



SEDIMENT-MEDIATED TRANSFER OF HEAVY METALS TO AQUATIC BIOTA IN AN AGRICULTURALLY IMPACTED FRESHWATER SYSTEM

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Abstract:

The paper determines how heavy metals are transferred through the sediment to the aquatic biota of a freshwater system subjected to agricultural activities. The agricultural runoff is a major contributor of pollution, which usually contaminates the water body with heavy metals. These metals are cadmium, lead and mercury, which may be attached on the sediments in the water bodies affecting their movement and bioavailability. The paper will discuss the importance of sediments in the transfer of such contaminants to aquatic life, especially based on food web. Bioaccumulation studies have shown that some of the heavy metals including lead were effectively transferred onto the biota and particularly benthic organism, through sediment. The paper has identified the significance of the sediment properties, including the content of organic matters, and the size of particles in determining the movement of metals. The results emphasize the importance of ensuring that agricultural run offs are controlled through proper management practices to ensure that fresh waters are not contaminated with sediments-bound heavy metals that would lead to the degradation of the aquatic ecosystem and food safety.

Keywords: Heavy Metals, Bioaccumulation, Degradation, Aquatic Ecosystem.

1. Introduction

Rapid agricultural expansion and intensification have emerged as major global environmental concerns due to their contribution to heavy metal contamination of freshwater ecosystems [1,2]. Unlike organic pollutants, heavy metals are non-biodegradable and persist in aquatic environments for extended periods, posing long-term ecological risks [3]. Common trace metals introduced into surface waters through agricultural activities include cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr), originating from fertilizers, pesticides, manure, and irrigation return flows [1]. Although dissolved metal concentrations in the water column are often low due to rapid adsorption onto suspended particles, sediments gradually accumulate metals and act as

geochemical archives of historical contamination [2,4]. Consequently, sediments play a crucial role in regulating the exposure of aquatic organisms to heavy metals. The theoretical framework addressed in this review emphasizes the role of sediments as mediators of metal transfer to aquatic biota in agriculturally impacted freshwater systems.

2. Heavy metals

Heavy metals enter agricultural soils through multiple pathways. Phosphate fertilizers are well-recognized sources of Cd and Pb impurities, while Cu and Zn are commonly introduced via fungicides, animal feed additives, and manure application [1]. These metals are subsequently transported into adjacent rivers, lakes, wetlands, and streams through soil erosion and surface runoff during rainfall events [5]. Repeated seasonal inputs lead to progressive enrichment of bottom sediments, increasing the probability of metal remobilization and biological uptake over time, even when external inputs decline [4].

3. Sources of heavy metals in sediments and their role as secondary sources

3.1 Metal binding and sediment geochemistry

Sediments retain heavy metals primarily through adsorption onto fine particles, clay minerals, iron and manganese oxides, and organic matter [2]. The strength and stability of metal binding are controlled by sediment texture, organic carbon content, redox potential, and pH [6]. Metals such as Pb and Cu exhibit strong affinity for organic matter and oxide phases, whereas Cd and Zn remain comparatively more mobile and bioavailable within sediment matrices [1,4].

3.2 Remobilization processes

Although sediments function as sinks for heavy metals, they are not permanently stable. Variations in environmental conditions—including oxygen depletion, pH changes, bioturbation, and hydrodynamic disturbances—can result in the release of sediment-bound metals into pore water and the overlying water column [5]. In agricultural landscapes, monsoon-driven flooding and seasonal runoff substantially increase sediment disturbance, thereby enhancing metal fluxes to aquatic organisms [2].

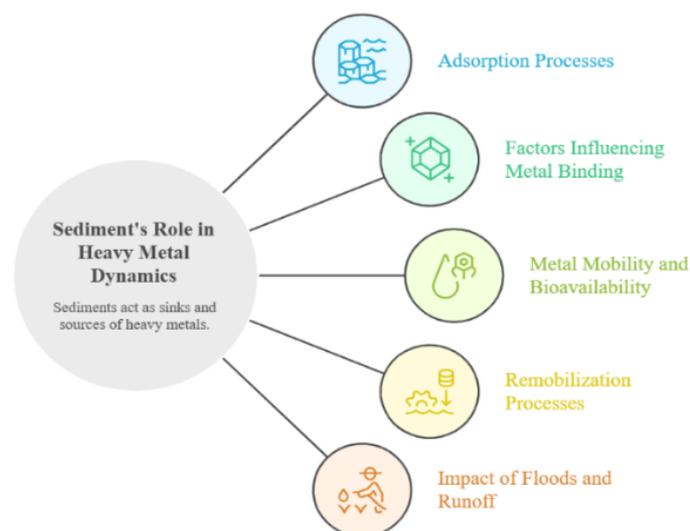


Figure 1: Role of sediments in heavy metal dynamics within freshwater ecosystem

Table 1: Conceptual framework describing sediment-mediated transfer of heavy metals to aquatic biota in agriculturally impacted freshwater systems

Component	Theoretical basis	Key controlling factors	Ecological implication
Agricultural sources	Introduction of trace metals via fertilizers, pesticides, manure, and irrigation runoff	Type of agrochemicals, application intensity, soil erosion rate	Continuous metal input to freshwater systems
Sediment accumulation	Adsorption of metals onto fine particles, organic matter, Fe-Mn oxides	Sediment grain size, organic carbon, redox potential, pH	Sediments act as long-term metal sinks
Metal speciation	Partitioning of metals into exchangeable, carbonate-bound, oxide-bound, and residual fractions	Geochemical conditions, microbial activity	Determines metal mobility and bioavailability
Remobilization processes	Release of sediment-bound metals under disturbed conditions	Flooding, bioturbation, resuspension, oxygen depletion	Transformation of sediments into secondary pollution sources
Benthic uptake	Direct ingestion and dermal absorption by benthic macroinvertebrates	Feeding strategy, exposure duration, sediment contamination level	High bioaccumulation at lower trophic levels
Trophic transfer	Dietary uptake of metals by fish and higher consumers	Food-web structure, metal type, assimilation efficiency	Biomagnification and chronic toxicity
Bioaccumulation dynamics	Balance between metal uptake, storage, and detoxification	Metal essentiality, organism physiology, metabolic rate	Tissue-specific accumulation (liver > gills > muscle)
Ecological effects	Sub-lethal and lethal metal toxicity	Concentration, exposure time, species sensitivity	Reduced growth, reproduction, and biodiversity
Human health risk	Consumption of contaminated fish and water	Dietary habits, metal concentration in edible tissues	Potential long-term health effects

4. Sediment-biota interaction and exposure pathways

4.1 Direct uptake by benthic organisms

Benthic macroinvertebrates are directly exposed to contaminated sediments through ingestion of sediment particles and dermal contact. Due to their limited mobility and prolonged contact with sediments, these organisms effectively integrate long-term sediment contamination and serve as reliable indicators of metal bioavailability [4,7].

4.2 Indirect uptake by higher trophic levels

Fish and other higher trophic organisms accumulate metals indirectly through dietary intake of contaminated benthic fauna and detritus. As a result, sediment-associated metals enter aquatic food webs, where bioaccumulation occurs and non-essential metals such as Cd and Pb may biomagnify across trophic levels [3,7].

5. Bioaccumulation and trophic transfer

Bioaccumulation is governed by metal bioavailability, organism physiology, and exposure duration [7]. Even metals with high sediment partitioning coefficients may exhibit substantial bioaccumulation if desorption rates and biological uptake efficiencies are high [6]. Bioaccumulation factors (BAF) are commonly used to quantify sediment-to-biota transfer and provide insight into ecological risk [8]. At higher trophic levels, metals preferentially accumulate in metabolically active tissues such as liver and kidney, while muscle tissues reflect long-term exposure trends [3]. Chronic sub-lethal exposure can lead to oxidative stress, enzyme inhibition, impaired reproduction, and altered physiological performance [8].

6. Ecological and human health implications

Sediment-mediated metal transfer poses significant threats to aquatic biodiversity by altering species composition, reducing benthic diversity, and impairing ecosystem functioning [4]. In agriculturally dependent regions, consumption of contaminated fish represents a major pathway of human exposure, raising serious concerns related to food safety and public health [8]. The persistence of metals in sediments implies that ecological recovery may be slow even after reductions in agricultural inputs, underscoring the importance of sediment management in pollution mitigation strategies [2].

7. Knowledge gaps and future research directions

Despite significant advances in understanding sediment-metal interactions, several gaps remain. These include limited integration of sediment geochemistry with biological uptake models, insufficient long-term monitoring datasets, and inadequate consideration of climate-driven hydrological variability [5,3]. Future research should prioritize coupled sediment-biota modeling approaches, multi-trophic assessments, and the role of microbial processes in metal transformation.

Conclusion

The centrality of sediments to the destiny, movement, and ecological effects of heavy metals in freshwater systems affected by agriculture is undisputed. Sediments, as repositories and sources, facilitate the process of transfer of metals to aquatic biota by a series of complex geochemical and biological mechanisms. The development of effective management strategies because of the prevention of freshwater ecosystem damage due to rising agricultural pressures requires a theoretical understanding of sediment-mediated pathways to be used in effective ecological risk assessment.

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Conflict of interest

The authors declare no conflict of interest.

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