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Review

Effects of sediment geochemical properties on heavy metal bioavailability



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ABSTRACT

As the largest container and resource of metals, sediment has a special role in the fate of metals. Factors influencing bioavailability of heavy metals in sediment have never been comprehensively considered and the sediment properties still fail to understand and even controversial. In this review, the mechanisms of sediment properties such as acid-volatile sulfides (AVS), organic matter, texture (clay, silt or sand) and geology, organism behaviors as well as those influencing the bioavailability of metals were analyzed. Under anoxic condition, AVS mainly reduce the solubility and toxicity of metals, while organic matters, Fe–Mn oxides, clay or silt can stabilize heavy metals in elevated oxidative–reductive potential (ORP). Other factors including the variation of pH, redox potential, aging as well as nutrition and the behavior of benthic organism in sediment also largely alter metals mobility and distribution. These factors are often inter-related, and various toxicity assessment methods used to evaluate the bioavailability of trace metals have been also discussed. Additionally, we expect that some novel synthetic materials like polysulfides, nano-materials, provide the substantial amendments for metals pollution in sediment.

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1. Introduction

In aquatic ecosystem, sediments are the main sink and source of heavy metals, serving as a significant role in the transportation and storage of potentially noxious metals (Alonso Castillo et al., 2013; Burton et al., 2006b; Durán et al., 2012; Superville et al., 2014). Sediment available to the river mainly from channel sources (the bed and banks of its catchment) and non-channel sources (the rainfall runoff, flooding, and the erosion of bare soil, particularly) (Wood and Armitage, 1997). Thus, sediments are heterogeneous assemblages of multitudinous sorbent phases (such as organic matter, oxide, sulfides, carbonates and clay or silt minerals), whose relative abundance depends on pH, redox conditions, hydrological regime and the depositional environment (Burton et al., 2006b). The sediments have provided more significant tools for the better clarification of the origin identification and partitioning dynamics of heavy metals than the analysis of the overlying water column as a result from discontinuity and fluctuations in water flows (Alonso Castillo et al., 2013).

Toxic metals pollution in sediment have been proved to be an increasingly global problem (Fernandes et al., 2008; Kucuksezgin et al., 2008) and is considered to pose a serious threat to the aquatic environment result from their toxicity, non-biodegradable and persistent nature, and the bio-enrichment ability in food chain (Gopinath et al., 2009; Nobil et al., 2010). Heavy metals in aquatic system are increasingly identified as important intermediate sources for subsequent the occurrence of pollution in aquatic ecosystems, even public health, due to rapid urbanization and industrialization (Alonso Castillo et al., 2013). Besides, high variation loads in heavy metal occur among impervious surfaces along with different urban land uses (Zhao et al., 2010). These elements are deposited onto sediment surfaces and immobilized through adsorption, coagulation or flocculation and incorporation into the lattice structure of minerals (e.g., Fe–Mn oxides), and precipitation by forming insoluble fractionation (such as metal sulfides) (Du Laing et al., 2009; Lin et al., 2013). Only a small portion of free metal ions, however, stay dissolved in water (Hou et al., 2013) and in comparable, more than 90% of heavy metals load in aquatic systems have been found to be related to suspended particles and sediments (Amin et al., 2009; Zahra et al., 2013; Zheng et al., 2008). Thus, the distribution of trace metals in sediment adjacent to populated areas (includes industries, mining exploitation in particular) can give us the evidence of anthropogenic influence on aquatic system and convenience in assessing the potential risks associated with human waste discharge.

Given the importance of aquatic environment, numerous studies have been focused on heavy metals pollution (Atkinson et al., 2007; Luoma and Rainbow, 2005; Saeedi et al., 2013; Simpson, 2005) and the metals geochemical nature associations in sediments (Lee et al., 2000a; Simpson et al., 2012a). In aquatic sediments, the bioavailability of metals to benthic organisms depends not only on metals chemical form (Besser et al., 2003; Riba et al., 2004; Simpson, 2005), but also sediment geochemical properties (Nobil et al., 2010; Rainbow, 2007) and varies exposure pathways of the organisms (Simpson et al., 2012b). The calculation of toxicity of metal contaminants in sediments to benthic organisms is particularly challenging due to the significant influence of the properties of the sediments (Campana et al., 2012; Costello et al., 2011; Strom et al., 2011) as well as the changes of sediment supply and post-depositional processes (Fernandes et al., 2011). The partitioning of metals between different phases is strongly influenced by sediment attributes such as pH, redox potential, particle size and its distribution, and the important metal-binding phases such as AVS, organic matter (OM) and iron and manganese oxyhydroxides (Chapman et al., 1999; Simpson et al., 2012a).

Factors influencing bioavailability of heavy metals in sediment have never been comprehensively considered and the mechanisms of solid phases binding with metals are still constricted. What's more, sediment geochemical properties are often mutual correlated, and it is not adequate to assess the metals behavior in sediment through considering

just several factors among those properties. Thus, understanding their relationships requires knowledge of sediment geochemistry and organic behaviors (Hou et al., 2013; Nizoli and Luiz-Silva, 2012). To further our understanding of the influence of sediment geochemical properties on the bioavailability of metals to benthic organisms, the consideration and analysis of mechanisms turns into a necessity. Besides, know of partitioning and distribution of heavy metals in the sediments will give us insights into the source of pollution in the aquatic systems (Nobil et al., 2010; Silva et al., 2009) and the effects on aquatic biotas. Here, we comprehensively depicted for the first time the contribution of AVS, OM, sediment texture, diagenesis as well as benthic organism behavior and other drivers in affecting metals behavior, particularly bioavailability in sediment area, so as to provide further information for researches and sediment management.

2. Metal forms in sediment

It is universally accepted that a large portion of heavy metals in non-polluted sediment present in the crystal lattice of minerals and residual fraction which constitute the bottom mud (Du Laing et al., 2009; Lin et al., 2013). When polluted, the form and distribution of heavy metals in sediment is altered. These elements in sediment mainly exist in the forms of soluble, ion-exchangeable, Fe–Mn oxides, organic matters/sulfides and carbonates (Hou et al., 2013). In consideration of characterizing the solid-phase partitioning of trace metals in sediments, sequential extraction procedures become an increasingly popular method, which employ a series of reagents to selectively extract metals associated with operationally defined fractions (Burton et al., 2005a, 2006a; Morillo et al., 2004).

In the present study, the four-step sequential extraction method established by Tessier et al. (1979) in sediment is introduced to determine and fractionate heavy metals chemical fractions (Hou et al., 2013; Peng et al., 2009; Tessier et al., 1979). This extraction method then divides the heavy metals into five fractions via four steps: extractable and exchangeable (F1), carbonate bound (F2), iron and manganese oxides bound (F3), organic matter bound (F4) and residual metal (F5). The descending order of bioavailability of the heavy metals in sediments may be based on the metal fractionation ($F1 > F2 > F3 > F4 > F5$ in general), and most spiked metals preferential adsorb onto phases that apt to exchangeable and reducible. Normally, the exchangeable fractions of metals can be used to evaluate the extent of environmental bioavailability of sediment component (Jones et al., 2008). Whilst the residual fraction, which associated with anthropogenic or geogenic components, represents the more stable metal forms (Saeedi et al., 2013).

Nowadays some novel extraction methods emerge around us. The modified Community Bureau of Reference (BCR) three-step sequential extraction procedure has been used to the study of metals in soils or sediment (Pueyo et al., 2008). Besides, the technology of diffusive gradients in thin-films (DGT) can efficiently determine labile species of metals in soil or sediment and thus better predict the assimilation of these elements by living beings (Davison and Zhang, 1994; Simpson et al., 2012b). Different popular sequential extraction procedures are depicted as follows in Table 1.

3. Influence factors for metals bioavailability in sediment

What influence the metals bioavailability and toxicity in sediments and waters can be enumerated as the following: (1) solid phases, especially metal binding phases, such as AVS, particulate organic carbon, iron and manganese oxyhydroxides (Campana et al., 2012; Simpson and Batley, 2007); (2) aquatic phases, i.e., overlying and pore water physical–chemical attributes, such as pH, redox potential (Eh), hardness/salinity, and ligand complexes; and (3) sensitivity and behavior of benthic organisms, e.g., taxa, lifestyle (such as bioturbation, burrowing), and prior exposure history (Chapman et al., 1999).

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