ensure that spent oils break down in a manner that minimises long-term ecological harm (Danilov *et al.*, 2021). The methodologies employed in biodegradability testing are comprehensive, involving a range of international and national standards designed to provide accurate assessments of environmental friendliness of spent oil. These methods typically assess how quickly and completely spent oils break down in environmental conditions (Mengounou *et al.*,

2022). International standards, like Organisation for Economic Cooperation and Development (OECD) guidelines offer a series of tests such as the OECD 301 series, which evaluate the biodegradability of substances by measuring the oxygen demand in closed respirometers or the amount of CO<sub>2</sub> produced (Strotmann *et al.*, 2023). National standards may vary as methodologies are tailored to address specific environmental concerns and regulatory requirements within different countries. Table 4 presents the tests used to assess biodegradability. These tests are critical to ensure that once treated or disposed of, spent oils will not persist in the environment and pose risks to ecosystems and human health.

Table 4: Test used to assess potential aerobic biodegradability of chemical compounds in water

OECD Test	International Organisation for Standardisation (ISO) Norm	Parameter Monitored	Referances
301 A DOC Die-away	Rapid biodegradability assessment test. Water quality. Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds. Method by analysis of Dissolved Organic Carbon (DOC).	DOC <sup>1</sup>	(Chowdhury <i>et al.</i> , 2021; Strotmann <i>et al.</i> , 2023)
301 B CO <sub>2</sub> Evolution Test	Water quality. Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium. Carbon dioxide evolution test.	CO <sub>2</sub> production	(García <i>et al.</i> , 2022; Menzies <i>et al.</i> , 2023)
301 C MITI I Test Modified MITI I Test	No equivalent. Test used in Japan.	BOD5 <sup>2</sup>	(Strotmann <i>et al.</i> , 2023)
301 D Closed Bottle Test	Water quality. Evaluation in an aqueous medium of the “ultimate” aerobic biodegradability of organic compounds. Method by analysis of biochemical oxygen demand (closed bottle test).	BOD5 <sup>2</sup>	(Almutairi, 2020)
301 E Modified OECD <sup>3</sup> Screening Test	Water quality. Evaluation of the “ready”, “ultimate” aerobic biodegradability of organic compounds in an aqueous medium. Method by analysis of Dissolved Organic Carbon (DOC).	DOC <sup>1</sup>	(Takekoshi <i>et al.</i> , 2021; Strotmann <i>et al.</i> , 2023)
301 F Manometric Respiratory Test	Water quality. Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium by determination of oxygen demand in a closed respirometer.	BOD5 <sup>2</sup>	(Strotmann <i>et al.</i> , 2023; Suk <i>et al.</i> , 2023)
310 CO <sub>2</sub> Headspace Test	Water quality. Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium. Method by analysis of inorganic carbon in sealed vessels (CO <sub>2</sub> headspace test).	CO <sub>2</sub> production	(Dalmijn <i>et al.</i> , 2021)

<b>Test for Potential Biodegradability</b>			
302 A Modified SCAS Test	Water quality. Evaluation of the aerobic biodegradability of organic compounds in an aqueous medium. Semi-Continuous Activated Sludge method (SCAS). {Poursat, 2020 #675}.	DOC <sup>1</sup>	(Poursat <i>et al.</i> , 2020)
302 B Zahn-Wellens Modified Test	Water quality. Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium. Static test (Zahn-Wellens method).	DOC <sup>1</sup>	(Menzies <i>et al.</i> , 2023)
302 C Modified MITI <sup>4</sup> II Test	No equivalent. Test used in Japan.	BOD <sub>5</sub> <sup>2</sup>	-
302 D CONCAWE <sup>5</sup> Test	No equivalent.	CO <sub>2</sub> production	-

Toxicity standards for spent oil are designed to evaluate the potential harm these substances may cause to human health and the environment. These criteria involve assessing the presence and concentrations of hazardous chemicals within spent oils such as heavy metals, carcinogens, and other toxic compounds (Takeshita *et al.*, 2021). Standards typically reference thresholds beyond which substances are considered harmful, drawing on research and guidelines from environmental and health agencies. These standards are crucial for guiding spent oil management practices, ensuring that oils are treated or disposed of in ways that minimise toxic impacts on ecosystems and reduce risks to human health.

An example of toxicity standards for spent oil can be found in regulations like those set by the United States Environmental Protection Agency (EPA), which include the Toxicity Characteristic Leaching Procedure (TCLP) (Barron *et al.*, 2020). This procedure identifies spent oils that may pose a threat to public health or the environment due to leachable toxic contaminants. It determines if spent oil contains hazardous substances at concentrations above regulatory thresholds, necessitating special handling and disposal methods to mitigate harm. This integration of specific examples such as the TCLP into toxicity standards illustrates the practical application of these guidelines in managing the risks associated with spent oil.

In Malaysia, toxicity standards for spent oil would typically align with guidelines and regulations set by the Department of Environment (DOE) under the Ministry of Natural Resources, Environment and Climate Change. These standards are designed to manage the environmental and health impacts of hazardous substances, including spent oil (Shami *et al.*, 2011; Alam *et al.*, 2015). While specific details on the toxicity standards for spent oil in Malaysia would be outlined in national environmental regulations and guidelines, they would similarly aim to identify and control the levels of toxic contaminants such as heavy metals and hydrocarbons. These measures ensure that the disposal and treatment of spent oil would have minimal potential harm to both human health and the environment, reflecting a commitment to sustainable waste management practices within the country.

However, there are gaps in these standards. These gaps may arise from the evolving nature of spent oil composition and the complex interactions between various pollutants and the environment. These gaps may include insufficient coverage of emerging contaminants, which are not adequately addressed by existing regulations (Loughery *et al.*, 2023). Therefore, identifying gaps in current standards and testing methods for spent oil is crucial for fully protecting ecosystems and human health.

Additionally, the variability in spent oil composition, which is influenced by diverse sources and treatment processes can challenge the effectiveness of standardised testing methods. Another significant gap is the potential lack of alignment between national and international standards, leading to inconsistencies in enforcement and compliance (Northrop *et al.*, 2016).

Furthermore, current standards may not fully account for the long-term environmental impacts of spent oil such as soil and water contamination that persists beyond initial disposal or treatment (Andersson *et al.*, 2015; Khan *et al.*, 2021). Addressing these gaps requires a comprehensive review of existing regulations, a commitment to updating standards in line with scientific advancements, and a global approach to harmonising testing methodologies. This will ensure that environmental protection measures keep pace with the complexities of spent oil management and its evolving challenges.

To address these shortcomings, recommendations for enhancing biodegradability and toxicity standards are vital. These improvements could involve refining testing methodologies, updating safety criteria based on the latest scientific research, and adopting more stringent regulatory measures to ensure broader environmental protection and public health safety (Shakir *et al.*, 2023c). One critical step involves regularly updating and expanding the list of contaminants that toxicity standards cover, ensuring that emerging pollutants are recognised and managed effectively (Farrington, 2020; Wang *et al.*, 2020). Achieving international harmonisation of these standards could significantly improve global compliance and the overall success of spent oil management initiatives.

Furthermore, the adoption of advanced testing methods is necessary to accurately assess the complex compositions of spent oils, providing a more reliable basis for regulatory decisions (Halappanavar *et al.*, 2020). Conducting long-term environmental and health impact studies on spent oils can offer invaluable

insights, informing the development of more comprehensive standards and management strategies.

Strengthening regulatory frameworks to ensure strict enforcement of these standards, including imposing penalties for non-compliance is another vital recommendation. Encouraging the development and use of less toxic and more biodegradable oils through research incentives can lead to safer industrial and mechanical processes, reducing the environmental footprint (Wojcieszuk *et al.*, 2023). Lastly, enhancing education and awareness among industry stakeholders and the public about the importance of adhering to these standards is crucial for fostering a culture of environmental responsibility and health protection.

In summary, the review of biodegradability and toxicity standards for spent oils is a critical component of environmental management strategies. It not only highlights the importance of rigorous testing and assessment in promoting sustainability but also calls for ongoing adjustments to these standards. This ensures they remain effective in the face of changing spent oil characteristics and emerging environmental challenges, ultimately contributing to the goal of achieving sustainable spent oil management.

### **Advances in Environmental Sustainability Practices**

In the quest for environmental sustainability, managing spent oils stands at the forefront of innovative and improved practices. As shown in Figure 5, the field is witnessing a revolution with the introduction of cutting-edge recycling technologies, strategic repurposing of spent oil, and the development of biodegradable oils. Furthermore, the adoption of lifecycle assessment practices offers a comprehensive method for evaluating the full environmental impact of spent oil production, usage, and disposal, ensuring that sustainability efforts are grounded in rigorous analysis (Moses *et al.*, 2023). Simultaneously, there is a growing recognition of the importance of robust

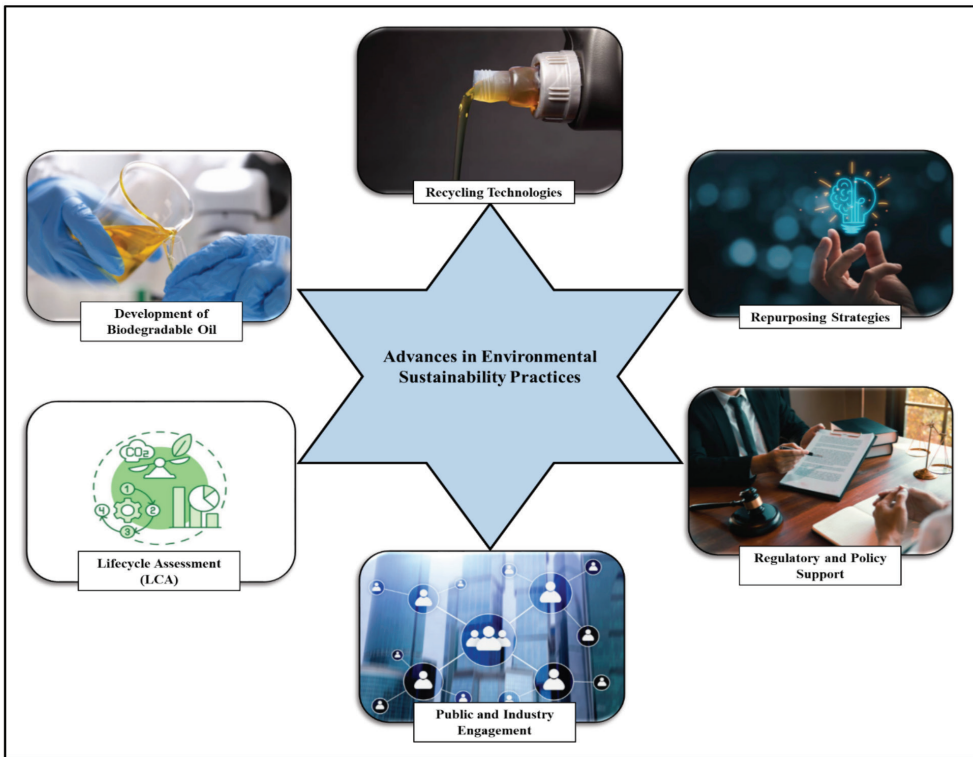


Figure 5: The integrative framework of advances in environmental sustainability practices for spent oil management

regulatory and policy support to provide a framework that encourages and enforces sustainable practices (Sivanandhini *et al.*, 2021).

Last but not least, public and industry engagement has become instrumental in driving change. Through awareness campaigns, educational programmes and collaborative efforts, a diverse range of stakeholders is coming together to champion sustainability in oil management (Qureshi *et al.*, 2022). In summary, this exploration into transformative practices in environmental sustainability showcases their critical role in reducing the ecological footprint of spent oils.

**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).

A previous study reported that acid-clay treatment is the least expensive but also the most environmentally risky method for treating spent oil, compared to other treatments (Oladimeji *et al.*, 2018). 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). Previous work by Wang *et al.* (2017) demonstrated that co-hydrotreating microalgae with spent oil results in an upgraded oil, with fuel characteristics comparable to those of conventional liquid transportation fuels obtained from fossil fuels. 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.

### ***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 (Yaseen *et al.*, 2021). These repurposing efforts are integral to the principles of a circular economy, where waste is minimised, and resources are utilised efficiently and sustainably (Shakir *et al.*, 2020). By embracing such strategies, industries not only mitigate environmental impact but also uncover new economic opportunities, reinforcing the viability of sustainable practices.

### ***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 (Raju *et al.*, 2017). 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 pollution associated with conventional oil spills and leaks.

Innovations in this field include the engineering of oil molecules to enhance their biodegradability while maintaining, or even improving, performance characteristics such as lubricity and thermal stability. The shift towards bio-based and biodegradable oils not only helps protect ecosystems but also aligns with global sustainability goals, offering a promising pathway for industries to reduce their environmental impact (Ntekpe *et al.*, 2023).

### ***Lifecycle Assessment (LCA) Practices***

The adoption of Lifecycle Assessment (LCA) practices marks a comprehensive approach to understanding and mitigating the environmental impacts of oil production, usage, and disposal (Revuru *et al.*, 2020). LCA provides a framework for evaluating the cumulative environmental effects associated with all stages of a product life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. By applying LCA to oil-related products, stakeholders can identify key areas, where improvements can be made to enhance sustainability (Dudak *et al.*, 2021).

This holistic view enables the industry to make informed decisions that reduce environmental footprints such as optimising production processes, choosing more sustainable raw materials, and developing more efficient recycling and disposal methods. Ultimately, LCA practices guide industries toward more sustainable practices, ensuring that efforts to reduce environmental impacts are grounded in comprehensive and accurate assessments.

### **Regulatory and Policy Support**

The evolving landscape of regulations and policies, alongside initiatives aimed at engaging both the public and industry stakeholders, plays a pivotal role in promoting sustainable oil management practices (Sánchez *et al.*, 2021). Governments worldwide are updating regulatory frameworks to combat the environmental and health impacts of improper oil management (Farajzadeh *et al.*, 2022). These efforts encourage sustainable practices such as adopting biodegradable oils and recycling. These regulations often come with incentives designed to motivate companies to pursue greener alternatives, demonstrating a clear commitment to environmental stewardship.

### **Public and Industry Engagement**

Simultaneously, the importance of public and industry engagement cannot be overstated. Through educational programmes, awareness campaigns and partnerships, there is a growing movement to involve all sectors of society in the transition towards sustainable oil management (Tannock, 2020). These efforts aim to increase understanding of the issues at hand, share knowledge on best practices, and foster collaborations that leverage the strengths of various stakeholders (Shah *et al.*, 2021). By combining regulatory support with active engagement strategies, there is a powerful synergy being created, driving the shift towards more environmentally responsible oil management practices that promise to benefit both the planet and its inhabitants.

### **Conclusions**

This review explores the multifaceted challenges and opportunities presented by the management of spent oils, emphasising the critical role of stringent regulations, advanced testing methods, and sustainable practices in mitigating environmental and health impacts. The examination of current biodegradability and toxicity standards, alongside innovative recycling technologies, repurposing strategies,

and the development of biodegradable oils, underscores a clear path towards enhancing environmental sustainability. The analysis highlights significant gaps in existing standards and the urgent need for harmonisation of international practices to ensure comprehensive protection against the adverse effects of spent oils.

Innovations in recycling and repurposing not only promise reduced environmental footprints but also present valuable opportunities for economic development within a circular economy framework. In conclusion, this review advocates for a concerted effort among policymakers, industry stakeholders, and the scientific community to embrace and advance sustainable oil management practices. Recommendations encompass updating toxicity and biodegradability standards, adopting lifecycle assessments for improvement guidance, and promoting research into eco-friendly oil alternatives. By addressing these critical areas, we can ensure a sustainable future that prioritises both environmental integrity and public health.

### **Acknowledgements**

The authors would like to thank Universiti Sains Malaysia for the Research University Grant Scheme with Project Code, 1001/PTEKIND/8014124 for funding this study.

### **Conflict of Interest Statement**

The authors declare that they have no conflict of interest.

### **References**

- Adeola, A. O., & Forbes, P. B. (2021). Advances in water treatment technologies for removal of polycyclic aromatic hydrocarbons: Existing concepts, emerging trends, and future prospects. *Water Environment Research*, 93(3), 343-359.

- Akpan, E. E. (2022). Environmental consequences of oil spills on marine habitats and the mitigating measures—The Niger Delta perspective. *Journal of Geoscience and Environment Protection*, 10(6), 191-203.
- Al-Ruzouq, R., Gibril, M. B. A., Shanableh, A., Kais, A., Hamed, O., Al-Mansoori, S., & Khalil, M. A. (2020). Sensors, features, and machine learning for oil spill detection and monitoring: A review. *Remote Sensing*, 12(20), 3338.
- Al-Shami, S. A., Salmah, M. R. C., Hassan, A. A., & Azizah, M. N. S. (2011). Evaluation of mentum deformities of *Chironomus* spp.(Chironomidae: Diptera) larvae using modified toxic score index (MTSI) to assess the environmental stress in Juru River Basin, Penang, Malaysia. *Environmental Monitoring and Assessment*, 177, 233-244.
- Alabdullah, M., Rodriguez-Gomez, A., Shoinkhorova, T., Dikhtiarenko, A., Chowdhury, A. D., Hita, I., & Castaño, P. (2021). One-step conversion of crude oil to light olefins using a multi-zone reactor. *Nature Catalysis*, 4(3), 233-241.
- Alam, L., Mokhtar, M. B., Alam, M. M., Bari, M. A., Kathijotes, N., Ta, G. C., & Ern, L. K. (2015). Seasonal variation and preliminary risk assessment of trace element pollution in surface water from Langat River, Malaysia. *International Journal of Applied Environmental Sciences*, 10(1), 19-40.
- Almutairi, M. (2020). Method development for evaluating the effectiveness of hydrocarbons on BOD, UBOD, and COD removal in oily wastewater. *Water Science and Technology*, 81(12), 2650-2663.
- Andersson, J. T., & Achten, C. (2015). Time to say goodbye to the 16 EPA PAHs? Toward an up-to-date use of PACs for environmental purposes. *Polycyclic Aromatic Compounds*, 35(2-4), 330-354.
- Atmanli, A., & Yilmaz, N. (2020). An experimental assessment on semi-low temperature combustion using waste oil biodiesel/C3-C5 alcohol blends in a diesel engine. *Fuel*, 260, 116357.
- Barron, M. G., Bejarano, A. C., Conmy, R. N., Sundaravadivelu, D., & Meyer, P. (2020). Toxicity of oil spill response agents and crude oils to five aquatic test species. *Marine Pollution Bulletin*, 153, 110954.
- Barron, M. G., Vivian, D. N., Heintz, R. A., & Yim, U. H. (2020). Long-term ecological impacts from oil spills: Comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon. *Environmental Science & Technology*, 54(11), 6456-6467.
- Chowdhury, S., Rakshit, A., Acharjee, A., & Saha, B. (2021). Biodegradability and biocompatibility: Advancements in synthetic surfactants. *Journal of Molecular Liquids*, 324, 115105.
- Cvengroš, J., Liptaj, T., & Prónayová, N. (2017). Study of polyaromatic hydrocarbons in current used motor oils. *International Journal of Petrochemical Science & Engineering*, 10.
- da Silva Correa, H., Blum, C. T., Galvão, F., & Maranhão, L. T. (2022). Effects of oil contamination on plant growth and development: A review. *Environmental Science and Pollution Research*, 29(29), 43501-43515.
- Dalmijn, J. A., Poursat, B. A., Van Spanning, R. J., Brandt, B. W., De Voogt, P., & Parsons, J. R. (2021). Influence of short-and long-term exposure on the biodegradation capacity of activated sludge microbial communities in ready biodegradability tests. *Environmental Science: Water Research & Technology*, 7(1), 107-121.
- Danilov, A., Antonov, S., Bartko, R., & Nikulshin, P. (2021). Recent advances in biodegradable lubricating materials (A review). *Petroleum Chemistry*, 61(7), 697-710.
- Department of Environment (DOE). (2010). *Guidelines on standard and specification of*

- recovered waste oil in Malaysia. Ministry of Natural Resources, Environment and Climate Change, Malaysia.
- Department of Environment (DOE). (2022). *Environmental Quality Report 2022*. Ministry of Natural Resources, Environment and Climate Change, Malaysia.
- Duđak, L., Milisavljević, S., Jocanović, M., Kiss, F., Šević, D., Karanović, V., & Orošnjak, M. (2021). Life cycle assessment of different waste lubrication oil management options in Serbia. *Applied Sciences*, 11(14), 6652.
- Farajzadeh, R., Eftekhari, A. A., Kahrobaei, S., Mjeni, R., Boersma, D., & Bruining, H. (2022). *Chemical enhanced oil recovery and the dilemma of more and cleaner energy*. Paper presented at the SPE EOR Conference at Oil and Gas West Asia.
- Farrington, J. W. (2020). Need to update human health risk assessment protocols for polycyclic aromatic hydrocarbons in seafood after oil spills. *Marine Pollution Bulletin*, 150, 110744.
- García-Depraect, O., Lebrero, R., Rodríguez-Vega, S., Bordel, S., Santos-Beneit, F., Martínez-Mendoza, L. J., & Muñoz, R. (2022). Biodegradation of bioplastics under aerobic and anaerobic aqueous conditions: Kinetics, carbon fate and particle size effect. *Bioresource Technology*, 344, 126265.
- Halappanavar, S., Van Den Brule, S., Nymark, P., Gaté, L., Seidel, C., Valentino, S., & Wolff, H. (2020). Adverse outcome pathways as a tool for the design of testing strategies to support the safety assessment of emerging advanced materials at the nanoscale. *Particle and Fibre Toxicology*, 17(1), 1-24.
- Hamidon, M. L. H., Jumadi, R., Khalid, A., Jaat, N., Salleh, H., & Samion, S. (2022). Research on biodegradable lubricant in combustion engine. *Journal of Automotive Powertrain and Transportation Technology*, 2(2), 42-50.
- Hoang, S. A., Lamb, D., Seshadri, B., Sarkar, B., Choppala, G., Kirkham, M., & Bolan, N. S. (2021). Rhizoremediation as a green technology for the remediation of petroleum hydrocarbon-contaminated soils. *Journal of Hazardous Materials*, 401, 123282.
- Ikhajiagbe, B., & Ogwu, M. C. (2020). Hazard quotient, microbial diversity, and plant composition of spent crude oil-polluted soil. *Beni-Suef University Journal of Basic and Applied Sciences*, 9, 1-9.
- Islam, M. S., Sanzida, N., Rahman, M. M., & Alam, M. D. (2021). From the value chain to environmental management of used lube oil: A baseline study in Bangladesh. *Case Studies in Chemical and Environmental Engineering*, 4, 100159.
- Johnson, P., Trybala, A., Starov, V., & Pinfield, V. J. (2021). Effect of synthetic surfactants on the environment and the potential for substitution by biosurfactants. *Advances in Colloid and Interface Science*, 288, 102340.
- Kariyawasam, T., Doran, G. S., Howitt, J. A., & Prenzler, P. D. (2022). Polycyclic aromatic hydrocarbon contamination in soils and sediments: Sustainable approaches for extraction and remediation. *Chemosphere*, 291, 132981.
- Khan, S., Naushad, M., Lima, E. C., Zhang, S., Shaheen, S. M., & Rinklebe, J. (2021). Global soil pollution by toxic elements: Current status and future perspectives on the risk assessment and remediation strategies—A review. *Journal of Hazardous Materials*, 417, 126039.
- Kiran, S., Martin, M. L. J., Sonthalia, A., & Varuvel, E. G. (2023). Synergistic effect of hydrogen and waste lubricating oil on the performance and emissions of a compression ignition engine. *International Journal of Hydrogen Energy*, 48(60), 23296-23307.
- Li, J., Lin, F., Li, K., Zheng, F., Yan, B., Che, L., & Yoshikawa, K. (2021). A critical review on energy recovery and non-hazardous disposal of oily sludge from petroleum industry by pyrolysis. *Journal of Hazardous Materials*, 406, 124706.

- Liu, B., Chen, B., Ling, J., Matchinski, E. J., Dong, G., Ye, X., & Lee, K. (2022). Development of advanced oil/water separation technologies to enhance the effectiveness of mechanical oil recovery operations at sea: Potential and challenges. *Journal of Hazardous Materials*, *437*, 129340.
- Lokman, N. A., Ithnin, A. M., Yahya, W. J., & Yuzir, M. A. (2021). A brief review on biochemical oxygen demand (BOD) treatment methods for palm oil mill effluents (POME). *Environmental Technology & Innovation*, *21*, 101258.
- Loughery, J. R., Coelho, G. M., Lee, K., & Jourdan, B. (2023). Setting the stage to advance oil toxicity testing: Overview of knowledge gaps, and recommendations. *Aquatic Toxicology*, 106581.
- Lu, Z., Liu, W., Bao, M., Zhao, L., Sun, X., Lu, J., & Li, Y. (2021). Oil recovery from polymer-containing oil sludge in oilfield by thermochemical cleaning treatment. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *611*, 125887.
- Mamaghani, F. A. A., Salem, A., & Salem, S. (2022). Pilot plant study for management of toxic solid waste collected in landfill of spent lubricant oil refinery by conversion into zeolite packed bed via continuous extrusion and fusion techniques. *Process Safety and Environmental Protection*, *159*, 500-510.
- Mehr, M. R., Keshavarzi, B., Moore, F., Fooladivanda, S., Sorooshian, A., & Biester, H. (2020). Spatial distribution, environmental risk and sources of heavy metals and polycyclic aromatic hydrocarbons (PAHs) in surface sediments-northwest of Persian Gulf. *Continental Shelf Research*, *193*, 104036.
- Mengounou, G. M., Imano, A. M., Mayi, O. S., Beyeme, Y. A., Massako, C. B., & Nkouetcha, E. T. (2022). Biodegradability and ecotoxicity of bio-insulating oils in aqueous and soil environments in Douala, Cameroon. *Scientific African*, *18*, e01413.
- Menzies, J., Wilcox, A., Casteel, K., & McDonough, K. (2023). Water soluble polymer biodegradation evaluation using standard and experimental methods. *Science of The Total Environment*, *858*, 160006.
- Moses, K., Aliyu, A., Hamza, A., & Mohammed-Dabo, I. (2023). Recycling of waste lubricating oil: A review of the recycling technologies with a focus on catalytic cracking, techno-economic and life cycle assessments. *Journal of Environmental Chemical Engineering*, *11*(6), 111273.
- Nelyubov, D. V., Fakhrutdinov, M. I., Sarkisyan, A. A., Sharin, E. A., Ershov, M. A., Makhova, U. A., & Tikhomirova, E. O. (2023). New prospects of waste involvement in marine fuel oil: Evolution of composition and requirements for fuel with sulfur content up to 0.5%. *Journal of Marine Science and Engineering*, *11*(7), 1460.
- Northrop, E., Biru, H., Lima, S., Bouye, M., & Song, R. (2016). Examining the alignment between the intended nationally determined contributions and sustainable development goals. *World Resources Institute*.
- Nowak, P., Kucharska, K., & Kamiński, M. (2019). Ecological and health effects of lubricant oils emitted into the environment. *International Journal of Environmental Research and Public Health*, *16*(16), 3002.
- Nteke, M., Ekpo, M., Ndubuisi-Nnaji, U., Mbong, E., & Ntino, E. (2023). Influence of spent lubricating oil spiked compost on microbial counts and hydrocarbon degradation rate in soils. *Biotechnology Journal International*, *27*(4), 15-25.
- Oladimeji, T. E., Sonibare, J. A., Omoleye, J. A., Emetere, M. E., & Elehinafe, F. B. (2018). A review on treatment methods of used lubricating oil. *International Journal of Civil Engineering and Technology*, *9*(12), 506-514.

- Oliveira, L. M., Saleem, J., Bazargan, A., Duarte, J. L. d. S., McKay, G., & Meili, L. (2021). Sorption as a rapidly response for oil spill accidents: A material and mechanistic approach. *Journal of Hazardous Materials*, 407, 124842.
- Osra, F. A., Ciner, M. N., & Özcan, H. K. (2024). Integrated management of hazardous waste from vehicles in Makkah City, Saudi Arabia. *Arabian Journal of Geosciences*, 17(1), 1-10.
- Ouyang, P., & Zhang, X.-M. (2019). Research on the regeneration of waste lubricating oil based on flyash adsorption. *Science of Advanced Materials*, 11(2), 196-202.
- Pabsetti, P., Murty, R., Bhoje, J., Mathew, S., Rahul, K., & Feroskhan, M. (2023). *Performance of hydraulic oils and its additives in fluid power system: A review*. Paper presented at the IOP Conference Series: Earth and Environmental Science.
- Pinheiro, C. T., Quina, M. J., & Gando-Ferreira, L. M. (2021). Management of waste lubricant oil in Europe: A circular economy approach. *Critical Reviews in Environmental Science and Technology*, 51(18), 2015-2050.
- Poursat, B. A., van Spanning, R. J., Braster, M., Helmus, R., de Voogt, P., & Parsons, J. R. (2020). Long-term exposure of activated sludge in chemostats leads to changes in microbial communities composition and enhanced biodegradation of 4-chloroaniline and N-methylpiperazine. *Chemosphere*, 242, 125102.
- Qureshi, J. A., Shamsi, A. F., & Arif, F. (2022). Pakistan state oil: Multidimensional strategic issues of a market leader. *Emerald Emerging Markets Case Studies*, 12(1), 1-27.
- Raju, M. N., Leo, R., Herminia, S. S., Morán, R. E. B., Venkateswarlu, K., & Laura, S. (2017). Biodegradation of diesel, crude oil and spent lubricating oil by soil isolates of *Bacillus* spp. *Bulletin of Environmental Contamination and Toxicology*, 98, 698-705.
- Revuru, R. S., & Posinasetti, N. R. (2020). *Performance and life cycle analysis of soybean oil-based minimum quantity lubrication in machining of Ti6Al4V*. Paper presented at the Advances in Applied Mechanical Engineering: Select Proceedings of ICAMER 2019.
- Sánchez-Alvarracín, C., Criollo-Bravo, J., Albuja-Arias, D., García-Ávila, F., & Pelaez-Samaniego, M. R. (2021). Characterisation of used lubricant oil in a Latin-American medium-size city and analysis of options for its regeneration. *Recycling*, 6(1), 10.
- Sarkar, S., Datta, D., Deepak, K., Mondal, B. K., & Das, B. (2023). Comprehensive investigation of various re-refining technologies of used lubricating oil: A review. *Journal of Material Cycles and Waste Management*, 1-31.
- Shah, R., Woydt, M., & Zhang, S. (2021). The economic and environmental significance of sustainable lubricants. *Lubricants*, 9(2), 21.
- Shakir, M. A., Ahmad, M. I., Ramli, N. K., Yusup, Y., Alosaimi, A. M., Alorfi, H. S., & Rafatullah, M. (2023). Review on the influencing factors towards improving properties of composite insulation panel made of natural waste fibers for building application. *Journal of Industrial Textiles*, 53, 1-33.
- Shakir, M. A., Ahmad, M. I., Yusup, Y., & Rafatullah, M. (2023a). From waste to wealth: Converting rubber wood sawdust into green mycelium-based composite. *Biomass Conversion and Biorefinery*. <https://doi.org/10.1007/s13399-023-05113-9>
- Shakir, M. A., Ahmad, M. I., Yusup, Y., Wabaidur, S. M., Siddiqui, M. R., Alam, M., & Rafatullah, M. (2023b). Effect of fibrillation degree of empty fruit bunch fiber on

- sandwich composite incorporate with spent mushroom substrate. *Journal of Industrial Textiles*, 53, 15280837231153661.
- Shakir, M. A., Ahmad, M. I., Yusup, Y., Wabaidur, S. M., Siddiqui, M. R., Alam, M., & Rafatullah, M. (2023c). Sandwich composite panel from spent mushroom substrate fiber and empty fruit bunch fiber for potential green thermal insulation. *Buildings*, 13(1), 224.
- Shakir, M. A., Azahari, B., Salehabadi, A., Yusup, Y., Yhaya, M. F., & Ahmad, M. I. (2020). Structural, thermal, and mechanical properties of spent mushroom substrate (SMS) and rubberwood sawdust (rws) binderless particleboards. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 75(2), 113-124.
- Singh, H., Bhardwaj, N., Arya, S. K., & Khatri, M. (2020). Environmental impacts of oil spills and their remediation by magnetic nanomaterials. *Environmental Nanotechnology, Monitoring & Management*, 14, 100305.
- Sivanandhini, T., Unnikrishnan, S., & Gedam, V. V. (2021). Planning and optimisation framework for lubricant supply chain with a focus on spent oil-A circular economy approach. *International Journal of Sustainable Engineering*, 14(3), 368-377.
- Strotmann, U., Thouand, G., Pagga, U., Gartiser, S., & Heipieper, H. J. (2023). Toward the future of OECD/ISO biodegradability testing-new approaches and developments. *Applied Microbiology and Biotechnology*, 107(7-8), 2073-2095.
- Su, G., Ong, H. C., Mofijur, M., Mahlia, T. I., & Ok, Y. S. (2022). Pyrolysis of waste oils for the production of biofuels: A critical review. *Journal of Hazardous Materials*, 424, 127396.
- Suk, M., Lorenz, S., & Kümmerer, K. (2023). Identification of environmentally biodegradable scaffolds for the benign design of quinolones and related substances. *Sustainable Chemistry and Pharmacy*, 31, 100947.
- Takekoshi, S., Takano, K., Matoba, Y., Sato, M., & Tachibana, A. (2021). Investigation of OECD 301F ready biodegradability test to evaluate chemical fate in a realistic environment. *Journal of Pesticide Science*, 46(2), 143-151.
- Takeshita, R., Bursian, S. J., Colegrove, K. M., Collier, T. K., Deak, K., Dean, K. M., & Esbaugh, A. J. (2021). A review of the toxicology of oil in vertebrates: What we have learned following the Deepwater Horizon oil spill. *Journal of Toxicology and Environmental Health, Part B*, 24(8), 355-394.
- Tannock, S. (2020). The oil industry in our schools: From Petro Pete to science capital in the age of climate crisis. *Environmental Education Research*, 26(4), 474-490.
- Ukalska-Jaruga, A., & Smreczak, B. (2020). The impact of organic matter on Polycyclic Aromatic Hydrocarbon (PAH) availability and persistence in soils. *Molecules*, 25(11), 2470.
- Wang, B., Duan, P.-G., Xu, Y.-P., Wang, F., Shi, X.-L., Fu, J., & Lu, X.-Y. (2017). Co-hydrotreating of algae and used engine oil for the direct production of gasoline and diesel fuels or blending components. *Energy*, 136, 151-162.
- Wang, C., He, S., Zou, Y., Liu, J., Zhao, R., Yin, X., & Li, Y. (2020). Quantitative evaluation of in-situ bioremediation of compound pollution of oil and heavy metal in sediments from the Bohai Sea, China. *Marine Pollution Bulletin*, 150, 110787.
- Wojcieszek, M., Kroyan, Y., Kaario, O., & Larmi, M. (2023). Prediction of heavy-duty engine performance for renewable fuels based on fuel property characteristics. *Energy*, 285, 129494.
- Wu, B., Guo, S., & Wang, J. (2021). Assessment of the human health risk of polycyclic aromatic hydrocarbons in soils from areas

- of crude oil exploitation. *Environmental Research*, 193, 110617.
- Xu, L., Yu, J., Wan, G., & Sun, L. (2021). Emission characteristics and source identification of Polycyclic Aromatic Hydrocarbons (PAHs) from used mineral oil combustion. *Fuel*, 304, 121357.
- Yaseen, M., Ullah, M., Subhan, S., Ahmad, W., Subhan, F., & Shakir, M. (2021). Recovery and characterisation of useful benzene derivatives from spent engine oil through solvent extraction. *Chemical Engineering Research and Design*, 175, 51-60.
- Zgheib, N., & Takache, H. (2021). Recycling of used lubricating oil by solvent extraction: Experimental results, Aspen Plus simulation and feasibility study. *Clean Technologies and Environmental Policy*, 23, 65-76.