

Speciation and Potential Mobility of Lead and Cadmium in Sediments of River Jama'are, Bauchi State, Nigeria

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ABSTRACT

The speciation and potential mobility of lead (Pb) and cadmium (Cd) in sediments are important for assessing their environmental behaviour and potential remobilization. This study investigated the geochemical fractionation and potential mobility of Pb and Cd in sediments of River Jama'are, Bauchi State, Nigeria, using sequential extraction and mobility-factor assessment. A single composite sediment sample formed from five sampling points was fractionated into exchangeable, reducible, oxidizable, and residual fractions, and Pb and Cd concentrations were determined by atomic absorption spectrophotometry (AAS). Both metals were predominantly associated with the residual fraction, followed by the reducible, exchangeable, and oxidizable fractions, indicating relatively stable retention within the sediment. However, their occurrence in non-residual fractions indicated potential susceptibility to remobilization under changing environmental conditions. The mobility factors of Pb and Cd were 19.5% and 19.6%, respectively, classifying both metals as presenting medium potential mobility risk. The comparable mobility factors suggest similar potential mobility despite differences in their fractionation patterns. Overall, River Jama'are sediments may function as relatively stable sinks for Pb and Cd under prevailing conditions but could become secondary sources if environmental conditions promote remobilization. Continued monitoring of metal speciation and relevant sediment physicochemical properties is recommended to improve assessment of their long-term environmental behaviour.

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INTRODUCTION

Heavy metals in aquatic environments are of environmental concern because of their persistence, toxicity, and potential to accumulate in sediments and aquatic organisms (Ali *et al.*, 2019; Edo *et al.*, 2024). Lead (Pb) and cadmium (Cd) are particularly important contaminants due to their toxicity and potential adverse effects on aquatic ecosystems and human health (Sharma *et al.*, 2025). River sediments can act as important sinks for these metals by retaining them through association with mineral particles, iron and manganese oxides, organic matter, and sulfide phases (Aggarwal *et al.*, 2025; Aggarwal *et al.*, 2026). However, sediment-associated metals may be remobilized when environmental conditions such as pH, redox potential, ionic composition, or organic matter change, potentially increasing their bioavailability and ecological risk (Geng *et al.*, 2024; Maqsood & Lobos-Moysa, 2025).

Assessment based solely on total metal concentrations provides limited information about the environmental behavior and potential mobility of sediment-associated metals. Chemical fractionation provides additional insight by distinguishing metals associated with operationally defined geochemical phases of different stability and mobility (Świetlik & Trojanowska, 2022; Makangila *et al.*, 2026; Garcia-Ordiales *et al.*, 2026). Sequential extraction procedures commonly differentiate exchangeable, reducible, oxidizable, and residual fractions, with the residual fraction generally representing the most strongly retained metal pool and the non-residual fractions being comparatively more susceptible to remobilization (Garcia-Ordiales *et al.*, 2026; Garba *et al.*, 2026). The mobility factor, calculated from the

proportion of metal associated with the more mobile fractions, can further provide an indication of potential metal mobility and environmental risk (Goswami & Kalamdhad, 2023).

River Jama'are is an important aquatic system in Bauchi State, Nigeria, and its sediments may receive metals from natural and anthropogenic sources. However, information on the geochemical partitioning and potential mobility of Pb and Cd in its sediments remains limited. Characterizing their distribution among sedimentary fractions is therefore important for understanding their environmental behaviour and identifying the extent to which the sediments may function as either sinks or potential secondary sources of these metals. This study investigated the geochemical fractionation and potential mobility of Pb and Cd in sediments of River Jama'are using sequential extraction and mobility-factor assessment. The study provides information on the sedimentary associations of these metals and their potential susceptibility to remobilization under changing environmental conditions.

MATERIALS AND METHODS

Study Area and Sample Collection

Sediment samples were collected from River Jama'are in Bauchi State, Nigeria, using a systematic W-shaped sampling pattern. Five sampling points, designated A–E, were established along the sampling pattern, with approximately 500 meters between successive sampling points. At each sampling point, sediment was collected from the upper 0–20 cm layer using a clean stainless-steel auger. The samples collected from the five sampling points were combined and

thoroughly homogenized to obtain a single representative composite sediment sample for the study. The composite sample was transferred into a clean, appropriately labelled polyethylene bag and transported to the laboratory for further preparation and analysis. Composite sampling was adopted to obtain an overall representative sample of the investigated section of River Jama'are and to minimize the influence of small-scale spatial variability in sediment metal concentrations.

Sample Preparation

The composite sediment sample was air-dried at room temperature and gently disaggregated to remove large aggregates. The dried sediment sample was homogenized and passed through a suitable plastic sieve to obtain a uniform particle-size fraction for the sequential extraction procedure. The prepared sample was stored in clean, labelled plastic container until analysis.

Sequential Extraction and Metal Speciation

The geochemical fractionation of Pb and Cd in the composite sediment sample was determined using a sequential extraction procedure based on the method originally proposed by Tessier *et al.* (1979), with modifications consistent with the BCR sequential extraction approach reported by Rauret *et al.* (1999), Rauret *et al.* (2000), and Passos *et al.* (2010). The procedure operationally separated Pb and Cd into four geochemical fractions: exchangeable, reducible, oxidizable, and residual fractions. Three replicate portions, each weighing 1.0 g, were taken from the dried and homogenized composite sediment sample and subjected independently to the sequential extraction procedure. The three replicate portions were subsamples of the same composite sediment and therefore represent procedural/analytical replicates rather than independent spatial samples. Consequently, the reported mean $\pm$ SD reflects analytical variability associated with the extraction procedure and does not represent spatial variability across the river. For the exchangeable fraction, 8 cm³ of 1.0 M MgCl₂ solution adjusted to pH 7 was added to each 1.0 g sediment portion. The mixture was continuously agitated at room temperature (approximately 28 °C) for 1 h and subsequently centrifuged for 30 min. The supernatant was carefully separated and retained for Pb and Cd determination, while the solid residue was washed with deionized water and used for the subsequent extraction step. For the reducible fraction, the residue obtained from the exchangeable extraction was treated with 20 cm³ of 0.04 M ascorbic acid in 25% (v/v) acetic acid. The suspension was heated at approximately 96 °C in a water bath for 1 h with occasional stirring. Following extraction, the suspension was centrifuged, and the supernatant was collected for Pb and Cd determination. The remaining solid residue was washed with deionized water and retained for the next extraction step. For the oxidizable fraction, the residue from the reducible extraction was treated with 3 cm³ of 0.02 M HNO₃ and 5 cm³ of 30% H₂O₂, with the mixture adjusted to pH 2 using HNO₃. The suspension was heated at 85 °C with occasional stirring for 1 h. A further 3 cm³ portion of 30% H₂O₂, adjusted to pH 2 with HNO₃, was then added, and the mixture was maintained at 85 °C for an additional 1 h with occasional stirring. After cooling, 5 cm³ of 3.2 M ammonium acetate solution prepared in 20% HNO₃ (v/v) and 4 cm³ of deionized water were added, and the mixture was continuously agitated for 30 min. The suspension was subsequently centrifuged, and the supernatant was collected for Pb and Cd determination. The resulting solid residue was washed with deionized water and used for the residual fraction. For the

residual fraction, the residue remaining after the oxidizable extraction was digested with 7 cm³ of concentrated HNO₃ (65%) and 7 cm³ of HCl (40%). The digest was evaporated to near dryness and subsequently redissolved using 2 cm³ of HNO₃, 2 cm³ of HCl, and 10 cm³ of deionized water. The resulting solution was diluted to 50 cm³ with deionized water and retained for subsequent determination of residual Pb and Cd concentrations.

Determination of Pb and Cd Concentrations

The concentrations of Pb and Cd in the extracts obtained from the four sequential extraction steps were determined by atomic absorption spectrophotometry (AAS) using an Agilent Technologies 200 Series AA instrument. Appropriate analytical blanks and calibration standards were included during the measurements to ensure analytical accuracy. The analyses were performed in triplicate, and the results were expressed as mean concentration $\pm$ standard deviation for each geochemical fraction. The measured concentrations were used to determine the distribution of Pb and Cd among the exchangeable, reducible, oxidizable, and residual fractions.

Calculation of Mobility Factor

The potential mobility of Pb and Cd in the sediment was assessed using the mobility factor (MF), which represents the proportion of each metal associated with the operationally defined mobile fraction relative to its total concentration in the sediment. The mobility factor (MF) was calculated using the following equation:

$$MF (\%) = \frac{C_{\text{mobile}}}{C_{\text{total}}} \times 100$$

Where C_{mobile} represents the concentration of metal in the exchangeable fraction and C_{total} represents the sum of the concentrations of the metal across all four operationally defined fractions. The calculated MF values were used to assess the potential susceptibility of Pb and Cd to remobilization under changing environmental conditions. The mobility-risk classification was based on the adopted classification scheme, with higher MF values indicating a greater proportion of the metal occurring in the potentially mobile fraction.

RESULTS AND DISCUSSION

The geochemical fractionation and concentrations of Pb and Cd in the River Jama'are sediment are presented in Table 1, while their distribution among the individual geochemical fractions is illustrated in Figure 1. Pb concentrations ranged from 15.00 $\pm$ 2.00 to 33.67 $\pm$ 4.51 mg/kg, whereas Cd concentrations ranged from 6.33 $\pm$ 2.52 to 13.00 $\pm$ 2.00 mg/kg across the four operationally defined fractions. For Pb, the highest concentration occurred in the residual fraction (33.67 $\pm$ 4.51 mg/kg), followed by the reducible fraction (27.00 $\pm$ 4.00 mg/kg), exchangeable fraction (18.33 $\pm$ 2.52 mg/kg), and oxidizable fraction (15.00 $\pm$ 2.00 mg/kg). A similar distribution pattern was observed for Cd, with concentrations of 13.00 $\pm$ 2.00, 10.67 $\pm$ 2.52, 7.33 $\pm$ 1.53, and 6.33 $\pm$ 2.52 mg/kg in the residual, reducible, exchangeable, and oxidizable fractions, respectively. The predominance of the residual fraction for both metals indicates that the largest measured proportions of Pb and Cd were associated with the relatively less readily mobilizable sediment fraction, whereas the exchangeable, reducible, and oxidizable fractions collectively accounted for substantial portions of both metals. The graphical distribution in Figure 1 is consistent with the concentration patterns reported in Table 1. This distribution pattern indicates that while a major portion of the heavy

metals is safely bound within the lithogenic sediment core, a substantial quantity is retained in the more unstable non-residual fractions.

The calculated mobility factors and corresponding mobility-risk classifications for Pb and Cd are presented in Table 2. The mobility factors were 19.5% for Pb and 19.6% for Cd, and both metals were classified as presenting a medium mobility risk. The closely comparable mobility factors indicate that Pb and Cd exhibited similar potential mobility in

the investigated sediment, despite differences in their concentrations among the individual geochemical fractions. Overall, the fractionation and mobility results suggest that although a substantial proportion of both metals was retained in the residual fraction, approximately one-fifth of the total metal content was represented by the operationally more mobile fractions, resulting in a medium potential mobility risk for both Pb and Cd.

Table 1: Geochemical Fractionation and Concentrations of Pb and Cd in Sediments of River Jama'are

Geochemical fraction	Concentration (mg/kg)	
	Pb	Cd
Exchangeable fraction	18.33 ± 2.52	7.33 ± 1.53
Reducible fraction	27.00 ± 4.00	10.67 ± 2.52
Oxidizable fraction	15.00 ± 2.00	6.33 ± 2.52
Residue fraction	33.67 ± 4.51	13.00 ± 2.00

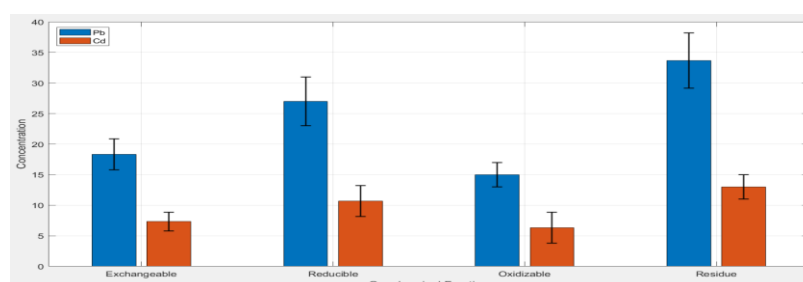


Figure 1: Distribution of Pb and Cd among the exchangeable, reducible, oxidizable, and residual fractions of River Jama'are sediments

Table 2: Mobility Factors and Potential Mobility Risk of Pb and Cd in Sediments of River Jama'are

Heavy metal	Mobility factor (%)	Comment
Pb	19.5	Medium risk
Cd	19.6	Medium risk

Discussion

The distribution of Pb and Cd among the geochemical fractions of River Jama'are sediments indicates that both metals were predominantly associated with the residual fraction, followed by the reducible, exchangeable, and oxidizable fractions. The dominance of the residual fraction indicates that a substantial proportion of both metals was associated with relatively stable sedimentary phases and was therefore less susceptible to short-term remobilization, whereas the non-residual fractions represent potentially more mobile pools that may respond to environmental changes (Shi *et al.*, 2026; Kumar *et al.*, 2026; Duan *et al.*, 2026; Heo *et al.*, 2026). This distribution is consistent with reports of Pb and Cd predominantly associated with stable mineral phases in river sediments (Hou *et al.*, 2013; Yuan *et al.*, 2014; Wang *et al.*, 2020a). The relatively high contribution of the reducible fraction suggests an important association with Fe and Mn oxides, which can act as reservoirs for trace metals and may release associated metals under changing redox conditions (Zhu *et al.*, 2019; Garba *et al.*, 2026; Derstila *et al.*, 2026). In contrast, the lower oxidizable fraction indicates a comparatively smaller association with organic matter-bound phase and sulfide-bound phase. Changes in pH, redox conditions, ionic composition, or organic matter may nevertheless alter the partitioning and mobility of Pb and Cd (Rao *et al.*, 2008; Nijeje *et al.*, 2023). Although both metals exhibited similar fractionation patterns, this should not be interpreted as evidence of a common source because metal partitioning is also influenced by sediment properties such as

mineralogy, particle size, organic matter, and Fe/Mn oxide content (Garba *et al.*, 2026; Vdović *et al.*, 2021).

Both Pb and Cd exhibited medium potential mobility risk based on their mobility factors, indicating that a measurable proportion of each metal occurs in potentially mobilizable fractions. However, the mobility factor represents potential rather than actual environmental mobility, and the non-residual fraction should not be interpreted as the quantity that will necessarily be released into the aquatic environment (Fathollahzadeh *et al.*, 2014; Wang *et al.*, 2020b; Gao *et al.*, 2022). The results therefore suggest that River Jama'are sediments may function as a relatively stable sink for Pb and Cd under prevailing conditions but could become a secondary source if environmental conditions promote remobilization. The mobility of sediment-associated metals is site-dependent and should therefore be interpreted within the specific geochemical context of the river.

An important limitation is that sequential extraction provides operationally defined fractions rather than unequivocal mineralogical or chemical species. The extract used in sequential extraction procedures may not be completely selective, and redistribution or incomplete extraction of metals can occur during the analytical procedure (Jahangir *et al.*, 2023; Ali *et al.*, 2024). Accordingly, the fractions identified in this study should be interpreted as indicators of relative geochemical association rather than definitive identification of individual metal species. Moreover, because supporting sediment properties such as pH, organic matter, Fe/Mn oxide content, particle-size distribution, and mineralogical composition were not considered here, the

specific mechanisms controlling Pb and Cd partitioning cannot be established conclusively. An additional limitation is that the study was based on a single composite sediment sample prepared from five sampling points. Although three replicate portions were analyzed, these were subsamples of the same composite and therefore do not provide independent spatial replicates. Thus, the reported variability reflects analytical/procedural variation rather than spatial heterogeneity across River Jama'are, and the findings should not be generalized to the entire river without further spatially replicated sampling.

CONCLUSION

This study demonstrates that Pb and Cd in River Jama'are sediments are predominantly associated with the stable residual fraction, indicating relatively strong retention under prevailing conditions. However, their occurrence in non-residual fractions confers medium potential mobility risk, suggesting that the sediments could become a secondary source of these metals under conditions that promote remobilization. Continued monitoring of metal speciation and relevant sediment physicochemical properties is recommended to better assess their long-term environmental behaviour.

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