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Lead contamination, bioaccumulation, and ecotoxicological risks associated with industrial effluents from the REGIDESO Lemba Imbu Plant in the N'djili River, Democratic Republic of the Congo

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ABSTRACT

Introduction

Industrial effluent discharges constitute a major source of aquatic pollution in many developing countries. In Kinshasa, Democratic Republic of the Congo, the REGIDESO water treatment plant at Lemba Imbu discharges effluents directly into the N'djili River, potentially affecting water quality, aquatic organisms, and human health.

Purpose

This study assessed the physicochemical characteristics, lead contamination levels, and ecotoxicological impacts associated with effluents discharged from the REGIDESO Lemba Imbu plant into the N'djili River.

Methods

A field-based cross-sectional study was conducted during the 2025 rainy season in the N'djili Kilambu neighbourhood of Mont-Ngafula Municipality. A total of 45 samples comprising 15 water samples, 15 sediment samples, and 15 specimens of *Oreochromis niloticus* were collected from three sampling stations (upstream, discharge point, and downstream). Physicochemical parameters including dissolved oxygen, pH, temperature, conductivity, and total dissolved solids were measured. Lead concentrations were determined in water, sediments, and fish tissues. Bioconcentration factors were calculated to evaluate lead accumulation in fish. Data were analysed using one-way analysis of variance, Fisher's Least Significant Difference test, and Spearman's rank correlation at a 5% significance level.

Results

Significant spatial variations were observed for all physicochemical parameters ($p < .05$). Dissolved oxygen concentrations were highest at the discharge point (22.67 ± 7.50 mg/L) and lowest upstream (1.50 ± 0.30 mg/L). Although pH, temperature, conductivity, and total dissolved solids remained within recommended limits, lead concentrations exceeded applicable guideline values in all environmental matrices. Water lead concentrations ranged from 1.008 ± 0.032 mg/L upstream to 1.156 ± 0.008 mg/L at the discharge point. Sediment lead concentrations reached 2.040 ± 0.004 mg/L at the discharge point, while concentrations in *Oreochromis niloticus* ranged from 7.12 ± 0.22 mg/kg upstream to 12.08 ± 0.08 mg/kg at the discharge point, substantially exceeding the FAO/WHO permissible limit of 0.3 mg/kg. Bioconcentration factors demonstrated significant lead accumulation in fish, with strong positive associations between lead concentrations in water, sediments, and fish tissues.

Conclusion

The findings suggest that effluents discharged from the REGIDESO Lemba Imbu plant contribute to elevated lead contamination and bioaccumulation within the N'djili River ecosystem. Although most physicochemical parameters remained within recommended limits, lead concentrations in water, sediments, and *Oreochromis niloticus* exceeded applicable environmental and food-safety standards. The observed contamination raises concerns regarding ecosystem health and potential human exposure through fish consumption, highlighting the need for continuous environmental monitoring and improved wastewater management.

INTRODUCTION

Industrialisation plays a critical role in socioeconomic development by stimulating economic growth, generating employment, and supporting technological advancement. However, industrial activities also produce substantial quantities of wastewater that may adversely affect aquatic ecosystems when discharged without adequate treatment. Industrial effluents often contain organic pollutants, nutrients, suspended solids, and toxic substances, including heavy metals, which can degrade water quality and threaten both environmental and human health (Obaideen et al., 2022).

In many developing countries, rapid urbanisation and industrial expansion have outpaced environmental management and wastewater treatment infrastructure. Consequently, rivers and streams frequently serve as recipients of domestic and industrial effluents, resulting in increasing levels of environmental contamination (Lautier & Chaponnière, 2022). Industrial wastewater discharges have been associated with elevated concentrations of suspended solids, nutrients, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and potentially toxic elements that can alter aquatic ecosystems and reduce biodiversity (Deroo, 2021; Mamadou et al., 2022).

Heavy metals are among the most concerning contaminants released into aquatic environments because of their persistence, toxicity, and ability to accumulate in sediments and living organisms. Unlike many organic pollutants, heavy metals do not degrade naturally and may remain in aquatic systems for extended periods. Their accumulation in sediments creates long-term reservoirs of contamination, while their uptake by aquatic organisms can lead to bioaccumulation and biomagnification through food webs (Chanel et al., 2017). Among these contaminants, lead is of particular concern because of its adverse effects on neurological, renal, reproductive, and developmental health in both humans and wildlife (Manitoba Health, 2019; Morneau, 2020).

The Democratic Republic of the Congo (DRC) faces significant challenges related to water pollution, particularly in rapidly growing urban centres such as Kinshasa. The city's rivers receive increasing quantities of domestic, commercial, and industrial wastes, often without adequate treatment. As a result, many aquatic ecosystems are exposed to multiple sources of contamination that compromise water quality and ecosystem functioning (Salakiaku et al., 2022). The N'djili River, one of the major tributaries of the Congo River within Kinshasa, is particularly vulnerable because it receives wastewater from residential areas, agricultural activities, and industrial installations situated along its course (Mufungizi et al., 2023).

In addition to conventional pollutants, recent studies have reported increasing levels of environmental degradation within the N'djili River watershed, including contamination by plastics and other anthropogenic wastes that negatively affect aquatic habitats and fishing activities (Tchomba et al., 2023). Such contamination threatens the ecological integrity of the river and may compromise the safety of aquatic resources used for human consumption.

The REGIDESO water treatment plant located in Lemba Imbu, Mont-Ngafula Municipality, discharges treated and operational effluents into the N'djili River. Although the plant plays an essential role in supplying potable water to Kinshasa, concerns remain regarding the potential environmental impacts of its effluent discharges. Previous studies have documented general water-quality challenges within the N'djili River system; however, limited information exists regarding the combined physicochemical and ecotoxicological effects of REGIDESO effluents, particularly with respect to lead contamination in water, sediments, and aquatic organisms. Furthermore, few studies have simultaneously examined contamination pathways linking river water, sediments, and fish tissues in the vicinity of the REGIDESO discharge point. Understanding these relationships is essential for evaluating ecological risks, assessing the potential for contaminant transfer within aquatic ecosystems, and determining possible public health implications associated with fish consumption.

Therefore, this study assessed the physicochemical characteristics, lead contamination levels, and ecotoxicological impacts associated with effluent discharges from the REGIDESO Lemba Imbu plant into the N'djili River. Specifically, the study evaluated water-quality parameters, quantified lead concentrations in water, sediments, and *Oreochromis niloticus*, and examined the bioaccumulation of lead within the aquatic ecosystem.

Study Objectives

The main objective of this study was to assess the physicochemical characteristics, lead contamination levels, and ecotoxicological impacts associated with industrial effluents discharged from the REGIDESO Lemba Imbu plant into the N'djili River.

The specific objectives were to:

1. Characterise the physicochemical quality of river water upstream, at the discharge point, and downstream of the REGIDESO effluent outfall.
2. Determine lead concentrations in water, sediments, and *Oreochromis niloticus* collected from the study area.
3. Evaluate the bioaccumulation of lead in *Oreochromis niloticus* using bioconcentration factors.
4. Assess the potential ecological implications of lead contamination within the N'djili River ecosystem.

Research Hypotheses

The study tested the following hypotheses:

H_1: Physicochemical characteristics of the N'djili River differ significantly among the upstream, discharge-point, and downstream sampling stations.

H_2: Lead concentrations in water, sediments, and *Oreochromis niloticus* differ significantly among the sampling stations.

H_3: Lead contamination is positively associated with bioaccumulation in *Oreochromis niloticus*.

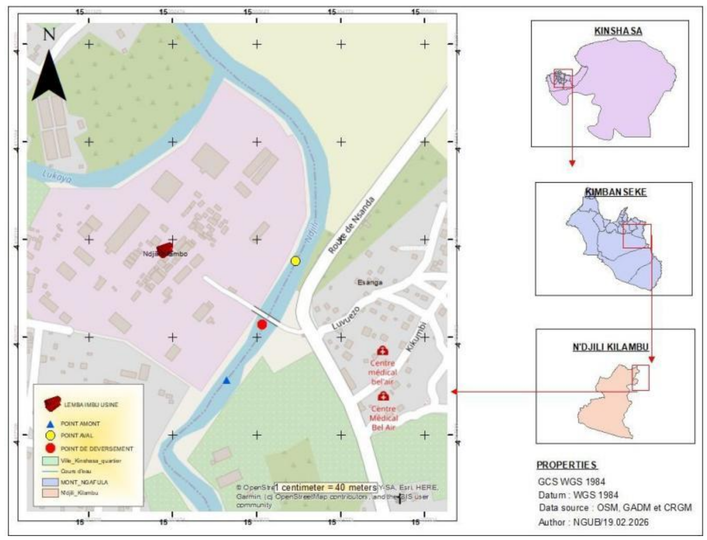
H_4: Sediments act as important reservoirs of lead contamination within the N'djili River ecosystem.

METHODS

Study Area

This study was conducted in the N'djili Kilambu neighbourhood of Mont-Ngafula Municipality, Kinshasa, Democratic Republic of the Congo. The study area is located along the N'djili River, where the REGIDESO Lemba Imbu water treatment plant discharges operational effluents into the river. The municipality comprises residential, agricultural, and industrial activities that may influence river water quality. The N'djili River serves as an important freshwater resource for domestic use, fishing, irrigation, and other socioeconomic activities, making its environmental quality a matter of public health and ecological significance.

Figure 1:
Google Map of the Sampling Sites. (a) Democratic Republic of the Congo. (b) Location of the city of Kinshasa within the Democratic Republic of the Congo. (c) Mont-Ngafula commune, N'djili Kilambu district, identifying the upstream point, downstream point, and discharge point



Three sampling stations were established to evaluate the influence of the REGIDESO effluent discharge on river water quality:

- **Station 1 (Upstream):** Located approximately 100 m upstream of the effluent discharge point and regarded as the reference site.
- **Station 2 (Discharge Point):** Located at the point where REGIDESO effluents enter the N'djili River.
- **Station 3 (Downstream):** Located approximately 100 m downstream of the discharge point to evaluate the immediate impact of the discharged effluent.

The geographical coordinates of the sampling stations are presented in Table 1, while the location of the study area is illustrated in Figure 1.

Study Design

A cross-sectional field study was conducted during the rainy season between September and December 2025 to assess the physicochemical characteristics, lead contamination, and ecotoxicological impacts associated with effluent discharges from the REGIDESO Lemba Imbu plant.

Sample Collection

A total of 45 environmental samples were collected from three sampling stations comprising upstream, discharge point, and downstream locations. The samples included 15 water samples, 15 sediment samples, and 15 specimens of *Oreochromis niloticus*. At each station, five independent samples of each environmental matrix were collected, yielding 15 samples per matrix and 45 samples in total.

Table 1:
Geographical coordinates of sampling stations

Point designation	Latitude	Longitude
Upstream site	4°27′24.6′′	15°21′11.56′′
Discharge point	4°27′21.88′′	15°21′13.31′′
Downstream site	4°27′18.79′′	15°21′14.97′′

Water Sampling

Water samples were collected in pre-cleaned and sterilised glass bottles following standard environmental sampling protocols. Prior to collection, each bottle was rinsed with site-specific surface water to minimise contamination. Samples were collected facing upstream to reduce the risk of contamination from disturbed sediments and were transported to the laboratory in insulated containers under controlled temperature conditions.

Sediment Sampling

Surface sediment samples were collected from the riverbed using a clean stainless-steel shovel. The upper 5–10 cm of sediment was carefully sampled at each location to capture recently deposited contaminants. Samples were placed in labelled polyethylene containers and transported to the laboratory for further analysis.

Fish Sampling

Specimens of *Oreochromis niloticus* were collected using a 45-mm mesh fishing net. This species was selected due to its abundance in the study area and its relevance as a commonly consumed freshwater fish species.

Fish of comparable size were selected to reduce biological variability. Morphometric measurements were recorded prior to laboratory analysis. All handling procedures were conducted in accordance with standard environmental and biosafety protocols for aquatic organism sampling.

Physicochemical Analysis

In situ measurements were conducted for the following parameters:

- Dissolved oxygen (DO)
- pH
- Temperature
- Electrical conductivity (EC)
- Total dissolved solids (TDS)

Measurements were performed using calibrated portable multiparameter instruments. Dissolved oxygen was measured using a portable oximeter, while pH, temperature, EC, and TDS were determined using a calibrated multiparameter meter in accordance with World Health Organization guidelines (WHO, 2017). Instruments were calibrated prior to each sampling session following manufacturer specifications.

Determination of Lead Concentration

Lead concentrations in water, sediment, and fish tissue samples were determined using standard analytical procedures.

Water samples were analysed following appropriate filtration and preparation. Sediment and fish tissue samples were first subjected to acid digestion prior to analysis. Lead concentrations were quantified using a HACH DR/2400 UV–Visible spectrophotometer and confirmed using Energy Dispersive X-ray Fluorescence (ED-XRF) spectrometry (XEPOS III).

Quality assurance and quality control procedures included instrument calibration, analysis of blanks, and the use of certified reference standards.

Results for water samples were compared with Quebec Surface Water Quality Criteria (MDDEP, 2009), while fish tissue concentrations were evaluated against FAO/WHO Codex Alimentarius maximum permissible limits for food safety.

Bioconcentration Factor (BCF)

The bioconcentration factor (BCF) was used to assess the accumulation of lead in *Oreochromis niloticus* relative to its concentration in the surrounding water.

The BCF was calculated using the equation:

$BCF = C_{fish}/C_{water}$

Where:

- C_{fish} = lead concentration in fish tissue
- C_{water} = lead concentration in water

A higher BCF indicates a greater capacity of the organism to accumulate lead from the aquatic environment.

Statistical Analysis

Data were analysed using IBM SPSS Statistics, Microsoft Excel 2019, and OriginPro version 6.1.

Descriptive statistics were calculated and are presented as mean ± standard deviation (SD). One-way analysis of variance (ANOVA) was used to compare physicochemical parameters and lead concentrations among the three sampling stations. Where statistically significant differences were detected, Fisher's Least Significant Difference (LSD) post hoc test was applied for pairwise comparisons. Relationships among physicochemical parameters, lead concentrations, and bioconcentration factors were assessed using Spearman's rank correlation coefficient.

All statistical tests were two-tailed, and statistical significance was established at $p < .05$.

Quality Assurance and Quality Control

To ensure analytical reliability, all sampling equipment was cleaned before use, analytical instruments were calibrated according to manufacturers' recommendations, and laboratory analyses were performed using standard operating procedures. Blank samples and calibration standards were included during laboratory analyses to minimise analytical bias and maintain quality control.

Ethical Considerations

At the time of this study (2025), a formal Institutional Animal Care and Use Committee (IACUC) or national equivalent for evaluating environmental and ecotoxicological research involving vertebrate animals was not available in the Democratic Republic of the Congo. Existing ethical boards (e.g., CER-UNIKIN, CNES) are strictly dedicated to human subject research. Consequently, no formal protocol approval number was obtained. However, the sampling of 15 *Oreochromis niloticus* specimens was restricted to the minimum required for ecotoxicological assessment. All field sampling and tissue harvesting procedures were conducted strictly according to internationally accepted scientific guidelines for animal welfare to minimize suffering and environmental impact.

Sampling was conducted in accordance with relevant institutional and administrative permissions obtained from local authorities overseeing environmental and fisheries activities in the study area. Fish specimens were collected using standard ecological sampling procedures, and laboratory analyses were performed following established environmental and toxicological protocols.

Study Limitations

Sampling was conducted during a single rainy season and therefore may not capture seasonal variability in physicochemical conditions and contaminant dynamics within the N'djili River. Furthermore, only lead was investigated as the target heavy metal. Future studies should incorporate multi-seasonal monitoring and assess additional heavy metals and other emerging contaminants to provide a more comprehensive evaluation of environmental quality.

RESULTS

Physicochemical Characteristics of River Water

Dissolved Oxygen

Figure 2 presents the dissolved oxygen concentrations, which range from 6.20 ± 1.3 mg/L at the discharge point and 4.80 ± 1.0 mg/L downstream to 1.5 ± 0.3 mg/L. The values measured at the discharge point and downstream comply with the regulatory standard (≥ 5 mg/L), whereas the upstream value is significantly lower.

https://doi.org/10.4314/orapj.v7i5.47

Figure 2:
Dissolved oxygen concentration in water samples

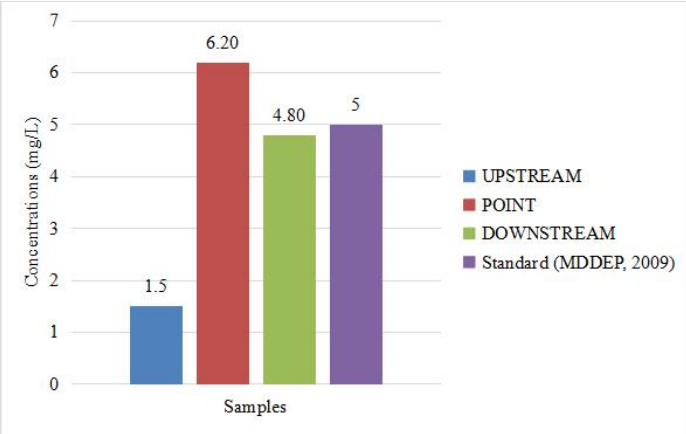


Table 2 presents the analysis of variance, revealing a statistically significant difference between the groups ($F = 40.7369$; probability = 8.6619×10^{-7}). The F-value exceeds the critical comparison value (3.68232034), with an LSD value of 21.167.

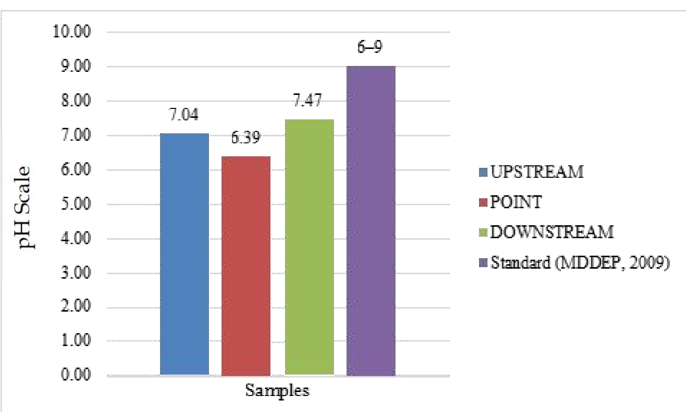
Table 2:
Analysis of variance for dissolved oxygen

Degreesof freedom	*p-values*	*F value*
2	8.6619×10^{-7}	3.68232034
15		
17		

pH

The mean pH values were 7.47 ± 0.04 downstream, 7.04 ± 0.10 upstream, and 6.39 ± 0.11 at the discharge point **(Figure 3)**.

Figure 3:
pH values of water samples



All pH values were within the recommended range of 6.0–9.0 for surface water. Nevertheless, statistically significant differences were observed among sampling stations ($F = 237.25$, $p < .001$) **(Table 3)**.

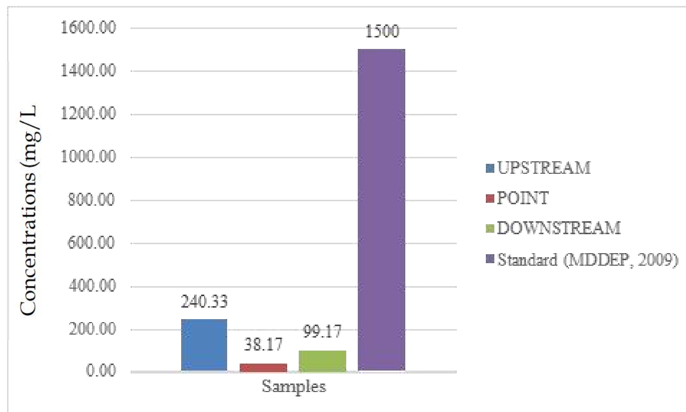
Table 3:
Analysis of variance for pH values

Degreesof freedom	*p-values*	*F value*
2	4.4412×10^{-12}	3.68232034
15		
17		

Total Dissolved Solids

The highest mean total dissolved solids (TDS) concentration was recorded upstream (240.33 ± 10.48 mg/L), followed by downstream (99.17 ± 2.64 mg/L) and the discharge point (38.17 ± 7.78 mg/L) **(Figure 4)**.

Figure 4:
TDS concentration in water samples



Although significant differences were detected among the three stations ($p < .001$), all measured TDS values remained below the applicable guideline value of 1,500 mg/L **(Table 4)**.

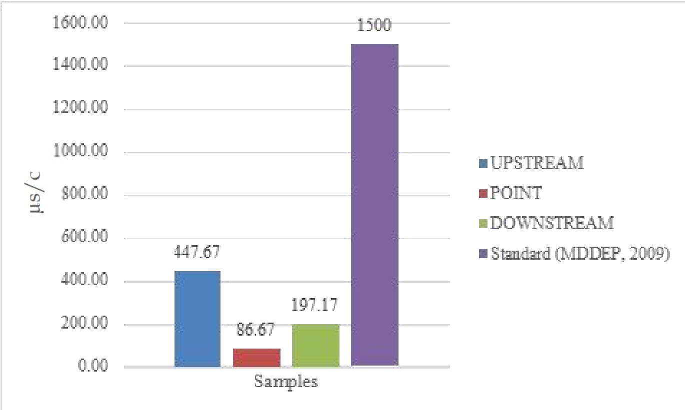
Table 4:
Analysis of variance of TDS in water samples

Degreesof freedom	*p-values*	*F value*
2	5.7103×10^{-17}	3.68232034
15		
17		

Electrical Conductivity

Electrical conductivity varied significantly across the study sites **(Figure 5)**. The upstream station recorded the highest mean conductivity (447.67 ± 28.80 µS/cm), followed by the downstream station (197.17 ± 2.40 µS/cm) and the discharge point (86.67 ± 7.34 µS/cm).

Figure 5:
Variations in the conductivity of water samples



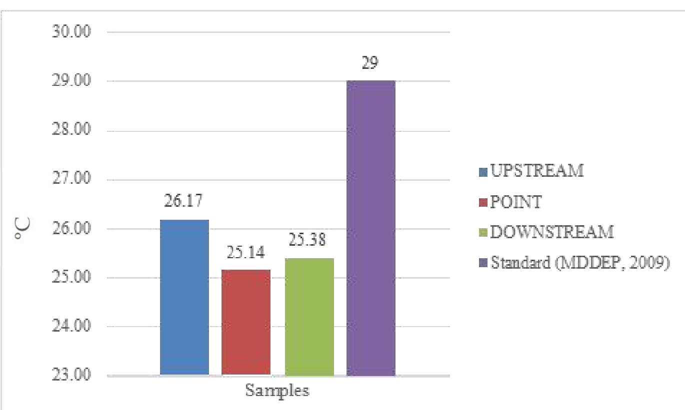
One-way ANOVA confirmed statistically significant differences among stations ($F = 692.66$, $p < .001$) (Table 5).

Table 5:
Analysis of variance for the conductivity of water samples

Degreesof freedom	*p-values*	*F value*
2	1.6749×10^{-15}	3.68232034
15		
17		

Temperature
Mean water temperature ranged from 25.14 ± 0.12°C at the discharge point to 26.17 ± 0.12°C upstream and 25.38 ± 0.29°C downstream (Figure 6).

Figure 6:
Variations in temperature values in water samples



Temperatures remained within the recommended range for tropical freshwater ecosystems. Significant differences were detected among sampling stations ($F = 45.04$, $p < .001$) (Table 6).

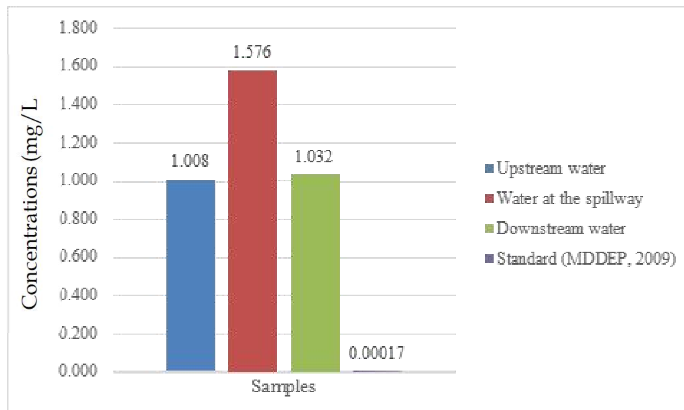
Table 6:
Analysis of variance for water sample temperatures

Degreesof freedom	*p-values*	*F value*
2	4.5665×10^{-7}	3.68232034
15		
17		

Lead Concentrations in Environmental Samples

Lead Concentrations in Water
Lead concentrations in water differed significantly among the sampling stations (Figure 7). The discharge point exhibited the highest mean concentration (1.156 ± 0.008 mg/L), followed by the downstream station (1.032 ± 0.034 mg/L) and the upstream station (1.008 ± 0.032 mg/L).

Figure 7:
Lead concentrations in water samples



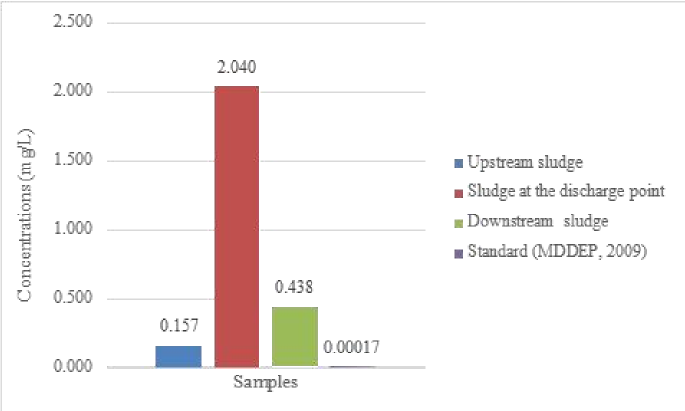
All measured concentrations exceeded the MDDEP (2009) guideline value for surface water. ANOVA confirmed statistically significant differences among sampling stations ($F = 691.83$, $p < .001$) (Table 7).

Table 7:
Analysis of variance for lead concentrations in water

Degreesof freedom	*p-values*	*F value*
2	4.0402×10^{-13}	3.3.88529383
15		
17		

Lead Concentrations in Sediments
Mean lead concentrations in sediments also varied significantly among stations (Figure 8). The highest concentration was recorded at the discharge point (2.040 ± 0.004 mg/L), followed by downstream (0.438 ± 0.013 mg/L) and upstream (0.157 ± 0.006 mg/L).

Figure 8:
Lead concentrations in sludge



The discharge-point concentration exceeded the applicable sediment quality criterion, whereas the upstream station recorded the lowest concentration. One-way ANOVA indicated highly significant differences among sampling stations ($F = 74{,}107.80$, $p < .001$) **(Table 8)**.

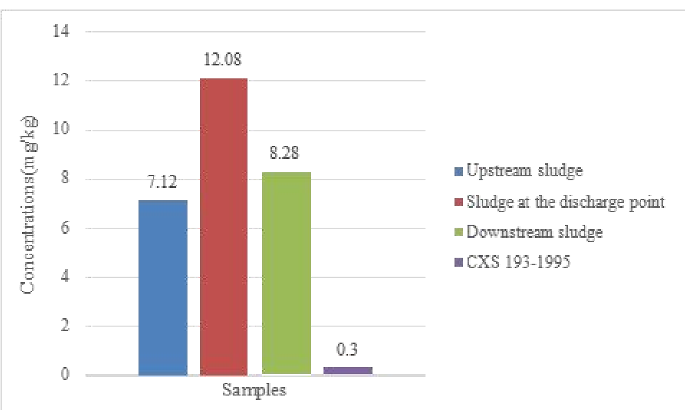
Table 8:
Analysis of variance for lead concentrations in sludge

Degreesof freedom	*p-values*	*F value*
2	2.8152×10^{-25}	3.3.88529383
15		
17		

Lead Concentrations in Oreochromis niloticus

Lead concentrations measured in *Oreochromis niloticus* differed significantly among the sampling stations (Figure 9). The highest concentration was observed in fish collected at the discharge point (12.08 ± 0.08 mg/kg), followed by downstream (8.28 ± 0.55 mg/kg) and upstream (7.12 ± 0.22 mg/kg).

Figure 9:
Lead concentrations in the species *Oreochromis niloticus*



All measured concentrations substantially exceeded the FAO/WHO Codex Alimentarius maximum permissible limit of 0.3 mg/kg for fish intended for human consumption. ANOVA demonstrated statistically significant differences among sampling stations ($F = 419.53$, $p < .001$) **(Table 9)**.

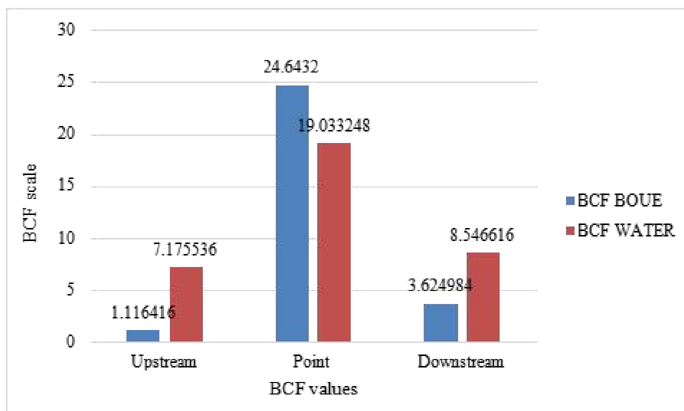
Table 9:
Analysis of variance for lead concentrations in fish of the species *Oreochromis Niloticus*

Degreesof freedom	*p-values*	*F value*
2	6.831×10^{-14}	3.68232034
15		
17		

Lead Bioaccumulation

Bioconcentration factor (BCF) analysis demonstrated the accumulation of lead by *Oreochromis niloticus* from the surrounding aquatic environment **(Figure 10)**. BCF values were consistently greater than one, indicating active bioaccumulation of lead by fish. Accumulation relative to sediment-associated lead was greater than that associated with dissolved lead in water, suggesting that sediments constitute an important environmental reservoir contributing to lead uptake.

Figure 10:
Bioconcentration factors for lead in *Oreochromis Niloticus* samples



Correlation Analysis

Spearman's rank correlation analysis revealed positive associations between lead concentrations in water, sediments, and fish tissues **(Table 10)**. Increasing lead concentrations in environmental media were accompanied by higher lead concentrations in *Oreochromis niloticus*, supporting the occurrence of lead transfer from the aquatic environment into fish tissues.

Table 10:
Spearman's rho correlation coefficients for BCFs of sludge and water

	Upstream	Discharge point	Downstream
BCF SLUDGE	1.116416	24.6432	3.624984
BCF WATER	7.175536	19.033248	8.546616
	Column 1	*Column 2*	*Column 3*
Column 1	1		
Column 2		1	
Column 3			1

Summary of Findings

Overall, statistically significant spatial differences were observed for all physicochemical parameters and lead concentrations among the three sampling stations. Although conventional physicochemical parameters generally remained within recommended guideline values, lead concentrations in water, sediments, and *Oreochromis niloticus* consistently exceeded relevant environmental and food-safety standards. The highest lead concentrations were recorded at the REGIDESO effluent discharge point, while elevated bioconcentration factors indicated substantial accumulation of lead within the aquatic food chain.

DISCUSSION

This study evaluated the physicochemical characteristics, lead contamination, and ecotoxicological impacts associated with effluent discharges from the REGIDESO Lemba Imbu plant into the N'djili River. Significant spatial variations were observed for all measured physicochemical parameters and lead concentrations across the upstream, discharge-point, and downstream sampling stations. Although most conventional water-quality parameters remained within recommended guideline values, lead concentrations in water, sediments, and *Oreochromis niloticus* exceeded applicable environmental and food-safety standards, indicating potential ecological and public health concerns.

Physicochemical Characteristics

The significant differences observed in dissolved oxygen, pH, electrical conductivity, total dissolved solids, and temperature demonstrate that the physicochemical characteristics of the river vary along the study reach. Such spatial variability is expected in river systems receiving point-source discharges and reflects the combined influence of natural hydrological processes and anthropogenic activities (Deroo, 2021; Mamadou et al., 2022).

The measured pH values remained within the range recommended for freshwater ecosystems, indicating that the river generally maintains conditions favourable for aquatic life. Nevertheless, the relatively lower pH observed at the effluent discharge point may increase the mobility and bioavailability of dissolved metals, thereby enhancing their transfer into aquatic organisms. Previous studies have shown that slight reductions in pH can increase the solubility of heavy metals and promote their uptake by aquatic biota (Ibe et al., 2025; Solano, 2024).

Electrical conductivity and total dissolved solids differed significantly among sampling stations, reflecting variations in dissolved ionic constituents within the river. Although all measured values remained below recommended guideline limits, these parameters provide evidence of changing water chemistry associated with the discharge zone. Similar observations have been reported in rivers receiving industrial effluents, where changes in conductivity and dissolved solids serve as indicators of anthropogenic inputs (Mamadou et al., 2022).

Water temperature varied only slightly among the sampling stations and remained within the expected range for tropical freshwater ecosystems. Consequently, temperature is unlikely to have been a major determinant of the observed differences in lead concentrations or bioaccumulation within the study area.

The exceptionally high dissolved oxygen concentrations recorded at the discharge point and downstream are unusual for tropical river systems and may reflect local hydraulic turbulence, aeration associated with effluent discharge, or measurement conditions at the time of sampling. These values should therefore be interpreted cautiously and verified through repeated monitoring.

Lead Contamination in Water and Sediments

Lead concentrations in water exceeded the applicable environmental guideline values at all sampling stations, indicating widespread contamination within the study area. The highest concentrations were recorded at the REGIDESO effluent discharge point, with lower concentrations observed upstream and downstream.

Although the study design does not permit definitive attribution of contamination to a single source, the spatial pattern suggests that effluent discharge from the REGIDESO plant may contribute substantially to local lead contamination.

Sediments contained considerably higher lead concentrations than river water, particularly at the discharge point. This finding is consistent with the well-established tendency of heavy metals to adsorb onto suspended particles and accumulate within bottom sediments, where they may persist for prolonged periods (Chanel et al., 2017). Sediments therefore function not only as repositories of historical contamination but also as potential secondary sources of pollution when environmental conditions favour metal remobilisation.

The observed spatial distribution agrees with previous studies demonstrating that industrial wastewater discharges often produce localised accumulation of heavy metals within river sediments (Obaideen et al., 2022; Salakiaku et al., 2022). Continuous deposition of contaminated particulates may therefore contribute to long-term deterioration of sediment quality and aquatic ecosystem health.

Bioaccumulation of Lead in Oreochromis niloticus

Lead concentrations measured in *Oreochromis niloticus* substantially exceeded the maximum permissible limit established by the FAO/WHO Codex Alimentarius for fish intended for human consumption. Fish collected at the discharge point exhibited the highest concentrations, followed by those collected downstream and upstream, reflecting the spatial distribution of lead observed in water and sediments.

Bioconcentration factor analysis demonstrated that *Oreochromis niloticus* accumulated lead from the surrounding aquatic environment. This finding is consistent with the known ability of fish to absorb heavy metals through the gills, digestive tract, and skin, followed by accumulation within body tissues (Chanel et al., 2017). The higher accumulation associated with sediment-rich environments further supports the role of sediments as important reservoirs of bioavailable lead.

Because *Oreochromis niloticus* occupies an important position within local food systems, elevated tissue concentrations have implications that extend beyond ecological health to food safety and human exposure. Similar patterns of heavy-metal bioaccumulation have been reported in contaminated freshwater ecosystems elsewhere in Africa and other developing regions (Alcénat et al., 2025).

Ecological and Public Health Implications

The findings indicate that conventional physicochemical parameters alone may underestimate environmental degradation within aquatic ecosystems. Although pH, temperature, conductivity, and total dissolved solids generally complied with recommended guideline values, the elevated lead concentrations observed in water, sediments, and fish demonstrate the presence of ecotoxicological risks that are not adequately captured by routine water-quality monitoring.

Long-term accumulation of lead in sediments and aquatic organisms may adversely affect fish health, reduce reproductive success, alter aquatic biodiversity, and compromise ecosystem functioning. Furthermore, consumption of contaminated fish represents a potential pathway for human exposure, particularly among communities that depend on the N'djili River for subsistence fishing. While the present study did not undertake a quantitative human health risk assessment, the measured concentrations exceeded internationally recognised food-safety limits and therefore warrant public health attention.

Strengths and Limitations

A major strength of this study lies in its integrated assessment of physicochemical water quality, sediment contamination, and bioaccumulation in fish within a single river system. Simultaneous evaluation of these environmental compartments provides a more comprehensive understanding of contaminant behaviour than studies focusing on water quality alone.

However, several limitations should be acknowledged. Sampling was undertaken during a single rainy season and therefore does not capture seasonal variability in river conditions. In addition, only lead was investigated, whereas industrial effluents may contain numerous other potentially toxic metals and organic contaminants. Future investigations should include multi-seasonal sampling, expanded contaminant profiles, and quantitative ecological and human health risk assessments to better characterise the long-term consequences of industrial effluent discharges.

Overall Interpretation

Collectively, the findings suggest that the REGIDESO Lemba Imbu effluent discharge is associated with elevated lead contamination within the N'djili River ecosystem. While conventional physicochemical indicators generally reflected acceptable water quality, lead accumulated in sediments and *Oreochromis niloticus* at concentrations exceeding relevant environmental and food-safety standards. These observations highlight the importance of incorporating heavy-metal monitoring and bioaccumulation assessments into routine environmental surveillance programmes to support evidence-based management of aquatic ecosystems and protection of public health.

CONCLUSION

This study assessed the physicochemical characteristics, lead contamination levels, and ecotoxicological impacts associated with effluent discharges from the REGIDESO Lemba Imbu plant into the N'djili River, Kinshasa, Democratic Republic of the Congo. Significant spatial variations were observed in the measured physicochemical parameters and lead concentrations among the upstream, discharge-point, and downstream sampling stations.

Most conventional physicochemical parameters, including pH, temperature, electrical conductivity, and total dissolved solids, remained within internationally accepted guideline values, indicating that routine water-quality indicators alone may not adequately reflect the extent of environmental contamination. In contrast, lead concentrations in water, sediments, and *Oreochromis niloticus* exceeded applicable environmental and food-safety standards, demonstrating substantial heavy-metal contamination within the study area.

The highest lead concentrations were consistently recorded at the REGIDESO effluent discharge point, while elevated concentrations in sediments and fish tissues indicate that lead is retained within the aquatic environment and transferred through the food chain. Bioconcentration factor analysis further confirmed the accumulation of lead in *Oreochromis niloticus*, highlighting the ecological significance of sediment-associated contamination and the potential for human exposure through fish consumption.

Although the cross-sectional design does not permit definitive attribution of contamination to a single source, the spatial distribution of lead suggests that effluent discharges from the REGIDESO Lemba Imbu plant may constitute an important contributor to local environmental contamination. These findings underscore the importance of integrating heavy-metal monitoring with routine physicochemical water-quality assessments when evaluating the environmental performance of industrial wastewater discharges.

Overall, the study achieved its objectives by characterising the physicochemical quality of the N'djili River, quantifying lead contamination in water, sediments, and fish, and demonstrating lead bioaccumulation within the aquatic ecosystem. The findings contribute to the growing body of evidence on industrial effluent pollution in urban river systems within the Democratic Republic of the Congo and provide a scientific basis for strengthening environmental monitoring and pollution-control strategies.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. REGIDESO should strengthen wastewater management practices and implement regular monitoring of effluent quality to minimise the release of heavy metals into the N'djili River.
2. Environmental regulatory authorities should establish continuous monitoring programmes that include both conventional physicochemical parameters and heavy-metal assessments in water, sediments, and aquatic organisms.
3. Periodic surveillance of fish intended for human consumption should be undertaken to evaluate food-safety risks and guide public health interventions where necessary.

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4. Future studies should investigate additional heavy metals and emerging contaminants, conduct multi-seasonal monitoring, and incorporate quantitative ecological and human health risk assessments to provide a more comprehensive understanding of contaminant dynamics within the N'djili River ecosystem.

The implementation of these measures will contribute to the sustainable management of the N'djili River, the protection of aquatic biodiversity, and the safeguarding of public health.

Data Availability: The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Author Contributions: N.M.B.E. designed the study, mapped the study area and carried out the field sampling; N.M.B.E., L.S.W., I.L.P. and K.N.A. contributed to the laboratory analysis, statistical analyses and processing of the results. N.M.B.E., G.V.R., M.K.S. and N.B. contributed to the interpretation of the results. TTT, K.N.A., G.V.R. and B.M.E. contributed to the revision of the manuscript. B.M.E. provided methodological advice, supervision and a critical review of the manuscript.

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Ethical Approval: At the time of this study (2025), a formal Institutional Animal Care and Use Committee (IACUC) or national equivalent for evaluating environmental and ecotoxicological research involving vertebrate animals was not available in the Democratic Republic of the Congo. Existing ethical boards (e.g., CER-UNIKIN, CNES) are strictly dedicated to human subject research. Consequently, no formal protocol approval number was obtained. However, the sampling of 15 *Oreochromis niloticus* specimens was restricted to the minimum required for ecotoxicological assessment. All field sampling and tissue harvesting procedures were conducted strictly according to internationally accepted scientific guidelines for animal welfare to minimize suffering and environmental impact. Sampling was conducted in accordance with relevant institutional and administrative permissions obtained from local authorities overseeing environmental and fisheries activities in the study area.

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