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Cadmium (Cd) Contamination Status in Cisanti Lake (West Java, Indonesia) Analysis on Water, Sediment, and Bioaccumulation in Invasive Mussels *Sinanodonta pacifica* (Heude, 1878)

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ABSTRACT

Cisanti Lake, the strategic zero point of the Citarum River, faces the threat of cadmium (Cd) pollution from surrounding agricultural activities. Conducted during the dry season of 2024, this pioneering study assesses the Cd pollution status using a multicompartment approach (water, sediment, and bioindicator organism *Sinanodonta pacifica*, Heude 1878). Samples from the three stations were analyzed using Atomic Absorption Spectrophotometry (AAS). The concentration of Cd in water was very low (0.0012–0.0030 mg/L), but it accumulated significantly in sediment (0.37–0.65 mg/kg) and mussel tissue (0.20–0.30 mg/kg). Although the concentration in water and biota was below quality standards, ecological risk analysis revealed that the sediment has moderate contamination (Contamination Factor: 1.25–2.15) and acts as a long-term pollutant sink. *S. pacifica* proved effective in accumulating Cd from the water column, demonstrated by a high Bioconcentration Factor from water to biota (BCF b-w >75), making it a reliable bioindicator of Cd pollution. This study provides crucial baseline data on environmental management in the upstream Citarum and establishes sediment monitoring as a vital early warning tool for future pollution risks.

1. Introduction

Cadmium (Cd), a highly toxic metal commonly associated with phosphate fertilizers and pesticides, poses a significant threat to global freshwater ecosystems (Harikumar *et al.* 2010; Bao *et al.* 2012). This threat is particularly critical in headwater regions like Cisanti Lake, the "ground zero" of the Citarum River, a river of immense strategic importance for West Java, Indonesia. Cisanti Lake not only serves as the primary water source for the Citarum (Diana 2021) but also supports local livelihoods through irrigation for agriculture, fisheries, and the development of ecotourism. The ecological health of this lake is therefore directly linked to the success of national revitalization efforts such as the "Citarum Harum" program and the well-being of millions of people downstream who depend on the river for water supply. Given the intensive agricultural and plantation activities surrounding the lake, which have the potential to release heavy metals (Mulyadi *et al.* 2017; Anwar & Khadijah 2024), there is a pressing need to investigate the status of key agricultural pollutants like Cd.

Despite its strategic importance, there is a critical lack of published data regarding the concentration and distribution of specific heavy metals within Cisanti Lake's key environmental compartments (water, sediment, and biota). This data deficiency creates a significant knowledge gap, hindering accurate ecological risk assessment and preventing the formulation of evidence-based management policies for the Citarum's headwaters. Therefore, this study aims to answer

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the following research questions: (1) What are the concentrations of Cd in the water, sediment, and the tissues of *Sinanodonta pacifica* in Cisanti Lake? (2) What does Cd pose the ecological risk level in the lake's sediment? (3) How effective is the invasive mussel S. pacifica as a bioindicator for Cd contamination in this ecosystem?

To address these questions, this study employs a biomonitoring approach utilizing the invasive T*aiwanese mussel, Sinanodonta pacifica* (Heude, 1878). Biomonitoring using dominant, filter-feeding bivalves offers a more time-integrated and cost-effective assessment of bioavailable pollutants compared to discrete water sampling alone. *S. pacifica* was chosen due to its high abundance in the lake, high environmental tolerance in polluted habitats (Sahidin *et al.* 2021), and its known capacity as an effective accumulator of heavy metals, which has been demonstrated in numerous studies (Li *et al.* 2015; Jing *et al.* 2019; Chen *et al.* 2021). As a filter feeder, a single mussel can filter approximately 40 liters of water daily (Tankersley & Dimock 1993; Al-Mamun & Khan 2011), making it a suitable sentinel organism for this pioneering study.

This study provides the first comprehensive baseline data on Cd contamination in the Citarum upstream ecosystem by integrating analysis across water, sediment, and biota. The findings will offer a crucial scientific foundation to inform local environmental agencies in developing targeted conservation strategies. Furthermore, this research contributes vital upstream data that can support and refine the objectives of broader regional policies, including the Citarum Harum program, by highlighting the importance of managing pollution at its source.

2. Materials and Methods

2.1. Study Area and Sampling Design

This research was conducted at Cisanti Lake, a small freshwater volcanic lake located at the headwaters of the Citarum River watershed in Bandung Regency, West Java, Indonesia (Figure 1). The lake has a surface area

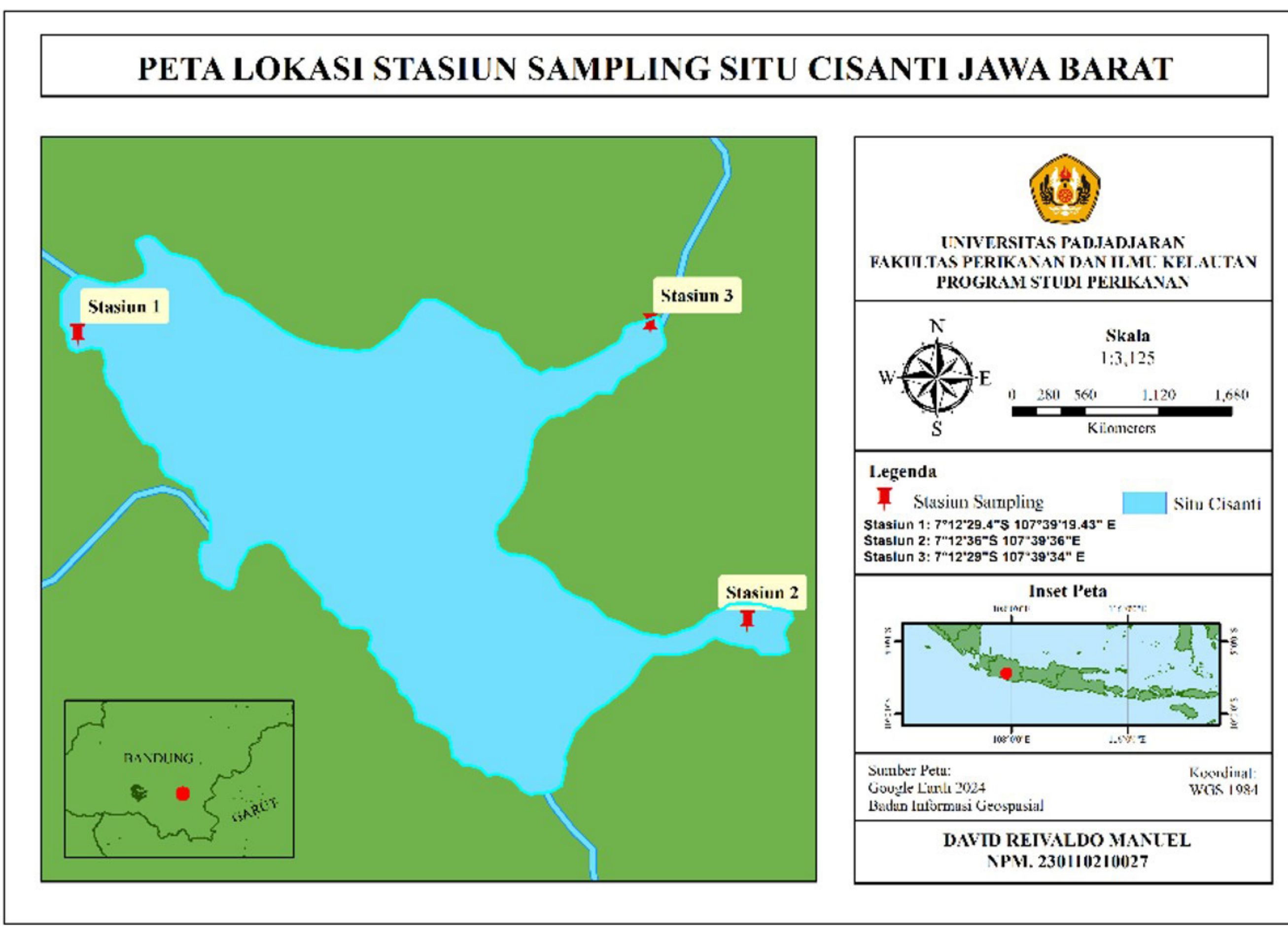

Figure 1. Research location and sampling station

of approximately 7 hectares and an average depth of 3-4 meters. The surrounding land use is dominated by intensive agricultural activities and forestry plantations, which represent potential non-point sources of heavy metal pollution, including cadmium (Cd), through surface runoff.

Sampling was carried out monthly from July to September 2024, representing the dry season. The dry season was purposively selected to measure Cd concentrations under stable hydrological conditions with a minimal dilution effect from rainwater, a condition considered representative of the chronic pollution status in the lake ecosystem.

Samples were collected from three purposively selected stations chosen to represent a potential pollution gradient and the lake's zonation:

- Station 1 (Inlet; S 7°12'29.4" E 107°39'19.43"): Located at the Cihaniwung spring inlet, representing the primary water input, expected to have the lowest direct anthropogenic influence, and serving as a local baseline.
- Station 2 (Middle-Littoral; S 7°12'36" E 107°39'36"): Located in the littoral zone on the southern side, which is geographically in the central part of the lake. This station was chosen to represent a potential point of direct entry for surface runoff from the surrounding agricultural and plantation areas.
- Station 3 (Outlet; S 7°12'29" E 107°39'34"): Located at the point where water exits the lake into the Citarum River, representing a potential zone of accumulation for contaminants before they are discharged downstream.

2.2. Sample Collection and Handling

At each station, sampling was conducted to obtain three temporal replicates (n = 3) for water and sediment (one sample collected each month for three consecutive months). To prevent cross-contamination, all sampling equipment was thoroughly cleaned, and sample containers were pre-rinsed with lake water from the respective station prior to collection.

- Water samples (500 mL) were taken 30 cm below the surface using Polyethylene (PE) bottles and immediately preserved with concentrated HNO_3 to a pH of ≈ 2.
- Surface sediment samples (top 0-10 cm layer) were collected using an Ekman Grab Sampler, and 250 g from each collection was stored in a labeled plastic bag.
- For the bioindicator, one individual (n = 1) of the Taiwanese mussel with a shell length of 6–8 cm was collected manually at each station during each sampling month. The collection of a single individual is acknowledged as a study limitation for inferential statistical purposes; therefore, the mussel data were analyzed descriptively.

Immediately after collection, all samples were placed in a cool box for transport to the laboratory. Samples were then stored in a refrigerator at 4°C and were processed for digestion and analysis within 72 hours of collection to ensure sample integrity.

2.3. *In-Situ* Water Quality Measurement

Physicochemical water quality parameters were measured in situ at each station during each monthly sampling event. A single measurement for each parameter was recorded at a depth of 30 cm, concurrent with the water sample collection. Temperature and Dissolved Oxygen (DO) were measured using a DO meter (Lutron PDO-519), and pH was measured using a pH meter (Lutron PH-207). These three parameters were specifically selected as they are the primary factors influencing the chemical speciation, solubility, and bioavailability of heavy metals like cadmium in aquatic ecosystems, as well as affecting the metabolic processes of the bioindicator organism.

2.4. Ethical Approval

The animals in this study originated from the local area and underwent no testing or treatment. Ethical clearance does not apply to this study.

2.5. Cadmium Concentration Analysis

The concentration of cadmium (Cd) in all sample digestates was determined at the Central Laboratory of Padjadjaran University. The detailed sample preparation and digestion protocols are described in Section 2.5.

2.5.1. Instrumental Analysis and Calibration

Quantitative analysis was performed using a PerkinElmer AAnalyst 400 Atomic Absorption Spectrometer (AAS) with an air-acetylene flame at a wavelength of 228.8 nm. The instrument was calibrated using an external calibration curve constructed from a series of certified Cd standard solutions. The linearity of the calibration curve was confirmed with a correlation coefficient (r^2) of 0.9991.

2.5.2. Quality Assurance and Quality Control (QA/QC)

Robust Quality Assurance/Quality Control (QA/QC) protocols were implemented to ensure the accuracy and precision of the results. Procedural blanks were processed with each batch of samples, and all blank results were below the detection limit. Each final sample solution was analyzed in triplicate (n = 3 technical replicates), with a relative standard deviation (RSD) maintained below 5%. The instrument's Limit of Detection (LOD) and Limit of Quantification (LOQ) for Cd were determined to be 0.0374 mg/L and 0.1247 mg/L, respectively. All reported concentrations were above the LOQ.

2.6. Sample Preparation

All sample preparations were conducted in a controlled laboratory environment to prevent cross-contamination. Analytical-grade reagents (HNO_3 and $HClO_4$) and high-purity deionized water were used for all procedures. All glassware and equipment were acid-washed (soaked in 10% HNO_3 for 24 hours) and rinsed thoroughly with deionized water prior to use. As stated in Section 2.2, samples were stored at 4°C and processed within 72 hours of collection. Each field sample was prepared and digested in triplicate (n = 3 technical replicates) to ensure analytical precision. A procedural blank was included with each batch of digestions to monitor for potential contamination.

2.6.1. Water Samples

The preparation of water samples followed the SNI 6989.84.2019 procedure as described by Rachmawati *et al.* (2023). Briefly, 100 mL of a water sample was placed in a 250 mL beaker, and 5 mL of concentrated HNO_3 was added. The mixture was gently heated on a hot plate until the volume was reduced to approximately 10-20 mL. Digestion was considered complete when the solution remained clear and colorless upon cooling. The remaining digestate was then quantitatively transferred to a 100 mL volumetric flask and diluted to the mark with deionized water before AAS analysis.

2.6.2. Sediment Samples

The sediment samples were prepared following the SNI 06-6992.4-2004 procedure as referenced by Aristawidya *et al.* (2023). Samples were first oven-dried at 60°C to a constant weight and cleared of foreign objects (e.g., twigs, debris). The dried sediment was then ground into a fine, homogeneous powder using a ceramic mortar and pestle. A total of 3.0 g of the homogenized powder was weighed and mixed with 25 mL of deionized water, followed by the addition of 5-10 mL of concentrated HNO_3 and 1–3 mL of concentrated $HClO_4$. The mixture was heated at 105–120°C until white fumes appeared and the solution became clear with no visible solids remaining. After cooling, the solution was filtered, placed in a 100 mL volumetric flask, and diluted to the mark with deionized water for AAS analysis.

2.6.3. Mussel Tissue Samples

Mussel tissue samples were prepared according to the SNI 2354.5.2011 procedure as described by Agustina *et al.* (2021). The entire soft tissue from each individual was liquefied using a blender (cleaned between samples) to create a uniform homogenate paste. A subsample of approximately 1.0 g (wet weight) of the homogenate was then taken for digestion. The subsample was digested with concentrated HNO_3 and $HClO_4$, heated at 60–70°C for 2-3 hours. Digestion was considered complete when the solution was clear and colorless. The resulting solution was then cooled and quantitatively diluted to a final volume of 50 mL in a volumetric flask using deionized water.

For all sample types, the final metal concentration in the original sample was calculated by accounting for the initial sample weight or volume and the final dilution volume, ensuring all results were reported in the correct units (mg/L for water and mg/kg for sediment and biota).

2.7. Data Analysis

2.7.1. Data Handling and Descriptive Statistics

All raw data were compiled and inspected for anomalous values prior to statistical analysis; no outliers that warranted removal were identified. Descriptive statistics, including the mean, standard deviation (SD), minimum, and maximum values (range), were calculated for all parameters. The results were visualized using tables for data presentation and bar graphs for spatial comparisons.

2.7.2. Inferential Statistics

To compare Cd concentrations in water and sediment among the three stations, inferential statistics were employed. Prior to analysis, data were tested for the assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test). For the ANOVA test, a visual inspection of the residuals was also performed to check for major deviations from model assumptions. Since only one variable (Cd concentration) was compared across the three stations for each matrix, a correction for multiple comparisons (e.g., Bonferroni) was not deemed necessary. As the primary ANOVA and

Kruskal-Wallis tests did not yield significant results ($p>0.05$), subsequent post-hoc tests were not performed.

Due to the limited sample size for the bioindicator (n = 1 per station per month), which provides low statistical power for meaningful inference, inferential tests were not applied to the mussel data. Instead, the mussel concentration data were analyzed descriptively.

2.7.3. Benchmark Comparison

To assess the level of contamination, the mean Cd concentration for each matrix was directly compared to the established threshold values from the relevant quality standards (Government Regulation No. 22/2021 for water; ANZECC/ARMCANZ (2000) for sediment; BSN 7378-2009 for mussels) to determine compliance.

2.7.4. Software and Data Availability

All statistical analyses were performed using RStudio (Version: 2025.05.1+513) with R (Version: 4.5.1). The primary packages used were stats for core statistical tests and ggplot2 for data visualization. The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request.

2.8. Ecological Risk Assessment

The contamination factor evaluates the extent of heavy metal contamination. It is determined by calculating the ratio of the concentration of each element present in the sediment to the established background value (Kumari 2018). The natural value of heavy metal cadmium is 0.3 ppm or 0.3 mg/Kg (Dewi *et al.* 2021). CF value is divided into 4 classifications: $CF < 1$ signifies low contamination; $1 \leq CF < 3$ suggests moderate contamination; $3 \leq CF < 6$ indicates considerable contamination; and $CF \geq 6$ shows very high contamination. The CF value can be determined using the formula proposed by Harikumar (Harikumar *et al.* 2009).

$$CF = \frac{Cn}{Bn} \tag{1}$$

Geo-accumulation Index (Igeo) is a criterion index used to assess the intensity of heavy metal pollution. The geoaccumulation index value is divided into 7 classifications: $Igeo \leq 0$ indicates uncontaminated; $0 < Igeo < 1$ denotes lightly polluted; $1 < Igeo < 2$ signifies moderately polluted; $2 < Igeo < 3$ reflects moderately to severely polluted; $3 < Igeo < 4$ refers to heavily polluted; $4 < Igeo < 5$ represents heavily to extremely polluted; and $Igeo > 5$ indicates extremely polluted (Xu *et al.* 2021). The following equation expresses the Igeo value (Sojka *et al.* 2018).

$$Igeo = \log 2 \times \left(\frac{Cn}{1.5 \times Bn}\right) \tag{2}$$

2.9. Bioconcentration Factor

The bioconcentration factor (BCF) formula is utilized to assess the capacity of Taiwanese mussels, sediments, and water to accumulate heavy metals. The analysis of the BCF factor is conducted based on the ratio of the concentration of heavy metals in biota to the concentration of metals in sediment and the concentration of metals in water. The BCF value can be derived using the formula (Mountouris *et al.* 2002; Potipat *et al.* 2015):

$$BCF = \frac{{}^{C}B}{C_w} \tag{3}$$

BCF value categories of polluting properties are divided into 4 classifications: BCF > 1,000, very high; BCF 100–1,000, high; BCF 30 -100, moderate; and BCF < 30, low (Allison *et al.* 2024).

3. Results

3.1. Physicochemical Water Parameters

The measurement of the physicochemical parameters of water in Cisanti Lake during the study period is presented in Table 1. During the study period in the dry season, the water temperature ranged from 21.03 to 23.50°C, the pH value tended to be neutral to slightly alkaline (7.06–7.29), and the dissolved oxygen (DO) concentration was in the range of 6.13 mg/L to 6.46 mg/L. The values of these parameters, in general, still meet Class I water quality standards based on Government Regulation No. 22/2021.

3.2. Cadmium (Cd) Concentrations in Environmental Compartments

The mean concentrations of Cadmium (Cd) in water, sediment, and *S. pacifica* shellfish tissue samples from the three stations are presented in Table 2. The

Table 1. Average and standard deviation (SD) of water quality parameters with guidelines

Station	Parameters		
	Temp. (°C)	DO Conc. (mg/L)	pH
1	23.50±1.323	6.46±0.473	7.27±0.398
2	22.13±0.808	6.30±0.917	7.06±0.306
3	21.03±3.821	6.13±0.971	7.29±0.749
Class I quality standard*	ΔT ≤ 3°C	6	6-9

*Adapted from government regulation No. 22/2021 regarding environmental protection and management

Table 2. Average and standard deviation (SD) of cadmium concentrations in all samples with the guidelines for Cd metal

Station	Cd concentration			
	Water (ppm)	Sediment (ppm)	*S. pacifica* (ppm)	Reference
1	0.0012±0.0006	0.37±0.158	0.29±0.196	
2	0.0030±0.0020	0.53±0.074	0.20±0.243	
3	0.0014±0.0007	0.64±0.350	0.30±0.305	
Maximum permissible levels (National)*	0.01	-	-	(Hartiningsih *et al.* 2024)
Quality guidelines in sediments (ANZACC/ ARMCANZ)**	-	1.5	-	(Harmesa & Cordova 2021)
Permission standard limit in food, especially shellfish (bivalve) (SNI)***	-	-	1.0	(Yulyana *et al.* 2023)
The permission standard limit in food (WHO)	-	-	1.0	(Potipat *et al.* 2015)

*National criteria based on Indonesian government regulation No. 22/2021, class I is water that the designation can be used for raw drinking water, and/or other uses that require the same quality of water as that used

**ANZECC/ARMCANZ (2000): Australian and New Zealand environment and conservation council and agriculture and resource management council of Australia and New Zealand

*** SNI: Standard Nasional Indonesia (Indonesia National Standard 2009)

concentration of dissolved Cd in water is very low, ranging from 0.0012±0.0006 to 0.0030±0.0020 mg/L. This value is below the set water quality standard based on Government Regulation No. 22/2021.

The concentration of Cd in the sediment showed a much higher value than in water, with the lowest value at Station 1 (0.37±0.158 mg/kg) and the highest at Station 3 (0.64±0.350 mg/kg). There is a trend of increasing concentration from the inlet area to the lake outlet. Nonetheless, all values are still below the sediment quality guidelines of ANZECC/ARMCANZ (1.5 mg/ mg/kg).

In *S. pacifica* shellfish tissue, the highest concentration of Cd was descriptively observed in individuals from Station 3 (0.30±0.305 mg/Kg). All measured Cd concentration values in shellfish tissue are still below the maximum permissible limit for consumption according to SNI and WHO (1.0 mg/kg).

3.3. Ecological Risk and Bioconcentration Assessment

Ecological risk assessments based on Cd concentrations in sediments are presented in Table 3. Contamination Factor (CF) shows values between 1.25 to 2.15. Based on the classification, all stations are included in the category of moderate contamination, because they have a value of $1 \leq CF < 3$. The Geo-accumulation Index (Igeo) shows that Station 1 is classified as unpolluted ($Igeo \leq 0$), while Stations 2 and 3 are classified as lightly polluted ($0 < Igeo < 1$).

The results of the calculation of the Bioconcentration Factor (BCF) to assess the accumulation capacity of *S. pacifica* are presented in Table 4. The BCF value of water (BCF b-w) shows a range of 67.27 to 232.64, which indicates high accumulation ability. In contrast, the BCF value of the sediment (BCF b-s) shows a much lower value (0.38 – 0.79), which falls into the category of low accumulation.

3.4. Statistical Comparison Among Stations

Inferential statistical analysis was performed to compare the concentration of Cd among stations in water and sediment media. The test results showed no statistically significant difference in the concentration of Cd between the three stations, both in the water medium (Kruskal-Wallis test, $p>0.05$) and in the sediment medium (One-Way ANOVA test, $p>0.05$). Inferential statistical analysis was not performed for shellfish data due to the limitation of the number of samples ($n = 1$ per station per month), which makes it impossible to estimate within-group variance, a fundamental requirement for tests like ANOVA.

4. Discussion

4.1. Pollution Status at the Cisanti Lake

This study provides the first assessment of cadmium (Cd) contamination status in Cisanti Lake, an ecosystem of high strategic importance as the headwaters of the Citarum River. The findings reveal a paradox: while the Cd concentration in the water column is very low, the lake sediment shows clear signs of contamination. Specifically, ecological risk analyses revealed moderate contamination (CF: 1.25-2.15) and lightly polluted

Table 3. Ecological risk index values and categories

Station	Contaminating factor (CF)	CF category	Geo-accumulation index (Igeo)	Igeo category
1	1.25	Moderate	-0.263	Unpolluted
2	1.79	Moderate	0.253	Lightly polluted
3	2.15	Moderate	0.522	Lightly polluted

Table 4. Definitions are swapped. Please change to: (b-w) = bioconcentration factor biota-water; (b-s) = bioconcentration factor biota-sediment

Station	BCF (b-s)	BCF (b-w)
1	0.79	232.64
2	0.38	67.27
3	0.47	211.53

conditions (Igeo: 0.25-0.52) in most of the lake area. This indicates that the sediment acts as a long-term sink (reservoir) for Cd pollutants. This phenomenon is consistent with findings from other Indonesian volcanic lakes, such as Lake Lau Kawar, where Cd concentrations in water were also reported to be very low while being much higher in the sediment (Malau *et al.* 2021).

4.2. Factors Affecting Cadmium Accumulation in Sediment

The low concentration of Cd in water and its high concentration in sediment can be explained by deposition and sedimentation processes. The measured pH level strongly influences this deposition in Cisanti Lake, which tends to be alkaline and facilitates the precipitation of heavy metals (Li *et al.* 2013). This is in contrast to low pH conditions, which can increase metal solubility (Chou *et al.* 2018; Kang *et al.* 2019). This stability is consistent with findings from other Indonesian freshwater systems, where research by Putri *et al.* (2015) also reported that heavy metals remained strongly bound to sediments across different seasons. In addition to water chemistry, sediment properties, such as high organic matter content and fine-grained particles (clay/silt), have a large capacity to adsorb and bind Cd ions, effectively trapping them at the bottom of the lake.

4.3. Effectiveness of *Sinanodonta pacifica* as a Bioindicator

S. pacifica proved capable of accumulating Cd, although the concentrations in its tissues remained below food safety standards. Its effectiveness as a bioindicator is most clearly demonstrated by the Bioconcentration Factor (BCF) results. The high BCF value from water to biota (BCF b-w) strongly suggests that the water column is the primary pathway for the uptake of bioavailable Cd. This finding aligns with the filter-feeding mechanism of *S. pacifica*, which can filter large volumes of water, reportedly up to 40 liters per day (Tankersley & Dimock Jr. 1993). However, it should be acknowledged that other exposure routes, such as the ingestion of resuspended sediment particles, cannot be entirely ruled out without further experimental studies.

4.4. Analysis of Spatial Distribution and Contamination Sources

Within the spatial scope of this study, no significant differences in Cd concentrations were detected among the three stations. This may indicate a relatively uniform distribution of Cd in the sampled areas, but does not preclude the existence of unobserved hotspots. This condition can be attributed to the characteristics of Cisanti Lake as a relatively calm and enclosed water system. The source of Cd is likely diffuse runoff from the surrounding agricultural activities, which would naturally result in a more homogeneous distribution than a single point source. This inference is supported by findings in similar ecosystems where agricultural activities were identified as the main source of Cd contamination (Malau *et al.* 2021) and the association of the Geo-accumulation Index with human activities (Hotijah *et al.* 2024).

4.5. Long-Term Ecological Risk, Implications, and Study Limitations

The moderate level of sediment contamination serves as an important warning. Although Cd is currently bound in the sediment, this bond is not necessarily permanent. The sediment can act as a "chemical time bomb," potentially re-releasing Cd into the water column (remobilization) if environmental conditions change. This potential for remobilization poses a long-term ecological risk to the health of the Cisanti Lake ecosystem and the water quality of the Citarum River downstream.

The finding that the Citarum headwaters have already received an initial pollutant load has serious implications for the river's revitalization efforts. However, the conclusions of this study must be considered within the context of its significant methodological limitations. First, the very limited number of mussel samples (n = 1 per station per month) severely restricts the statistical power and generalizability of the bioaccumulation findings; therefore, interpretations of BCF patterns should be considered preliminary. Second, sampling only during the dry season likely underestimates the total annual Cd loading, which is expected to peak during the rainy season due to agricultural runoff. Therefore, essential future research should include a higher replication of biota samples, a multi-season sampling design, and analysis of sediment properties to validate these findings.

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