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Environmental Bioavailability of Chemical Contaminants: Implications for Toxicity and Ecological Risk Assessment

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ABSTRACT

One of the important concepts in environmental toxicology is bioavailability, as it helps in explaining how environmental contaminants interact with the living organisms by influencing their health and survival. The main aim of this review is to explore the role of bioavailability in understanding the chemical pollutants' toxicity and their potential effects on the environment and ecological systems. This review highlights that the toxicity of environmental chemicals depends not only on their concentration in the environment but also on how easily they can be absorbed and utilized by living organisms. The factors that influence the availability of these contaminants and their potential toxic effects are chemical properties of pollutants, environmental conditions and the characteristics of organism. These interactions can generally affect individual organisms, disrupt ecological balance, and threaten the overall health of ecosystem. This review emphasizes that evaluating bioavailability alongside contaminant concentration provides a more comprehensive understanding of environmental risks than concentration-based assessments alone. In conclusion, bioavailability is a key factor in environmental risk assessment, as it helps identify the potential impacts of chemical pollutants on organisms and ecosystem and supports the development of more effective strategies for environmental monitoring and pollution management.

INTRODUCTION

The environment generally comprises of all the physical, chemical and biological factors that surround living organisms and influence their growth, development, survival and reproduction. However, the release of chemical contaminants from natural processes and human activities can disturb natural processes and threaten the health of living organisms and ecosystems. Environmental toxicology focuses on understanding how pollutants affect organisms and alter the structure and functioning of ecosystems. Likewise, ecotoxicology examines the effects of environmental contaminants on individual organisms, populations, communities and the environment. These fields help explain how environmental contamination influences biological processes and ecological balance [1,2].

Environmental chemicals originate from both natural processes and

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human activities. Industrial operations, agricultural practices, transportation, improper waste disposal and the burning of fossil fuels are among the major sources of chemical contamination. Although many chemicals are essential for life or have useful applications, others can cause harmful effects when organisms are exposed to them at sufficient levels. Although the presence of a chemical indicates potential contamination, its total concentration alone may not accurately represent the extent of its biological effects. The availability of a chemical for uptake by an organism is therefore an important consideration in understanding environmental toxicity and assessing the risk associated with chemical exposure [1,3].

Environmental contaminants can be broadly classified into different groups according to their chemical characteristics, sources and environmental behavior. **Persistent Organic Pollutants (PoA),** including polychlorinated biphenyls (PCBs), dioxins and certain organochlorine pesticides are of concern because of their persistence and potential to get accumulated in organisms. **Volatile Organic Compounds (VoCs)** like benzene, toluene and xylene may be released from fuel emissions, industrial processes and solvent use. **Pesticides,** including insecticides, herbicides and fungicides are used extensively in agriculture and pest management, but the unintended exposure may affect non-target organisms. **Industrial Chemicals,** including certain plasticizers and per and polyfluroalkyl substances (PFAS) are used in a variety of manufacturing and commercial applications and may enter environmental compartments during production, use and disposal. **Inorganic Contaminants** includes heavy metals and metalloids like lead, mercury, cadmium and arsenic, may originate from mining, industrial discharges, agricultural activities and natural geological sources. All these above mentioned groups differ in their persistence, mobility, chemical reactivity and potential for biological uptake, making it important to consider their individual characteristics when evaluating environmental risks [1,2,4].

Bioavailability generally refers to the fraction of a chemical that is accessible to an organism for uptake and may subsequently contribute to the biological effects. Therefore, understanding bioavailability is essential for evaluating the environmental risks associated with chemical pollutants. The bioavailability of a contaminant depends on several interacting factors, including its chemical form, solubility, interactions with soil and sediment particles, organic matter content, Ph, temperature and the characteristics of the exposed organism.

Ex. The contaminants that are strongly bound to soil or sediment may be less readily available for uptake than contaminants present in more accessible forms. However, these relationships vary with the contaminant, environmental conditions and exposure pathway. Consequently, bioavailability cannot be assumed to be the same for all chemicals or organisms [1,5].

Despite improvements in environmental monitoring and chemical risk assessment, understanding how environmental contaminants affect living organisms remains a challenge. Environmental assessments often focus on the total concentration of pollutants present in soil, water, or sediments. However, the amount of a chemical present in the environment does not always indicate how much of it can be taken up by living organisms or cause harmful effects. Previous studies have emphasized the importance of bioavailability in understanding contaminant exposure and evaluating the risks associated with environmental pollution, particularly in contaminated soils and sediments. However, bioavailability is influenced by several factors that differ among chemicals and environmental conditions, making its measurement and application in risk assessment challenging [1,3,6].

Although bioavailability is recognized as an important factor in environmental toxicology, further understanding is needed of how it affects the uptake and toxic effects of different types of environmental contaminants. Even when present at similar concentrations, chemicals may produce different effects on living organisms depending on their properties, surrounding environmental conditions, and the characteristics of the organisms exposed to them. Therefore, understanding the relationship between contaminant concentration, bioavailability, and toxic effects is essential for evaluating the potential risks to ecosystems and human health. Bringing together findings from studies on different groups of contaminants can help explain why concentration alone may not provide a complete picture of environmental toxicity and why bioavailability deserves greater consideration in risk assessment.

In view of these concerns, this review aims to explore the role of bioavailability in environmental toxicology, focusing on the major groups of chemical contaminants, the factors that influence their availability to living organisms, and their potential harmful effects. It also examines how bioavailability can contribute to environmental monitoring, ecological risk assessment, and pollution management. By bringing together information on the properties of contaminants,

environmental conditions, and their uptake by living organisms, this review seeks to improve the understanding of how and why environmental chemicals cause toxic effects. Ultimately, a better understanding of bioavailability can support more reliable assessments of environmental risks and contribute to the protection of human health and ecosystem integrity.

DISCUSSION

Environmental Contaminants: Sources, Concentration-Dependent Effects, and Bioavailability

The effects of environmental chemicals on human health and ecological systems mainly depend on several factors like their concentration, chemical properties, bioavailability and duration and frequency of exposure. Generally, the same chemical may produce different effects under different environmental conditions as its availability for biological uptake can change with pH, temperature, organic matter, solubility and interactions with soil and sediment particles. Some chemicals may produce limited or undetectable effects at relatively low concentrations, whereas prolonged exposure or increasing concentrations may lead to toxicity, accumulation and disruptions of biological processes. Thus, understanding both contaminant concentrations and their bioavailability is essential for evaluating environmental risks.

Environmental contaminants originate from various industrial, agricultural, commercial and domestic activities. Based on the chemical characteristics and environmental behavior the contaminants are grouped in the following groups:

Table 1: Classification of Environmental Contaminants with Examples

Category	Representative chemicals	Major environmental sources
1. Persistent organic pollutants (POPs)	PCBs, Dioxins (TCDD), DDT	Industrial fluids, combustion by-products, agricultural chemicals
2. Pesticides	Chlorpyrifos, Atrazine, Glyphosate	Agricultural runoff, pesticide application, contaminated soil
3. Volatile and semi-volatile organic compounds (VOCs and SVOCs)	Benzene, Toluene, Styrene	Fuel emissions, industrial solvents, petroleum processing
4. Industrial chemicals	Phthalates (DEHP), Bisphenol A (BPA), PFOS/PFOA	Plastic manufacturing, consumer products, industrial processes
5. Other organic and inorganic contaminants	Benzo[a]pyrene, Lead, Mercury	Combustion, mining, industrial discharge, waste disposal

These categories are consistent with classifications and contaminant examples discussed by WHO, UNEP, the US Environ - mental Protection Agency (EPA), and the National Research Council [1,2,4,7-11].

Persistent Organic Pollutants (PoPs)

Persistent organic pollutants are chemicals that remain in the environment for long periods because they resist natural degradation. Many of these compounds are lipophilic, allowing them to accumulate in the fatty tissues of organisms and become concentrated along food chains.

The following three chemicals can be discussed:

Polychlorinated Biphenyls (PCBs): PCBs were widely used in electrical transformers, capacitors, coolants, and industrial fluids. Their persistence and strong affinity for organic matter allow them to accumulate in sediments and the tissues of aquatic organisms. At increasing environmental concentrations, PCBs can accumulate in fish and other wildlife, potentially causing reproductive, developmental, immune, and endocrine-related effects. Their bioavailability depends on the degree of chlorination, sediment composition, and organic matter content.

Dioxins (particularly 2,3,7,8-TCDD): Dioxins are mainly formed as unintended by-products of industrial processes, waste incineration, and combustion. They are highly persistent and can accumulate in soil, sediments, and animal fat. Increasing exposure may lead to reproductive and developmental disturbances, immune system effects,

and increased cancer risk. Their transfer through food chains makes them particularly important environmental contaminants.

Dichlorodiphenyltrichloroethane (DDT): DDT is an organochlorine insecticide that was extensively used for agricultural pest control and disease-vector management. It degrades slowly and can accumulate in soil, aquatic sediments, and animal tissues. Increasing concentrations may cause reproductive disturbances in wildlife, particularly eggshell thinning in birds, and can affect aquatic organisms. Its persistence and bioaccumulation make it an important example of pesticide-related environmental contamination.

Pesticides

Pesticides are widely used in agriculture to control insects, weeds, fungi, and other organisms that affect crop production. However, excessive or inappropriate application can result in contamination of soil, groundwater, and surface water through runoff, leaching, and spray drift.

Chlorpyrifos: Chlorpyrifos is an organophosphate insecticide used for controlling agricultural pests. At elevated concentrations, it can adversely affect aquatic organisms, including fish and aquatic invertebrates, mainly through inhibition of acetylcholinesterase. Its toxicity depends on the concentration reaching aquatic environments, exposure duration, and bioavailability. Soil properties and organic matter influence its movement and availability.

Atrazine: Atrazine is a triazine herbicide commonly used for controlling weeds in agricultural fields. It can enter surface water and groundwater through agricultural runoff and leaching. Increasing concentrations may interfere with aquatic plant growth and affect non-target aquatic organisms. Its persistence and movement through soil depend on environmental conditions, including soil composition, microbial activity, and water availability.

Glyphosate: Glyphosate is a widely used herbicide that controls unwanted vegetation. It may reach aquatic environments through agricultural runoff and improper application. At sufficiently high concentrations, glyphosate-based formulations can affect aquatic plants and other non-target organisms. Its adsorption to soil minerals and sediments influences its mobility and bioavailability.

Volatile and Semi-Volatile Organic Compounds (VOCs and SVOCs)

Volatile and semi-volatile organic compounds are released into the environment from industrial operations, petroleum products, fuel combustion, solvents, and chemical manufacturing. VOCs can readily evaporate into the atmosphere, while SVOCs generally have lower volatility and may remain associated with soil particles, sediments, and organic matter.

Benzene (VOC): Benzene is commonly released through petroleum refining, vehicle emissions, fuel storage, and industrial activities. Increasing concentrations in air can contribute to human exposure through inhalation, while contamination of groundwater can create additional exposure pathways. Long-term exposure is associated with bone marrow toxicity and an increased risk of leukaemia. Benzene also contributes to photochemical air pollution.

Toluene (VOC): Toluene is widely used as an industrial solvent and is present in petroleum products, paints, adhesives, and chemical formulations. At elevated concentrations, it can cause adverse effects on the nervous system and may affect aquatic organisms when released into water. Its relatively high volatility allows it to enter the atmosphere, while its environmental distribution depends on evaporation, degradation, and partitioning between environmental compartments.

Styrene (VOC): Styrene is primarily used in the manufacture of plastics, synthetic rubber, and polystyrene products. It can be released into the environment during manufacturing, processing, and disposal. At high exposure levels, styrene vapours can irritate the respiratory system and affect the central nervous system. Its release into the atmosphere also contributes to photochemical reactions involved in ground-level ozone formation.

Industrial Chemicals

Industrial chemicals are used in the manufacture of plastics, electronic materials, textiles, packaging, and other commercial products. Their release during manufacturing, use, and disposal can lead to environmental contamination. Some of these compounds are particularly concerning because of their persistence, endocrine-disrupting potential, or ability to accumulate in organisms.

Phthalates (particularly DEHP): Phthalates are widely used as plasticizers to improve the flexibility of plastics, particularly polyvinyl chloride (PVC). They can enter the environment through the release and degradation of plastic products, industrial wastewater, and landfill leachate. Increasing concentrations may affect aquatic organisms and interfere with hormonal and reproductive processes. Their bioavailability depends on their chemical properties and interactions with organic matter and sediments.

Bisphenol A (BPA): BPA is an industrial chemical commonly used in the production of polycarbonate plastics and epoxy resins. It can enter aquatic environments through industrial wastewater, landfill leachate, and the degradation of consumer products. At sufficient exposure levels, BPA may interfere with endocrine functions and affect reproductive and developmental processes in aquatic organisms and other species.

Per- and polyfluoroalkyl substances (PFAS), particularly PFOS and PFOA: These chemicals have been used in applications such as surface coatings, water-resistant materials, and certain industrial processes. Their environmental release can occur through industrial wastewater, firefighting foam residues, and waste disposal. Their persistence and potential for accumulation in organisms make them important contaminants of concern. Increasing exposure may affect liver function, immune responses, development, and other biological processes. Their bioavailability varies with the individual PFAS compound, environmental conditions, and organism characteristics.

Other Organic and Inorganic Contaminants

This category includes contaminants that do not necessarily belong to the previous groups but are important because of their environmental persistence, toxicity, and potential for biological accumulation.

Benzo[a]pyrene (PAH): Benzo[a]pyrene is a polycyclic aromatic hydrocarbon (PAH) formed mainly during the incomplete combustion of organic materials, including coal, petroleum, wood, and other fuels. It can accumulate in soil and sediments because of its low water solubility and strong affinity for organic matter. At elevated exposure levels, it can cause toxic and carcinogenic effects. Its bioavailability is strongly influenced by its binding to soil and sediment organic matter.

Lead (Pb): Lead is a toxic heavy metal released into the environment through mining, metal processing, industrial emissions, battery manufacturing, and improper waste disposal. Increasing lead concentrations in soil and water can adversely affect plants, aquatic organisms, and wildlife. In humans, exposure can damage the nervous system, kidneys, and other organs, with children being particularly vulnerable. Its bioavailability depends on its chemical form, soil pH, and interactions with minerals and organic matter.

Mercury (Hg): Mercury enters the environment through natural processes, coal combustion, mining, and industrial activities. In aquatic environments, certain microorganisms can convert inorganic mercury into methylmercury, a highly toxic form that accumulates in aquatic organisms and biomagnifies through food chains. Increasing mercury contamination can affect fish populations, wildlife, and human consumers. Methylmercury exposure is particularly associated with neurological and developmental effects.

The following table can be included in your review manuscript to provide a concise comparison of the selected contaminants.

Table 1: Chemical concentrations and their environmental effects

Chemical	Environmental effect at increasing exposure levels
PCBs	Bioaccumulation, reproductive and developmental toxicity
Dioxins (TCDD)	Endocrine, immune, reproductive, and carcinogenic effects
DDT	Persistence, food-chain accumulation, reproductive toxicity in wildlife
Chlorpyrifos	Acetylcholinesterase inhibition and aquatic toxicity
Atrazine	Effects on aquatic plants and non-target organisms
Glyphosate	Potential toxicity to aquatic organisms and non-target plants
Benzene	Air and groundwater contamination; carcinogenic effects
Toluene	Nervous system toxicity and aquatic effects at sufficient exposure
Styrene	Respiratory irritation, nervous system effects, photochemical air pollution
DEHP	Endocrine and reproductive effects
BPA	Endocrine disruption and developmental effects
PFOS/PFOA	Persistence, bioaccumulation or accumulation, immune and developmental effects
Benzo[a]pyrene	Sediment contamination and carcinogenic effects
Lead	Neurotoxicity and toxicity to plants and aquatic organisms
Mercury	Methylmercury formation, bioaccumulation, and neurological toxicity

Note: These are qualitative descriptions, not universal concentration thresholds. Actual effects depend on chemical speciation, exposure route, duration, bioavailability, and species sensitivity. Specific environmental concentration ranges should be reported separately using measured values and regulatory guidelines.

CONCLUSION

Environmental pollution caused by the release of chemical contaminants from industrial, agricultural, and domestic activities remains a major concern for human health and ecosystem stability. As discussed in this review, different groups of environmental contaminants, including persistent organic pollutants, pesticides, volatile and semi-volatile organic compounds, industrial chemicals, and inorganic contaminants, can affect living organisms in different ways depending on their chemical properties, environmental concentrations, and exposure conditions. Some contaminants persist in the environment for extended periods, while others may undergo degradation or transformation into products that can also influence environmental quality. Their accumulation in soil, water, sediments, and living organisms can disrupt biological processes and contribute to long-term ecological problems.

An important finding highlighted in this review is that the toxicity of environmental contaminants cannot be determined by their total concentrations alone. Bioavailability plays an essential role in determining how much of a chemical can be taken up by living organisms and potentially produce harmful effects. Factors such as chemical speciation, solubility, pH, temperature, organic matter content, and interactions with soil and sediment particles influence the movement, availability, and uptake of contaminants. Consequently, chemicals present at similar concentrations may produce different toxic effects depending on their bioavailability and the sensitivity of the exposed organisms. This highlights the importance of considering environmental conditions and biological exposure when evaluating chemical toxicity.

The review also emphasizes the need to incorporate bioavailability into environmental monitoring and risk assessment rather than relying exclusively on conventional concentration-based approaches. Combining chemical measurements with bioavailability assessments and biological response studies can provide a more realistic understanding of contaminant exposure and its potential effects on ecosystems. Further research is needed to develop reliable methods for measuring bioavailable fractions across different contaminant groups and environmental conditions. Greater attention should also be given to the combined effects of chemical mixtures, long-term exposure, contaminant transformation, and the potential transfer of pollutants through food chains.

In conclusion, bioavailability is a fundamental consideration in environmental toxicology because it helps establish the relationship between the presence of chemical contaminants and their actual biological effects. A better understanding of this relationship can improve the accuracy of environmental risk assessments, strengthen pollution monitoring strategies, and support the development of more effective environmental management practices. Integrating bioavailability into the evaluation of chemical contaminants is therefore important for reducing environmental risks, protecting human health, preserving biodiversity, and maintaining the long-term stability of ecosystems.

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