Ecotoxicology of oil and petroleum products: from complex mixtures to ecological risk

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Abstract. Oil and petroleum products represent some of the most widespread environmental contaminants, affecting aquatic and terrestrial ecosystems through complex mixtures of hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), unresolved complex mixtures (UCMs), and associated metals. This review synthesizes recent advances in the ecotoxicology of petroleum-derived pollutants, emphasizing the role of chemical complexity, bioavailability, and exposure dynamics in determining ecological risk. In aquatic environments, PAHs and crude oil mixtures induce a wide range of adverse effects, including impaired growth and photosynthesis in microalgae, developmental abnormalities in fish embryos, and disruptions of aquatic food webs through bioaccumulation and trophic transfer. Emerging evidence highlights the importance of polar UCM fractions as significant contributors to toxicity, even in the absence of detectable PAHs. In terrestrial ecosystems, petroleum hydrocarbons alter soil structure, microbial communities, plant development, and invertebrate survival, with toxicity strongly influenced by hydrocarbon composition and environmental conditions. The review further examines ecotoxicological assessment methods, quantitative toxicity thresholds across taxa, and current remediation approaches, including bioremediation and phytoremediation. Overall, contemporary research demonstrates that ecological risks associated with petroleum pollution cannot be explained solely by individual compounds, but must account for mixture effects, organism sensitivity, food-web interactions, and environmental context. Integrating ecotoxicological testing with risk assessment and remediation strategies is essential for improving environmental management and protecting ecosystem and human health.

Keywords: petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), ecotoxicology, environmental contamination, bioaccumulation, ecological risk assessment, bioremediation.

Introduction. Oil and petroleum products contaminate air, water and soils from extraction through transport and accidental spills, creating complex chemical mixtures that affect microorganisms, plants, invertebrates, fish and birds. Recent work emphasizes that toxicity depends not only on individual compounds such as polycyclic aromatic hydrocarbons (PAHs), but also on unresolved complex mixtures, exposure conditions, and ecosystem context (Sharma et al., 2024; Honda & Suzuki, 2020; Meador & Nahrgang, 2019; Hook et al., 2022; Incardona, 2017; Harsha et al., 2024; Kuppusamy et al., 2019; Wu et al., 2024).

Aim of the Mini-Review. The aim of this mini-review is to synthesize recent scientific advances regarding the ecotoxicology of petroleum hydrocarbons, exploring how chemical complexity, bioavailability, and exposure dynamics dictate ecological risk across different trophic levels. Moving beyond individual contaminants, this work evaluates the multi-taxa impacts of complex mixtures in both aquatic and terrestrial ecosystems, while establishing the critical pathways of bioaccumulation and trophic transfer. Crucially, from a Public Health perspective, this review aims to bridge environmental data with human toxicology, outlining the downstream physiological and carcinogenic risks posed to human health through dietary exposure and xenobiotic metabolic pathways.

Conceptual Framework and Environmental Distribution. Oil, crude and waste oils contain alkanes, aromatics, PAHs, benzene derivatives, heteroatom compounds and associated metals, which disperse into aquatic systems, soils and the atmosphere, altering ecosystem structure and posing indirect risks to human health (Sharma et al., 2024; Falih et al., 2024; Majeed et al., 2025; Kuppusamy et al., 2019). From a medical perspective, these indirect risks are primarily driven by the dietary ingestion of lipophilic contaminants, which cross the human intestinal barrier and undergo hepatic biotransformation, converting stable compounds into highly reactive, toxic intermediates (Klaassen & Amdur, 2013). PAHs and broader total petroleum hydrocarbons (TPHs) are globally detected in surface waters, sediments, biota and even remote regions, with levels and profiles driven by shipping, combustion, industrialization and climate/seasonality (Honda & Suzuki, 2020; Othman et al., 2022; Mai et al., 2024; Kuppusamy et al., 2019; Wang et al., 2024; Zhang et al., 2020). Bioavailability, rather than total concentration, largely controls toxicity, with more hydrophilic or particle-associated fractions becoming accessible to benthic organisms and food webs (Honda & Suzuki, 2020; Othman et al., 2022; Mai et al., 2024; Kuppusamy et al., 2019; Wang et al., 2024) (Table 1).

Table 1

Key environmental behaviour and risk features
of petroleum-derived contaminants

Aspect	*Main points*	*References*
Chemical complexity	PAHs, polar UCM, metals, aliphatic and aromatic fractions; mixture effects	Sharma et al., 2024; Meador & Nahrgang, 2019; Harsha et al., 2024; Kuppusamy et al., 2019; Wu et al., 2024
Media & transport	Soil, water, sediments, air; long-range transport of PAHs	Falih et al., 2024; Majeed et al., 2025; Kuppusamy et al., 2019; Wang et al., 2024
Bioaccumulation & food webs	Trophic transfer, biomagnification, species- and habitat-specific accumulation	Honda & Suzuki, 2020; Othman et al., 2022; Mai et al., 2024; Wang et al., 2024; Zhang et al., 2020
Risk endpoints	Carcinogenicity, mutagenicity, developmental and sublethal effects, human seafood risk, hepatic DNA adduct formation, xenobiotic metabolism, bone marrow/leukemogenic risks.	Honda & Suzuki, 2020; Othman et al., 2022; Mai et al., 2024; Kuppusamy et al., 2019; Wang et al., 2024; Zhang et al., 2020; Luch, 2005.

Aquatic Ecotoxicology: PAHs, Crude Oil Mixtures and Mechanisms. PAHs from spills and combustion are major toxicants in marine and freshwater systems, affecting invertebrates, fish and primary producers (Honda & Suzuki, 2020; Achyani et al., 2021; Othman et al., 2022; Mai et al., 2024). Microalgae show species- and dose-dependent impairments of growth, chlorophyll, photosynthesis and antioxidant defenses; benzo[a]pyrene is much more toxic than low-ring PAHs, and freshwater assemblages appear more sensitive than marine ones (Othman et al., 2022).

In fish, early life stages are particularly sensitive (Alămorean et al., 2015). Crude oil and associated PACs cause cardiac malformations, edema, arrhythmias and craniofacial defects via both aryl hydrocarbon receptor (AHR)–dependent pathways (for strong agonists) and AHR-independent interference with cardiomyocyte ion currents and calcium homeostasis (Incardona, 2017; Sørhus et al., 2020; Harsha et al., 2024; Cherr et al., 2017; Incardona et al., 2024). Very low PAH levels can alter heart rate and contractility, reducing swimming performance, and some PAHs become highly phototoxic under sunlight (Cherr et al., 2017).

However, attributing crude oil embryotoxicity solely to PAHs is challenged: water-soluble fractions contain thousands of other compounds, and observed syndromes may represent baseline narcosis from membrane disruption and altered ion homeostasis rather than specific receptor-mediated effects (Meador & Nahrgang, 2019; Kuppusamy et al., 2019). Experimental work with alkyl-phenanthrenes shows that multiple cardiotoxic mechanisms and synergistic interactions within this subfraction alone can explain much of crude oil's high potency (Incardona et al., 2024).

Short-term versus continuous exposures and preparation methods of oil-in-water mixtures (WAF, HEWAF, chemically enhanced WAF) strongly influence apparent toxicity. Total PAH (TPAH) concentrations relate well to effects, with HEWAF typically most toxic due to higher dissolved oil, and dispersants contributing to toxicity in some invertebrates (Hook et al., 2022; Gissi et al., 2021). Fish embryos may show deformities even under brief pulses at elevated concentrations, whereas copepods and sea urchins respond mainly to longer exposures (Hook et al., 2022; Gissi et al., 2021). New findings also identify polar unresolved complex mixtures (UCM), including photoproduced hydrocarbon oxidation products, as major drivers of embryotoxicity in the absence of detectable PAHs, producing canonical edema and cardiac defects at low dissolved organic carbon levels (Harsha et al., 2024).

Food web studies demonstrate that PAHs bioaccumulate with trophic level but can "block" in lower trophic organisms such as zooplankton, which may retain much higher concentrations and bioaccumulation factors than fish, simplifying food webs and reducing fish reproduction via pathways such as NOD-like receptor signaling (Mai et al., 2024). Field investigations in marine fishing grounds show that 2–3 ring PAHs often dominate organism tissues, with coal combustion an important source and excess lifetime cancer risk from seafood consumption slightly above guideline benchmarks but below priority concern levels (Zhang et al., 2020). Physiologically, chronic human exposure to these biomagnified subfractions (such as benzo[a]pyrene) triggers Cytochrome P450 (specifically CYP1A1) enzymatic pathways (Baird et al., 2005). This metabolic activation leads to the formation of reactive diol-epoxides that covalently bind to cellular DNA, forming DNA adducts; this mechanism induces genotoxicity, cellular oxidative stress, and long-term carcinogenic pathways in target organs like the liver and bone marrow (Baird et al., 2005; Luch, 2005). Reviews at the global scale confirm increasing PAH burdens, clear geographic risk patterns, and strong links between bioaccumulation and aquatic pollution, emphasizing carcinogenic PAHs such as benzo[a]pyrene (Honda & Suzuki, 2020; Wang et al., 2024).

Terrestrial Ecotoxicology of Petroleum Hydrocarbons. In soils, oil leakage alters physical structure, chemistry, microbiota and plant performance, threatening fertility and ecosystem services (Sharma et al., 2024; Falih et al., 2024; Majeed et al., 2025; Kuppusamy et al., 2019; Wu et al., 2024). TPH contamination can impair earthworm survival and behavior, with EC50 values in the hundreds of mg TPH/kg and high mortality around 1000 mg/kg, and reduce seed germination and growth of crops such as Avena sativa, especially at higher contamination levels (Hentati et al., 2013). Terrestrial plants experience oil penetration into cells, reduced transpiration, disrupted photosynthesis and genotoxic effects, while some aquatic and wetland plants may also act as oil sorbents in remediation (Sharma et al., 2024; Wu et al., 2024).

Comparative analyses indicate that toxicity of PHs tends to increase with molecular weight, with low-molecular-weight cyclic alkanes particularly toxic to aquatic organisms and aromatic hydrocarbons generally more toxic than aliphatics in soils (Kuppusamy et al., 2019). Bioavailable (often more hydrophilic) fractions drive acute and sublethal outcomes, ranging from lesions and developmental defects to behavioral perturbations in feeding and reproduction, with narcosis resulting from partitioning into cell membranes and nervous tissue under high, short-term exposures (Kuppusamy et al., 2019).

Soil-focused reviews highlight that differences in bioavailability and biodegradability of aliphatic versus aromatic fractions, and mismatches between hydrocarbon removal and toxicity reduction, complicate risk-based remediation (Majeed et al., 2025; Wu et al., 2024). Bioremediation strategies such as biostimulation, bioaugmentation and phytoremediation are widely explored, but require better understanding of ecotoxicity differentiation among fractions, unified risk indicators, and the fate and transformation of hydrocarbons under varying soil and climatic conditions (Majeed et al., 2025; Wu et al., 2024).

Ecotoxicological Assessment, Risk and Remediation Strategies. Ecotoxicological methods are increasingly recognized as essential for assessing the real impacts of oil spills and chronic contamination, complementing chemical analyses and hydrodynamic models (Falih et al., 2024; Abessa, 2023; Hentati et al., 2013; Majeed et al., 2025; Wu et al., 2024). Bioassays with aquatic invertebrates, fish embryos, earthworms, springtails and plants provide cost-effective tools to link contaminant levels, mixture composition and exposure scenarios to biological responses, including acute mortality, sublethal development and reproductive endpoints (Hook et al., 2022; Abessa, 2023; Hentati et al., 2013; Gissi et al., 2021; Cherr et al., 2017; Wu et al., 2024).

Risk assessments must account for mixture toxicity, exposure duration, life-stage sensitivity and food-web processes such as biomagnification and "blocking" at intermediate trophic levels (Meador & Nahrgang, 2019; Hook et al., 2022; Mai et al., 2024; Gissi et al., 2021; Kuppusamy et al., 2019; Wang et al., 2024). For PAHs in surface waters and seafood, integrated frameworks now combine spatiotemporal distribution data, source apportionment, bioaccumulation metrics and human health endpoints (e.g., excess cancer risk) (Honda & Suzuki, 2020; Wang et al., 2024; Zhang et al., 2020). For soils, modern approaches emphasize toxicity-based endpoints alongside concentration-based thresholds and advocate combined bioremediation techniques tailored to site-specific oil types, soil properties and climates (Falih et al., 2024; Hentati et al., 2013; Majeed et al., 2025; Wu et al., 2024).

Overall, current research converges on several cross-cutting themes: the central role of complex mixtures beyond PAHs; critical vulnerability of early developmental stages in aquatic vertebrates; the importance of bioavailability, exposure dynamics and food-web structure; and the need to embed ecotoxicological testing within regulatory and remediation frameworks to more accurately capture ecological and human risks from oil and petroleum products (Sharma et al., 2024; Honda & Suzuki, 2020; Meador & Nahrgang, 2019; Hook et al., 2022; Othman et al., 2022; Incardona, 2017; Mai et al., 2024; Harsha et al., 2024; Abessa, 2023; Gissi et al., 2021; Cherr et al., 2017; Kuppusamy et al., 2019; Wang et al., 2024; Wu et al., 2024; Zhang et al., 2020; Incardona et al., 2024) (Figure 1).

Comparative Quantitative Toxicity of Petroleum Pollution: Key Experimental Values. Petroleum hydrocarbons and associated PAHs show highly variable toxicity across taxa, compounds, and exposure conditions. Below is a compact comparative table with experimentally reported or synthesized quantitative endpoints from the provided literature (Table 2).

Table 2

Cross-taxa quantitative toxicity metrics for petroleum and PAHs

System / taxon & exposure	*Substance / mixture & metric*	*Quantitative value (units)*	*Notes on effect / sensitivity*	*References*
Microalgae, mixed taxa (freshwater vs marine)	Single PAHs, HC5 from SSD (all PAHs combined)	Overall HC5 ≈ 4.72 μg/L	Harmful concentration for 5% of species across PAHs; SSD-based	Othman et al., 2022
Freshwater microalgae	PAHs, HC5 (all PAHs)	1.09 μg/L	Freshwater taxa notably more sensitive than marine	Othman et al., 2022
Marine microalgae	PAHs, HC5 (all PAHs)	26.3 μg/L	Indicates higher average tolerance in marine phytoplankton	Othman et al., 2022
Microalgae, single-PAH ranking	Naphthalene	HC5 = 650 μg/L	Among least toxic PAHs to microalgae	Othman et al., 2022
Microalgae	Acenaphthene	HC5 = 274 μg/L	Intermediate toxicity	Othman et al., 2022
Microalgae	Fluorene	HC5 = 76.8	More toxic than	Othman et

System / taxon & exposure	*Substance / mixture & metric*	*Quantitative value (units)*	*Notes on effect / sensitivity*	*References*
		μg/L	naphthalene/acenaphthene	al., 2022
Microalgae	Benzo[a]pyrene	HC5 = 0.834 μg/L	Among most toxic PAHs to microalgae	Othman et al., 2022
Fish embryos (Pacific herring)	Polar UCM from crude oil, dark – edema EC50	0.47 mg/L NVDOC (95% CI 0.02–2.49)	Developmental edema at sub-mg/L dissolved organic carbon	Harsha et al., 2024
Fish embryos (Pacific herring)	Polar UCM, light – edema EC50	1.01 mg/L NVDOC (95% CI 0.46–2.31)	Photomodified mixture somewhat less potent than dark UCM	Harsha et al., 2024
Fish embryos (general; phenanthrenes)	Phenanthrene + alkyl-phenanthrenes, EC50 range	39–116 μg/L (single compounds)	Example used for toxic-unit ($\Sigma TU=1$) mixture modeling; mixture EC50 cannot be < most toxic single EC50	Meador & Nahrgang, 2019
Fish embryos (yellowtail kingfish)	Condensate WAF, pericardial edema EC10 / EC50 (24 h)	EC10 ≈ 0.01 μg/L TPAH (0–0.03); EC50 ≈ 1.2 μg/L TPAH (0.63–1.8)	Extremely low TPAH concentrations induce cardiac deformity; estimates from continuous exposure	Gissi et al., 2021
Fish embryos (yellowtail kingfish)	Crude oil HEWAF, deformities EC10 / EC50 (1 h vs continuous)	Continuous: EC50 ≈ 496–771 μg/L TPAH; 2 h pulse: EC50 ≈ 11–38 μg/L TPAH	Short pulses at higher TPAH can approach or exceed continuous-effect levels; cardiac deformities	Hook et al., 2022
Copepods & sea urchins	Crude oil WAF/CEWAF/HEWAF, EC10/EC50 (TPAH basis)	EC10–EC50 often at low–mid μg/L TPAH; overlapping CIs among preparations	Toxicity driven largely by total PAH concentration; HEWAF generally most toxic	Hook et al., 2022
Earthworm (*Eisenia* sp.) in soil	TPH-contaminated soil, EC50 (avoidance/mortality)	644 mg TPH/kg soil (14 d)	67% mortality at 1,000 mg/kg after 14 d exposure	Hentati et al., 2013
Terrestrial plants (*Avena sativa*)	TPH-contaminated field soil	Germination 64–74% at low TPH; <50% at high TPH	Clear inverse relationship between TPH level and seed germination	Hentati et al., 2013
Marine organisms (field biota)	Σ16 PAHs in tissues	86.37–350.53 ng/g dw	2–3-ring PAHs dominant; BSAF decreases with logKow	Zhang et al., 2020
Human health from seafood PAHs	Excess cancer risk	Slightly > 10^{-6} but ≪ 10^{-4}	Above minimal guideline but below priority risk; site-specific	Zhang et al., 2020.

Across studies, fish embryos and microalgae exhibit very low effect thresholds (sub-μg/L to low-μg/L for many PAHs and TPAH mixtures), whereas soil invertebrates and plants tolerate far higher mass-based TPH levels before strong responses occur. Toxicity often correlates with total PAH concentration and compound structure (e.g., benzo[a]pyrene and polar UCM being highly potent), and short high-concentration pulses can approximate effects of longer continuous exposures in some developmental endpoints.

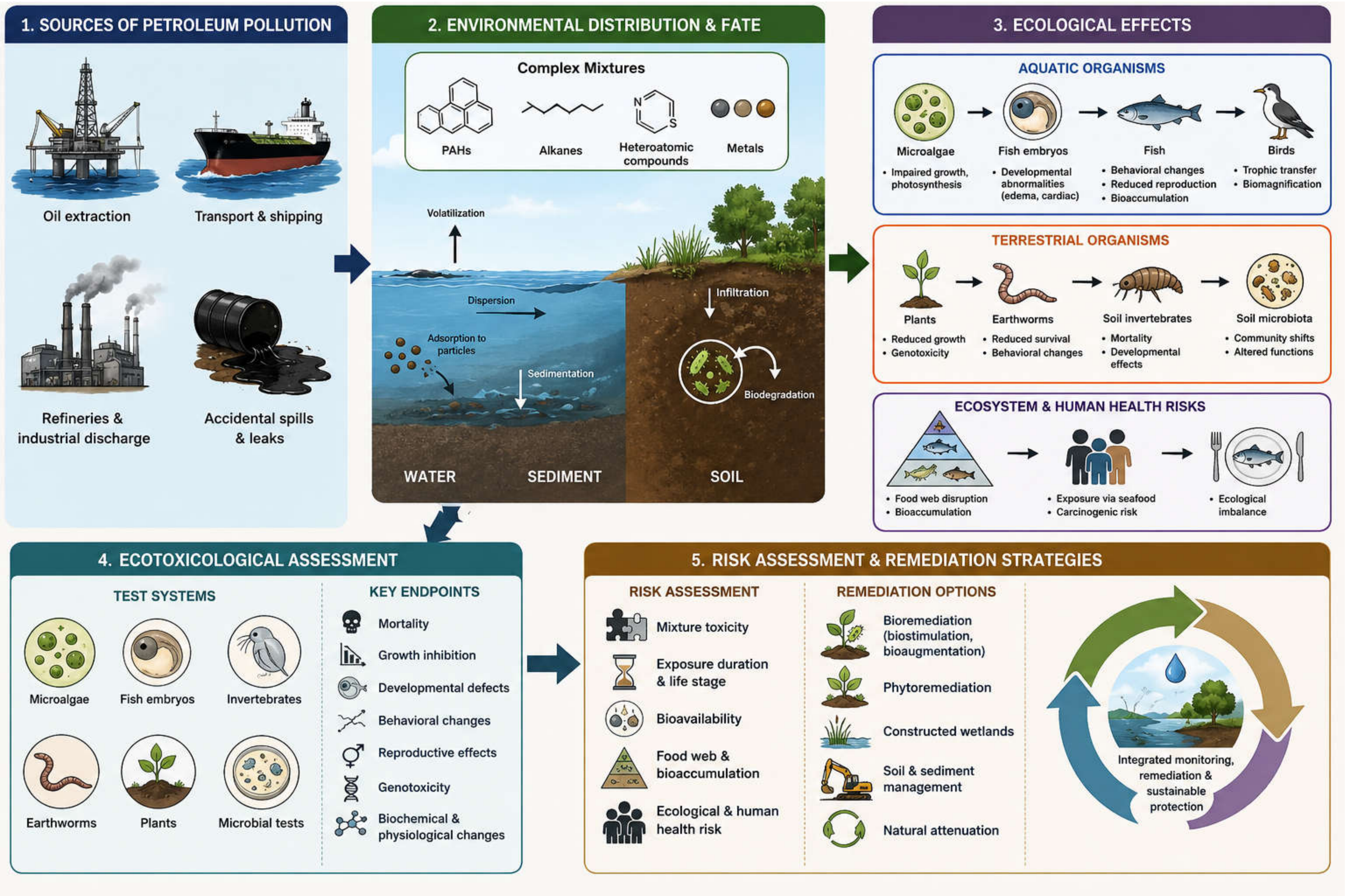

Figure 1. Ecotoxicology of oil and petroleum products: from complex mixtures to ecological risk.

Conclusions. Petroleum hydrocarbons and petroleum products represent a major source of environmental contamination, affecting aquatic and terrestrial ecosystems through complex chemical mixtures with diverse toxicological properties. The reviewed literature demonstrates that ecological impacts are determined not only by the presence of PAHs, but also by unresolved complex mixtures, bioavailability, exposure duration, and environmental conditions.

Aquatic organisms, particularly fish embryos and microalgae, exhibit high sensitivity to petroleum-derived contaminants, with adverse effects occurring even at very low concentrations. In terrestrial ecosystems, petroleum pollution alters soil properties, microbial communities, plant growth, and the survival of soil invertebrates, ultimately reducing ecosystem functioning and productivity.

Current research highlights the importance of considering mixture toxicity, trophic transfer, and bioaccumulation processes when assessing ecological risk. Traditional chemical analyses alone are insufficient to fully characterize environmental impacts, making ecotoxicological bioassays essential tools for risk assessment.

Effective management of petroleum contamination requires integrated approaches that combine chemical monitoring, ecotoxicological evaluation, and remediation strategies such as bioremediation and phytoremediation. Future studies should focus on improving the understanding of complex mixture toxicity and developing standardized, risk-based assessment frameworks to better protect environmental and human health.

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