

ENVIRONMENTAL TOXICOLOGY AND RISK ASSESSMENT

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ABSTRACT

Environmental toxicology and risk assessment have become increasingly important fields of environmental science because of the growing release, persistence, transformation, and biological accumulation of hazardous substances in ecosystems. Rapid industrialization, urbanization, agricultural intensification, mining, transportation, pharmaceutical consumption, plastic production, and inadequate waste management have introduced a wide range of chemical contaminants into air, water, soil, sediments, and biological systems. Conventional pollutants such as heavy metals, pesticides, petroleum hydrocarbons, industrial chemicals, and persistent organic pollutants continue to pose serious ecological and human-health concerns, while emerging contaminants such as pharmaceuticals, personal-care products, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances (PFAS), microplastics, nanoplastics, and transformation products have created additional challenges for environmental risk assessment. Recent research emphasizes that many contaminants cannot be evaluated adequately through traditional single-chemical and single-species approaches because environmental exposure commonly involves mixtures, chronic low-dose exposure, transformation products, bioaccumulation, trophic transfer, and interactions among chemical and biological stressors. (DOI) Environmental toxicology provides the scientific basis for understanding how contaminants interact with organisms at molecular, cellular, physiological, population, community, and ecosystem levels. Toxicological endpoints such as oxidative stress, endocrine disruption, genotoxicity, neurotoxicity, reproductive impairment, immunotoxicity, altered metabolism, behavioral changes, and mortality are increasingly used to characterize environmental hazards. Risk assessment complements toxicological research by evaluating the probability and magnitude of adverse effects under realistic exposure conditions. The process generally involves hazard identification, dose-response assessment, exposure assessment, and risk characterization. However, uncertainty remains a major component of environmental risk assessment because environmental concentrations fluctuate, contaminants undergo transformation, organisms differ in sensitivity, and data are often unavailable for many species and chemical combinations.

KEYWORDS: Environmental Toxicology, Risk Assessment, Ecotoxicology, Emerging Contaminants, Environmental Pollution, Toxicity, Exposure Assessment, Ecological Risk, Heavy Metals, PFAS, Microplastics, Environmental Health.

INTRODUCTION

Environmental pollution has become one of the most important challenges affecting ecological stability, public health, and sustainable development. The expansion of industrial activities, agricultural production, transportation, urban settlements, mining, energy generation, pharmaceutical use, plastic manufacturing, and modern consumer lifestyles has increased the quantity and diversity of substances released into the environment. These substances may enter environmental compartments through industrial wastewater, municipal sewage, agricultural runoff, atmospheric deposition, landfill leachate, accidental releases, mining activities, and inappropriate disposal of chemicals and consumer products. Once released, pollutants can move among air, water, soil, sediment, and living organisms. Their environmental behavior depends on properties such as solubility, volatility, persistence, adsorption, degradation rate, bioavailability, and capacity for bioaccumulation. Consequently, environmental contamination is not simply a problem of pollutant concentration; it is a complex interaction between chemical properties, environmental processes, biological

responses, and patterns of human exposure. Environmental toxicology is the scientific discipline concerned with understanding the harmful effects of environmental contaminants on living organisms and ecosystems. It combines concepts from toxicology, ecology, environmental chemistry, physiology, molecular biology, and public health to determine how pollutants affect biological systems. Traditional toxicological research frequently concentrated on individual chemicals and relatively acute effects, whereas contemporary environmental toxicology increasingly examines chronic exposure, low-dose effects, mixtures, multiple environmental stressors, transformation products, and effects across several biological levels. This broader perspective is necessary because organisms in natural ecosystems are rarely exposed to a single pollutant.

Instead, they may encounter complex mixtures of pesticides, pharmaceuticals, metals, industrial chemicals, plastics, pathogens, and other stressors simultaneously. The increasing recognition of emerging contaminants has further complicated environmental toxicology. Emerging contaminants include substances that may not have historically been regulated or routinely monitored but have the potential to cause adverse environmental or health effects. Pharmaceuticals, personal-care products, endocrine-disrupting chemicals, PFAS, microplastics, nanoplastics, engineered nanomaterials, and various industrial chemicals are among the groups receiving significant scientific attention. Recent reviews indicate that these contaminants can occur across aquatic and terrestrial environments and may persist, transform, bioaccumulate, or move through food webs. (Springer) Water environments are particularly important in environmental toxicology because rivers, lakes, groundwater, wetlands, estuaries, and coastal systems receive pollutants from multiple sources. Wastewater treatment plants can reduce many conventional contaminants, but some pharmaceuticals, personal-care chemicals, PFAS, microplastics, and transformation products may remain in treated effluent. Agricultural runoff may introduce pesticides, fertilizers, veterinary pharmaceuticals, and metals into surface waters. Industrial discharges may contain solvents, dyes, metals, hydrocarbons, and other hazardous substances. These pollutants may interact with aquatic organisms and produce effects at biochemical, physiological, behavioral, reproductive, and population levels. Recent research demonstrates that emerging pollutants can affect aquatic organisms through several mechanisms. Oxidative stress is particularly important because excessive production of reactive oxygen species can damage lipids, proteins, DNA, and cellular structures. Endocrine-disrupting chemicals can interfere with hormonal signaling and reproductive processes. Genotoxic substances may damage genetic material, while neurotoxic substances can alter nervous-system functions and behavior. Immunotoxicity can reduce the ability of organisms to resist disease, whereas reproductive toxicity can reduce population sustainability.

A recent 2026 review reported that pharmaceuticals, pesticides, microplastics, nanoparticles, and heavy metals can induce oxidative stress, endocrine disruption, genotoxicity, and immunotoxicity in aquatic organisms. (DOI) Soil is another important environmental compartment in toxicological studies. Agricultural pesticides, sewage sludge, industrial waste, mining residues, petroleum hydrocarbons, and heavy metals can accumulate in soil. Contaminated soil may affect microorganisms, plants, soil invertebrates, and terrestrial animals. Pollutants can also enter agricultural crops and subsequently reach humans through the food chain. Persistent contaminants may remain in soils for long periods, while some substances can migrate into groundwater. Therefore, soil contamination should be evaluated

not only according to pollutant concentration but also according to mobility, bioavailability, degradation, and potential food-chain transfer. Air pollution also represents an important component of environmental toxicology. Particulate matter, volatile organic compounds, persistent organic pollutants, heavy metals, combustion products, and other airborne contaminants can affect respiratory, cardiovascular, neurological, and immune systems. Atmospheric contaminants may subsequently deposit on soil and water surfaces, creating connections between air pollution and other environmental compartments. Environmental toxicology therefore requires an integrated understanding of pollutant movement across the environment rather than treating air, water, and soil as completely separate systems. One of the most important challenges in modern environmental toxicology is the assessment of contaminants at very low concentrations. Advances in analytical chemistry have allowed scientists to detect substances at trace and ultra-trace levels that previously could not be measured. High-performance liquid chromatography, gas chromatography, mass spectrometry, high-resolution mass spectrometry, biosensors, molecular techniques, and non-target screening have expanded the ability to identify contaminants. However, improved detection creates another challenge: detecting a chemical does not automatically establish its ecological risk. Toxicological information, exposure levels, environmental fate, biological sensitivity, and dose-response relationships must also be considered. Risk assessment provides a framework for connecting environmental contamination with potential adverse effects. Environmental risk assessment generally involves hazard identification, dose-response assessment, exposure assessment, and risk characterization. Hazard identification determines whether a substance has the potential to produce harmful effects. Dose-response assessment examines the relationship between exposure and biological response. Exposure assessment determines how, where, when, and at what concentration organisms or humans encounter contaminants. Risk characterization integrates these components to estimate the likelihood and magnitude of adverse outcomes.

A major limitation of conventional risk assessment is its dependence on available toxicity and exposure data. Many emerging contaminants have limited toxicological information, particularly regarding chronic exposure, mixture effects, sensitive life stages, and long-term ecological consequences. In addition, risk assessment frequently relies on laboratory species because comprehensive testing across natural communities is difficult and expensive. Differences between laboratory and natural conditions can therefore introduce uncertainty. Transformation products represent another major concern. Environmental contaminants rarely remain unchanged after entering the environment. Microbial activity, photolysis, hydrolysis, oxidation-reduction reactions, and wastewater treatment processes can transform parent chemicals into new compounds. Some transformation products may be less toxic, but others can be more persistent, mobile, or biologically active than their parent substances. Recent research emphasizes that environmental risk assessment should therefore consider transformation products rather than focusing exclusively on original chemicals. (Springer)

Mixture toxicity is similarly important. Organisms may simultaneously encounter several chemicals that affect the same biological pathway or different pathways. Mixtures may produce additive, synergistic, or antagonistic effects. For example, several endocrine-disrupting compounds may collectively interfere with hormonal regulation even when individual concentrations are below their respective effect thresholds. Similarly, metals and

organic pollutants may interact with environmental stressors such as temperature, salinity, oxygen deficiency, or pathogens. Climate change adds another dimension to environmental risk. Changes in temperature, precipitation, flooding, drought, ocean conditions, and extreme weather events can modify contaminant transport, degradation, bioavailability, and exposure. Flooding can redistribute contaminants from contaminated soils and sediments, while drought can concentrate pollutants in water bodies. Higher temperatures may influence metabolic rates and toxicity. Therefore, environmental risk assessment increasingly needs to consider changing environmental conditions. Technological developments are creating new opportunities for environmental toxicology. Artificial intelligence, machine learning, high-throughput screening, omics technologies, computational toxicology, and big-data integration can improve the speed and scale of environmental assessment. Recent work suggests that integrating chemical measurements with biological responses can reveal relationships that are difficult to identify through conventional approaches. (Nature) However, AI should complement rather than replace experimental evidence because model predictions can be affected by biased datasets, limited validation, and differences between chemical classes and ecosystems. (Springer) Therefore, environmental toxicology and risk assessment should be viewed as interconnected components of modern environmental protection. Toxicological studies explain how pollutants produce biological effects, while risk assessment evaluates whether those effects are likely to occur under real-world exposure conditions. Integrating these fields can support evidence-based environmental regulation, pollution prevention, monitoring, remediation, and public-health protection.

RESEARCH OBJECTIVES

1. To examine the major environmental contaminants, their sources, exposure pathways, and toxicological effects on humans and ecosystems.
2. To evaluate contemporary environmental risk-assessment approaches used to identify, characterize, and manage risks associated with chemical and emerging contaminants.
3. To identify major challenges and future directions for improving environmental toxicology, monitoring, risk assessment, and sustainable pollution management.

RESEARCH QUESTIONS

1. What are the major environmental contaminants and how do they affect human health and ecological systems?
2. How are toxicological information, exposure assessment, and dose-response relationships integrated into environmental risk assessment?
3. What emerging approaches can improve the accuracy, efficiency, and reliability of environmental toxicology and risk assessment?

LITERATURE REVIEW

Recent literature demonstrates that environmental contamination has become increasingly complex because of the diversity of chemicals entering natural ecosystems. Conventional contaminants such as heavy metals, pesticides, petroleum hydrocarbons, industrial solvents, and persistent organic pollutants remain important, but they are now accompanied by pharmaceuticals, personal-care products, endocrine-disrupting chemicals, PFAS,

microplastics, nanoplastics, and engineered nanomaterials. A 2024 comprehensive review reported that emerging contaminants can persist in environmental systems, accumulate in food chains, and cause ecological and human-health concerns. The review also emphasized the need for improved analytical methods, standardized detection procedures, stronger regulatory frameworks, and interdisciplinary management. (DOI)Boahen, Owusu, and Adjei-Anim (2025) highlighted the global importance of emerging contaminants, particularly pharmaceuticals, PFAS, endocrine-disrupting chemicals, micro- and nanoplastics, and industrial chemicals. Their review showed that advanced analytical techniques such as gas chromatography, high-performance liquid chromatography, mass spectrometry, high-resolution mass spectrometry, biosensors, and molecular approaches are increasingly important for identifying and quantifying contaminants. The authors also emphasized that contaminant distribution is not restricted to highly industrialized environments because long-range environmental transport can introduce pollutants into relatively remote ecosystems. (Springer)Recent 2026 research further demonstrates the importance of studying environmental contaminants as complex mixtures. Salaudeen et al. (2026) reported that emerging contaminants are characterized by persistence, complex transformation pathways, bioaccumulation, and potential trophic transfer. Their systematic review identified endocrine disruption, genotoxicity, antimicrobial resistance, and ecological imbalance among important reported effects. These findings suggest that environmental monitoring must move beyond traditional priority pollutants and consider a wider range of chemicals and biological endpoints.

Environmental toxicology has increasingly focused on mechanisms through which pollutants cause biological damage. Oxidative stress is one of the most widely recognized mechanisms because many pollutants stimulate excessive production of reactive oxygen species. When antioxidant defenses cannot adequately control these reactive molecules, oxidative damage may occur in cellular membranes, proteins, and genetic material. Endocrine disruption is another major mechanism, particularly for pharmaceuticals, pesticides, plastic additives, and industrial chemicals capable of interfering with hormone receptors or hormone synthesis. Genotoxicity is also important because DNA damage may affect cellular function, reproduction, development, and long-term population health. Neurotoxicity can affect behavior, feeding, movement, and predator avoidance. Immunotoxicity can reduce disease resistance, while reproductive toxicity can decrease fertility and population growth. Recent evidence from aquatic organisms indicates that emerging pollutants may affect multiple physiological systems simultaneously. Sefali et al. (2026), for example, reported that pharmaceuticals, pesticides, microplastics, nanoparticles, and heavy metals may cause oxidative stress, endocrine disruption, genotoxicity, and immunotoxicity in aquatic organisms. (DOI)The ecological significance of toxicological effects depends on biological organization. Molecular changes may initially appear minor, but repeated exposure can produce cellular damage, physiological dysfunction, altered behavior, reduced reproductive success, population decline, and community-level changes. Therefore, ecological risk assessment should consider multiple levels of biological organization. A pollutant that produces a measurable biochemical effect may not necessarily produce population-level damage, while a pollutant causing moderate physiological effects across multiple life stages may have substantial long-term consequences. Environmental risk assessment traditionally combines hazard identification, dose-response assessment, exposure assessment, and risk characterization.

However, contemporary environmental problems require more sophisticated approaches. For emerging pollutants, risk quotients can provide an initial comparison between environmental exposure and effect thresholds. Species Sensitivity Distributions can provide information about differences in species sensitivity, while probabilistic approaches can incorporate variability and uncertainty. A 2024 review of ecological risk assessment methods for oxidation by-products emphasized the value of assessment factors, Species Sensitivity Distributions, microcosm and mesocosm approaches, ecological models, risk quotients, probabilistic ecological risk assessment, and pollution indices. These methods have different strengths and limitations, and their suitability depends on the availability of data and the complexity of the environmental problem. (ScienceDirect) Recent research also supports integration of chemical and biological big data. Cui et al. (2026) argued that conventional approaches may oversimplify emerging-contaminant risks by focusing on individual chemicals or species. Integrating chemical measurements with biological responses can provide a more comprehensive understanding of environmental effects and improve identification of important risk drivers. (Nature) Artificial intelligence represents another emerging direction. Recent research indicates that machine-learning models can integrate chemical descriptors, high-throughput screening data, biological information, omics profiles, and environmental measurements to support toxicity prediction and chemical prioritization. Nevertheless, AI-based approaches require transparent datasets, external validation, uncertainty characterization, and clearly defined applicability domains.

METHODOLOGY

This study adopted a qualitative research approach based on systematic and integrative literature analysis. The approach was selected because the purpose of the research was to synthesize existing scientific knowledge concerning environmental toxicology, environmental contaminants, toxicological mechanisms, exposure pathways, and risk-assessment approaches. Rather than generating primary laboratory data, the study examined published scientific evidence and identified common patterns, research gaps, methodological developments, and emerging directions in the field. Recent peer-reviewed literature published primarily between 2023 and 2026 was emphasized to ensure that the review reflected contemporary developments in environmental toxicology and risk assessment. The literature was examined thematically according to major areas including contaminant sources, environmental fate, exposure pathways, toxicological mechanisms, ecological effects, human-health implications, risk assessment, monitoring technologies, uncertainty, and emerging computational approaches. Particular attention was given to studies addressing pharmaceuticals, pesticides, heavy metals, PFAS, microplastics, nanoplastics, endocrine-disrupting chemicals, industrial pollutants, and transformation products. Recent evidence demonstrates that these contaminants may occur across multiple environmental compartments and can create complex exposure scenarios. (ScienceDirect)

RESEARCH DESIGN

The study employed a descriptive and systematic review research design. The descriptive component was used to organize information concerning major categories of environmental contaminants, their sources, exposure pathways, toxicological mechanisms, and ecological effects. The systematic component was used to identify and synthesize recent scientific

evidence concerning risk-assessment methodologies and emerging environmental toxicology practices. Research articles and authoritative scientific publications relevant to environmental toxicology, ecotoxicology, chemical risk assessment, emerging contaminants, environmental monitoring, and ecological risk were considered. The research design also incorporated a comparative thematic framework. Findings from different studies were compared according to pollutant category, environmental compartment, biological endpoint, exposure pattern, assessment method, and risk-management implication. Studies were prioritized when they provided recent empirical evidence, systematic reviews, advanced analytical approaches, or methodological contributions. The review considered conventional toxicological approaches alongside newer approaches involving probabilistic assessment, high-resolution analytical chemistry, non-target screening, big-data integration, artificial intelligence, and new approach methodologies.

DATA ANALYSIS

The collected literature was analyzed through thematic content analysis. First, information was organized into broad categories including contaminant sources, environmental occurrence, exposure pathways, toxicological mechanisms, ecological effects, human-health concerns, risk-assessment approaches, and management strategies. Within each category, recurring findings were identified and compared. This process allowed the study to determine common patterns across recent research rather than relying on the conclusions of individual studies. The second stage of analysis involved identifying emerging themes and methodological developments. Particular attention was given to mixture toxicity, transformation products, chronic low-dose exposure, bioaccumulation, trophic transfer, uncertainty, advanced analytical techniques, probabilistic ecological risk assessment, computational toxicology, and artificial intelligence. Risk-assessment studies were compared according to their ability to incorporate exposure variability, species sensitivity, uncertainty, and environmental complexity. Recent research suggests that probabilistic methods and integrated chemical-biological datasets can improve environmental risk characterization when compared with approaches focused only on individual contaminants. (ScienceDirect)

FINDINGS

The analysis indicates that environmental toxicology is increasingly challenged by the growing diversity and complexity of environmental contaminants. Conventional pollutants remain significant, but emerging contaminants have expanded the range of substances that must be considered in environmental monitoring and risk assessment. Pharmaceuticals, personal-care products, PFAS, endocrine-disrupting chemicals, microplastics, nanoplastics, pesticides, heavy metals, and industrial chemicals can occur in environmental compartments and may interact with organisms through multiple exposure pathways. Recent literature indicates that these substances can persist, transform, bioaccumulate, and move through food webs, making environmental risk difficult to characterize using conventional single-contaminant approaches. (Springer) The findings further demonstrate that toxicological effects occur at multiple levels of biological organization. At the molecular and cellular levels, contaminants may cause oxidative stress, DNA damage, altered enzyme activity, mitochondrial dysfunction, and changes in gene expression. At the physiological level, exposure may produce endocrine, neurological, reproductive, metabolic, and immune

disturbances. At higher organizational levels, these effects may contribute to altered behavior, reduced reproduction, population-level changes, and disruption of ecosystem functions. Evidence concerning aquatic organisms particularly demonstrates the importance of oxidative stress, endocrine disruption, genotoxicity, and immunotoxicity. (DOI) Another important finding is that environmental concentration alone is insufficient for determining ecological risk. A pollutant present at a low concentration may still represent a concern if it is highly persistent, bioaccumulative, biologically active, or capable of producing effects through chronic exposure. Conversely, a pollutant detected at a relatively higher concentration may have limited biological effects if it is poorly bioavailable or rapidly degraded. Therefore, environmental risk assessment must integrate concentration, bioavailability, exposure duration, physicochemical properties, toxicity thresholds, species sensitivity, and environmental fate. The analysis also identified transformation products as an important risk-assessment gap. Chemical contaminants can undergo biological and abiotic transformation in natural ecosystems and engineered treatment systems.

CONCLUSION

Environmental toxicology and risk assessment are essential for understanding and controlling the adverse effects of chemical contamination on human health and ecological systems. The present review demonstrates that environmental contamination is becoming increasingly complex because of the growing number of conventional and emerging contaminants, multiple exposure pathways, chronic low-dose exposure, transformation processes, chemical mixtures, bioaccumulation, and trophic transfer. Environmental toxicology provides critical information about the mechanisms through which pollutants affect organisms, while risk assessment provides a structured framework for evaluating the likelihood and magnitude of adverse effects under realistic environmental conditions. The integration of toxicological evidence with exposure information is therefore fundamental for effective environmental management and policy development. The study concludes that future environmental risk assessment should move toward integrated, predictive, precautionary, and data-driven approaches. Greater consideration should be given to transformation products, mixture toxicity, vulnerable species, chronic exposure, ecosystem-level effects, and climate-related changes in contaminant behavior. Advanced analytical technologies, probabilistic models, computational toxicology, big-data integration, and artificial intelligence can strengthen environmental monitoring and risk prediction, but they should be supported by high-quality experimental evidence and transparent validation. Effective environmental protection will ultimately require collaboration among toxicologists, environmental chemists, ecologists, public-health specialists, data scientists, policymakers, industries, and communities. Strengthening monitoring systems, improving chemical regulation, reducing pollutant release at source, adopting sustainable production practices, and applying scientifically robust risk-assessment frameworks are essential for protecting environmental quality and ensuring long-term human and ecosystem health.

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