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Environmental dynamics of heavy metals in recipient waters of produced water effluents: Bioaccumulation patterns in fish and ecological risks

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Abstract

Environmental discharge of water produced, the highest amount of waste that is generated during petroleum extraction, is a significant source of heavy-metal pollution in water bodies of the Niger Delta. Recent empirical evidence (2020-2025) on the environmental dynamics of produced-water recipient systems, bioaccumulation dynamics of trace metals in fish and the related ecological and human-health risk underwent the synthesis in this review. Sixty-three peer-reviewed and regulatory studies in the water, sediment, and the biotic matrices were next analyzed inception to PRISMA 2020 systematic review principles. The findings indicate that, cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) are found in amounts that are above national (NESREA, DPR) and international (WHO) standards in the various sites especially around the oil-production and gas-flaring areas. Metal burdens were always maximum in sediments compared to water, which proved their long-term sinks and secondary sources of contamination. Bioaccumulations in benthic and demersal fish species tended to be above FAO/WHO allowable levels, and hazard indices (HI > 1) and incremental lifetime cancer-risks (ILCR > 10^{-3}) were above levels of hinting at chronic toxicity in the local biological. Most of the sites in the Niger Delta fall under categories of moderate-to-considerable risks as per ecological indices (Igeo, CF, PERI). These results show that the discharge of produced-water is one of the biggest sources of the enrichment and bioaccumulation of heavy-metals in the aquatic food chains of the region. The paper concludes with the idea that the successful management of pollution issues demanded the combination of pollution control methods, incorporation of zero-discharge technology, and the improvement of the communication with people as well as their health. The enforcing the environmental policies can be developed stronger as well as the scientific investigations on the metal speciation and transfer, trophic mobility as well as the search on the links with climate, is necessary to preserve the system on ecosystem health and livelihood in the Niger Delta.

Keywords: Produced water; Heavy metals; Niger Delta; Bioaccumulation; Ecological risk; Fish contamination; Human health

1. Introduction

Nigeria has one of the most oil- and gas-rich regions in the world in the Niger Delta, which accounts for more than 90% of Nigeria's foreign exchange earnings (Amakiri *et al.*, 2023). Nevertheless, decades of intense petroleum exploration and production have caused significant environmental issues, mainly due to the discharge of generated water, the most

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significant waste stream, along with oil production. Formation water is a complex mixture of formation water, injected fluids, dissolved salts, hydrocarbons, and trace metals that are released directly into water bodies or seep from ill-maintained plants (Ekperusi *et al*., 2024). With the development of oil fields, both the quantity of water produced grows significantly and poses risks to the ecological pollution of the destination rivers, creeks, and estuaries of the Niger Delta (Umeoguaju *et al*., 2023). Critical with their persistence, toxicity, and potential to accumulate or bioaccumulate in aquatic ecosystems are heavy metals, including cadmium (Cd), lead (Pb), mercury (Hg), and nickel (Ni), as well as chromium (Cr) (Obi *et al*., 2024). These metals cannot be biodegraded; they attach to sediments and organic matter and enter the food web, posing a danger to aquatic life and humans through consumption (Ibigbami *et al*., 2025). Recent analyses have recorded high levels of Pb, Cd, and Ni in water and sediments of Bodo Creek, Bonny River, and Forcados estuary, which are usually beyond World Health Organisation (WHO) and Nigerian Environmental Standards and Regulations Enforcement Agency (NESREA) guidelines (Ekperusi *et al*., 2024; Umeoguaju *et al*., 2023). Likewise, Amadi *et al*. (2022) found that the levels of cadmium and lead in the muscles of fish from the Andoni River exceeded the maximum allowable concentrations for these metals in human consumption, highlighting the risk of dietary exposure for local people who rely on fish as a source of protein.

Produced-water discharge recipient environments, such as estuaries, mangroves, creeks, and brackish channels, are dynamic systems in which complex interactions among metals, sediments, and biota occur (Dhara & Dutta, 2025). Adsorption, precipitation, and resuspension are among the processes that control the fate of heavy metals and determine their bioavailability to aquatic life. Subsequently, in the Niger Delta, hydrological forces (e.g., tidal mixing, rainfall variability, and organic matter content) and physicochemical parameters (e.g., salinity, pH, and redox potential) also further alter the mobility and partitioning of metals (Imaji *et al*., 2025). As a result, bioaccumulation of the metals in the fish gills, liver, and muscle is a sensitive predictor of chronic contamination (Okoye *et al*., 2022). A characteristic of the lack of comprehensive syntheses of the contamination of produced water with heavy metals and, to a lesser extent, bioassessments of fish bioaccumulation and the ecological hazards of the situation is evident in the Niger Delta, despite most site-specific studies. Earlier studies tended to investigate specific elements, i.e., either water or sediment quality, but they never linked this information to food-web transfer and human health consequences (Umeoguaju *et al*., 2023; Amadi *et al*., 2022). Also, variations in sampling, analytical methods, and ecological risk models make the comparability of studies difficult (Ekperusi *et al*., 2024). The absence of coherent methods for monitoring and risk assessment of the area hindered the development of coherent policy and mitigation measures. The purpose of the review is hence to give an extensive overview of recent data (20202025) on the environmental dynamics of heavy metals in produced-water-receiving systems of the Niger Delta. Particularly, it (a) analyses the structure and destiny of heavy metals in water and sediment, (b) assesses ecological and economic migratory patterns in fish furans of both ecological and economic significance, and (c) determines the ecological and human-health risks. This synthesis enables the review to identify a research gap, methodological weaknesses, and strategic suggestions for improving environmental surveillance and sustainable produced-water management in the Niger Delta.

2. Methodology

2.1. Study Design and Review Framework

This review used a systematic literature review design that adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines (Page *et al*., 2021). PRISMA provides a clear, specific framework for identifying, screening, and synthesising scientific literature. The methodology involved five significant steps and included the following steps: (1) defining the scope and questions used to conduct the review; (2) locating relevant literature; (3) screening and selecting suitable literature; (4) data extraction and coding; and (5) critical analysis and reviewing the risks. The overall objective was to generalise the empirical data on the environments of heavy metals generated by produced-water discharges in the Niger Delta, and on the bioaccumulation and ecological risk potentials of the heavy metals in aquatic environments. The review was meant to examine both spatial and temporal differences in heavy-metal contamination and to identify patterns in fish bioaccumulation, as well as the risks involved in human exposure.

2.2. Research Questions

The review addressed the following research questions:

- What are the dominant heavy metals reported in produced-water effluents and recipient aquatic systems of the Niger Delta (2020–2025)?
- How do these metals partition across environmental matrices (water, sediment, and fish)?

- What are the bioaccumulation and biomagnification patterns of these metals in fish species commonly consumed by humans?
- What are the ecological and human health risk levels associated with these metal concentrations, based on recent quantitative assessments?
- What are the significant knowledge gaps and management challenges limiting effective environmental control of produced-water discharges in the Niger Delta?

2.3. Literature Search Strategy

In order to be both comprehensive and to target peer-reviewed studies, the literature search was carried out using five large scholarly databases: Scopus, Web of Science (WoS), Google Scholar, and SpringerLink. The combination of various Boolean operators and keywords associated with the scope of the study was used as the search strategy:

- (produced water OR oilfield effluent OR petroleum wastewater)
- AND (heavy metals) OR (trace metals) OR (toxic elements).
- AND (bioaccumulation) or (biomagnification) or (fish) or (ecological risk) or (human health risk).
- AND ("Niger Delta" OR "Nigeria").

The filters were used to narrow the results to peer-reviewed journal articles in English, published between 2020 and 2025. The search yielded 218 initial results, which were imported into the Zotero reference manager to be organised, duplicated, and assigned metadata tags. To make the literature review inclusive, the sources of grey literature were also consulted, such as environmental impact assessment (EIA) reports, technical bulletins, and monitoring publications by the Nigerian Environmental Standards and Regulations Enforcement Agency (NESREA), the Department of Petroleum Resources (DPR, currently NUPRC), and the Niger Delta Development Commission (NDDC). These gave regulatory and context-level information applicable to the management of produced water.

2.4. Screening Criteria

The retrieved studies were screened in three stages:

- Title Screening: Title and abstract screening were applied to all articles to ensure that their content is on the topic of produced water, heavy metal, or aquatic pollution in the Niger Delta. At this stage, papers focused solely on hydrocarbons or non-metal pollutants were eliminated.
- Abstract and Methodology Review: Abstracts were evaluated to make sure that the study contained at least some quantitative measurement of the concentration of the heavy metal in produced water, surface water, sediment, or fish.
- Full-Text Review: Full articles were assessed based on both methodological transparency (sampling design, analytical procedures, QA/QC) and relevance to ecological or human risk assessments.

2.5. Eligibility Criteria

2.5.1. Inclusion criteria

- Research has been carried out in the Niger Delta (particularly in Bayelsa, Rivers, Delta, Akwa Ibom, or Ondo States);
- Published between 2020 and 2025;
- Concentration of at least one of the heavy metals (Cd, Pb, Cr, Ni, Zn, Cu, Mn, Fe, Hg);
- Interpreted data/results obtained through proven methods like Atomic Absorption Spectrophotometry (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS);
- Introduced indicators of ecology (CF, Igeo, PERI) or risk to humans (EDI, HQ, HI, ILCR).

2.5.2. Exclusion criteria

- Non-Nigerian or non-2020-2025 appropriate publication studies;
- Articles that lack quantitative data or are not quantitative methodologically;
- Comments or reviews of data not original;
- abstracts of conferences and dissertations in unpublished manuscripts.
- After this step, 63 articles were retained for analysis and synthesis.

2.6. Data Extraction and Coding

A data extraction template was designed in Microsoft Excel to capture quantitative and qualitative details from each study systematically. Extracted data included:

- Bibliographic information (author, year, journal);
- Sampling locations and coordinates;
- Type of matrix (produced water, sediment, or fish);
- Analytical method used and quality-control measures;
- Mean, minimum, and maximum concentrations of heavy metals (mg/L or mg/kg);
- Reported bioaccumulation metrics (BCF, BAF, or TTF);
- Ecological indices (CF, Igeo, PERI, EF);
- Human health risk indices (HQ, HI, ILCR);
- Reference to applicable regulatory standards (e.g., WHO, DPR, NESREA).

All concentration values were then standardised to allow inter-study comparability (mg/L of water, and mg / kg of dry weight of sediments and tissues). When ranges were reported, the arithmetic mean was calculated and used as a representative value (Amadi *et al*., 2022; Ekperusi *et al*., 2024). For graphical data, only numerical values were obtained using the WebPlotDigitizer 5.0 software.

2.7. Data Integration and Statistical Treatment

Though, as a review, this is more of a qualitative study, there has been some use of quantitative synthesis, with different studies presenting similar numbers. Mean, standard deviation, and range were used as descriptive statistics to determine metal concentrations across various matrices. To the extent possible, contamination gradients (upstream, downstream, near-field versus far-field) were evaluated to demonstrate spatial patterns. Patterns in the correlation of metals (e.g., the association of Pb with Cd and Zn) were explained by the coincidental occurrence of geochemical and industrial sources (Imaji *et al*., 2025). It also categorised its data by Niger Delta sub-regions (Eastern, Central, and Western zones) to examine differences in pollution intensity and ecological risk across areas.

2.8. Risk Assessment Framework

2.8.1. Ecological Risk Indices

To evaluate environmental impact, three commonly applied indices were synthesised:

Contamination Factor (CF):

$$CF = \frac{C_{smple}}{C_{background}}$$

C_{sample} = measured concentration of the metal

$C_{background}$ = geochemical background/reference concentration

Interpretation categories:

- CF < 1: Low contamination
- 1 ≤ CF < 3: Moderate contamination
- 3 ≤ CF < 6: Considerable contamination
- CF ≥ 6 : Very high contamination

Geo-accumulation Index (Igeo):

$$I_{geo} = log_2(\frac{C_n}{1.5B_n})$$

Cn = measured metal concentration

Bn = background concentration

The factor 1.5 compensates for natural fluctuations in background metals.

Igeo classification:

Igeo ≤ 0: Unpolluted

0–1: Unpolluted to moderately polluted

1–2: Moderately polluted

2–3: Moderately to strongly polluted

3–4: Strongly polluted

4–5: Strongly to extremely polluted

≥ 5: Extremely polluted

Potential Ecological Risk Index (PERI):

$$PERI = \sum (T_r \ x \ CF)$$

Tr = toxic response factor

2.8.2. Human-Health Risk Assessment

For fish consumption, risk assessments followed U.S. EPA (2021) guidelines:

$$EDI = \frac{C_m \ x \ IR}{BW}$$

Where:

Cm = metal concentration in fish (mg/kg)

IR= ingestion rate of fish (kg/day)

BW = body weight (kg)

2.8.3. Quality Assurance and Control (QA/QC)

Only studies that used internationally standardised methods of analysis (AAS, ICP-OES, or ICP-MS) and had clear descriptions of the QA/QC were included to enable reliability (Ekperusi *et al*., 2024). Studies that mentioned the use of certified reference materials (CRMs), blanks, and replicates were given priority. The studies were compared on the detection limits and recovery percentages to ensure analytical validity.

The bias-mitigation process was used by:

- Data triangulation of the same studies by different research groups;
- Considering multi-matrix studies of the single-compartment analyses; and
- The use of various publication sources is necessary in order to ensure that no single locality is overrepresented.

2.8.4. Regulatory and Ethical Factors.

The critique was done in accordance with academic integrity and ethical research practices. All second-hand information was referenced correctly. The regulatory standards were aligned with the Environmental Guidelines and Standards of the Petroleum Industry in Nigeria (EGASPIN, DPR, 2021), which set limits on heavy metals in produced water discharges. These norms (e.g., Cd 0.01 mg/L, Pb 0.05 mg/L, and Cr 0.1 mg/L) served as reference levels to assess contamination levels in the Niger Delta.

3. Results

Table 1 Heavy-metal concentrations in water & sediments

S/N	Study	Matrix (water / sediment / produced water)	Location (Niger Delta)	Metals reported (summary)
1	Amakiri *et al.,* 2023.	Produced water & receiving water	Oilfield case study (Niger Delta)	Cd, Pb, Ni, Cr, other trace metals
2	Umeoguaju *et al.,* 2023.	Surface water, sediment, seafood composites	Multiple Niger Delta locations	Cd, Pb, Cr, Ni, Zn, Cu, Mn
3	Ekperusi *et al.,* 2024.	Sediment, shrimps, fish	Escravos Estuary	Cd, Pb, Cr, Ni, Zn
4	Allison, 2024.	Surface water & fish muscle	Four creeks, Bonny Estuary	Fe, Ni, Pb, Cd, Cr
5	Agbabiaka *et al.,* 2024(Bodo Creek).	Fish tissues (As, Hg, Pb), sediment	Bodo Creek	As, Hg, Pb (and others)
6	Ibubeleye *et al.,* 2024.	Fish & paired sediment/water	Tilapia guineensis sites (Niger Delta)	Pb, Cd, Cr, Ni, Zn
7	Wang *et al.,* (2018).	Surface water & sediment	Multiple riparian communities	Zn, Pb, Cu, Cd, Fe, As
8	Osuji (2025) — produced water preliminary.	Produced water	Obigbo-North oilfield	Heavy metals (AAS measurements reported)
9	Udeagbara *et al.,* (2025)— produced water treatment study.	Produced water	Niger Delta oilfields	Heavy/toxic metals (AAS results)
10	Ekperusi *et al* . (2024 ScienceTotalEnv abstract).	Coastal food chain (sediment, biota)	Escravos Estuary	Cd, Pb, Cr, Ni, Zn
11	Wang *et al.,* (2018).	Surface waters, monthly sampling	Delta State riparian sites	As, Cd, Pb, Zn, Cu
12	Nwokoma *et al.,* (2024) — produced water characteristics.	Produced water characterization	Niger Delta oilfields	Salinity, metals (overview)
13	Chris *et al.,* (2021).	Surface water	Bonny River upper reaches	Pb, Cd, Zn reported
14	Bardi *et al.,* (2025) gas-flaring areas.	Surface water near gas flares	Delta State (Amukpe, Ekpan etc.)	Pb, Cd, other metals
15	AKPOBI *ET AL.,* (2025) — Okwagbe River fish study.	Fish tissues	Okwagbe River, Ughelli South	Pb, Cd, Zn, Cu

Table 2 Bioaccumulation in fish species

S/N	Study	Fish species	Location	Reported tissue metals
1	Umeoguaju *et al.,* 2023.	Mixed seafood (various)	Multiple sites	Cd, Pb, Cr, Ni (in fish tissues)
2	Ekperusi *et al.,* 2024.	Shrimp, local fish	Escravos Estuary	Cd, Pb, Cr, Ni, Zn — tissue partitioning
3	Allison, 2024.	Various tilapia & demersal species	Bonny creeks	Pb, Cr, Cd, Ni (muscle)

4	Agbabiaka *et al.,* 2024.	Edible fish species	Bodo Creek	As, Hg, Pb in edible organs
5	Ibubeleye *et al.,* 2024.	Tilapia guineensis	Multiple estuarine sites	Pb, Cd, Zn accumulation
6	Akpobi *et al.,* (2025).	Local river fish	Okwagbe River	Pb, Cd, Zn, Cu in muscle
7	Bardi *et al.,* (2025).	Bagrus, Oreochromis, Clarias spp.	(regional)	Cu, Cd, Cr, As, Ni, Mn, Fe, Zn
8	Wang *et al.,* (2018).	Mixed fish	Riparian communities	As, Cd, Pb, Zn, Cu in tissues
9	Allison *et al.,* (2024) — local report collated.	Oreochromis, Clarias spp.	Bonny/Atuka Creek	Pb & Cd often above FAO/WHO limits in muscle

4. Discussion

4.1. Heavy-metal distribution and partitioning in produced-water recipient systems

The results of various Niger Delta surveys demonstrate that heavy metals are consistently higher in sediments than in surface waters, and this specificity is corroborated by the fact that the metals adsorb onto particulate matter and form bottom deposits (Umeoguaju *et al*., 2023). This pattern of distribution describes the fact that the divalent metals Cd2+, Pb2+, and Cu2+ are strongly attracted to organic matter and clay minerals, leading to sediment accumulation and permanence (Ekperusi *et al*., 2024). Amakiri *et al*. (2023), in a systematic review of heavy metals in the area, found that Ni, Cd, and Pb often exceeded the WHO-allowed concentrations of heavy metals in drinking and surface water. The water produced and released by oil fields contains complexes of metals, hydrocarbons, and salts, which can affect the mobility of metals and their bioavailability (Udeagbara *et al*., 2025). After treatment, effluent samples frequently contain detectable levels of toxic metals, which further increases the load in receiving creeks and estuaries (Osuji, 2025). The presented observations lead to the identification of the significance of sediment as a sink and a secondary contaminants source because the processes of sediment mobilisation under different redox or salinity conditions can be relocated (Ekperusi *et al*., 2024). The levels of contamination are also highly heterogeneous, and hotspots are associated with oil production zones, gas flaring facilities, and discharge channels (Wang *et al*., 2018). Ecological stress at the local scale is everyday, as the Bonny River Estuary, Bodo Creek, and Escravos region are often identified as high-risk areas. This spatial inconsistency requires region-specific management and remedial measures rather than a homogeneous regional approach (Agbabiaka *et al*., 2024).

4.2. Bioaccumulation and trophic transfer in fish

The analysed data show that bioaccumulation of heavy metals in fish tissues is high and, in most cases, exceeds international safety limits. In the study, Clarias gariepinus and Oreochromis niloticus were also studied by Adenuga *et al*. (2022), who found Pb of 10.88 -37.12 mg/kg and Cd of around 1 mg/kg in the Bonny Estuary- values which are much higher than the allowable levels of FAO/WHO. On the same note, Allison (2024) detected high levels of Pb, Cr, and Cd in fish in the Bonny River creeks. She found that the ambient water levels were positively correlated with fish tissue by concentrations. Bioaxon accumulation is species- and tissue-specific. Gill uptake, ingestion of food, and contact with sediment result in the most significant accumulation, whereas the liver and kidney have the highest burden, as they detoxify the body (Davies *et al*., 2024). Benthic or demersal species are more accumulated than pelagic species, which is consistent with the dynamics of sediment-water interaction (Ibubeley *et al*., 2024). These processes are in line with the global bioaccumulation models, including that proposed by Javed and Usmani (2016), in which the partition coefficient and lipid levels dominate metal retention in tissues. The bioaccumulation factors (BAF) and bioconcentration factors (BCF) observed in Niger Delta studies have been moderate (when the metals in question are essential, i., Fe and Zn) and high (when the metals in question are not essential, i., Pb and Cd). These results indicate a clear potential for trophic transfer consequences in regional food webs, which represent ecological and dietary exposure hazards (Ekperusi *et al*., 2024; Umeoguaju *et al*., 2023).

4.3. Ecological and Human-Health Risk Implications

Ecological-risk indices prepared in 202025 indicate that Cd and Pb are consistently the main contributors to overall risk, and the factors of ecological contamination of sediments (CF) and potential ecological risk indices (PERI) at all sites were rated as moderate to considerable (Ekperusi *et al*., 2024). Such results are consistent with past findings worldwide, showing that an increase in trace-metal enrichment of estuarine sediments is concomitant with the loss of biodiversity and oxidative stress in benthic fauna (Li *et al*., 2022). Regarding hazard quotient (HQ) and index of hazard (HI) in fish consumers in the Niger Delta, the values tend to be more than unity (HQ > 1; the index of hazard (HI) > 1) and can provide non-carcinogenic risks (Adenuga *et al*., 2022). Some fish samples have carcinogenic risk (ILCR) levels of Pb and Cd as high as 10-2-10-3, which are far above the acceptable range set by the U.S. EPA (10-6-10-4) (Davies *et al*., 2024). The Niger Delta is more complex in terms of the contamination matrix than other oil-producing estuaries worldwide, i.e., the Persian Gulf and the Gulf of Mexico, due to legacy spills, artisanal refining, and poor enforcement of regulations governing effluent discharge (Olagoke *et al*., 2021). The combination of these risk factors confirms that consumption of fish is a significant exposure route for the local population, and the local diet requires regular surveillance and specific risk warnings for individuals at increased risk (pregnant women and children).

4.4. Environmental Management and Policy Perspectives

Alleviating heavy-metal pollution in the Niger Delta requires a combined intervention comprising regulatory policies for industries, monitoring, and environmental education for communities. Sampling, analysis, and reporting precautions must be standardised so that data are inter-study comparable (wang *et al*., 2018). Treatment plants utilised to treat produced water should be enhanced to achieve reduced discharge limits for metals, including Pb, Cd, Ni, and Cr, and to include real-time compliance checks (Udeagbara *et al*., 2025). Guidance on fish diets should also be issued by public health agencies, in line with site-contaminant information, as in the U.S. and Europe (EPA, 2022). Moreover, legacy contamination could be minimized through piloting sustainable remediation technologies such as phytoremediation with native macrophytes, sediment capping, or electrochemical treatment of effluents (Thakur *et al*., 2023). These activities should be accompanied by capacity-building in environmental forensics, toxicology, and risk modelling amongst researchers and regulators in Nigeria.

4.5. Limitations and Research Gaps

While there is an increase in the literature on the dynamics of the Niger Delta regarding heavy metals, there remain research gaps. The majority of studies are cross-sectional, which provides little information about time. The influence of seasons on metal mobility and bioavailability is poorly understood. Not many studies describe metal speciation, which is important to determine actual toxicity and mobility. Also, trophic transfer research is still mainly confined to fish, invertebrates, and planktonic intermediates that mediate ecological exposure and are still overlooked. The longitudinal and multi-trophic studies, total analysis by speciation, stable-isotope tracing, and modeling of chronological exposure pathways should be incorporated into future work (Ekperusi *et al*., 2024; Umeoguaju *et al*., 2023).

5. Conclusion

The current review highlights the complex environmental relationships of heavy metals in receiving waters from produced-water effluents in the Niger Delta, which show a disturbing trend of ongoing pollution/contamination, bioaccumulation in aquatic organisms, and increasing ecological and human health hazards. Artificial-generated evidence between 2020 and 2025 indicates that metals like lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) are found in excess of their levels in both the national and global standard levels of safety in surface waters and sediments, as well as biota. The high concentration of these metals in bottom sediments is associated with a strong affinity of the metals for particulate organic matter, whereas repeated remobilization under varying redox conditions both enhances the ecological half-life and the exposure routes of the metals. Fish species, especially those living on the bottom (demersal and benthic feeders), act as warning signals of pollution, accumulating heavy metals to the point of interfering with ecological equilibrium and human safety in the diet. This bioaccumulation, together with indicated indices of hazard (HI>1) and carcinogenic risk factors (ILCR>10 -3), is a physical threat to populations dependent on the local fisheries as a livelihood. Besides, the Niger Delta is a prime example of the overlap of industrial pollution challenges with governance and environmental justice challenges, where uncontrolled effluent releases, historic spills, and handcrafted refining exacerbate environmental pollution in the area. The sustainability of heavy metals poses long-term risks to aquatic biodiversity, water quality, and human well-being, underscoring the importance of scientifically informed regulatory implementation and enhanced monitoring systems. Finally, the summary of these conclusions supports the idea that the effects of heavy metals must be mitigated through both technological and structural modifications, including policy coherence, community education, and consistent environmental education. This is holistic management that is essential to achieving sustainable management of water resources and ecosystem resilience in the Niger Delta region.

Recommendations

The ecological integrity of the aquatic environments in the Niger Delta has been threatened, and therefore, a complex and science-based approach is necessary. One, the policies for produced-water management should be reinforced to meet global and environmental discharge standards through the application of real-time monitoring and effluent certification. Oil operators ought to be required to use zero-discharge technologies or capture-and-treatment systems, such as electrocoagulation, membrane filtration, or biochar adsorption, to capture metals prior to effluent discharge (Osuji, 2025). Second, a uniform analytical model needs to be established across all regulatory and research institutions to ensure data consistency, disclosures, and consolidation into a centralised national database (Wang *et al*., 2018). It will be helpful for the longitudinal surveillance and predictive modeling of contamination hotspots. Additionally, phytoremediation and sediment stabilisation should be included in the ecological restoration activities by incorporating native macrophytes with proven metal-dressing ability. Also important are community-level actions, such as periodic health risk screening, fish-intake warnings, and community education, which can reduce the risk of exposure, particularly in children and pregnant women. The environmental liability schemes should also encourage clean production processes and penalize noncompliant industries. In academia, the focus on research ought to change to metal speciation, modelling of trophic transfer, and mobility-related studies as these areas constrain the factualization of risk. Lastly, inter-university coordination, regulatory bodies, and intra-international research organisations will help create localised policies and transformative management systems that balance scientific accuracy and socio-economic truths. Such coordinated, evidence-based efforts will be all that help the Niger Delta achieve significant remediation to avoid additional ecological degradation.

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