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REVIEW PAPER

Ecotoxicological effects, human and animal health risks of pollution and exposure to waste engine oils: a review

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Abstract Waste engine oils are hazardous waste oils originating from the transportation sector and industrial heavy-duty machinery operations. Improper handling, disposal, and miscellaneous misuses cause significant air, soil, sediments, surface water, and groundwater pollution. Occupational exposure by prolonged and repeated contact poses direct or indirect health risks, resulting in short-term (acute) or long-term (chronic) toxicities. Soil pollution causes geotoxicity by disrupting the biocenosis and physicochemical properties of the soil, and phytotoxicity by impairing plant growth, physiology and metabolism. Surface water pollution impacts aquatic ecosystems and biodiversity. Air pollution from incineration causes the release of greenhouse gases creating global warming, noxious gases and particulate matter eliciting pulmonary disorders. The toxicity of waste engine oil is due to the total petroleum hydrocarbons (TPH) composition, including polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, ethylbenzene, xylene (BTEX), polychlorinated biphenyls (PCBs) congeners, organometallic compounds, and toxic chemical additives. The paper aims to provide a comprehensive overview of the ecotoxicological effects, human and animal health toxicology and exposure to waste engine oils. It highlights the properties and functions of engine oil and describes waste engine oil generation, disposal and recycling. It provides intensive evaluations and descriptions of the toxicokinetics, metabolism, routes of exposure and toxicosis in human and animal studies based on toxicological, epidemiological and experimental studies. It emphasises the preventive measures in occupational exposure and recommends risk-based remediation techniques to mitigate environmental pollution. The review will assist in understanding the potential risks of waste engine oil with significant consideration of the public health benefits and importance.

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Introduction

Waste engine oils form one of the greatest sources of environmental pollution and one of the largest contributors to hazardous wastes globally (Frassin, 2024). Waste engine oils are primarily generated in transportation sectors from routine oil changes during maintenance and servicing operations from vehicles, aircraft, trains, and ships (Anisuzzanan et al., 2021; Patel and Shadangi, 2020; Zitte et al., 2016) and from the industrial sectors during periodic maintenance and service of heavy-duty industrial machinery operating with pressurised hydraulic power systems such as those in mining, drilling, and metalworks (Habibu, 2017; Olugboji & Ogunwole, 2008; Riyanto et al., 2018). The high volume of waste engine oils generated from the various operations correlates with the increase in global automotive, marine, aviation, railway, machinery, mining, and drilling operations (Moses et al., 2023). This high volume of waste engine oil forms about 10% of hazardous wastes introduced into the environment (Bonomi et al., 2022).

In the engine and machinery systems, during operations, the engine oils lubricate the internal combustion engines in automotive systems and transfer power to hydraulic systems in industrial machinery. After prolonged usage, the engine oils gradually become unsuitable for their original purpose due to the presence of contamination and impurities and lose their original quality and properties (Chen et al., 2023; Hegazi et al., 2017; Szyszlak-Bargłowicz et al., 2021). Thus, the engine oils must be periodically evacuated and collected as waste engine oils after the engine oils have outlived their usefulness, become unsuitable, and underperform in their functional systems (Pelitli et al., 2017; Vural, 2020).

Engine oil global market

The high demand for engine oils and the high supply to the target industries correspond with an increase in the global engine oil market, which is estimated at 157.6 billion dollars (Mishra et al., 2021). The global market is projected to supply 41.7 million metric tonnes (MMT) with a rise of 2.3% per year to reach $182.6 billion in 2025 (Market Analysis Report, 2020). The market share is projected to continue to rise at a compound annual growth rate (CAGR) between 3 and 4% in revenue from 2023 to 2030 (Market Analysis Report, 2020; Moses et al., 2023). In terms of production size, the market size is estimated at 22.70 billion litres in 2024., and expected to reach 26.89 billion litres by 2029, at a CAGR of 3.45% during the forecast period from 2024 to 2029 (Mordor Intelligence, 2024).

The global engine oil market is segmented based on end-user industries and geographic regions. The end-user industries comprise power generation, automotive and other transportation, heavy equipment, metallurgy and metalworking, chemical manufacturing, and other end-user industries (Mordor Intelligence, 2024). However, in terms of regional consumption, demand, and supply, the Asia Pacific region represents the highest share of 43% of global consumption and demand due to the rise in population density, and the growing demand for automotive production and power generation industries. Europe represents 19%, North America 18%, South America 9%, Africa 6%, and the Middle East 5% (Pinheiro et al., 2021).

Consumption and generation of waste oils

Out of the global consumption, demand, and supply of engine oils, the annual generation is approximately 5.2 billion gallons per year worldwide. Out of the estimated volume generated, more than 2.5 billion gallons are recovered for reuse and recycling (United States Department of Energy, 2020a, 2020b). Less than 45% is available for recycling, and the remaining 55% ends up in miscellaneous uses, misuse, and indiscriminate disposal into the environment (Mishra et al., 2021; Pelitli et al., 2017). In the United States, the annual local consumption of engine oil is about 2.47 billion gallons. Out of the consumed volume, about 1.3 billion gallons are collected each year, of which 14% is recycled and re-refined, 11% is re-used as space-heater fuel, and 75% is marketed as an ancillary fuel oil for miscellaneous industrial applications (Boughton & Horvath, 2004; United States Department of Energy, 2020b). In the United Kingdom, the estimated consumption of engine oil is about 212,000 metric tonnes, of which 60,500 metric tonnes (29%) are recycled; the remaining 71% is reused in power station boilers, roadstone coating, and cement kilns (Norris et al., 2006). In Japan, 194,000 metric tonnes are consumed, while 98,000 metric tonnes (51%) of waste engine oil are generated, from which 83,000 metric tonnes (47%) are recycled (Yu et al., 2012).

The high volume of waste engine oils generated from the various sectors significantly impacts the environment and the economy, making adequate management of waste engine oils essential for society (Frassin, 2024; Katiyar & Husain, 2010; Shahbaz et al., 2023). Figure 1a illustrates the global estimate for the generation of waste engine oils from automotive and industrial machinery operations, indicating the automotive industry with the highest yield of about 55–60%. The high amount of waste engine oil generated makes the transportation sector, industrial operations, and heavy machinery operations major contributors to hazardous pollution and environmental degradation (Aminzadegan et al., 2022; Rosli, 2006).

Waste engine oil storage, spillage and pollution

In developing countries, the generation of waste engine oils has become a growing concern, particularly in most urban and rural areas, due to indiscriminate disposal and inadequate recycling and reuse (Bekibele et al., 2022). Disposal becomes a significant environmental issue, resulting in indiscriminate discharge on the surface soil, drainages, sewers, and

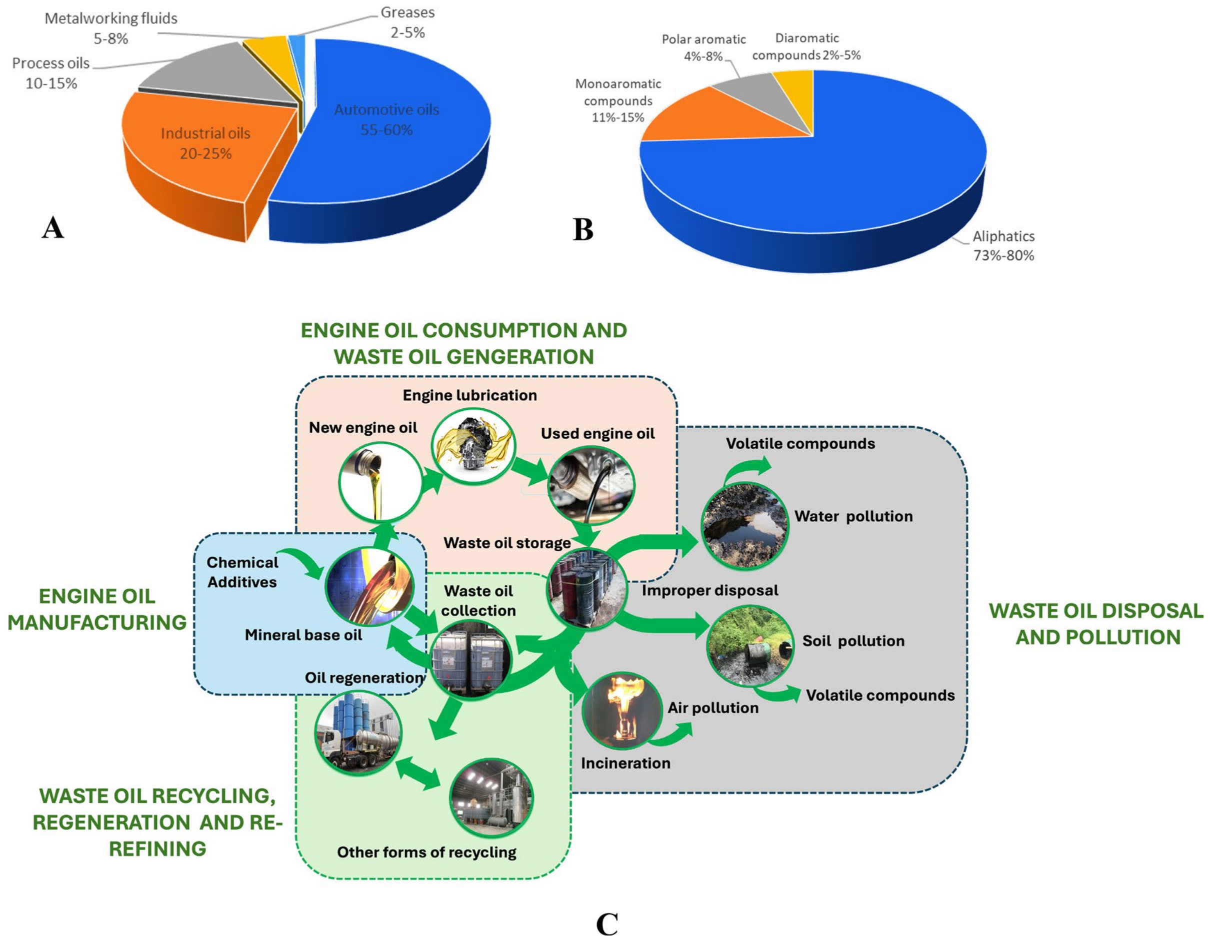


Fig. 1 **a** Generation of waste engine oils (Collins et al., 2017), **b** chemical composition of mineral base oil (*Source*: Papke, 2013), **c** life cycle of engine oil from the manufacturing, consumption, disposal, recycling and environmental impact (*Source*: Ossai, 2023)

canals, causing contamination of the subsoil, surface water, sediments, and groundwater (Kajdas, 2014; Singh et al., 2009; Wu et al., 2017). The engine oil end-user industries generating the waste engine oils are required by legal regulations and guidelines to store waste oils in tanks or containers and maintain the tanks and containers in good shape, ensuring that the containers are free from leaks and spills. The tanks and containers are supposed to be stored above ground and labelled appropriately as "waste oil" (Urs, 1992). But sporadic spills, overfilled waste oil drums, and containers are familiar sights, creating environmental problems in some vehicle service centres and heavy-duty machinery facilities where inadequate and poor storage, handling, transportation, disposal facilities, and management procedures are common (Bulai et al., 2021). As a result of spills, leakages, and illegal disposal, the environment becomes constantly bombarded and overwhelmed with high doses of TPH including polycyclic aromatic hydrocarbons (PAHs) and heavy metals from hazardous waste engine oils (Sakari et al., 2010).

The effects of pollution by waste engine oils in the environment are usually widespread due to many physicochemical properties such as the amount, and state of the contaminants; biogeochemical processes including soil properties and weathering processes; and environmental conditions such as pH, temperature salinity, electrical conductivity, turbidity, as well as soil and water interaction (Nwogu et al., 2015; Wang et al. 2020). The pollution affects the ecosystem by disrupting the trophic interaction, the natural community structure, and the population dynamics of the soil biocenoses and microbiota (Burgess, 2013; Souza et al., 2014). Pollution may enter the food chain through nutrition by ingesting contaminated food sources and constitute a direct or indirect health risk to humans and animals (Peivasteh-roudsari et al., 2023; Sajna et al., 2015). Due to the pollutive nature of waste engine oil and the propensity to spread quickly in the environment, 1 L of waste engine oil can contaminate up to 1 million litres of surface water and render the water unfit for human consumption (Zitte et al., 2016). Also, 5 L of waste engine oil can cover the surface of a small lake to cause BOD depletion, the formation of oil films, and the death of aquatic life and benthic organisms through toxicity effects (United States Environmental Protection Agency (USEPA), 1996). In addition, about 50–100 mg/L of waste engine oil can contaminate and foul the sewage treatment systems if disposed of in drainage and sewer systems (Hamad et al., 2004). One litre of waste engine oils can pollute about 3784 m^2 of farmland and render the soil infertile and unproductive for agricultural crop production (Gaur et al., 2023).

Compared to petroleum crude oil, which has been extensively studied, there is scant information, limited clinical data, and epidemiological studies specifically on the toxicological effects of waste engine oils, especially the toxicology on human and animal health. Against this background, the review comprehensively describes the ecotoxicological effects, and human and animal health risks associated with pollution and exposure to waste engine oils. It highlights the characteristic roles and functions with the description of manufacture, chemical composition and properties of engine oils. It describes the disposal methods, ecotoxicological effects with toxicokinetics and metabolism in humans and animals. It contains detailed information on toxicosis and toxicological effects as well as toxicity assessments based on toxicological and epidemiological studies. It recommends preventive measures for occupational exposure and emphasises the recycling and regeneration of waste engine oils with risk-based remediation techniques for soil remediation. However, unlike many other hazardous petroleum chemical products that have been thoroughly researched and studied, there are few systematic studies done on the various toxicological effects associated with exposure to waste engine oils. As a result, gathering the accessible information available is essential to comprehend the ecotoxicological impacts of pollution and exposure to waste engine oils while also considering the benefits and relevance for public health.

Roles and functions of engine oils

The engine oils generally serve as hydrodynamic fluids for the lubrication of the moving parts in internal combustion engines and heavy-duty machinery equipment to protect and prevent robbing, friction, wearing, and tearing and to accord smooth and frictionless motion in the engine and machinery systems (Oladimeji et al., 2018; Rațiu et al., 2022; Wang et al., 2024). The engine oils also help to clean the engine systems from sludges, neutralise acids created by the by-products of internal engine combustions, and prevent rust, corrosion, dirt, water, and cooling of engine parts (Armioni et al., 2020; Rațiu et al., 2022). In machinery systems, the engine oils minimise oxidation, deliver insulation properties in transformer applications, and convey mechanical power in pressurised hydraulic fluid power systems (Ahmed & Nassar, 2013).

Manufacture, composition and properties of engine oil

Engine oils are produced as either synthetic, semi-synthetic, or non-synthetic oils and contain highly refined mineral-based oil molecules mixed with various organic compounds (Halderman, 2012; Papke, 2013). The mineral base oils are produced from naturally occurring petroleum feedstocks that undergo fractional distillation at high temperatures of 420 °C (788 °F), high vacuum and atmospheric pressure to obtain vacuum distillates and residual fractions that are further refined into mineral base oils after undergoing series of refining processes involving distillation, de-asphalting, solvent extraction, solvent dewaxing, hydro-finishing, and conversion (Suthers et al., 1986). The mineral base oils are composed of non-aqueous and hydrophobic components made up of low molecular weight aliphatic (C_5–C_{14}) and high molecular weight aliphatic (C_{15}–C_{50}) saturated petroleum hydrocarbon compounds or paraffin, including long-chain and branched-chain alkanes (*n*-alkanes) (Adeleye et al., 2018; Bouchiat et al., 2023; Speight & Exall, 2014). These constituents form the total petroleum hydrocarbons (TPH) in their composition. The TPH describes a broad family of several chemical compounds found in mineral-base oils (Muneeswari et al., 2022). The TPH is commonly used as a measure of oil contamination in the environment and as a forensic source investigation identifier (Society of Brownfield Risk Assessment, 2013).

The chemical composition of the mineral base oil is illustrated in Fig. 1b. The mineral base oil contains 73–80% aliphatic hydrocarbons, 11–15% monoaromatics, 4–8% polyaromatics, and 2–8% diaromatics and 20–30% of several chemical additives by volume in the finished product (Katiyar & Husain, 2010; Lee et al., 2022; Speight & Exall, 2014). Several types of lubricating oils are used in the transportation sector for the operation and maintenance of vehicles which include motor engine oils, automatic and manual transmission oils, differential gear oils, axle oils, and hydraulic brake oils. Many types of mechanical oils are used in high-performance machinery and heavy-duty equipment including process oils, heat transfer oils, compressor oils, dielectric fluids, transformer oils, industrial oils, ball-bearing lubricants, metal cutting oils, and greases. Others include marine oil and aviation engine oil (Osman et al., 2018; Udonne, 2011).

Chemical additives

A wide range of chemical additives is used in manufacturing engine oils at varying concentrations ranging from a few parts per million to about 20% to modify the physical and chemical characteristics of the mineral base oils. These chemical additives include (1) surface-active adsorbing additives comprising rust and corrosion inhibitors, friction conditioners, anti-wear additives and high-pressure additives (Gatto, 2017), (2) interfacial surface-active additives including anti-foaming agents, emulsifiers and demulsifier agents (Kang et al., 2018), (3) physically bulk active additives including viscosity index conditioners, pour point pacifiers (depressants and dispersants) (Abdel Azim et al., 2009), (4) chemical bulk active additives including antioxidants and detergents (Gatto, 2017), (5) polychlorinated biphenyl (PCB) congeners (Pelitli et al., 2017), (6) chlorodibenzofurans (CDFs) (Narang et al., 1989), (7) organometallic compounds of chromium (Cr), nickel (Ni), molybdenum (Mo), lead (Pb), zinc (Zn), copper (Cu), and cadmium (Cd) (Gidney et al., 2010), including zinc diaryl, molybdenum disulphide, and zinc dialkyl dithiophosphate (ZDDP) or dialkyl dithiophosphate (ZDTP) (Suarez et al., 2010), tricresyl phosphates, magnesium, sodium, calcium sulphonates, and calcium alkyl phenates (Stout et al., 2018), methyl *tert*-butyl ether (MTBE) and tertiary amyl methyl ether (TAME) (Baker et al., 2002; Topgül, 2015). These chemical additives are added to improve the quality and achieve special performance and efficiency in the lubrication systems of automotive engines and machinery (Halderman, 2012; Toebacke et al., 2014). The chemical additives also help provide maximum engine and machinery systems protection under extreme temperature, pressure, speed, and operating conditions (Ahmed & Nassar, 2013; Pelitli et al., 2017; Sánchez-Alvarracín et al., 2021), and provide the performance requirements of specific applications (Suthers et al., 1986). Table 1 summarises the chemical composition, contaminants, chemical additives, and toxic heavy metals in the mineral base oil and waste engine oils.

Toxic heavy metals

In terms of toxicity, the toxic heavy metal contents increase in the internal combustion engine systems. The concentrations increase during usage, time,

Table 1 Chemical composition, contaminants, additives and heavy metals in waste engine oil

Mineral base oil from crude oil	
Contaminants	
Polycyclic aromatic hydrocarbons (PAH)	9-Phenanthrene methanol
Anthracene	Chlorinated paraffins
Benzo[*a*]anthracene	Formaldehyde/formalin
Benzo[*a*]pyrene	Nitrosamines
Benzo[*b*]fluoranthene	*N*-nitrosodimethylamine
Benzo[*k*]fluoranthene	Dibenzo[*a*,*h*]anthracene
Chrysene	Indeno[1,2,3-*cd*]pyrene
Fluoranthrene	*N*-nitrosodiethylamine
Perylene	*N*-nitrosodibutylamine
Pyrene	*N*-nitrosodibutylamine
Phenanthrenes	*N*-nitrosodiethanolamine
Triphenylene	N-nitrosomorpholine
BTEX	
Benzene	Polychlorinated biphenyl (PCB) congeners
Toluene	Chlorodibenzofurans (CDFs)
Ethylbenzene	
Xylene	
Additives	
Aryl dialkyl phosphates	Polybutene
Dithiophosphates/zinc dialkyl	Silicome polymers
Di-*tert*-butyl-para-cresol	Sulphonates
Long chain aliphatics	Sulphur
Methacrylate polymers	Thiazole
2-Naphthol	Thiophenes/
N-phenyl-2-naphthylamine	dibenzothiophene
Phenates/calcium alkyl	Triazine
Phosphorus	Triazole
	Tricresyl phosphates
Heavy metals	
Arsenic (As)	Lead (Pb)
Cadmium (Cd)	Manganese (Mn)
Chromium (Cr)	Mercury (Hg)
Copper (Cu)	Molybdenum (Mo)
Hexavalent chromium (CrVI)	Nickel (Ni)
Iron (Fe)	Zinc (Zn)

and amount (Szyszlak-Barglowicz et al., 2021). The increase depends on the internal combustion engine fuel type and mechanical conditions. The toxic heavy metals such as lead (Pb) can increase up to 13,000 µg/g; zinc (Zn) 2500 µg/g; copper (Cu) 50 µg/g; chromium (Cr) 20 µg/g; nickel (Ni) 5 µg/g; and cadmium (Cd) 0.1 µg/g. Other metals in significant amounts in the composition include calcium (Ca) at 4000 µg/g; magnesium (Mg) at 1000 µg/g; and sodium (Na) at 600 µg/g (Vazquez-Duhalt, 1989). Table 2 compares the concentrations of heavy metals in the waste engine oils generated from petrol engine vehicles, diesel engine vehicles, and local petrol stations. The toxic heavy metals in the combustion effluents of petrol engines are higher than the amount generated from diesel engines due to the difference in the combustion processes and the fuel composition (Hall et al., 1983).

Polycyclic aromatic hydrocarbons (PAHs)

The compounds of high and significant concentrations in engine oils are the polycyclic aromatic hydrocarbons (PAHs) and their analogues (Scheepers & Bos, 1992), benzene, ethylbenzene, toluene, and xylene (BTEX) (Baker et al., 2002). Nevertheless, the PAH content in new engine oils is generally relatively low but increases with use and duration of operation (Lu & Kaplan, 2007). In other words, the PAHs in waste engine oils are higher in concentration than those of the new engine oils (Van Donkelaar, 1990). In contrast, new engine oils are relatively non-toxic, while waste engine oils are toxic due to the accumulation and increase of toxic hazardous substances during prolonged usage in the engines and machinery systems (Beck et al., 1984).

The waste engine oil from vehicles and heavy engine systems in operation can contain up to 670 times more PAHs than the new engine oil but varies according to the internal combustion engines and heavy-duty machinery (Cvengros et al., 2017). Table 3 compares the PAH composition in waste engine oils derived from petrol and diesel engine vehicles. The PAH content in waste engine oils from diesel vehicles is three times higher than that of the new engine oil, while for diesel buses, it is six times higher, and for diesel cars, it can be 30 times higher than that of the new engine oil. The PAH concentration in waste engine oils from petrol vehicles can be 180 times higher than the new engine oil. The PAHs escape the engine systems to accumulate in the environment through different means, such as particulate matter from exhaust emissions during operation and oil leaks from the engine (Cvengros et al., 2017).

Engine oil contaminants

Fresh or new engine oils are usually light in colour; some are amber to yellowish but subsequently darken or change to brownish-black after prolonged usage in the engine systems. The colour change is due to oxidation, nitration, sulphation, and contamination in the internal combustion chamber with fuel, carbon, water, antifreeze, soot, and metallic particles from the moving components of the engines and machinery systems (Hönig et al., 2020). These substances increasingly and continuously accumulate during engine operation, contaminating the engine oils (Rațiu et al., 2021). The extent of the chemical change and the accumulation of contaminants in the engine oils increases with prolonged usage in internal combustion engines, causing changes in the oil viscosity and deterioration in the chemical composition of the

Table 2 Heavy metal concentration in waste engine oils generated from petrol engine vehicles and diesel engine vehicles. *Source*: Vazquez-Duhalt (1989)

Metals	Waste engine oils from			
	Petrol engine vehicles (µg/g)	Diesel engine vehicles (µg/g)	Local petrol stations (µg/g)	Waste engine oil (µg/g)
Pb	7500	75	1075.0–3950.0	7097.0–13885
Zn	1500	1300	265.0–1128.5	1061–2500
Cu	17	18	27.5–40.0	28.0–56.0
Cr	21	3	0.1–1.0	10.5–24.0
Ni	Below detection	Below detection	0.6–8.5	1.2–5.0
Cd	Below detection	Below detection	0.1–0.5	0.1

Table 3 PAH concentration in waste engine oils derived from petrol and diesel engine vehicles

Polycyclic aromatic hydrocarbons	New engine oil (μg/g)	Waste engine oils from			
		Petrol vehicles (μg/g)	Diesel vehicles (μg/g)	Diesel lorries (μg/g)	Diesel buses (μg/g)
Anthracene	0.002–0.030	1.6–10.8	0.5–4.4	0.02.0.12	0.03–016
Benzo[*a*]pyrene	0.008–0.266	5.2–35.1	0.7–11.9	0.13–0.60	0.07–0.55
Benzo[*e*]pyrene	0.030–0.402	6.4–48.9	1.3–10.7	0.23–1.10	0.29–1.04
Benzo[*ghi*]pyrene	0.010–0.139	4.4–85.2	2.1–16.0	0.20–0.78	0.26–0.65
Benzo[*b*]naphtho[2,1-*d*] thohene	0.097–9.430	ND	0.7–4.3	0.78–6.20	1.60–4.80
Benzofluoranthene [*b* + *k* + *k*]	0.013–0.234	5.7–44.3	1.8–16.8	0.26–1.30	0.37–1.20
Chrysene + triphenylene	0.182–11.90	8.7–74.0	5.1–42.8	1.60–6.10	1.90–8.00
Coronene	0.001–0.016	2.8–29.4	0.1–6.4	0.10–0.13	0.00–0.08
Fluoranthene	0.008–2.750	3.4–109.0	1.3–58.9	0.18–2.90	0.40–2.70
Indeno[1,2,3-*cd*]pyrene	0.001–0020	2.1–12.5	0.8–9.0	0.06–0.28	0.07–0.25
Perylene	0.007–0.224	1.9–10.0	0.4–2.7	0.11–0.35	0.04–0.29
Pyrene	0.039–6.530	5.7–326	1.4–78.0	0.33–6.40	0.09–4.90

ND not detected

mineral base oils (Decote et al., 2023). The degradation or deterioration of the chemical composition also results from extreme temperatures, friction, nitration, oxidation, the breaking of chemical component polymers, and the decomposition of organometallics (Abbas, 2023; Bekibele et al., 2022). The deterioration significantly changes the chemical properties of the engine oil, reducing the oil quality such as viscosity, temperature stability, oxidation stability and performance and making the engine oil difficult to meet the requirements with optimum parameters (Armioni et al., 2020; Rațiu et al., 2021).

In engine systems, oxidation creates soluble acidic compounds (carboxylic acids) and semi-insoluble substances, causing the sulphur and nitrogen oxides to combine with water to form acids such as H_2SO_4, and H_nNO_x, which result in corrosion of the moving parts (Shinde & Bewoor, 2020). Partial oxidation products in fuel combustion contribute to the forming of carbon deposits as soots. The carbon particles cause the parts to wear through abrasion, adhesion, erosion, corrosion, and fatigue. The exhaust emissions from the combustion chamber contain sulphur, nitrogen oxides, water, carbon particles, and products of partial oxidation. (Armioni, et al., 2020; Rațiu et al., 2021). The fuel passes into the oil bath, leading to oil contamination, which reduces the oil life and severely limits the oil reusability (Sánchez-Alvarracín et al., 2021), shortens the engine systems and equipment operational life, and causes premature system failures (Speight & Exall, 2014). Continuous or protracted use of engine oils in automotive engine and equipment systems leads to a steady decline in oil performance and system operation. Thus, engine oils have a life span, after which the dirty oils must be drained or evacuated and replaced with new engine oil to enhance the system's performance and efficiency (Osman et al., 2018; Udonne, 2011). Figure 1c. illustrates the life cycle of engine oil comprising the manufacturing, consumption, disposal, and recycling as well as the environmental impact of the disposal to the environment.

Waste engine oil disposal

Waste engine oils are contaminants of concern, with large amounts entering the ecosystem from water runoffs (Irwin et al., 1997), forming common sources of contamination in urban stormwater runoffs, rivers, streams, deep wells, and surface sediments (Müller et al., 2020). A considerable proportion of waste engine oils end up in the municipal sewage system, making the presence of toxic compounds in the water-soluble components of the sewage effluent of utmost importance (Hamad et al., 2004). Studies have indicated an elevated level of PAHs in the soil, surface water, and stormwater runoffs around residential, industrial, and commercial areas due to land contamination by waste engine oil (Jurries & Ratliff, 2013). Often, soil pollution occurs when a huge volume of waste engine oils evacuated from vehicles by individual "do-it-yourself" oil changers are dumped at the source, resulting in soil contamination. Backstreets and alleys are largely dumping grounds in some metropolitan areas, whereas, pits, fields, ditches, and drainages are typically used in rural communities and are possibly the most undesired and indiscriminate disposal method due to the lack of control over the environmental effects (Kajdas, 2014). The waste engine oils are unacceptable for landfilling and to avoid illegal disposal by dumping, waste engine oils must be collected separately, recycled, or repurposed for a variety of uses and applications and miscellaneous reuse practices that can prevent illegal disposal such as used for industrial ancillary fuels, incorporation for asphalt rejuvenation for road construction, surface road application for dust control, weed killer, pesticide carriers, wood preservatives, all-purpose cleaner, floating and form oil, secondary lubricant, and vehicle undercoating oil (Jwaida et al., 2024; Pelitli et al., 2017; Raţiu et al., 2022).

Due to the volume of waste engine oil generated from transportation and machinery operations, the choice of disposal method and the consequential effect on the environment must be considered. When disposed of as solid wastes, the waste oils can cause disposal problems due to their flashpoint, sediment, ash, nitrogen, heavy metals, and PAHs (Urs, 1992). Indiscriminate burning and uncontrolled incineration cause serious maintenance problems for the burners and additional cause health problems due to the release of heavy metals particulate matter in the exhaust gas, and large amounts of greenhouse gases such as carbon (iv) oxide (CO_2) and methane (CH_4), which result in global warming (Olivier & Peters, 2020). In addition, open burning of waste engine oils produces several hazardous and toxic substances such as furans, dioxins, oxides of nitrogen, sulphur, phosphorus, hydrochloric acid, and particulate matter causing air pollution (Pinheiro et al., 2021). The burning of 1 L of waste engine oils may cause the evolution of about 800 mg of Zn and 30 mg of Pb particulates into the environment (Boughton & Horvath, 2004) and about 2.52 kg/L of CO_2 (Carroll et al., 2011).

In rare circumstances, waste engine oils can be disposed of in a landfill by mixing them with sorbent materials such as cement, lime, fly ash, and soil as solidifying agents before depositing the solidified bulk in a permitted hazardous waste-secure landfill. This is the only environmentally acceptable method to landfill waste engine oils (Canadian Council of Ministers of the Environment (CCME), 1989). The recommended disposal practice for waste engine oil, if cannot be recycled, is incineration in a controlled hazardous waste incinerator with an air pollution control system to remove the particulate matter and neutralise acid gases such as HCL, NOx and SOx (Miruna, 2020) and disposal through deep well technology by injecting waste engine oils under high pressure into the geologic rock formations which have no potential to allow oil migration into water aquifers (Kanagamani et al., 2020). Landfarming, or land application, is an excellent but uncommon disposal method, but, under the right conditions, it can be degraded by land application (Ossai et al., 2022). However, this method has a long-term environmental effect, which may constrain the future use of the affected site for crop production (Canadian Council of Ministers of the Environment (CCME), 1989). Other disposal methods such as sewer discharge are discouraged and unacceptable as the methods do not adequately control the ecotoxicological effects (Canadian Council of Ministers of the Environment (CCME), 1989). The most common and unacceptable method of disposal of waste engine oil is illegal dumping, also known as “midnight” dumping, through disposal on land, in surface water, and in the air in unauthorised and unpermitted areas, affecting the ecosystems and endangering human and animal health (Kanagamani et al., 2020).

Disposal on land

Waste engine oils end up in the soil when disposed of illegally in an unauthorised area, leading to various environmental problems, ecological damage, and social disasters by affecting the surface soil, subsoil, and sometimes the groundwater, forming a plume of contamination that alters the soil’s physicochemical properties, reducing the soil porosity and permeability, limiting the air circulation through the soil matrix, slowing down the activities of the soil microorganisms, and reducing the absorption of nutrients by the plants (Santos, 2018).

When poured or discharged on land, waste engine oils contaminate the underlying soil, clogging the soil pores, and reducing soil permeability, aeration, and water infiltration (Nowak et al., 2020). Waste engine oils can permeate downward vertically through the soil matrix to create a vapour plume in the saturated zone in a terrestrial environment (Trulli et al., 2016). The oil migration along the direction of soil depth is influenced by gravity, and the plume diffusion movement occurs under the influence of capillary force, as the oil spreads laterally or sideways (Rivett et al., 2011). Under certain conditions, waste engine oils penetrate deeper into the soil, reaching the groundwater through infiltration and migration, and spread across the capillary zone near the water table. The expansion may become more extensive than that along the groundwater level and transverse along the direction of the groundwater flow (Chen, 2000).

After discharge on the soil surface, the migration ability may be weakened while the waste engine oils are absorbed and concentrated on the soil surface (Hu, 2020), where they undergo weathering processes such as adsorption to soil and organic matter, volatilisation of the volatile components to the atmosphere (Esbaugh et al., 2016), and dissolution in water (Mishra & Kumar, 2015). The waste engine oil components that do not evaporate or volatilise remain in the soil for an extended period because they do not dissolve easily in water and are refractory to microbial biodegradation (Truskewycz et al., 2019).

In rains, the waste engine oil components accelerate under the infiltration water's deep penetration into the soil after an extended period of hydraulic gravity, diffusion, and mixing and slowly form a stable state (Yue and Jiang, 2006). The distribution of the waste engine oil components occurs by four different mechanisms, some dissolve in water, some sorb on solid organic matter, and some form soil gas and non-aqueous phase liquid (NAPL), and the components separate from the mix based on their physical and chemical parameters (Logeshwaran et al., 2018). Waste engine oils have a high affinity for organic materials and can readily adsorb organic particles and attach to soil particles and sediments due to their hydrophobicity characteristics (Clay, 2014). Organic matter promotes oil dissolution and plays a distributive role (Chu, 2006). The oil adsorption on the soil particles occurs through (physisorption) physical adsorption and (chemisorption) chemical adsorption (Yang et al., 2020). The force between the oil and the soil particles results from electrostatic attraction and intermolecular force (Hu, 2020).

If the groundwater is shallow, surface oil pollutants become more extensive, and the hydrodynamic drive increases. Figure 2a illustrates the biotic and abiotic processes that influence the environmental fate, transport, and distribution of waste engine oil in a terrestrial environment.

In terms of degradability and volatility, aliphatic hydrocarbon components are more biodegraded during weathering processes than aromatic hydrocarbon components (Nzila, 2018). Aliphatic hydrocarbons volatilise more than aromatic hydrocarbons because of their molecular nature (Mckee et al., 2015). When volatilisation becomes the primary weathering process, lower molecular weight aliphatic hydrocarbon components become the most dominant change and become the principal air pollutants (Maletic et al., 2013). Among the weathering processes, volatilisation is the most immediate and rapid, affecting the mass of the oil components (Lee et al., 2015). Volatilisation substitutes the residual non-aqueous phase liquid (NAPL), influencing the movement of the volatile components over time (Fine et al., 1997). The volatile components are conveyed to the gaseous phase by advection or diffusion, and the process depends upon the soil pore properties (Kristensen et al., 2010). The gaseous-phase mass transfer comprises volatilisation from the NAPL and partitioning in the gaseous-aqueous interphase (Balseiro-Romero et al., 2018).

Disposal in surface water

The presence of waste engine oil components in urban stormwater runoff originated from engine oil leaks accumulated on parking bays, garages, and roadway lanes, spills and leakages from storage tanks, and indiscriminate disposal in sewers and drainages (Pinheiro et al., 2021). During heavy traffic on motorways and highways, the stormwater runoff in heavy rains is usually contaminated with engine oils with TPH ranging from 0.20 to 24 mg/L (Van Donkelaar, 1990). The stormwater runoff mostly goes into the drainage and sewer systems. It sometimes bypasses

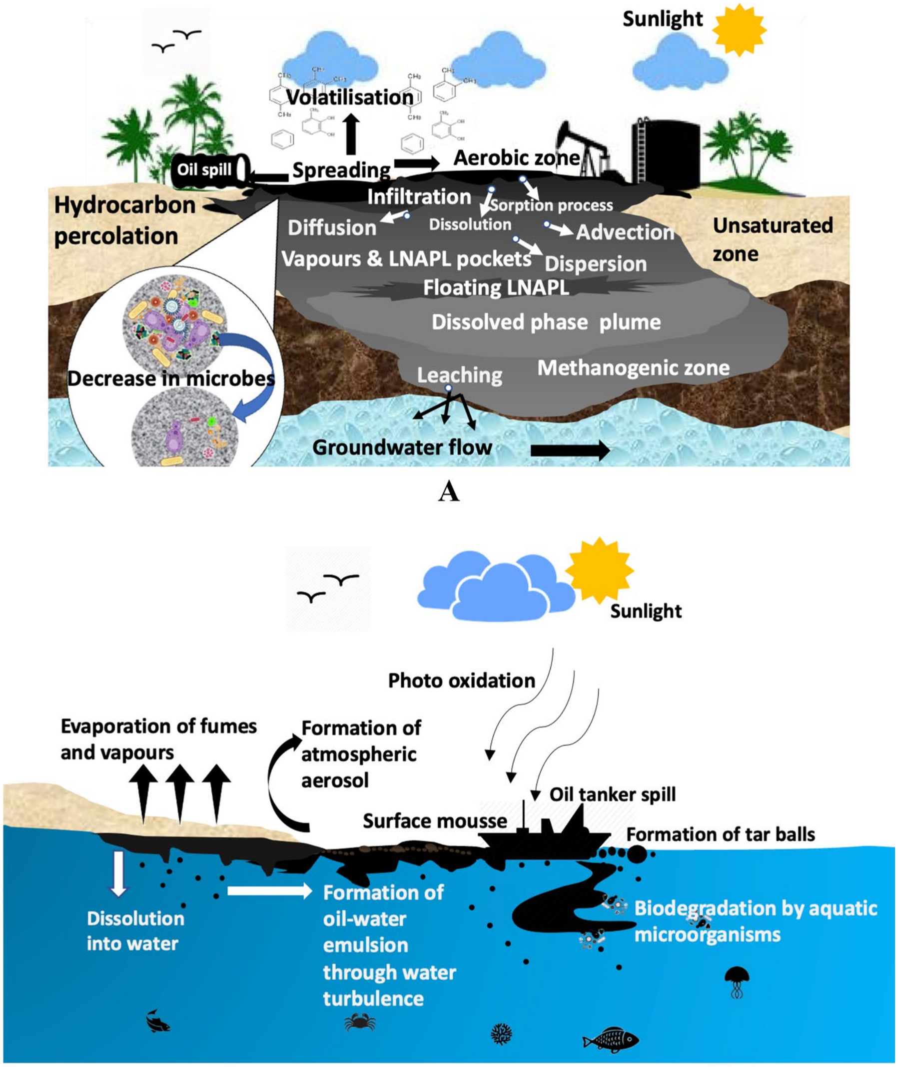


Fig. 2 **a** Biotic and abiotic processes that influence the environmental fate, transport, and distribution of oil by the discharge of waste engine oil in a terrestrial environment. **b** Transport and distribution of waste engine oil components in water environment (*Source*: Ossai et al., 2022)

the treatment facilities during heavy rainfalls to pollute the rivers and streams (Tanacredi, 1977), affecting aquatic life and benthic organisms by the formation of tiny films that reduce sunlight and oxygen penetration, resulting in the suffocation and death of aquatic organisms (Obinia & Afiukwaa, 2013).

In heavy water pollution, the waste engine oil floats on the water surface to form thin surface films and, under certain conditions, forms an emulsion, a viscous substance known as "mousse" (Rodriques & Totola, 2015). After heavy pollution of the water, waste engine oils undergo weathering processes involving physical, chemical, and biological processes comprising spreading, evaporation, dispersion, sinking, dissolution, emulsification, photo-oxidation, resurfacing, and mousse formation, (Abdel-Shafy & Mansour, 2016; Brassington et al., 2010; Souza et al., 2014). At the same time, high molecular weight oil fractions settle at the bottom of the water (Mishra & Kumar, 2015). The winds and currents influence the non-uniform spreading, increasing the surface areas affected and the probability of exposure to human and animal receptors and ecosystems. Ecological factors such as humidity, temperature, and precipitation influence the weathering process in the water environment (Truskewycz et al., 2019). The level at which the waste engine oil components degrade during weathering processes depends on their nature, composition, and physicochemical characteristics (Balseiro-Romero et al., 2018).

Figure 2b illustrates the transport and distribution of waste engine oil components in a water environment. The waste engine oil components that enter the surface water through weathering processes bind to small particles and settle at the bottom, where they remain for an extended period due to poor dissolvability (Bacosa et al., 2022). The waste engine oil components may cumulate in the tissues of aquatic organisms and enter the food chain. The toxic heavy metals contained in the composition can dissolve in the water and penetrate the soil, surface water, groundwater, and aquifers, gradually flowing underground and draining into the surface water. In the marine ecosystem, erosion of coastal sediments redistributes the waste engine oil components into a water column, causing them to be exposed to aquatic organisms (Mohammadi et al., 2020). External environmental factors comprising wind flow velocity, atmospheric pressure, temperature, turbulent flow, and surface characteristics influence the re-distribution and transport mechanism (Al-Majed et al., 2012; Giamagas et al., 2024).

Disposal in air

The combustion or incineration of waste engine oils generates by-products including dioxins, furans, volatile organic compounds (VOCs), greenhouse gases such as CO_2, and CH_4, organometallic oxides of Zn, Cr, Al, Ni, Cu, and other metal particles, sulphur, nitro compounds, SO_2, P, Ca, HCl, and NO_2 (Fayyazbaksh et al., 2022; Gullet et al., 2017; Makworo et al., 2022). These by-products are released into the atmosphere when waste engine oils are burned as the primary or ancillary fuel in space heaters, industrial heaters, marine heaters, commercial heaters, utility heaters, asphalt plants, pulp mills, steam boilers, domestic oil burners, utility steam boilers, rotatory cement kilns, and waste incinerators (Hassanain et al., 2017; Rauckyte et al., 2006; Vasquez-Duhalt, 1989). The VOCs in the waste engine oil may vaporise into the air and remain in the atmosphere, causing additional air pollution and deterioration of air quality (Obinia & Afiukwaa, 2013), while the greenhouse gases cause global warming (Olivier & Peters, 2020). Sometimes the by-products from combustion are released as aerosols when soot is blown out of large heaters, ovens, and kilns (Mueller Associates Inc., 1987).

In automotive engine systems, engine oils are burned at 0.1–0.25 L per 1000 km as particulate matter emissions with other by-products from the exhaust systems (Van Donkelaar, 1990). Heavy-duty diesel engines emit compounds such as nitrosamines from the combustion system, while the amount emitted depends on the type of engine oil used and the flow rate of nitrous oxide in the combustion engine systems (Baines, 1981).

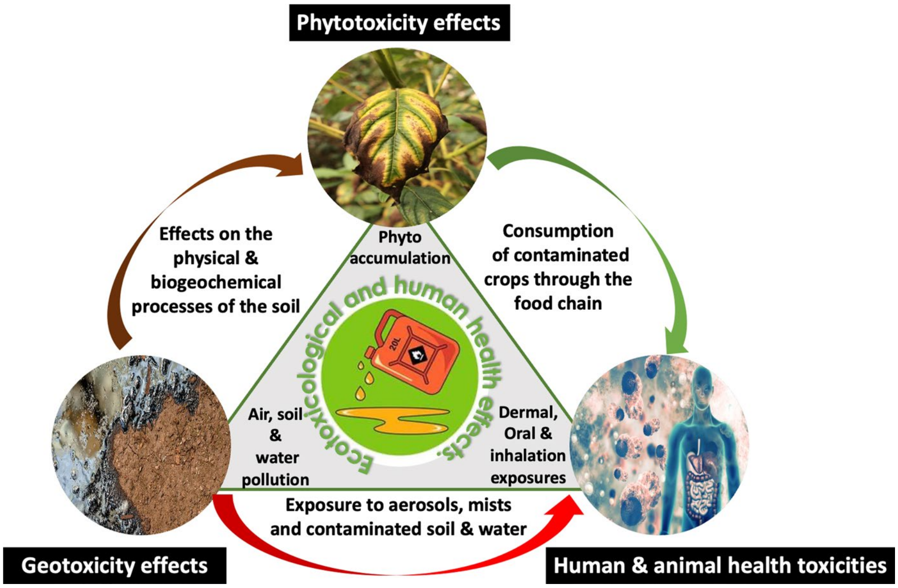
Ecotoxicological effects

The ecotoxicological effects of waste engine oils include the changes that result in the biological entity or the changes in the state or dynamics of an entity or other biological organisation caused by physical exposure to toxic chemicals such as waste engine oil. In essence, ecotoxicology examines the biological impacts of toxic substances that contaminate or have contaminated the environment, ranging from molecular effects in a species to effects on the entire biosphere (Sharma, 2023). Ecotoxicological effects can occur at multiple levels, including subcellular, cellular, tissue, individual, population, community, ecosystems, biosphere, and landscape levels. (Van Leeuwen, 1995). The ecotoxicological impacts of contaminants such waste engine oils can result in geotoxicity, phytotoxicity, and human and animal toxicity. Figure 3 depicts the ecotoxicological effects of waste engine oil on the environment causing geotoxicity and phytotoxicity with human and animal health toxicities.

Geotoxic effects (geotoxicity)

Geotoxic effects refer to the potential toxicity or harmful effects of hazardous substances or pollutants on the geosphere, specifically soil and geological systems. It involves the impact of toxic chemicals and contaminants on soil quality, soil organisms, and the overall geochemical processes within the earth's crust. Geotoxicity encompasses the chemical properties of the hazardous pollutants and their interaction with the soil environment, as well as the effects on the physical and biological properties of the soil. The key aspects of geotoxicity comprise soil contamination, effects on soil biocenosis, soil structure and function,

Fig. 3 The ecotoxicological effects of waste engine oils on the environment



and geochemical processes such as permeability, hydraulic conductivity, and compaction (Daâssi and Almaghribi, 2022).

In the terrestrial ecosystem, waste engine oils affect the soil's physicochemical properties, including soil texture, compaction, structural status, penetration resistance, saturated hydraulic conductivity, and heavy metal concentrations (Hreniuc et al., 2015). Table 4 summarises soil and plant toxicological effects with characteristics of the geotoxic effects on soil geochemistry. The negative effects constitute a high risk of damage to arable land. Soil contamination by waste engine oils adversely affects soil organisms, including microbes, plants, and invertebrates, and significantly affects and disrupts future land use for agriculture, recreation, or urban development unless expensive decontamination measures are undertaken (Nowak et al., 2019). When heavily contaminated, the components of waste engine oil slowly seep and infiltrate until they reach the underlying aquifer and then enter the pumping wells, posing a high risk to humans, ecosystems, and agricultural land. If the contaminated water is used for water supply or irrigation purposes, it introduces pollutants into the water supply and food chain (Ali et al., 2019). One litre of waste engine oil can pollute up to 3784 m^2 of soil, making it non-productive for agricultural use for up to 100 years (Gaur et al., 2023).

Waste engine oils tend to bind to organic materials and clay particles via the soil adsorption complex, migrate into the organism, seep into the soil, and accumulate there, damaging the soil biocenosis (Pelitli et al., 2017). The highly soluble metallic phases pose a significant risk to living organisms (Farombi et al., 2013), and the accumulation of heavy metals directs the soil's microbial functions and triggers toxicity and contamination of the food chain (Kathi, 2017). The waste engine oil components increase the toxicity level, reduce the fertility and productivity of the soil (Christensen and Argerbo, 1981), and cause the soil to erode and become useless for agriculture and any other purpose. The aesthetic value of the soil, including colour, texture, and properties, is affected. The soil surface colour becomes darker as a result of the low-light reflective properties of the soil. The light-reflective ability proportionally increases with time due to the contaminants' transformation. This effect facilitates the heating of the soil with a rise in temperature by absorbing and retaining more heat during the sunny period, which can reach a temperature of about 70 °C, which is lethal and affects the survival of biota in the soil (Donahue et al., 1990). The increase in hydrophobicity and light-reflective ability also causes the soil's upper layers to dry out, whereas the soil's lower layers suffer excessive moisture, leading to an imbalance of air and water conditions and the development of anaerobic processes, lowering the redox potential and causing surface waterlogging (Wang et al., 2021).

Table 4 Soil and plant toxicological effects of exposure to waste engine oil

Ecotoxicological effects	Route of exposure	Characteristic effects	References
Geotoxic effects (effects on the soil)	Spillage, leakages, fugitive emission, improper disposal	Decreases the aesthetic value of the soil Reduces soil biocenoses including microbes, plants and invertebrates Increases soil compaction, bulk density, pH Reduces soil structure, texture and porosity Reduces moisture retention capacity Reduces soil penetration resistance Saturates the hydraulic conductivity Increases heavy metal concentration Contaminates groundwater or aquifer Contaminates surface water and water supply Increases heat conductivity of the soil Causes water and air imbalance leading to waterlogging Disrupts nutrient cycling	Nowak et al. (2019) Ali and Khan (2019) Pelitli et al. (2017) Nwite and Alu (2015)

Table 4 (continued)

Ecotoxicological effects	Route of exposure	Characteristic effects	References
Phytotoxic effects (effects on plants)	Spillage, leakages, fugitive emissions, improper disposal, aerosols and oil mists	Causes plant hormonal imbalance for signalling and regulation Increases translocation of heavy metals in plant tissues Reduces moisture and water penetration Reduces plant photosynthetic rates Reduces stomatal conductance and transpiration Reduces plant-water–air interaction Reduces plant mycorrhizal fungi Reduces plant metabolic processes Delays seed germination and plant development Reduces pests and disease resistance Increases stunted growth, root and shoot deformations Increases chlorosis and necrosis Decreases plant nutrient and water absorption	Vwioko et al. (2006) Fernandes and Henriques (1991) Yao et al. (2013) Obinia and Afiukwaa (2013) Renault et al. (2000) Rusin et al. (2015) Shan et al. (2014)

The waste engine oils increase soil bulk density, reduce total porosity, and reduce the soil's moisture retention capacity and water transmission (Nwite & Alu, 2015). The abnormal water conditions lower the solubility and availability of micronutrients for soil biocenosis and inhibit nitrification and ammonification (Camenzuli and Friedman, 2015). Soil particles covered by hydrophobic films of high molecular weight components lose their ability to absorb and retain moisture, resulting in a significant loss of water conductivity and water-holding capacity. The water molecules adjacent to the waste engine oil components contain many sodium ions, which penetrate the soil sorption complex and replace pH-balancing cations, thereby altering the pH value of the soil and the redox potential of the soil (Klamerus-Iwan et al., 2015).

The waste engine oil induces changes in the microbial organism and metabolism in the nutrient cycle in the soil (Pinheiro et al., 2021), filling the pores between the particles, limiting access to oxygen, and causing an anaerobic environment, which induces the anaerobic microorganisms' metabolic activity (John et al., 2011). Organic carbon significantly increases, while the available nitrogen and phosphorus may not change correspondingly. The massive occurrence of carbon in the soil stimulates the growth of autotrophic microorganisms (Hu, 2020). The massive propagation of hydrophilic microorganisms fixes the nutrient elements, such as NO_3-N, resulting in a lack of nutrient supply and leading to competition between microorganisms and plants for nutrients. In addition, the waste engine oil components restrict the passage of nutrients from the soil particles into the soil (Hu, 2020).

However, understanding geotoxicity is crucial for environmental management, land remediation, and sustainable land use practices. It helps in the identification of contaminated sites, the development of mitigation strategies, and the implementation of measures to mitigate or prevent further soil degradation and ecotoxicological and geoenvironmental risks.

Phytotoxic effects (phytotoxicity)

Phytotoxic effects refer to the harmful effects of toxic components on plant growth, development, and overall health. When plants are exposed to phytotoxic substances such as waste engine oil, this leads to various negative phytotoxic effects, including an imbalance of plant signalling and regulatory hormones and an impairment of the plant's normal physiological processes (Haider et al., 2021). The toxic components of waste engine oil change the soil's physicochemical and microbiological properties to support the plant's growth and development (Ekundayo et al., 1989). The presence of toxic components in the soil causes an increase in heavy metal contents, which can eventually pass into plant tissue through bioaccumulation (Hu, 2020; Vwioko et al., 2006; Yong et al., 1992). Even though some of the metals at low concentrations are essential trace nutrients, at high concentrations, they become toxic and cause metabolic challenges in plants (Fernandes & Henriques, 1991; Nyiramigisha et al., 2021). The presence of waste engine oil components in the soil causes poor aeration and poor soil moisture content (Akoachere et al., 2008; Ezenwa et al., 2017) and lowers microbial activities by reducing the catalase and dehydrogenase activities (DHA), affecting energy production, metabolism, stress response, nutrient cycling, and soil fertility for plant growth (Achuba and Peretiomo-Clarke, 2007).

Table 4 summarises the soil and plant toxicological effects with the characteristics of the phytotoxic effects of plant physiological development. The waste engine oil components have inhibitory and negative effects that disrupt the metabolic process and compromise plant growth and development (Yao et al., 2013), such as obstruction or lowering water and mineral salt intake, reducing photosynthetic rates, and reducing stomatal conductance and transpiration rate (Han et al., 2016). The waste engine oils disrupt the plant-water–air relationship, affect soil microorganisms such as mycorrhizal fungi (Obinia & Afiukwaa, 2013; Renault et al., 2000), and hinder plant growth, causing the breakdown of plants' metabolic processes, delays in the germination of seeds, a reduction in the plant growth, and a deficiency of chlorophyll in plants and low nutrients (Adenipekun et al., 2008). The presence of waste engine oil components causes a decline or reduction in pests and disease resistance by the plants, the manifestation of stunted growth of shoots and root deformations, and chlorosis and necrosis in leaves and flowers (Rusin et al., 2015; Shan et al., 2014). The waste engine oil components form a mucous membrane layer on the plant's root systems, which impedes plants' respiration and absorption of nutrients and water. The absorbed waste engine oil components can move to the leaves and fruits, accumulate, amplify, and enter the food chain (Hu, 2020; Othman et al., 2011). The waste engine oils bound in the upper soil layers extrude air from reaching the soil's lower layers, resulting in an imbalance of aeration in the soil and causing plant hypoxia (Stepanova et al., 2022). Consequently, these imbalanced conditions adversely affect soil biocenosis by reducing the soil's microbial life and organic content, and causing massive negative influences on all the soil's physicochemical properties, ranging from the soil layer morphology to humic acid chemistry, which negatively impacts seed germination and plant growth (Aina et al., 2009).

Phytotoxic effects of waste engine oil on crop growth and development have been extensively reported from experimental studies by many researchers, including Anoliefo and Vwiko (1995), who investigated the growth of *Capsicum anum* L. and *Hycopersicon esculentum* Miller and reported growth retardation in tomatoes and pepper cultivated in waste engine oil-polluted soil. Odjegba and Atebe (2007) investigated the effects of waste engine oil on the carbohydrate, mineral content, and nitrate reductase activity of *Amaranthus hybridus* and reported defective germination of spinach seeds (*Amaranthus hybridus*) with poor seedling growth, chlorophyll, protein content, and low nitrate reductase activity. In another similar study, Swapna et al. (2021) investigated the effects of waste engine oil on soil characteristics and selected phytochemicals in *Amaranthus hybridus* and reported an increased concentration of antinutrient tannin and a decreased concentration of nutrients, alkaloids, flavonoids, saponins, total phenol, and phytic acid.

Adeko et al. (2023) also investigated the adverse effects of waste engine oil on *Amaranthus viridis* and reported a reduction in the number of leaves, plant height, and leaf area. Ezenwa et al. (2017) investigated the effects of waste engine oil on seed germination and seedling growth characteristics, and they reported a dose-dependent inhibition of seed germination and seedling growth characteristics of beans (*Phaseolus vulgaris*), maize (*Zea mays L.*), tomatoes (*Solanum lycopersicum*) and guinea corn (*Sorghum saccharatum*). Osunbor and Anoliefo (2003) investigated the effects of waste engine oil on the growth and respiratory function of *Arachis hypogea* L and reported a reduction in oxygen uptake in *Arachis hypogea* seedlings.

It is important to note that the severity of the phytotoxicity effects of waste engine oil on crops varies depending on the concentration and duration of exposure to the phytotoxic pollutants, plant species, and their sensitivity to specific chemical components. To mitigate phytotoxicity effects in crops, it is crucial to identify pollutants, minimise sources of phytotoxic substances, implement proper agricultural practices, and employ appropriate remediation strategies if contamination has occurred (Cui et al., 2023). Additionally, selecting pollutant-tolerant plant varieties and monitoring plant health are important measures to mitigate the risks associated with phytotoxic effects (Banerjee et al., 2023).

Toxicokinetics and metabolism in humans and animals

The toxicokinetics and metabolism of waste engine oil components have not been studied sufficiently, unlike petroleum crude oil, however, the toxicity and chemical properties are due to PAHs, BTEX, PCBs, POPs, organometallic compounds, chemical additives, and other contaminants (Tsaioun et al., 2016). The toxicokinetics are controlled by the physicochemical characteristics of the individual components of the waste engine oil and other co-existing toxic heavy metals (Brown et al., 2017; Thavamani et al., 2012). The toxicity in humans and animals is mostly related to the binding of the toxic components including PAH compounds to aryl hydrocarbon receptors (AhR) and thyroid hormone-related endpoints which have been used as a criterion for dioxin-like activity (Bekki et al., 2009) and the metabolites from these toxic compounds such as PAH hydroxides, ketone and quinones elicit several toxic and chemical responses such as the derivation of drug-metabolising enzymes (cytochrome P450 1A1, 1A2, 1B1, etc.) (Bekki et al., 2009; Mougin et al., 2013). However, it is difficult to completely determine the overall toxicokinetics and toxicodynamics of exposure to waste engine oil due to the variability in the composition and lack of conclusive data for human and animal exposures (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). Nevertheless, some information regarding the toxicokinetics related to the absorption, distribution, and transformation of the individual components, including PAHs, BTEX, and PCBs, is described in ATSDR profiles for the individual components (ATSDR, 1997).

The absorption and distribution of the hazardous components of waste engine oils depend upon the chemical properties of the individual components (United States Environmental Protection Agency (USEPA), 1999). However, how an organism is affected by the individual components is a function of the route of exposure, the concentration or dose of the individual components, and all the processes related to uptake, internal transport, and accumulation inside the organisms, as well as the skin integrity (Tsaioun et al., 2016). The distribution pattern depends on the specific properties of the toxic components of the waste engine oil. The metabolism of the individual components varies depending on their chemical nature (Fallgren & Jin, 2008). PAHs can undergo metabolic activation in the body, forming reactive intermediates that can bind to cellular DNA and proteins, potentially leading to toxic effects. Elimination from the organisms occurs through urine and faeces. The kidneys play an essential role in filtering and excreting water-soluble metabolites. Some toxic components of the waste engine oil may be eliminated through bile, sweat, or exhalation. The excretion rate depends on various factors, including the chemical properties of the toxic components and individual factors like renal function (Galea et al., 2014). Additionally, individual factors such as age, overall health, and pre-existing conditions can influence the toxicokinetic processes (Snape et al., 2001; Stroud et al., 2007; United States Environmental Protection Agency (USEPA), 1986).

The extent of potential exposure to waste engine oil appears to be minimal, but the risk associated with such exposure is expected if an individual is intermittently or repeatedly exposed to waste engine oil.

Chronic exposure occurs from continuous, prolonged, or repeated contact with the waste engine oil over a long period in a workplace, resulting in high occupational exposure (Tadesse & Admassu, 2006). Once an individual is exposed, the hazardous components are absorbed in the tissues over time. Some of the chemical components, such as PAHs, BTEX, PCBs, and toxic heavy metals, may be distributed throughout the body via the bloodstream and build up in the tissues and organs, such as the liver, kidney, lungs, and central nervous system, to cause long-term toxicological health effects (Rague et al., 2021).

However, it is difficult to determine the toxicokinetics of waste engine oil because of the extensive variability in the chemical composition and a lack of definitive data for human or animal experimental studies. However, the few experimental studies available indicate that waste engine oils are absorbed through ingestion, skin contact, and inhalation (Akintunde et al., 2015).

Human exposure to waste engine oils

Human exposure to waste engine oils in the form of mists, vapour, aerosol or particulate matter poses significant human health risks. Occupational exposure occurs during engine or machinery oil evacuation in vehicles and machinery during maintenance and repair works (Bekibele et al., 2022). The human populations with a high risk of exposure include auto mechanics (Oche et al., 2020), aviation mechanics (Khalili & Nasrabadi, 2023), ship engine mechanics (Lokhande, 2014), railway engine mechanics (El-Marakby, 2008), and heavy-duty machinery technicians (Ataro et al., 2018). These individuals may increase their chances of exposure if they spend a long duration of time in contact with waste engine oils during routine oil change and repair works. Non-occupational exposure is least likely to occur unless there are leakages and spills within the vicinity. Exposure is high and common if they do not implement good environmental health and safety practices (Instituto Nacional de Seguridad y Salud el Trabajo (INSST), 2023).

Other occupations at risk are those associated with the recovery, regeneration, or recycling of waste engine oils. These workers are involved in the collection of waste engine oils for recycling or re-refining and may also be exposed during the collection, re-refining, and recycling processes. These individuals may inhale particulate matter, aerosols, mists, or volatiles from storage tanks, treatment tanks, contaminated soil, sludge, sediment, or sorbent pads. Additional workers at risk are those who are involved in the remediation of waste engine oil-contaminated environments. They are also exposed to volatiles and particulate matter if adequate health and safety procedures are not implemented (Agency for Toxic Substances and Disease Registry (ATSDR), 1997).

Individuals who work in waste oil incineration facilities and those who live in buildings that use waste oils as heating fuel and ancillary fuel for heaters may be exposed to high levels of toxic heavy metal particulates in the respirable range. People living near roads treated with waste engine oils as dust binders may be exposed to dust particles saturated with the oils and are likely to be exposed to toxic heavy metal particles (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). Human exposure also occurs in some African cultures where waste engine oils are used as a traditional medicinal antidote for poisons and to ward off reptiles (Bekibele et al., 2022).

A prolonged and repeated form of exposure to waste engine oils in the form of mists, vapours, aerosols and particulate matter elicits a specific type of response. The exposure of an individual repeatedly undertaking a task may vary considerably due to behavioural and environmental factors, and there may be similarities or large differences in exposure between different people doing the same activity (Giles et al., 2014).

Routes of exposure to waste engine oils

Occupational or human exposure to waste engine oils in the form of mists, vapours, aerosols and particulate matter occurs mainly through various routes, including dermal or skin absorption (direct contact), inhalation or aspiration of aerosols and mists, and oral ingestion. Exposure may result in many toxicological health situations (Bekibele et al., 2022). If exposure to waste engine oils is to be determined and controlled, consideration of the physical characteristics, composition, concentration of the waste engine oil, and duration of exposure is essential (Suthers et al., 1986). The exposure can be at low or high levels. At the same time, the reaction outcome or response can be acutely manifested in the short term or chronically manifested in the long term, causing tumorigenesis and many forms of degenerative diseases (Tsatsakis et al., 2018).

Inhalation exposure

Inhalation exposure to engine oil mists, vapours and aerosols is the most common route of exposure in the workplace such as engine oil manufacturing facilities and waste engine oil recycling facilities (Anderson & Meade, 2014). Inhalation exposure to airborne particulate matter occurs from incineration, opening burning and vehicular emissions. The oil mists, vapours, aerosols and airborne particulate matter can enter the body and directly interact with the respiratory system (Schlesinger, 1988). The interaction is elicited by the intricate structure of the lungs, composed of millions of tiny air sacs (alveoli) which provide a vast surface area for transferring the oil molecules from the air into the bloodstream. The impact of inhaled oil mists, vapours aerosols and particulate matter can be multifaceted. Some may cause immediate irritation in the nose and nostrils or cause damage to the respiratory tract, while the oil molecules may get absorbed into the bloodstream to trigger systemic effects (Manisalidis et al., 2020). Prolonged or repeated exposure to oil mist, vapours, aerosols and particulate matter can lead to severe chronic respiratory diseases and other degenerative disorders (Duan et al., 2020).

Dermal exposure

Dermal exposure or skin absorption is determined by measuring the amount of the contaminant on the skin's surface, the area of skin contaminated, the duration of exposure, and the concentration of the contaminants on the skin (Galea et al., 2014; Sibomana et al., 2019). Dermal exposure is the primary route of occupational exposure for individuals working in automotive service centres and the machinery industry (Dalbey et al., 2014). However, a one-time dermal exposure is unlikely to cause severe toxicological effects (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). Factors such as dose, duration of exposure, route of exposure, individual characteristics including family traits, age, gender, nutrition, social life, and health status (Snyder, 1984; Tsatsakis et al., 2018), as well as absorption, distribution, metabolism, and excretion, may influence the severity of such health effects upon dermal exposures (Dehelean et al., 2016; Obinia & Afiukwaa, 2013). The severity of dermal exposure differs depending on whether the body surface exposed to waste engine oil is completely covered (occlusive), semi-occluded, or not covered at all. However, reports have indicated that skin occlusions enhance the hydration of the *stratum corneum* and exacerbate the irritant effects of the toxic constituents of the waste engine oil (Sibomana et al., 2019).

Oral exposure

Oral exposure to waste engine oils rarely occurs in adult humans, however, acute effects associated with oral exposure (ingestion) can occur in children who accidentally ingest engine oil (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). There are scant clinical studies regarding human or animal deaths after oral (ingestion) exposures to waste engine oils. However, high doses at lethal concentrations through oral exposure (ingestion) may result in high severity in humans and death in animals, depending on the concentration, properties of the oil components, frequency of exposure, duration of exposure, and exposure pathway (Tsatsakis et al., 2018).

Toxicosis and toxicities

Toxicosis describes the pathological conditions or abnormal state caused by the presence of hazardous or toxic substances such as waste engine oil, which occurs when an individual or an animal is exposed to high doses of the hazardous or toxic substances, which build up to cause adverse effects or health toxicities (Mostrom, 2021). Health toxicities are the adverse conditions that exposure to toxic substances can have on individuals, such as acute toxicity, the short-term effects of exposure, and chronic toxicity, or the long-term effects of repeated or continuous exposure to hazardous substances such as waste engine oil components (Ahmed et al., 2019). These effects can affect a single cell, an organ system, a group of cells, or the entire organism. The effects can be visible damage or cause a decrease in the performance or function of the organism (Mostrom, 2021).

The TPH components of the waste engine oils, including PAHs, BTEX, PCB congeners, POPs, and chlorodibenzofurans, together with the toxic heavy metal components, contribute to health toxicities (Omorowa et al., 2015; Van der Heul, 2009). A few volatile hydrocarbon components and some semi-volatile polycyclic aromatic components pose a carcinogenic risk, whereas aliphatic hydrocarbon components pose a non-carcinogenic risk (David & Niculescu, 2021). Although many aliphatic and polycyclic aromatic hydrocarbons may not be carcinogens, they can collectively pose a non-cancer hazard if present at high doses or concentrations. Table 5 lists the carcinogenic and non-carcinogenic components and toxic heavy metals in waste engine oils.

However, in terms of toxicity, fresh or new engine oils are less toxic but contain petroleum hydrocarbons that are more of a worry for acute (short-term) toxicity, whereas waste engine oils are toxic and contain more toxic heavy metals and PAHs that contribute to chronic (long-term) toxicity (Irwin et al., 1997). Although the toxicity of waste engine oil has not been thoroughly determined, unlike petroleum crude oil, the toxicity is attributed to PAHs constituents which include benzo[*a*]anthracene, benzo[*b*]fluoranthene, benzo[*j*]fluoranthene, benzo[*k*]fluoranthene, benzo[*ghi*]perylene, benzo[*a*]pyrene, chrysene, cyclopenta[*cd*]pyrene, dibenzo[*a,h*]anthracene, dibenzo[*a,e*]pyrene, dibenzo[*a,h*]pyrene, dibenzo[*a,i*]pyrene, dibenzo[*a,l*]pyrene, dibenzo[*e,l*]pyrene, indeno[1,2,3-*cd*]pyrene and 5-methylchrysene, as summarised in Table 5. These PAH constituents, either individually or in combination, are currently the possible indicators of the carcinogenic potency of PAHs in the waste engine oil (European Food Safety Authority (EFSA), 2008).

However, of the various toxic chemical compounds in engine oil, only a few of these toxic chemical components have been characterised for their toxicological effects through experimental laboratory studies (Agency for Toxic Substances and Disease Registry (ATSDR), 2011). Out of the PAH constituents in waste engine oil, benzo[*a*]pyrene is considered the most toxic and has been studied extensively and used as a benchmark mark, an indicator species or biomarker for PAH exposure for waste engine oil contamination in air, soil, water and food (Zelinkova & Wenzi, 2015). The effect of the benzo[*a*]pyrene is carcinogenic and genotoxic in humans and animals. However, the benzo[*a*]pyrene content of new engine oil can be up to 0.266 mg/kg but that of waste engine oil can be up to 216 mg/kg, i.e. 1000 times higher (Cvengros et al., 2017). Occupational exposure is largely through inhalation and skin absorption. The greatest levels of occupational exposure to benzo[*a*]pyrene are in aluminium production (up to 100 μg/m^3), with lesser exposure in roofing and paving (10–20 μg/m^3) and lesser still in coal processing, wood impregnation, chimney sweeping and in power plants (at or below 1 μg/m^3) (International Agency for the Research on Cancer (IARC), 2010).

Table 5 Carcinogens and non-carcinogens compounds and metals in waste engine oils

Carcinogenic compounds and toxic metals	Non-carcinogenic compounds and toxic metals
Benzene	Toluene
Ethylbenzene	Xylene
Anthracene	Acenaphtene
Benzo[*a*]anthracene	Benzoperylene
Benzo [*a*]pyrene	Fluorene
Benzo [*b*]fluoranthene	Naphthalene
Benzo[*j*]fluoranthene	Total chromium
Benzo [*k*]fluoranthene	Copper (Cu)
Benzo[*ghi*]perylene	Iron (Fe)
Chrysene	Manganese (Mn)
Cyclopenta[*cd*]pyrene	Mercury (Hg)
Dibenzo [*a,h*]anthracene	Zinc (Zn)
Dibenzo[*a,e*]pyrene	
Dibenzo[*a,h*]pyrene	
Dibenzo[*a,i*]pyrene	
Dibenzo[*a,l*]pyrene	
Dibenzo[*e,l*]pyrene	
Indeno [1,2,3-*cd*]pyrene	
5-methylchrysene	
Fluoranthene	
Phenanthrene	
Pyrene	
Polychlorinated biphenyl (PCB) congeners	
Chlorodibenzofurans (CDFs)	
Arsenic (As)	
Cadmium (Cd)	
Hexavalent Chromium (CrVI)	
Nickel (Ni)	
Lead (Pb)	

The median occupational exposure to benzo[*a*]pyrene for mean and high exposures varied between 235 ng/day (3.9 ng/kg body weight per day) and 389 ng/day (6.5 ng/kg body weight per day) respectively for PAH components such as benzo[*a*]pyrene, 641 ng/day (10.7 ng/kg body weight per day) and 1077 ng/day (18 ng/kg body weight per day) respectively for two PAHs, 1168 ng/day (19.5 ng/kg body weight per day) and 2068 ng/day (34.5 ng/kg body weight per day) respectively for four PAHs and 1729 ng/day (28.8 ng/kg body weight per day) and 3078 ng/day (51.3 ng/kg body weight per day) respectively for eight PAHs. The maximum estimated daily intake of benzo[*a*]pyrene for a 70 kg adult is 6–8 ng/kg (European Food Safety Authority (EFSA) (2008).

Even though limited data is available regarding clinical studies of the toxicological effects of the PAHs in waste engine oil exposure on human and animal health, in the few reported evaluations of occupational exposures based on toxicological and epidemiological studies, some toxicological health effects have been identified in human exposure on auto mechanic workers and in animal experimental studies indicating various forms of toxicities, including tumorigenesis, degenerative diseases, haematological disorders, decreased erythrocytes and haemoglobin, haematocrit, and platelet levels, and increased blood pressure (Naré et al., 2019).

The toxicosis of waste engine oils comprises multisystemic diseases characterised by three clinically distinct phases: an acute phase involving peripheral eosinophilia, pulmonary oedema, and endothelial damage; an intermediate phase involving severe myalgia, sensory neuropathy, liver damage, skin oedema, and sicca; and a chronic phase involving peripheral neuropathy, muscle wasting, scleroderma, and hepatopathy (Hard, 2000). The symptomatology of the acute phase of the toxicological effects of the exposure to waste engine oil included, in order of frequency: fever, respiratory distress, nausea and vomiting, skin eruptions and pruritis, general discomfort, abdominal pains, headache, coughing, anorexia, weakness, diarrhoea, and muscle pains.

The basic lesion is a non-necrotising vasculitis accompanied by thrombotic events. There is mounting evidence that the toxicological effects may have an immunological basis involving T-lymphocyte activation and cytokine release, particularly because of the peripheral eosinophilia, rise in serum IgE, similarities to graft-versus-host disease, and linkage to genetic susceptibilities involving specific subsets of HLA antigens (Hard, 2000). The signs of the central nervous system may be a result of the anaesthetic-like action of low-molecular-weight aliphatic hydrocarbon constituents and/or cerebral anoxia that can result from lung damage or displacement of oxygen by the more volatile hydrocarbon components. Ingesting waste engine oils in high doses can sensitise the heart muscle to endogenous catecholamines (Mostrom, 2021).

Figure 4 illustrates various short-term (acute) and long-term (chronic) toxicological effects of waste engine oils in humans and animals including the destruction of red blood cells (Haematoxicity)

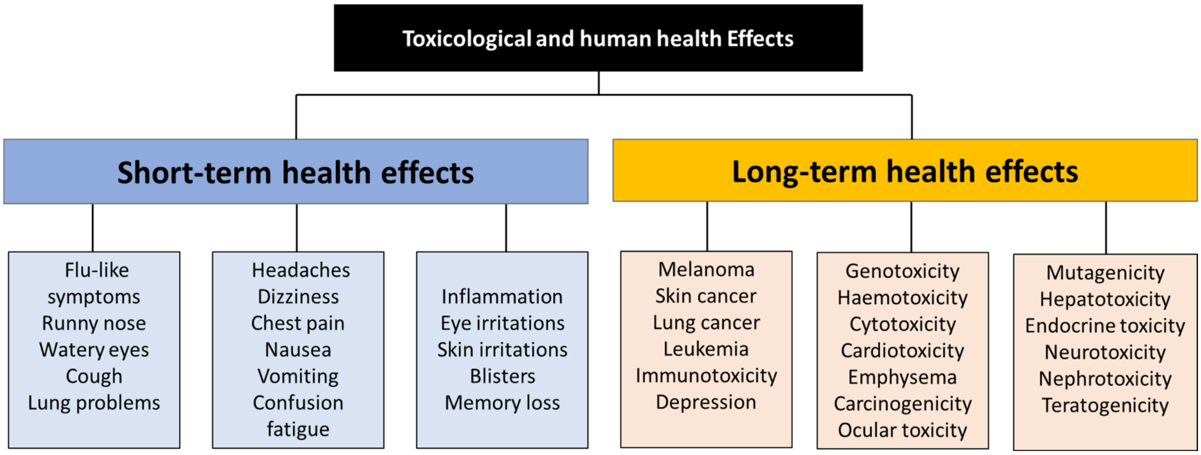


Fig. 4 Toxicological health effects of overexposure to waste engine oil

(Neghab et al., 2012); having the ability or tendency to induce cancer (carcinogenicity) (Khanna & Gharpure, 2017); ability to induce non-transmissible DNA damage (genotoxicity) (Gutzkow, 2015); capacity to incite or elicit transmissible genetic mutations (mutagenicity) (Srivastava et al., 2019), induction of malformation of embryo or foetus (teratogenicity) (Bada et al., 2019); the ability to be toxic to cells (cytotoxicity) (Zheng et al., 2014); damage to the brain and nervous system (neurotoxicity) (Sriram et al., 2011); capacity to repress the immune system (immunotoxicity) (World Health Organisation (WHO), 1986); damage to the kidney (nephrotoxicity), ability to elicit damage to the liver (hepatotoxicity) (Ogunneye et al., 2014); capacity to cause damage to heart muscles (cardiotoxicity) (Azeez et al., 2015), and ability to induce eye disorders (ocular toxicity) (Omoti et al., 2008). Table 6 summarises the toxicological effects of waste engine oil on human and animal health, the routes of exposure, and the characteristic symptomatic effects after repeated and prolonged exposure.

Respiratory effects

Waste engine oil particles can be inhaled once oil mist or aerosols are generated in the workplace. The location and possibility of deposition of oil mist in the respiratory tract depend on the oil particle size. Respirable oil particulate matters above 50 µm in diameter are unlikely to stay airborne long enough to be inhaled. However, oil particulate matters below 5 µm are likely to remain airborne for an extended period (Canadian Environmental Protection Act, 1999). The oil particulate matter may settle in the upper respiratory tract and nasal passages, and the smaller ones infiltrate deeper recesses of the lungs (Mack et al., 2019). Once settled, the oil particles may be eliminated through clearance mechanisms or absorbed into body fluids, thus causing both local and systemic toxicity. Respiratory symptoms can range from mild irritation to severe respiratory distress, depending on the nature and concentration of the toxic substance, eliciting coughing, wheezing, shortness of breath, chest tightness, sore throat, or irritation of the nose and throat (Burdon et al., 2023). The effects of aspirating mineral oil mist or aerosols into the lungs are well documented. A large amount of oil entering the lungs through inhalation exposure may cause chemical pneumonitis, which may be fatal or lead to more severe complications such as pulmonary fibrosis. Lipoid pneumonia has been reported following prolonged heavy inhalation exposure without sufficient ventilation (Suthers et al., 1986).

There is limited data available on the clinical, pathological, and epidemiological studies on the respiratory effects of human exposures. However, the available data from a case study conducted by Jones (1961) on 19 volunteer workers from a steel rolling mill factory who were occupationally exposed to repeated and prolonged exposure to aerosols and mists of waste engine oils reported radiological signs of increased linear striations in the lungs of twelve individuals among the volunteer workers (Jones, 1961). In another similar epidemiological study conducted on Norwegian workers in a cable plant by Skyberg et al. (1986), slight basal lung fibrosis was observed. In an additional study conducted on workers in a bearing ring manufacturing factory in Sweden by Järvholm et al. (1982), 164 workers were sampled for signs of respiratory symptoms using questionnaires and lung function tests. The radiological results showed no lung function abnormalities, but the workers complained more about respiratory systems consistent with irritations and chronic bronchitis (Järvholm et al., 1982).

In an experimental study reported by Dautrebande and Capps (1950), a ten-minute exposure of a few volunteers to inhalation exposure to waste engine oil aerosols resulted in mild to moderate throat and nose irritations with a feeling of chest tightness. When the volunteers wore respiratory filter masks, irritations were reduced to none-to-mild, even at twofold concentrations. Inhalation exposures also occurred due to leakages of aerosol and caused chest tightening without nose irritations (Dautrebande et al., 1951). However, the concentrations of waste engine oil in the ambient air were not determined in the study, but the effects were observed in one volunteer worker exposed to a concentration of 42 mg/m^3 and another to 84 mg/m^3 (Agency for Toxic Substances and Disease Registry (ATSDR), 1997).

Cardiovascular effects

There is limited data on clinical and pathological studies on the cardiovascular effects of prolonged exposure to waste engine oils in humans. However, some workers with occupational exposure due to the

Table 6 The human and animal toxicological effects of prolonged and repeated exposure to waste engine oil

Toxicological effects	Route of exposure	Characteristic symptoms	References
Respiratory effects	Inhalation of oil mist and aerosols Aspiration of oil mist and aerosols	Local and systemic toxicity from short-term exposure Chemical pneumonitis from prolonged exposure Pulmonary fibrosis from overexposure Lipoid pneumonia from heavy exposure Irritation and chronic bronchitis Nose irritation with chest tightness	Suther et al. (1986) Järvholm et al. (1982)
Cardiovascular effects	Inhalation of oil mist and aerosols Dermal contact to oil and oil mist	Diffuse pulmonary congestion from prolonged inhalation exposure Perivascular oedema from repeated dermal exposure	Dalbey et al. (2014)
Gastrointestinal effects	Dermal exposure to oil Oral exposure through ingestion of oil Inhalation of oil mist and aerosols	Constipation from repeated inhalation exposure Loss of appetite for food Laxative effect, loose stool, diarrhoea, stomach ache, belching from repeated ingestion or oral exposure	Vermot et al. (1990) Jolliff et al. (2013)
Haematologic effects	Dermal exposure to oil Inhalation of oil mist and aerosols	High Pb level in the blood Decrease in haemoglobin and anaemia Haematoxicity, Hodgkin disease and leukaemia from repeated exposure to oil mist	ATSDR (1993) Greene et al. (1979)
Hepatic effects	Dermal exposure to oil Inhalation of oil mist and aerosols	Elevated serum bilirubin High serum phosphate Hepatic lesions	Clausen and Rastogi (1977)
Skin effects	Dermal exposure to oil and oil mist and aerosols	Skin rashes from overexposure and repeated dermal exposure Dermal congestion, acanthosis, chronic inflammation, hyperkeratosis and oedema from prolonged dermal exposures	Beck et al. (1984)
Ocular effects	Direct contact with oil mist and aerosols	Eye irritations from acute exposure to aerosols Moderate eye irritations from overexposure to aerosols	Vermot et al. (1990)
Renal effects	Direct contact and dermal exposure to oil with occupational exposure	High level of plasma urea and creatinine	Omorowa et al. (2015)
Neurologic effects	Direct contact through ingestion of oil in animals	Manifestation of muscle tremors, twitching, weakness, blindness, convulsion and hyperirritability	Sas (1989)
Reproductive effects	Repeated and prolonged ingestion of oil in animals	Necrosis of spermatogonia and interstitial (Leydig) cells Degeneration of testicular seminiferous tubules with absence of lumen	Akintunde et al. (2015)
Developmental effects	Direct contact with oil in birds eggs	Embryotoxicity and teratogenicity in mallard birds. Malformation, anencephaly, exencephaly and microphthalmia	Hoffmann and Albers (1984)

inhalation of waste engine oil mist and aerosols have been reported to have increased blood pressure, which puts strain on the heart and results in angina (a chest pain caused by restricted blood flow to the heart muscle). A past epidemiological study by Clausen and Rastogi (1977) conducted in 10 automobile service centres in Denmark reported elevated blood pressure in 37% of auto mechanic workers, 7% of apprentices, and 18% of other workers. The interpretation of the result from the epidemiological study was limited due to the lack of comparison with a control population. However, the study cannot rule out the likelihood of prolonged or repeated inhalation exposures, other causative agents, and negligence regarding other confounding variables. It was also unclear whether other factors, such as environmental, genetic, pathophysiological, and behavioural, contributed to the increased blood pressure. However, animal studies conducted by Dalbey et al. (2014) on repeated inhalation exposure to waste engine oil at high doses, resulted in diffuse pulmonary congestion and perivascular oedema of moderate and high severity.

Gastrointestinal effects

Limited data is available on the clinical studies on the gastrointestinal effects of waste engine oil in humans. However, the epidemiological studies conducted by Clausen and Rastogi (1977) on auto mechanics and apprentices from automotive service centres in Denmark in occupational exposure to waste engine oil recorded gastrointestinal effects including stomach ache, constipation, and loss of appetite for food (Clausen & Rastogi, 1977). The interpretation of the results was limited due to a lack of comparison with a control population. The study cannot rule out the likelihood of repeated or long-term dermal exposure, inhalation exposures, other causative agents, or a lack of consideration for confounding variables. Decoufle (1978) reported occupational exposure to cutting oil aerosols in the workplace and certain forms of gastrointestinal cancer in the workers. There is a possibility that ingesting a large amount of waste engine oil can cause diarrhoea or stomach damage in humans (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). Children who accidentally ingested fresh engine oil showed laxative effects, loose stools, diarrhoea and sometimes nausea, mild stomach discomfort, and belching (Jolliff et al., 2013). In animal experimental studies, diarrhoea was reported in rats and cattle that ingested waste engine oils (Osweiler et al., 1973; Vemot et al., 1990).

Haematotoxic effects

Limited data is available on the clinical studies on the haematological effects of waste engine oil in humans. However, the epidemiological studies conducted by Clausen and Rastogi (1977) in auto mechanics, reported lower than usual haematocrit and mean corpuscular haemoglobin in the volunteer workers. A confounding factor was considered in the study through the observed correlation between Pb and delta-aminolaevulinic acid dehydratase (δ-ALAD) activity in the blood samples from non-auto mechanic workers. The Pb level in auto mechanic workers was higher than that of non-auto mechanic workers. The elevated blood Pb levels correlated with a decrease in haemoglobin, indicating that the health effects may have resulted from Pb levels in the blood. The study suggested that waste engine oil was a source of Pb exposure and had haematotoxicity effects in auto mechanic workers (Eastin et al., 1983). A high Pb level in the blood can result in anaemia (Agency for Toxic Substances and Disease Registry (ATSDR), 1993). Thus, there is a likelihood that anaemia may result in individuals being exposed to Pb from waste engine oils. Although waste engine oils are sources of Pb exposure, other sources such as exhaust gas and leaded petrol may also contribute to the exposure effects.

Another epidemiological study conducted by Greene et al. (1979) reported excess death from multiple myeloma, Hodgkin disease, and leukaemia in occupational exposure amongst workers employed as compositors and binders in a printing company who had repeated and prolonged exposure to engine oil mist from inhalation and dermal exposures (Greene et al., 1979). Animal studies conducted by Ahmed et al. (2019) investigated histological, haematological, biochemical, and molecular perspectives on the effects of waste engine oil on the health status of *Oreochromis niloticus* (Tilapia fish). They reported a significant reduction in red blood cell (RBC) count, haemoglobin concentration, and total proteins, as well as adverse effects on the liver and bronchial tissue of the fish (Ahmed et al., 2019).

Hepatotoxic effects

Limited data is available on the clinical studies on the hepatotoxic effects of waste engine oil in humans. An epidemiological study conducted by Clausen and Rastogi (1977) investigated a small proportion of auto mechanic workers in occupational exposure to waste engine oils and reported increased clinical chemistry values typical of liver damage. In the study, increased serum bilirubin levels and thymol reactions (typical of high serum phosphates) were recorded in the volunteer workers. The volunteer workers also showed increased serum alanine, aspartate aminotransferase, and lactate dehydrogenase activities, indicative of hepatic lesions (Clausen & Rastogi, 1977). The study cannot rule out the likelihood of dermal exposure, inhalation exposures, exposure to other causative agents, or a lack of consideration for confounding variables. However, no clinical studies were found on the effects on the liver in animals after exposure. Few animal experimental studies reported biochemical evidence or histopathological proof of hepatic toxicity after intermediate-duration inhalation and acute-duration dermal exposures (Beck et al., 1984; Eastin et al., 1983). But lipid metabolism in the fish liver showed lecithin-cholesterol-acyl-transferase (L-CAT) activity significantly decreased and a significant elevation in CYP1 A1 mRNA expression levels in hepatic tissues in prolonged or repeated exposure to waste engine oils in fishes (Ahmed et al., 2019).

Dermatologic effects

When skin is impregnated with waste engine oils, either directly or through contact with stained clothing, irritations and allergic reactions can occur. Effects such as eczema, excess oil on the skin, and acne have also been observed in occupational exposures. It is well established that poorly refined mineral oils or waste engine oils can elicit skin and scrotal cancer after prolonged, repeated, and heavy exposure to the human skin. Many clinical studies have confirmed the dermatologic effects. Skin effects such as skin rashes on the arms, dermatitis, and other skin disorders, including skin cancer, were reported in experimental and epidemiological studies in humans after long exposure or repeated dermal exposure to waste engine oils (Galea et al., 2014). Scrotal cancer is a rare disease associated with occupational exposure and was the first disease described and associated with chimney cleaning workers (Nowak et al., 2019).

In an epidemiological study conducted by Brown et al. (1975) on workers suffering from scrotal cancer, significant excess cases of second primary tumours of the skin were reported. The second primary tumour could not be ascertained, though the cause was suspected to be caused by dermal exposure to waste engine oil in their workplace. In animal experimental studies, multiple dermal exposures resulted in animal hair loss, and histopathological analysis indicated dermal congestion, acanthosis, chronic inflammation, hyperkeratosis, and oedema (Beck et al., 1984). In addition, studies in mice and rabbits have shown that dermal exposures result in mild-to-moderate skin irritation. Monkeys chronically and dermally exposed to waste engine oil mists and aerosols indicated extensive hair loss (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). In a skin painting study on mice, poorly refined waste engine oils containing a higher proportion of PAHs were reported to be carcinogenic to the skin (International Agency for Research on Cancer (IARC), 1984).

Ocular effects

Limited data is available on the clinical studies on the ocular effects of waste engine oil exposure in humans. However, ocular effects from acute exposures have been reported in workplaces where waste engine oil aerosols occur, causing eye irritations such as redness, tearing, burning, and stinging (ATSDR, 1997). No permanent damage to the eye was reported, but the conjunctiva, which has a greater surface area than other parts of the eye, is mostly affected by inflammation, congestion, or oedema (chemosis). This is usually observed as redness or hyperaemia in eyes exposed to waste engine oil aerosols and mist. Ocular effects result from direct contact with aerosols or volatile components in the tissues (Abu et al., 2016). It is not improbable that individuals working at waste engine oil-contaminated sites who are overexposed to oil aerosols may also have mild eye irritations.

An epidemiological study conducted by Clausen and Rastogi (1977) reported mild to moderate eye irritations in humans after prolonged exposure to waste engine oil aerosols. A study conducted by Abu et al. (2016) investigating the ocular health and safety assessment among mechanics in occupational exposure reported a high rate of eye injury, including oculo-visual disorder, anterior and posterior segment abnormalities, and visual impairment. In animal experimental studies, mild irritations have been observed in rabbits when 0.1 mL of waste engine oil was directly introduced into the animal's eye (Beck et al., 1984; Vemot et al., 1990).

Lymphoreticular and immunologic effects

There is limited data available on the clinical studies regarding the immunological and lymphoreticular effects of waste engine oil exposure in humans and animals (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). However, in the animal experimental study, dermal sensitisation on guinea pigs indicated negative sensitisation potential (Beck et al., 1984; Vemot et al., 1990), but the positive control failed to show any sensitisation. Other aspects of immune function were not determined. There is therefore a certain variability in the possibility of contact dermatitis following exposure to waste engine oils. Limited data shows that oral and dermal exposure to waste engine oil triggers autoimmune responses, unlike exposure to crude oil, which can cause immunomodulation in humans and animals (McLoone et al., 2019). Epidemiological reports suggest a link between waste engine oils and autoimmunity in humans. However, the presumption in such instances is that there is a high level of exposure by inhalation or via the skin. Most of the available data on the ability of waste engine oil to induce or exacerbate autoimmune reactions in experimental animals comes from studies in which exposure was by parenteral administration (Kimber & Carrillo, 2016).

Renal effects

There is limited data available on the clinical studies on the renal effects of waste engine oil exposure in humans and animals. However, the assessment of renal function status in humans was recorded through clinical studies reported by Omorowa et al. (2015), which indicated higher levels of plasma urea and creatinine in auto mechanic workers who were repeatedly and daily exposed to occupational exposure to waste engine oils than in human subjects without occupational exposure. The renal effect indicates a decrease in primary renal function, which triggers other renal dysfunctions with prolonged exposure. In an animal study of kidney functions in rabbits, the histopathologic examination of the kidneys and urinary bladders showed no adverse effects with no histopathologic evidence of toxicity after dermal exposure (Beck et al., 1984). Also, no reports of renal necrosis or chronic interstitial nephritis were indicated in mice dermally administered with doses of 1667 mg/kg/day, biweekly, for two years (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). No significant histopathologic changes were noted in the ureteral or bladder urothelium or the renal parenchyma in the animals injected with waste engine oil (McDougall et al., 1997).

Anorexic effect and body weight loss

No clinical studies were found regarding body weight effects in humans after exposure to waste engine oil. In animal studies, anorexia, a decrease in rumen motility, and mild depression may occur after ingestion of waste engine oil, depending on dose and content. Hypoglycaemia may occur several days after ingestion. These clinical signs and weight loss may be the only responses observed in animals that do not bloat or aspirate oil. Some animals do not reestablish normal rumen function after ingestion and can develop a chronic wasting condition (Mostrom, 2021). Acute bloat in ruminants has been reported after consumption of waste engine oil. In experimental studies, no evidence of body-weight effects on growth or weight gain was observed in mice dermally administered with a single dose of waste engine oils at 22,500 mg/kg TPH concentration (Beck et al., 1984). But anorexia (a decreased appetite for food consumption) and weight loss were observed after dermal exposure in rabbits to 8 mL/kg of waste engine oils for 24 h per day, five days a week for two weeks (Beck et al., 1984; Vemot et al., 1990; Agency for Toxic Substances and Disease Registry (ATSDR), 1997). However, the basis of the loss of appetite for food was not identified.

Neurologic effects

Limited data is available on the clinical studies of the neurologic effects of prolonged exposure to waste engine oils in humans and animals. However, the neurotoxic effects of waste turbine engine oils have been reported in aircraft personnel with prolonged and repeated exposure, resulting in symptoms such as headache, dizziness, nausea, respiratory issues, and neurological disorders. These symptoms considerably impacted the health of aviation service technicians, affecting their ability to perform their duties safely and effectively (Pilot John International, 2024). An epidemiological study conducted by Clausen and Rastogi (1977) on a small group of auto mechanic workers reported tremors of the hands and headaches from repeated and prolonged inhalation exposure to waste engine oil aerosols. However, it is uncertain whether the incidence of the findings is increased in the control population as exposure to a substance other than waste engine oils and other confounding variables such as pre-existing diseases, nutrition, and lifestyle may have contributed to the observed neurological effects (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). No clinical studies were found regarding neurological effects in animals after exposure to waste engine oils. Nevertheless, cattle that ingested waste engine oils have manifested muscle tremors or muscle twitching, weakness, blindness, convulsion, and hyperirritability (Osweiler et al., 1973). However, the cause of the neurological effects reported in the animal study resulted from Pb and molybdenum poisoning (Sas, 1989).

Reproductive effects

Limited data is available on the clinical studies on the reproductive effects of prolonged exposure to waste engine oils in humans and animals. However, in animal experimental studies, reproductive cytotoxicity was observed in Sprague Dawley rats repeatedly ingested with 0.1–0.4 mL of waste engine oils for 28 days. Histological analysis indicated testicular seminiferous tubules were slightly degenerated in the absence of Lumen. The germinal cell layer contained necrosis of spermatogonia and interstitial (Leydig) cells, with affected Sertoli cells at different maturation stages. The ingestion hampered germ cell development and testicular activities in producing viable spermatozoa (Akintunde et al., 2015) and negatively affected the male reproductive parameters in rats. Studies have reported anti-oestrogenic activities from exposure to waste engine oil, indicating reproductive health issues (Sseppebwa et al., 2004). The study also reported weight loss, reduced sperm count and motility, increased sperm deformation, and testicular damage in the Sprague Dawley rats (Sibomana & Mattie, 2020).

Developmental effects

There is limited data on clinical studies of the effects of exposure to waste engine oils on human embryonic development. However, animal experimental studies conducted by Şişman et al. (2016) investigated the toxicity of waste engine oil-contaminated water in various concentrations up to 40.0 v/v on the developmental effects of fertilised Zebrafish eggs. They reported abnormal embryonic development, vertebra column defects, scoliosis, incomplete gastrulation, weak pigmentation, head malfunction, and pericardial oedema. Hoffmann and Albers (1984) also studied the potential embryotoxicity and teratogenicity of mallard bird (*Anas platyrhynchos*) eggs. In their studies, they reported significant embryonic cytotoxicity with a high number of anomalies and malformations, including brain defects, anencephaly, exencephaly, and eye defects (microphthalmia).

In another study, an egg painting study with waste engine oils on quails and ducks indicated decreased growth and survival in duck and quail foetuses, oedema, incomplete ossification, exencephaly, and microphthalmia. In addition, the hatchlings indicated decreased haemoglobin with low blood and liver δ-ALAD (Hoffman and Albers, 1984). The toxicity was attributable to the Pb and PAH contents instead of asphyxiation. It is unspecified whether a comparable developmental effect would be observed in humans if exposed to waste engine oils. Egg painting or injecting eggs with waste engine oil differs from performing reproductive toxicity tests in humans (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). Circulatory, excretory, metabolic, and maternal influences determine the foetus's exposure, quantitatively and qualitatively, if a pregnant animal is treated or administered with waste engine oil in a mammalian experimental situation. Therefore, the relevance of humans to egg toxicity after exposure to waste engine oils is remote, and there is no clear indication of teratogenic effects on human embryos or foetuses as scant information exists on the reproductive effects in humans (Siegel et al., 2019).

Genotoxic effects

Limited data is available on the clinical studies of the genotoxicity effects of prolonged exposure to waste engine oils in humans and animals. However, an animal experimental study conducted on Wistar rats by Obiyo et al. (2020) evaluated long-term dermal exposure, histopathological changes, and sperm morphology. The study reported spermatozoan abnormalities and lesions in the livers, kidneys, lungs, skin, and testis in the exposed Sprague Dawley rats caused by damage to the DNA compared with the negative control. The study concluded that waste engine oils could initiate harmful physiological changes and damage the DNA of humans if exposed to them. However, studies by Schoket et al. (1989) and Carmichael et al. (1990) found DNA adducts resulting from acute-duration dermal exposure to waste engine oils suggested specific adducts may cause the reaction of PAHs with DNA. PAH induces drug-metabolising enzymes, mainly cytochrome P4501A and aryl hydrocarbon hydroxylase (AHH). These enzymes metabolise PAH to epoxides, which subsequently hydroxylate to dihydrodiols that are non-carcinogenic. Additional epoxidation of the dihydrodiols forms reactive electrophilic species able to bind the DNA by forming DNA adducts, causing cancer and necrosis. Most adducts are repaired, resulting in few genetic lesions (ATSDR, 1997).

DNA adducts can be formed when human skin cultures are treated with waste engine oils. The treatment with waste engine oils from diesel engines results in fewer adducts than the waste engine oils from a petrol engine in vivo and in vitro tests (Carmichael et al., 1991). The qualitative differences in the adducts in human and animal skin culture tests are consistent with the metabolism of PAH through species-specific pathways. However, data regarding the genotoxicity of waste engine oils from diesel engines is less available than that regarding waste engine oils from gasoline engines. The genotoxicity increases as the mileage increases since the last oil change (Agency for Toxic Substances and Disease Registry (ATSDR), 1997). The PAH components in the waste engine form reactive species on the human skin if exposed to sunlight irradiation to cause DNA single-cell cleavage, oxidation of DNA bases, and formation of DNA covalent adducts which are responsible for damage to cellular components including cell membrane, nucleic acid and proteins (Patel et al., 2020). A study conducted by Ayoola et al. (2012) demonstrated genotoxic effects on *Clarias gariepinus* (catfish) exposed to sublethal concentrations of waste engine oil. The result showed varied levels of micro-nuclei and bi-nucleated tendencies in peripheral erythrocytes, causing cytogenetic damage in the cells of the fish (Ayoola et al., 2012).

Carcinogenic effects

Limited clinical data exists regarding the carcinogenic effects of waste engine oils on humans after prolonged exposure. However, an epidemiological study of the auto mechanic workers occupationally exposed to waste engine oils in Sweden indicated a lower likelihood of developing renal pelvic and bladder cancer (Steineck et al., 1989), the development of other types of cancer was not indicated. However, in animal experimental studies, such as mice, chronic-duration dermal exposure to waste engine oils resulted in a high incidence of dermal papilloma and carcinomas (McKee and Plutnick, 1989). The tumour incidence corresponded with the PAH in the waste engine oil, and DNA adducts were found in the tissues of the skin and lungs of mice that were dermally exposed to waste engine oils for 1–4 days (Carmichael et al., 1990). The findings also indicated that tumour development in organs other than the skin might be possible. From the animal studies, the International Agency for Research on Cancer (IARC) established that one sample of waste engine oil indicated sufficient proof of carcinogenicity (IARC, 1984).

Notwithstanding the limited clinical data regarding the carcinogenicity effects of waste engine oil in humans and animals. The reported epidemiological studies on humans and animals after repeated and prolonged exposure and dosing indicated the likelihood of acute or chronic effects on humans and animals after repeated or prolonged exposure to waste engine oil.

Preventive measures for occupational exposure

The preventive measures for occupational exposure help to reduce the potential risks associated with exposure to waste engine oils in the workplace. To minimise human health risks associated with occupational exposures, it is important to implement adequate environmental health and safety management practices and preventive measures, which include the strict use of personal protective equipment (PPE) such as gloves, goggles, masks, respirators, protective clothing, and aprons (Bahadori, 2015) when handling, storing, transporting, and disposing of waste engine oils. Ensure sufficient air circulation or ventilation in the work area with oil mists or fumes to avoid inhalation of particulate matter (Cao et al., 2021). Implement adequate hygiene practices by hand washing after contact with the waste engine oil. Avoid touching the exposed body, including the face, mouth, nose, or eyes, after handling waste engine oils or any contaminated objects or surfaces (Zahara et al., 2012). These measures prevent direct skin contact and nose and eye exposure to the waste engine oil and contaminants.

Implement proper disposal strategies to prevent environmental pollution. Follow safe handling practices by using leakproof containers for waste engine oil storage, avoiding spillage, and minimising splashes and aerosols. Store the waste engine oils in designated and properly labelled containers to prevent accidental spills and leakages. Install engineering controls such as exhaust ventilation systems to minimise the release and dispersion of oil mists, aerosols, and fumes in the workplace (Wang et al., 2022). Use containment systems such as drip pans or absorbent materials to capture spills and prevent spreading. Provide training to the workers on the potential hazards by raising awareness about the importance of preventive measures and encouraging a culture of safety in the workplace (McSweeney et al., 2023). Ensure proper disposal according to regulations and guidelines by using the authorised collection stakeholder or recycling facility. Stay updated with the applicable regulations, guidelines, and standards relating to the handling, storage, transportation, and disposal of waste engine oils. The regulatory guidelines and occupational safety and health protocols should be adopted and followed strictly to protect the workers and mitigate the potential health risks associated with waste engine oil exposure (Swick et al., 2014). By implementing these preventive measures, the risks associated with exposure to waste engine oils can be minimised, protecting the safety and health of the workers and reducing environmental pollution.

Recycling and regeneration of waste engine oils

Due to the adverse environmental effects, including geotoxicity, phytotoxicity, and human and animal health risks associated with indiscriminate disposal and miscellaneous misuse of waste engine oil, it becomes imperative to explore options for regeneration, recycling, and re-refining the waste engine oils to produce new mineral oils to prevent or minimise illegal disposal and environmental pollution (Katiyar & Husain, 2010; Oladimeji et al., 2018; Sánchez-Alvarracín et al., 2021). The benefits of the regeneration of waste engine oil include conserving valuable oil reserves through recycling, an economic boost, reduced environmental degradation, a reduced burden on storage and disposal, and a reduced carbon footprint (Selvi et al., 2013). Re-refining waste engine oil requires recycling and good disposal techniques that minimise pollution (Nissar et al., 2023; Rațiu et al., 2022). According to a report, a total of 1.6 L of recycled waste engine oil is used to produce 1 L of new mineral oil (Duđak et al., 2021). Figure 5 illustrates waste engine oil's regeneration or recycling process in the manufacture of new engine oil.

The treatment and regeneration technology for waste engine oils encourages good environmental treatment practices for managing recycled waste engine oils. The treatment is environmentally friendly and considers air emissions and the risks of human health issues (United Nations Environmental Programme (UNEP), 2015). The process is critical due to the high cost and, in some cases, the environmental hazards from the PCBs, phosphoric acid esters, and alkylbenzenes. The regeneration process involves restoring the quality of the waste engine oil to a level comparable to the original quality. Modern regeneration methods include physical and physicochemical processes such as coagulation, sulphuric acid purification, and adsorptive purification by synthetic or natural sorbents such as bentonites and clays (Syrmanova et al., 2017). Other methods follow the basic steps involving acid treatment for the removal of gums and greases, sedimentation/decantation, bleaching, neutralisation, sedimentation/decantation, and filtration (Stan et al., 2018).

The yield of engine oils through the re-refining of waste engine oils is higher than the yield from crude petroleum refining. The process promotes the reduction of about 90% of the environmental impacts

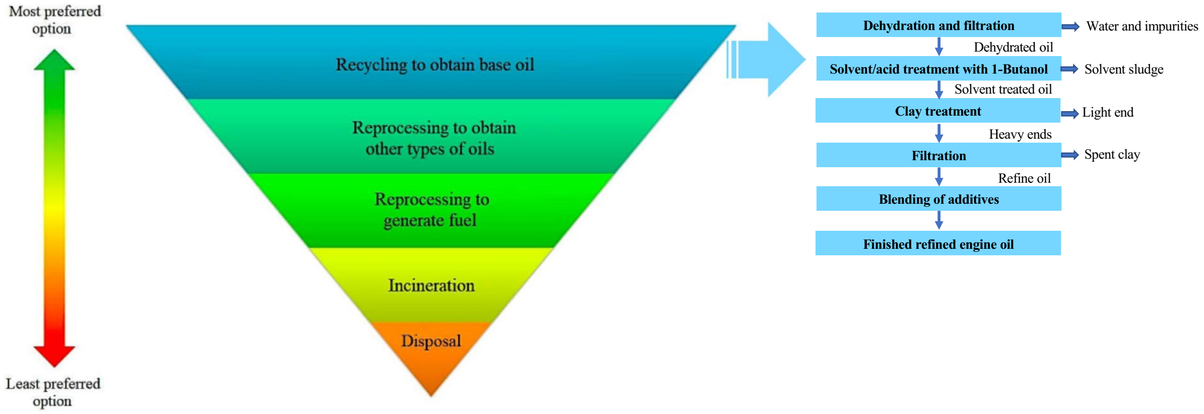


Fig. 5 Regeneration and recycling of waste engine oils (Armioni et al., 2020)

resulting from the manufacture of engine oils from crude oil (Mensah-Brown, 2015). Recycling and re-using waste engine oils are preferred over disposal and provide significant benefits to the environment. Recycled waste engine oils can be re-refined to manufacture new mineral-based oils. They can be processed into fuel oils and used as raw materials for the petroleum industries (Sánchez-Alvarracín et al., 2021). Regarding the benefits of recycling waste engine oils, El-Fadel and Khoury (2001) reported that 1 L of waste engine oils recycled and reprocessed as fuel contains about 8000 kJ of energy, enough to power a 100 W electric bulb for 24 h. The efficient recycling of waste engine oils could help reduce environmental pollution and gas emissions (greenhouse gases), thus creating environmental and economic benefits (Hsu et al., 2011). However, the major constraints facing the recycling, regeneration, and re-refining of waste engine oils are the cost of collection of waste engine oil from the generating sectors, storage facilities, and transportation to the recycling plant (Selvi et al., 2013).

In the recovery treatment processes for regenerating waste engine oils and incineration of waste engine oils by conventional methods, the impact generated by the incineration is higher than the impact in the regeneration, and the recycling by re-refining strategies is eco-friendly (Hassanain et al., 2017). However, de-asphalting, de-aromatisation, and dewaxing processes are the major processes that influence the environmental impacts during the processing of waste engine oils due to hazardous materials and toxic solvents used in the processes. Waste engine oils used as fuel oils in the refinery and power units are the main contributors to the environmental impacts during refining (Hassanain et al., 2017).

Risk-based-remediation technologies

The remediation technologies for waste engine pollution involve the treatment methods generally adopted for petroleum hydrocarbon pollution, including various containment, separation, and destruction methods (Ossai et al., 2020). The remediation methods comprise physical, chemical, and biological treatments. As waste engine oils cause environmental pollution and pose considerable threats, remediation and treatment technologies play an essential role in cleaning, containment, removal, reclamation, and restoring polluted environments. The remediation of polluted environments is site-specific and mainly dependent on the nature and composition of the waste engine oils and the physical, chemical, and biological conditions (Singh & Chandra, 2014) and comprises topsoil, subsoil, and sediment remediation (Godheja et al., 2016).

When selecting a suitable remediation technology, consideration is given to the cost, time constraints, mechanisms, and regulatory requirements (Khan et al., 2004). Figure 6 illustrates different remediation technologies available for treating petroleum hydrocarbon oil-polluted soil and water environments, including waste engine oil-polluted environments. The remediation of the oil-polluted water environment comprises the treatment of surface water or groundwater. Depending on the extent of the oil

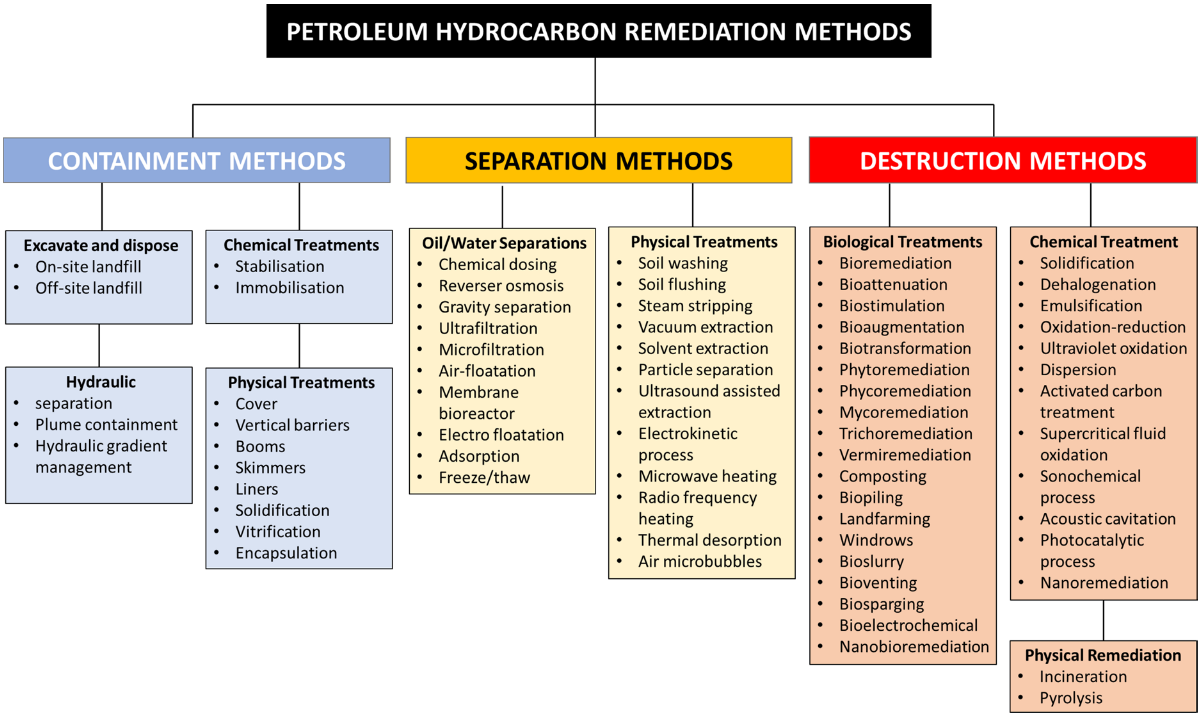


Fig. 6 Treatment and remediation technologies (Ossai et al., 2020)

pollution, soil and water remediation can be managed separately or jointly (Amro, 2004). Integrating one remediation technology with another simultaneously or sequentially may result in a synergistic or combined effect on the deployed remediation technology (Riser-Roberts, 1998).

The most widely used and studied remediation methodologies are biological treatment technologies, which use microorganisms, organic wastes, or plants to biodegrade environmental pollutants such as waste engine oil. The final products of biological treatment technologies are mostly H_2O and CO_2 (Montagnolli et al., 2009; Tamada et al., 2012). The biological treatment technologies are suitable for the remediation of waste engine oil-polluted environments with pollution levels less than 100,000 mg/kg for TPHs. In the biological treatment of the waste engine oil polluted soil, co-metabolism activity is enhanced by stimulating the growth of the indigenous microorganisms and providing suitable conditions such as adequate aeration, moderate pH, moisture, and nutrients from organic materials, including organic wastes and agricultural wastes (Azubuike et al., 2016; Kawedo et al., 2024; Ossai et al., 2022).

Remediation of the waste engine oil-polluted environment using conventional technologies involving physicochemical, thermal, and electromagnetics is challenging, laborious, and expensive (Ossai et al., 2022). The transition from costly conventional physicochemical treatment technologies to more environmentally friendly biological treatment technologies that reduce energy consumption, chemical usage, and cost of implementation, and enable more sustainable risk-based approaches towards environmental reclamation is recommended. The ecological effects and human health risks of waste engine oil pollution brought about the need for "green technologies" that remove environmental contaminants, and studies on engine oils with lower environmental impact and rapid biodegradation potential have become a practical option (Eisentraeger et al., 2002; Goyan et al., 1998). The research and development of fully synthetic, semi-synthetic, and plant-based oils are better alternatives to mineral-based oils from petroleum crude oil due to degradability by the microorganisms (Tamada et al., 2012; UNEP, 2015).

Legal restrictions on waste engine oils

Waste engine oils are among the waste oils listed as code A4060 under Annex VII, List A of the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes, and their Disposal 1989. The importation and exportation of such waste oil must follow the procedures of the Basel Convention. Most countries have various institutions that have a role to play in managing waste engine oils. Waste engine oils are classified as hazardous waste products that also require legal restrictions, including Environmental Regulations, Occupational Health and Safety Regulations, Product Safety and Standards, and special management strategies that minimise the negative environmental effects of their generation, disposal, and economic losses (Armioni et al., 2020; Rațiu et al., 2022). The management standard imposes requirements affecting commercial facilities' storage, transportation, burning, processing, and re-refining of waste engine oils. The regulations establish storage standards for facilities that heavily generate waste engine oils (United Nations Environmental Programme (UNEP), 2015). The local law requires the responsible storage, collection, and recycling of waste engine oils within the strict compliance requirements of the Waste Act. Several government regulators impose strict regulations on the re-using, handling, and disposal of waste engine oils to alleviate potential environmental hazards (Pinheiro et al., 2021).

For waste engine oil marketers, there is tracking and documentation. Transporters are responsible for determining the chemical analysis of the oil shipments and compliance with the requirements of the environment and transportation departments. The recyclers and re-refineries must comply with requirements for analysis of the oil, furnace type, and air pollution control systems. In most countries, governments have developed these standards, regulations, and procedures to reduce the risk of accidental spills and leakages in cooperation with the industry (Irwin et al., 1997). In the case of streams dispersed into the environment as oil mist or aerosol, such limitations are physically impossible, hence the need to initiate legal regulations and guidelines regarding the composition of the waste engine oil. Regulations for waste engine oils are still in creation and revision. The guidelines for inhalation, and oral and dermal exposures to waste engine oil can be found in the International Programme on Chemical Safety (IPCS), 2014).

The United States, the Environmental Protection Agency (USEPA), and some states have adopted regulations for managing and disposing of waste engine oils, recycling them, spreading them onto roads for dust control, and burning them as fuel. The USEPA also introduced new environmentally acceptable materials to produce engine oils that are less toxic and biodegradable, unlike mineral-based oils from petroleum (United States, the Environmental Protection Agency (USEPA, 2011).

In Canada, waste oils are regulated under the Environmental Protection Acts Provincial Hazardous Waste Regulation 1985 to control and regulate the handling, transportation, storage, processing, and disposal of hazardous wastes such as waste engine oils. The waste engine oil must be registered and disposed of at licensed facilities (Canadian Council of Ministers of the Environment (CCME), 1989).

In the United Kingdom, waste engine oils are classified as hazardous wastes and as special wastes under the Special Wastes Regulations. The regulations impose specific legal requirements for transportation, recovery, and disposal. The waste engine oils are also regulated jointly by the Environmental Agency for England and Wales, the Scottish Environment Protection Agency, and the Heritage Service in Northern Ireland under the Pollution Prevention and Control Regulations and Waste Management Licensing Regulations in the Environmental Protection Act 1990 and Water Resource Act 1991. These legal regulations protect the water and environment from contamination by waste engine oil pollution (Pollution Prevention Guideline (PPG8), 2004).

In Australia, waste engine oils are regulated under the Industrial Waste Management Policy (Prescribed Industrial Waste) in the Environment Protection Act 1993. It banned liquid waste from disposal in landfills and regulated all activities involving the transport, treatment, and disposal of liquid waste. The waste engine oil must be registered and disposed of in licensed waste disposal facilities (Industrial Waste Resource Guidelines (IWRG), 2009).

In China, waste engine oils are listed as a class 8 hazardous waste (HW08) in the National Hazardous Waste Catalogue of the Ministry of Ecology and Environment. The regulation enforces the recycling and regeneration of waste engine oils to prevent illegal disposal and pollution (Wu et al., 2017).

In Malaysia, waste engine oils are classified as scheduled wastes under the First Schedule of the Environmental Quality Act (Scheduled Wastes) Regulation 2005. According to the regulation, recycling and disposing of waste engine oil at licensed facilities is mandatory to prevent pollution (Mahmood et al., 2017).

In India, as per Schedule IV of the Hazardous Waste Rules 2008, waste engine oils are categorised as "hazardous wastes" and listed in Schedule I under the rules and classified as "Red" categories, requiring adequate recycling and re-refining of the waste engine oils for re-use (Selvi et al., 2013).

According to the European Union's list of oil wastes, waste engine oils are listed as hazardous entries and classified as hazardous wastes that present at least one hazardous property listed in Commission Regulation (EU) No. 1357/2014 (Pinheiro et al., 2021). According to the priority established by the hierarchy of waste management in the European Union (European Waste Directive 2008/98/EC Article 4.1.), The EU maintains the fundamental principle that waste engine oil generators are responsible for their safe collection and storage on-site and their eventual authorised removal (United Nations Environmental Programme (UNEP), 2012). There are existing laws and regulations for collecting, transporting, and disposing of waste engine oils. Regeneration technology must ensure best practices in environmental treatment for managing waste engine oils.

In Europe, manufacturers and importers of hazardous substances such as engine oil lubricants are required by the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulation to submit reports on the characteristics, hazards, uses, and risks associated with these hazardous chemical substances. The operating activities that utilise the engine oil and generate waste engine oil are subject to the REACH process. The requirements depend on the quantity generated, and the chemical safety report includes the exposure scenario describing the operational conditions and risk management measures under which the hazardous chemical substances can be safely handled and managed (Galea et al., 2014). Due to the effects of waste engine oil on the environment, the EU has proposed a ban on the marketing of new fuel combustion engine cars beginning in 2035 to facilitate the transition to zero-emission electric vehicles (EVs) as part of a comprehensive package of measures to mitigate the impact of waste engine oils and petrol as well as cut the emissions of CO_2 and CH_4 responsible for global warming (United Nations Environmental Programme (UNEP, 2015).

Conclusion and prospects

Waste engine oils are hazardous waste oils of environmental concern. The improper disposal and miscellaneous misuse result in pollution causing geotoxicity in the soil and phytotoxicity in plants. Prolonged and repeated exposures elicit severe health toxicities and degenerative disorders in humans and animals due to the toxic PAHs such as benzo[*a*]pyrenes and heavy metals such as Pb, Cd, Cr, Mn, Hg, Ni, Mo, Cu. Adequate handling and proper management of waste engine oil are key to reducing environmental pollution, and adopting occupational health and safety management practices is crucial in reducing occupational exposure in humans. The recycling of waste engine oils transforms the potential environmental hazard into a valuable resource and the regeneration of new engine oils reduces the disposal in landfills and incineration which cause adverse effects on the environment. Adequate occupational health and safety management procedures are required in handling waste engine oils during oil evacuation and storage which help to minimise or prevent dermal, inhalation, oral and ingestion exposures in the workplace. Risk-based remediation technologies help to mitigate the adverse environmental impact of pollution.

However, there is a need for more research studies on human subjects repeatedly exposed to waste engine oils, especially individuals working in waste oil recycling facilities for human toxicological and epidemiological studies. The prospect of preventing the consumption of engine oils, generation of waste engine oils, pollution and exposure is through the technological transition in the transportation sectors and industrial machinery operations by replacing conventional vehicles operating on internal combustion engine systems with battery electric vehicles, and replacement of industrial machinery operating on internal combustion engine systems and pressurised hydraulic fluid systems with electricity-operated machines and pneumatic pressure systems to eliminate the need for engine oils for lubrication and hydraulic power transfer. The technological transition will prevent the generation of waste engine oils and form a clean, non-polluting, and healthy environment. Nevertheless, further studies, research, and development are required to develop and replace, totally or partially, mineral-based oils with plant-based oils (bio-lubricant oils) with better degradability, less toxic, environmentally friendly, greenhouse gas-free, high viscosity index, good properties, function, and performance. Legal regulations are required to enforce the use of plant-based oils to replace the use of mineral-based oils and minimise overdependence on natural petroleum resources. These prospects will help to mitigate and prevent the ecotoxicological effects, and human and animal health risks posed by the pollution and exposure to waste engine oils.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare they have no competing interests and personal relationships that could influence the work reported in this research article.

Ethics approval and consent to participate The data in the manuscript are solely ours, and we are responsible for authenticity, validity, and originality. We also declare that the manuscript is our original research work and was not copied from anywhere else. Consent to participate is not applicable.

Consent for publication We undertake and agree that the manuscript submitted to the journal has not been published elsewhere and has not been simultaneously submitted to other journals.

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