Innovations

Green Clean-Up: Leveraging Duckweed (Lemna paucicostata) for Sustainable Phytoremediation of Heavy Metals in Dumpsite Leachate, Calabar, Nigeria

Udiba, Udiba U.,[1*] Jimmy, Emmanuel U.,[1]Anwana, Enoabasi D.,[2] John Ama[1], Sonowo, Olunimi[3], Akpan, Ekom Robert[4],Essien, Glory A.[1]

[1]Zoology and Environmental Biology Department, University of Calabar, Nigeria
Botany and Ecological Science Department, University of Uyo, Niigeria
[5]Cardiff Sixth Form College, Wales, England
[6]Institute of Oceanography, University of Calabar, Nigeria

Abstract: *Dumpsite leachates poses significant environmental and health risks.This study conducted an ex-situ experiment evaluating the effectiveness of Lemna paucicostata for phytoremediating heavy metals in leachates from Lemna dumpsite in Calabar, Nigeria. Duckweed biomass was cultured at varying densities (100g, 300g, and 500g) in 20L of leachate under ambient conditions over 28 days. Heavy metals such as Pb, Cd, Ni, Cu, Fe, and Zn were analyzed pre- and post-remediation using atomic absorption spectrophotometry. Reduction efficiency was calculated, and statistical analyses (t-test and ANOVA) determined significance. Significant reductions in metal concentrations were achieved with increasing duckweed biomass. The highest reduction efficiencies at 500g biomass were observed for Pb (82.40%), Cd (94.54%), and Cu (83.88%). Nickel, iron, and zinc also showed reductions exceeding 70%. In contrast, the control group exhibited no significant changes in metal levels, underscoring the plant's efficacy. Duckweed's dense biomass enhances heavy metal uptake through phytoextraction and phytostabilization. Comparisons with existing studies reveal Lemna paucicostata outperforms other aquatic plants in heavy metal removal, especially for Pb and Cd. However, post-remediation concentrations for some metals exceeded regulatory limits, indicating the need for extended remediation durations and optimization strategies. The study conclude that Lemna paucicostata is a viable, cost-effective solution for heavy metal remediation in dumpsite leachate, providing an eco-friendly approach to mitigating pollution. Its application could enhance water safety and environmental sustainability. Future research should explore higher biomass densities, prolonged exposure periods, and nutrient supplementation to optimize* *remediation efficacy. Large-scale trials are essential to validate scalability for industrial applications.*

***Key Words**: Heavy metals, dumpsite leachates, Lemna paucicostata, phytoremediation, water safety, environmental sustainability*

1.0: Introduction

Major dumpsites serve as the final disposal sites for a wide range of waste materials, including household, industrial, and hazardous wastes. Such dumpsites pose significant environmental risks due to the accumulation of both organic and inorganic pollutants. The open dumping of solid waste facilitates the release of hazardous substances that can lead to soil degradation, air pollution, and water contamination (Alabi*et al*., 2023). Furthermore, decomposing waste emits harmful gases such as methane and sulfur dioxide, contributing to air pollution and climate change (Idowu*et al*., 2022). Additionally, dumpsites foster the proliferation of disease-carrying vectors and pathogens, threatening local biodiversity and public health (Idowu*et al*., 2022). In developing nations, where proper waste management practices are often lacking, the environmental impacts of dumpsites are particularly severe, with widespread contamination extending to nearby ecosystems (Ekong & Akpan, 2023).

Heavy metals such as cadmium, lead, mercury, and chromium are commonly found in dumpsite leachate and are of particular concern due to their toxicity, persistence, and potential for bioaccumulation (Rajbhandari*et al*., 2022). Unlike organic pollutants, heavy metals do not degrade over time, leading to long-term environmental contamination (Oliveira *et al*., 2021). Chronic exposure to these metals can cause various health problems, including organ failure, neurological disorders, and cancer. Thus, addressing heavy metals in dumpsite leachate is essential to protect both environmental and human health.

Leachate generated from dumpsites, especially in regions, like Calabar, with high rainfall (2200-3500 mm), has severe implications for groundwater and surface water contamination (NiMet, 2024). Leachates containing heavy metals and other pollutants can percolate through soil layers, reaching groundwater, which can then spread to rivers, lakes, and other water sources (Abdel-Rahman *et al*., 2023; Ifon and Asuquo, 2021). Leachates can also reach surface water directly through surface runoffs. Contaminated water poses significant health risks to communities relying on these sources for domestic, agriculture, and aquaculture (Ekpo*et al*., 2023). Remediation strategies for heavy metal contamination in leachate include chemical precipitation, ion exchange, membrane filtration, and adsorption (Akinola & Afolabi, 2023). However, these methods are often costly, energy-intensive, and generate secondary waste. Phytoremediation, or green clean-up, uses plants to remove, stabilize, or detoxify contaminants, providing a sustainable, eco-friendly alternative that requires minimal energy and generates no secondary pollutants (Jadia & Fulekar, 2019). Moreover, phytoremediation has the added benefit of restoring soil and aquatic health and improving local biodiversity.

Green technology refers to environmentally sustainable innovations designed to minimize human impact on ecosystems. This approach incorporates materials, methods, and practices that reduce pollution and support resource conservation (Sanchez *et al.*, 2022). Green technology in remediation, such as phytoremediation, promotes ecological balance and offers a sustainable means of addressing environmental pollutants without relying on chemical-intensive methods. Phytoremediation involves a series of complex interactions that enable plants to extract, stabilize, and detoxify contaminants from soil and water. Root systems release organic acids that alter the solubility of metals, allowing for processes like phytoextraction (metal uptake and accumulation), phytostabilization (contaminant immobilization), and phytodegradation (pollutant breakdown) (Pulford & Watson, 2020). For instance, plants capable of phytoextraction concentrate heavy metals in their tissues, making subsequent harvesting and safe disposal feasible. Identifying plants with a natural ability to tolerate and accumulate metals is critical for enhancing phytoremediation. Ideal species should be fast-growing, possess extensive root systems, and exhibit high tolerance to heavy metals (Ali *et al.*, 2023). Discovering new hyperaccumulator species and evaluating efficacy of already discovered species in the clean-up of contaminants from different sources is essential for effective phytoremediation, as these plants can be employed in contaminated areas with specific metal profiles. Phyto-accumulating plants, or hyperaccumulators, are characterized by their capacity to absorb and concentrate metals in their biomass without suffering toxic effects. Duckweed (*Lemna paucicostata*) demonstrates great potential as a phyto-accumulator due to its rapid growth rate, extensive root structure, and tolerance to high levels of heavy metals (Bennicelli*et al.*, 2021a; Bennicelli*et al.*, 2021b). Moreover, duckweed's adaptability to aquatic environments makes it suitable for treating leachate from dumpsites with a high water content.

Calabar's Lemna Dumpsite serves as the central waste disposal location for all solid waste generated in the city. Spanning several acres, the site receives diverse waste, including industrial, medical, and household refuse (Ekong & Akpan, 2023. As waste decomposes, it produces leachate that percolate through the soil to ground water or washed directly into the adjourning creeks of the Great Kaw River and eventually into the river through surface runoffs, posing severe environmental and public health risks. While studies on phytoremediation exist, limited research has focused on the use of duckweed specifically for treating dumpsite leachate in Nigeria. Furthermore, data on its efficiency in removing heavy metals from Calabar's Lemna Dumpsite leachate are lacking. This research aims to fill these gaps by evaluating duckweed's capacity for heavy metal removal under local conditions. This study contributes to the body of knowledge on sustainable waste management and water safety in Nigeria. By exploring duckweed as a viable phytoremediation agent, this research supports eco-friendly remediation strategies that could be adopted widely to mitigate dumpsite pollution across developing regions.

2.0: Materials and Methods

2.1: Study Location

Calabar, the capital of Cross River State, is situated between latitudes 4°5'30" and 5°30'N and longitudes 8°18'0" and 8°22'30"E. It is bordered by the Calabar River to the west, the Great Kwa River to the east, and the Cross River estuary to the south. The city spans 406 km² and comprises Calabar Municipality and Calabar South LGAs. The area due to its coastal location experiences tropical rainforest conditions, characterized by high rainfall. The rainfall begins from April and ends in October, with temperatures ranging from 25°C to 34°C (Osang*et al*., 2013). Mangrove and rain forest ecosystems define Calabar's ecology, which consists primarily of freshwater swamp forests with a small amount of savanna vegetation and ornamental/avenue tree/shrub species. Clayey-loamy soils are the most common type of soil (Osang*et al*., 2013). The Lemna dumpsite located on Lemna Road in Ikot Effanga Mkpa, is managed by Patson Environmental Services Limited (PESL) and serves as the final dumpsite for solid waste generated within Calabar Metropolis.

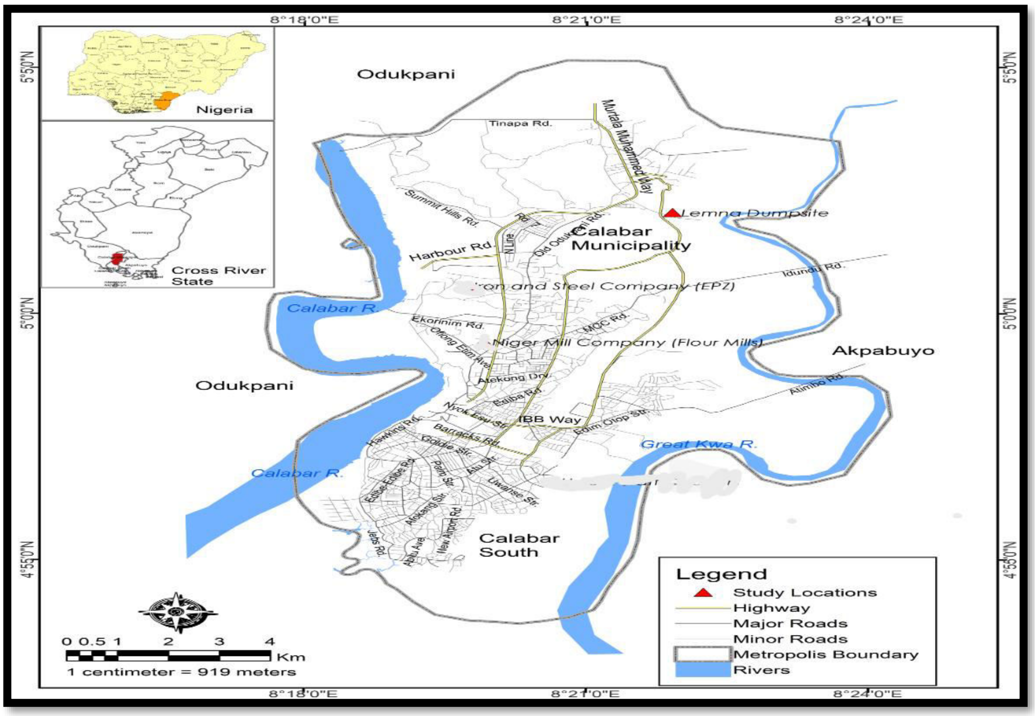

Figure 1: Map of Calabar showing the study sites

Plate 1: Lemna Dumpsite

2.2: Sample collection: Leachate from the dumpsite was collected at the edge of the canal (Plate 2) using a plastic bucket by simple scoop and emptied into a 60-liter gallon respectively.

2.3: Duckweed collection: Duckweed species was identified using identification guides of Edmondson (1959) **and** Newell and Newell (1975) at University of Calabar fish farm, obtained and cultured in a restricted pond at Akai Efa, Calabar. A simple strainer was made with mosquito netting (Plate 3) and used to harvest colonies of duckweedfrom where it was cultured. Duckweed was tempered to get used to the sampled waste water before introduction into experimental setup.

 

Plate 2: Leachate collection point **Plate 3**: Net used for harvesting duckweed

2.4: Experimental set-up

An ex-situ study was carried out to evaluate the detoxification potential of duckweed (*Lemna paucicostata*) on dumpsite leachate. Fresh duckweed biomass (Plate 4) in varying amounts (500g, 300g, and 100g) was introduced into triplicate basins, each containing 20 liters of dumpsite leachate collected from Lemna dumpsite, Calabar. Control setups, without duckweed (Plates 5), were established for comparison. The experimental setups (Plate 6) were monitored for 28 days under ambient conditions with temperatures ranging from 25–33°C and relative humidity between 55–62%. This procedure was conducted monthly from May to August 2023.

 

Plate 4: Colonies of duckweeds **Plate 5:** Wastewater without duckweed (control)

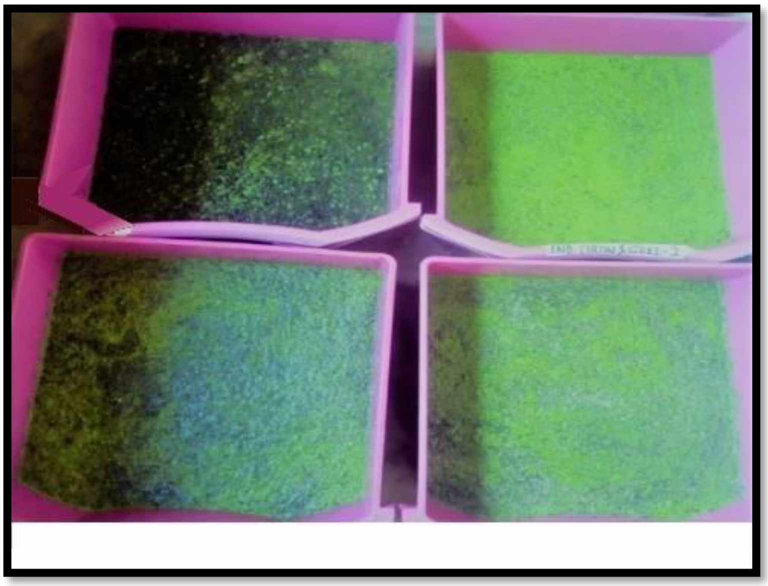

Plate 6: Duckweed mat in the waste water

2.4: Heavy Metals Analysis

Wastewater samples from the experimental setup were digested individually in 250 ml acid-washed conical flasks. A volume of 20 ml concentrated nitric acid was added, and the mixture was heated to a slow boil. The solution was then evaporated on a hot plate until nearly dry. Additional nitric acid was added as needed until a clear solution signified complete digestion. The digested sample was filtered into a 50 ml volumetric flask and diluted to the mark with distilled deionized water. Heavy metals (Pb, Cd, Ni, Cu, Fe, and Zn) in the wastewater were analyzed using an atomic absorption spectrophotometer (model AA-6800, Japan) at the Cross River State Water Board Laboratory, before and after the 28-day remediation period each month.

2.5: Statistical Analysis

A statistical test of significance was performed on the data collected. Independent t-test was used to compare metals levels in dumpsite leachates before and after phytoremediation. Analysis of variance (ANOVA) was used to compare metals levels between the three treatments (100g, 300g and 500g). Probabilities less than 0.05 were considered to be significant. Statistical analysis was carried out using IBM SPSS version 23 for windows.

2.6: Reduction Efficiency (RE)

The percentage reduction efficiency (RE) of contaminants was calculated using equation 1Ekperusi*et al.*, (2020b).

$$R(\%) = \frac{Co-Ct}{Ct} X\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where Ris Reduction efficiency of contaminant (%),

$C_o$is the initial contaminant level (mg/L),

C_t final contaminant level (mg/L)

Results

Heavy Metals Concentration in Dumpsite Leachates Before and After Phytoremediation

Results obtained from the analysis of heavy metal concentrations in dumpsite leachates before and after 28 days phytoremediation across the different duckweed concentration cultures (100g, 300g and 500g) are as presented in Table 1. Comparison of metals concentrations before and after remediation for the different treatments and the control is presented in Figure 2.

The mean value for lead, nickel, and copper before remediation were 5.86± 0.89g mg/L, 2.83±0.61mg/L, and 3.60± 0.58mg/L respectively (Table 1). The mean concentrations of the metals after 28 days of phytoremediation with 100g, 300g and 500g of duckweed cultures were: 2.10±0.35mg/L, 1.64±0.17mg/L and 0.99±0.16mg/L for lead, 1.27±0.36mg/L, 1.27±0.07mg/L and 0.59±0.21mg/L for Nickel, and 1.26±0.37mg/L, 1.10±0.08mg/L and 0.56±0.10mg/L for copper, respectively. The mean percentage reductions for the 100g, 300g and 500g treatments respectively were: 64.06%, 70.91% and 82.40% for lead, 54.99%, 52.89% and 78.95% for nickel, and 62.59%, 68.52% and 83.88% for copper (Table 1). In all cases, there was no reduction in metal concentrations in the control (leachates with no duckweed) before and after the 28 days of phytoremediation experiment but significant reductions were observed in the 100g, 300g and 500g of duckweed treatments (Figure 2). The difference in concentration of lead, nickel, and copper before and after remediation was significant ($p < 0.05$) at all concentration of duckweed (100g, 300g and 500g) treatment. The difference in the concentrations of Pb, Ni, and Cu between the different treatments (100g, 300g and 500g) after the 28 day remediation exercise were significant (ANOVA, $p < 0.05$), the concentration of lead in 100g treatment being significantly lower than 300g and 500g. The difference between 500g and 300g was not significant at 95% confidence level.

The mean value for cadmium, iron, and zinc before remediation were 1.32± 0.54mg/L, 18.31±2.10mg/L, and 15.54±1.73mg/L respectively (Table 1). The mean concentrations of the metals after 28 days of phytoremediation with 100g, 300g and 500g of duckweed cultures were: 0.13±0.11mg/L, 0.08±0.05mg/L and 0.09±0.12mg/L for cadmium, 6.45±2.10mg/L, 7.03±1.66mg/L and 4.67±0.36mg/L for iron, and the 6.36±0.59mg/L, 5.17±0.33mg/L and 4.71±0.31mg/L for zinc, respectively. The mean percentage reductions for the 100g, 300g and 500g treatments respectively were: 90.38%, 92% and 94.54% for cadmium, 65.21%, 61.53% and 73.98% for iron, and 58.38%, 66.45% and 69.25% for zinc. In all cases, there was no reduction in metal concentrations in the control (leachates with no duckweed) before and after the 28 days of phytoremediation experiment but significant reductions were observed in the 100g, 300g and 500g of duckweed treatments (Figure 2). The difference in concentration of lead, nickel, and copper before and after remediation was significant ($p < 0.05$) at all concentration of duckweed (100g, 300g and 500g) treatment. The difference in the concentrations of Cd, Fe, and Zn between the different treatments (100g, 300g and 500g) after the 28 day remediation exercise were not statistically significant (ANOVA, $p > 0.05$)

Table 1: Heavy metal concentration in dumpsite leachate before and after phytoremediation process

Metals	Sample Replicates (R)	100gDuckweed Conc.					300gDuckweed Conc.					500gDuckweed Conc.				
		May	June	July	Aug.	Mean/STDev.	May	June	July	Aug.	Mean/STDev.	May	June	July	Aug.	Mean/STDev.
Lead (Pb)	BeforePhytoremediation	7.22	5.11	5.03	6.06	5.86±0.89	7.22	5.11	5.03	6.06	5.86±0.89	7.22	5.11	5.03	6.06	5.86±0.89
	R1	2.05	2.14	2.05	2.66	2.23±0.25	1.15	2.05	2.06	2.00	1.82±0.38	0.63	0.5	1.01	1.11	0.81±0.25
	R2	3.01	2.01	1.83	1.66	2.13±0.52	2	2.13	2.06	1.06	1.81±0.44	1.32	1.13	1.14	1.25	1.21±0.08
	R3	2.95	1.01	2	1.88	1.96±0.69	1.13	0.94	1.53	1.61	1.30±0.28	0.25	1.33	1.36	0.85	0.95±0.45
	Mean	**2.67**	**1.72**	**1.96**	**2.07**	**2.10±0.35**	**1.43**	**1.71**	**1.88**	**1.56**	**1.64±0.17**	**0.73**	**0.99**	**1.17**	**1.07**	**0.99±0.16**
	% Reduction	63.02	66.34	61.03	65.84	64.06	80.2	66.54	62.62	74.26	70.91	89.89	80.63	76.74	82.34	82.40
Cadmium (Cd)	Before Phytoremediation	2.05	1.59	0.7	0.92	1.32±0.54	2.05	1.59	0.7	0.92	1.32±0.54	2.05	1.59	0.7	0.92	1.32±0.54
	R1	0.56	0.03	0.1	0.11	0.20±0.21	0.08	0.19	0.13	0.02	0.11±0.06	0.85	0.1	0.01	0.01	0.24±0.35
	R2	0.2	0.03	0.01	0.1	0.09±0.07	0.05	0.02	BDL	BDL	0.04±0.02	0.04	0.02	BDL	0.02	0.03±0.01
	R3	0.15	0.03	0.09	0.11	0.10±0.04	0.01	0.2	BDL	BDL	0.11±0.10	0.03	0.02	BDL	BDL	0.03±0.01
	Mean	**0.30**	**0.03**	**0.07**	**0.11**	**0.13±0.11**	**0.05**	**0.14**	**0.13**	**0.02**	**0.08±0.05**	**0.31**	**0.05**	**0.01**	**0.02**	**0.09±0.12**

	% Reduction	85.37	98.11	90	88.04	90.38	97.56	91.2	81.43	97.82	92.00	84.88	96.86	98.57	97.83	94.54
Nickel(Ni)	BeforePhytoremediation	2.06	3.05	3.7	2.5	2.83±0.61	2.06	3.05	3.7	2.5	2.83±0.61	2.06	3.05	3.7	2.5	2.83±0.61
	R1	1.01	1.05	2.1	0.9	1.27±0.49	1.3	1.01	1.11	0.93	1.09±0.14	0.5	0.2	1	1.05	0.69±0.35
	R2	1.5	1	2	0.96	1.37±0.42	1.36	1.55	2.01	2.00	1.73±0.28	0.36	0.2	0.4	0.66	0.41±0.17
	R3	0.95	1.25	1.52	0.95	1.17±0.24	1.09	0.95	0.89	1.05	1.00±0.08	0.3	0.83	1.3	0.32	0.69±0.41
	Mean	**1.15**	**1.10**	**1.87**	**0.94**	**1.27±0.36**	**1.25**	**1.17**	**1.34**	**1.33**	**1.27±0.07**	**0.39**	**0.41**	**0.90**	**0.68**	**0.59±0.21**
	% Reduction	44.18	63.93	49.46	62.4	54.99	39.32	61.64	63.78	46.8	52.89	81.07	86.56	75.68	72.5	78.95
Copper(Cu)	BeforePhytoremediation	3.00	4.05	4.3	3.05	3.60±0.58	3.00	4.05	4.3	3.05	3.60±0.58	3	4.05	4.3	3.05	3.60±0.58
	R1	1.91	1.03	1.06	1.95	1.49±0.44	1.32	0.87	0.85	0.8	0.96±0.21	1.05	0.52	0.85	0.21	0.66±0.32
	R2	1.65	1.03	0.94	1.32	1.24±0.28	1.3	1.42	1.05	1.15	1.23±0.14	0.55	0.21	0.68	0.35	0.45±0.18
	R3	1.85	0.46	1.08	0.83	1.06±0.51	1.01	1.09	1.11	1.2	1.10±0.07	0.22	0.52	0.55	1.05	0.59±0.30
	Mean	**1.80**	**0.84**	**1.03**	**1.37**	**1.26±0.37**	**1.21**	**1.13**	**1.00**	**1.05**	**1.10±0.08**	**0.61**	**0.42**	**0.69**	**0.54**	**0.56±0.10**
	% Reduction	40.00	79.25	76.04	55.08	62.59	59.66	72.10	76.74	65.57	68.52	79.66	89.62	83.95	82.29	83.88

Iron(Fe)	BeforePhytoremediation	20.57	18.75	14.88	19.04	18.31±2.10	20.57	18.75	14.88	19.04	18.31±2.10	20.57	18.75	14.88	19.04	18.31±2.10
	R1	9.5	6.8	3.05	9.5	7.21±2.64	10.31	4.8	6.15	6.18	6.86±2.07	6.6	5.1	5.55	5.08	5.58±0.62
	R2	8.61	4.3	4.1	4.5	5.38±1.87	7.5	10.2	6.1	4.1	6.98±2.22	4.62	4.55	6.3	2.8	4.57±1.24
	R3	11.05	6.7	4.5	4.8	6.76±2.62	9.5	9.11	6.3	4.11	7.26±2.20	3.52	3.6	3.51	4.8	3.86±0.55
	Mean	**9.72**	**5.93**	**3.88**	**6.27**	**6.45±2.10**	**9.10**	**8.04**	**6.18**	**4.80**	**7.03±1.66**	**4.91**	**4.42**	**5.12**	**4.23**	**4.67±0.36**
	% Reduction	52.74	68.37	73.92	65.82	65.21	55.76	57.12	58.46	74.78	61.53	76.13	76.42	65.59	77.78	73.98
Zinc(Zn)	BeforePhytoremediation	15.3	18.1	15.51	13.23	15.54±1.73	15.3	18.1	15.51	13.23	15.54±1.73	15.3	18.1	15.51	13.23	15.54±1.73
	R1	6.9	6.1	5.3	9.5	6.95±1.58	6.5	6.15	6.19	6.5	6.34±0.17	6.3	3.5	3.1	5.11	4.50±1.28
	R2	6.1	5.25	5.1	5.1	5.39±0.42	5.2	5.65	5.45	4.3	5.15±0.52	3.8	9.1	4.55	5.1	5.64±2.05
	R3	7.25	7.8	5.8	6.15	6.75±0.81	4.85	4.15	4.05	3.1	4.04±0.62	2.9	2.16	5.82	5.1	4.00±1.51
	Mean	**6.75**	**6.38**	**5.40**	**6.92**	**6.36±0.59**	**5.52**	**5.32**	**5.23**	**4.63**	**5.17±0.33**	**4.33**	**4.92**	**4.49**	**5.10**	**4.71±0.31**
	% Reduction	55.88	64.75	65.18	47.69	58.38	63.92	70.60	66.27	65.00	66.45	71.69	72.81	71.05	61.45	69.25

R1, R2 and R3 represent replicates 1, 2 and 3

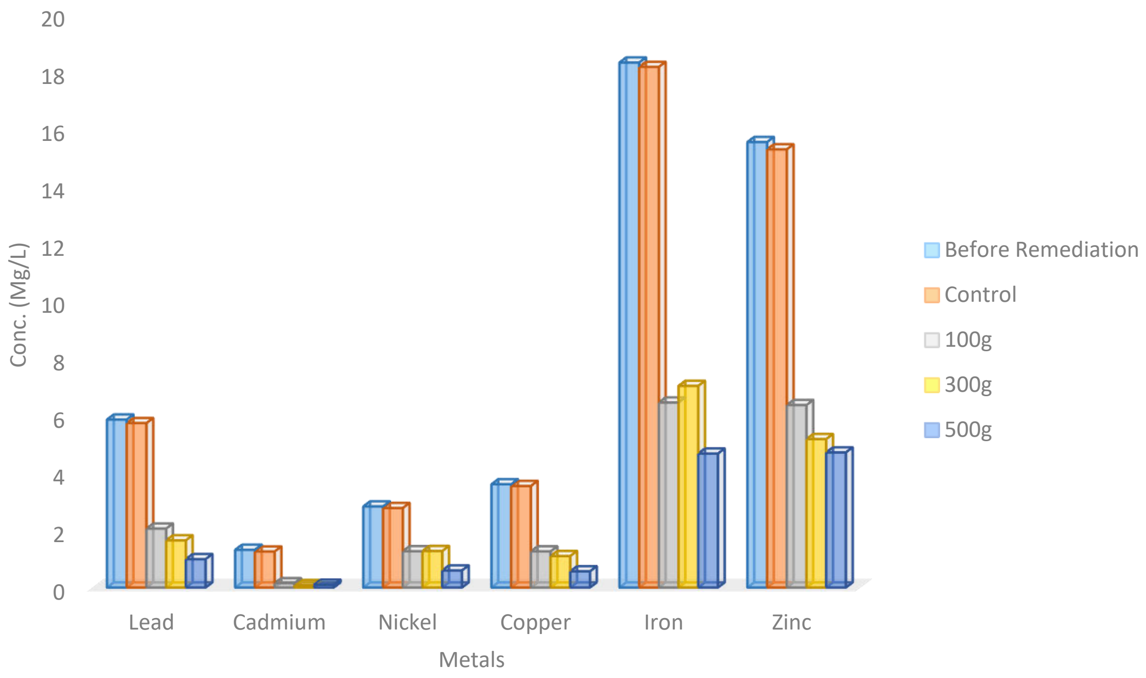

Figure 2: Comparison of heavy metal levels in Dumpsite Leachates before and after 28 days of remediation using different concentrations of duckweed

Discussion

Leachates, a toxic cocktail of organic and inorganic pollutants—including heavy metals, nutrients, pathogens, and hazardous chemicals, pose significant environmental hazards. Igelle*et al*. (2016) revealed extensive leachate contamination at the Lemna dumpsite through spatial analysis, while Igelle and Ekwok (2017) underscored the dangers of heavy metal transport in groundwater, threatening residents relying on borehole water. Their findings highlighted severe impacts on soil, water, and vegetation, underscoring the urgent need for remediation. Addressing leachate contamination at the Lemna dumpsite is critical to safeguarding groundwater, surface water, local ecosystems, and biodiversity.

Unlocking the Potential of *Lemna paucicostata* for Sustainable Heavy Metal Remediation in Lemna Dumpsite Leachate

This study highlights the exceptional efficacy of *Lemna paucicostata* in remediating heavy metal-laden leachate from the Lemna dumpsite, given that no significant reduction in metal levels was observed in the control (leachates with no duckweed). On the other hand, after the 28 days for effluents treated with Duckweed species *L. paucicostata*, lead concentrations, initially measured at 5.86 mg/L, were reduced by 64.06% (100g of duckweed), 70.91% (300g), and 82.40% (500g), demonstrating the plant's potential for significant remediation. Nickel levels dropped from 2.83 mg/L to 1.27 mg/L (100g), 1.27 mg/L (300g), and 0.59 mg/L (500g), achieving reduction efficiencies of 54.99%, 52.89%, and 78.95%, respectively. Cadmium concentrations saw an even more remarkable decline, from 1.32 mg/L to reductions of 90.38% (500g), 92% (300g), and 94.54% (100g). Iron, copper, and zinc levels also experienced substantial decreases, underscoring the plant's impressive phytoextraction potential. The findings emphasize duckweed's role as a powerful, innovative, and scalable eco-friendly tool for mitigating heavy metal pollution, paving the way for sustainable leachate management and environmental restoration.

Comparative Edge of *Lemna paucicostata* for Heavy Metal Remediation ofLemna Dumpsite Leachate

Lead (Pb) reductions of 75% and 80%, respectively, using *Spirodelapolyrhiza* and *Lemna minor*were reported by Ekperusi*et al*. (2020a) and Bennicelli*et al*. (2021). These results fall slightly below the 82.40% Pb reduction achieved in this study. Similarly, Jadia and Fulekar (2019) documented cadmium (Cd) reductions of 85% using *Eichhorniacrassipes*, which is notably lower than the remarkable 94.54% Cd reduction observed with *Lemna paucicostata*. For Pb remediation, *Eichhornia crassipes* achieved a 70% reduction (Jadia&Fulekar, 2019), again trailing behind the82.40% efficiency demonstrated here. While *Lemna minor* reduced Cd by88%(Bennicelli*et al*., 2021), it still fell short of the superior 94.54% reduction recorded in this study. These comparisons underscore *Lemna paucicostata*'s exceptional potential for heavy metal phytoremediation, outperforming other aquatic plants in both Pb and Cd removal.

Maximizing Metal Removal with 500g Duckweed Treatment

The 500g duckweed treatment consistently delivered superior reduction efficiencies across all metals, outperforming other treatments. This remarkable performance can be attributed to the larger biomass, which offered more adsorption sites, enhanced nutrient uptake, and elevated metabolic capacity for effective metal sequestration. Additionally, the higher biomass likely bolstered resilience to environmental stress, out competed leachate microbiota, and improved oxygenation and pH stabilization. These factors created optimal conditions for efficient metal removal, solidifying the 500g treatment as the most effective strategy for heavy metal remediation in this study (Prasad & Freitas, 2003; Vymazal, 2014).

Assessing Compliance and Optimization Needs in Metal Remediation

Post-remediation zinc concentrations fell within the Nigerian Environmental Standards and Regulation Enforcement Agency limit of 10 mg/Lfor wastewater discharge into land or surface water, showcasing the effectiveness of the remediation process (NESREA, 2011a; NESREA, 2011b).However, while significant reductions were achieved for lead, cadmium, nickel, copper, and iron, their post-remediation levels exceeded the NESREA standards of 0.01 mg/L, 0.003 mg/L, 0.1 mg/L, 0.01 mg/L, and 5.0 mg/L, respectively (NESREA, 2011a; NESREA, 2011b). These results highlight the need for additional remediation steps to ensure regulatory compliance, underscoring the importance of exploring optimization strategies for enhanced performance.

Optimization Strategies for Enhanced Regulatory Compliance in Heavy Metal Remediation

1. **Increasing Biomass Density**

Higher biomass densities, such as the 500g treatment, demonstrated improved metal reduction efficiencies by offering a larger surface area for adsorption. Utilizing biomass quantities exceeding 500g, as suggested by Banerjee *et al.*, (2018), could enhance absorption capabilities. Experiments with 700g to 1,000g of duckweed in the same wastewater volume (20L) may result in higher reduction rates for metals like Pb and Ni, which remain above regulatory thresholds (Yan *et al.*, 2020; Ma *et al.*, 2018). These higher biomasses are better suited to manage increased contaminant loads, particularly in industrial effluents.

2. **Extending Exposure Time**

Increasing the treatment duration beyond 28 days could allow for greater metal uptake by duckweed, especially for elements that exceed regulatory limits under shorter time frames. Investigating extended periods, such as 35, 45, or 60 days, could identify the optimal exposure time for maximum metal removal. Longer remediation durations have been shown to significantly reduce metal concentrations, as demonstrated in studies by Li *et al.* (2021).

3. **Periodic Nutrient Supplementation**

Periodic addition of essential nutrients, such as nitrogen and phosphorus, at controlled concentrations can support duckweed growth and sustain its metal uptake efficiency. Proper nutrient management can prevent deficiencies while avoiding eutrophication, thereby enhancing biomass vitality and metal absorption capacity (Sarwar*et al.*, 2010).

4. **Sequential Harvesting and Replanting**

Regularly harvesting duckweed (e.g., every two weeks) and replacing it with fresh biomass can sustain high absorption rates. Freshly replanted duckweed typically exhibits greater metal uptake potential, reducing the likelihood of saturation and improving overall remediation efficiency within the treatment period (Xu *et al.*, 2022).

5. Bio-Stimulation and Bio-Augmentation

- *Chelating Agents:* Adding chelating agents like EDTA can increase metal bioavailability, accelerating uptake by duckweed (Linger *et al.*, 2002).

- *Biochar as a Substrate:* Incorporating biochar can stabilize metals, enhance plant growth, and improve overall remediation effectiveness (Liu *et al*., 2018).
- *pH Optimization:* Adjusting pH to optimal levels can enhance metal solubility, improving uptake efficiency (Yan *et al*., 2020).
- *Temperature Regulation:* Maintaining optimal temperatures supports metabolic activity, further enhancing metal absorption (Liu *et al*., 2013).
- *Beneficial Microbes:* Introducing growth-promoting microbes can increase metal tolerance and uptake efficiency (Backer *et al*., 2019).
- *Genetic Engineering:* Genetic modifications to enhance duckweed's metal tolerance and absorption potential hold significant promise for future applications (Lyu*et al*., 2019).

6. Scaling Up for Industrial Applications

Large-scale trials are essential for evaluating the economic and operational feasibility of using duckweed for industrial effluent treatment. These trials can uncover challenges such as nutrient requirements, maintenance costs, and scalability issues, providing opportunities to refine the process for broader applications (Chen *et al*., 2016; Linger *et al*., 2002).

By implementing these optimization strategies, *Lemna paucicostata* can be further developed into a highly effective, sustainable solution for heavy metal remediation and regulatory compliance.

Conclusion

This study demonstrated the potential of *Lemna paucicostata* for remediating heavy metal-laden leachate from Calabar'sLemna dumpsite. Phytoremediation reduced metal concentrations significantly, with reduction efficiencies reaching 94.54% for cadmium and 82.40% for lead using 500g duckweed biomass. The findings highlight the plant's robust phytoremediation capabilities, outperforming many aquatic plants studied previously. However, some post-remediation metal levels exceeded regulatory standards, underscoring the need for enhanced strategies. The research validates *Lemna paucicostata* as an effective, sustainable alternative for heavy metal remediation, addressing environmental and public health concerns associated with dumpsite leachate. By integrating phytoremediation into waste management systems, stakeholders can leverage this green technology to protect water resources and biodiversity. Future studies should investigate the use of increased biomass densities, extended treatment durations, and nutrient enrichment to enhance remediation efficiency. Conducting large-scale trials is crucial to assess feasibility and scalability for industrial applications.

Acknowledgement: Sincere thanks go out to Department of Zoology and Environmental Biology, University of Calabar, for letting the authors use their lab for this research.

Conflict of interest: The authors declare that there are no conflicts of interest regarding the publication of this manuscript. No specific grant or funding was received for this research from public, private, or not-for-profit organizations.

References:

1. *Abdel-Rahman, M. A., Hassan, H. E., & Mahmoud, A. A. Impact of dumpsite leachate on groundwater quality: A review. Environmental Geochemistry and Health. 2023; 45(2): 409-422.*
2. *Akinola, J. O., & Afolabi, T. M. Remediation techniques for heavy metal polluted water: A review. Journal of Environmental Management. 2023; 307: 114590.*
3. *Alabi, O. A., Rotimi, F., & Adewumi, O. Solid waste dumpsites: Environmental and health risks. Environmental Science and Pollution Research. 2023; 30(3): 1897-1909.*
4. *Ali, H., Khan, E., & Sajad, M. A. Phytoremediation of heavy metals—Concepts and applications. Chemosphere 2023; 315: 137615.*
5. *Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E. & Smith, D. L. Plant growth-promoting rhizobacteria: Context, mechanisms of action, and new insight into application. Frontiers in Plant Science. 2019; 10: 1517.*
6. *Banerjee, G., Datta, S., Ghosh, M., & Ghose, T. (2018). Efficacy of duckweed in wastewater treatment: Metal remediation and biomass generation. Ecotoxicology and Environmental Safety. 2018; 150: 117–124.*
7. *Bennicelli, R. P., Stepniewska, Z., Banach, A., Szajnocha, K., & Ostrowski, J. The effect of heavy metals on the growth and accumulation of duckweed. Aquatic Botany. 2021; 94(4): 257-264.*
8. *Bennicelli, R., Stefaniak, S., Rękawek, H., & Szajnocha, K. Phytoremediation efficiency of duckweed species. Journal of Environmental Management. 2021; 283, 111223*
9. *Chen, J., Guo, W., Li, F., & Zeng, Q. Optimization and pilot-scale study on phytoremediation of heavy metal-contaminated soil using duckweed. Environmental Pollution. 2016; 219: 902–910.*
10. *Edmonson, W. T. 1959. Freshwater Biology. 2nd (ed.) John Wiley and Sons Incorporation, New York. pp. 1248.*
11. *Ekong, B. A., & Akpan, U. P. The waste management crisis in Calabar: Assessing the impact of the Lemna Dumpsite. Journal of Environmental Studies. 2023; 17(2): 212-223.*
12. *Ekperusi, A. O., Nwachukwu, E. O., and Sikoki, F. D. Assessing and Modeling the Efficacy of Lemna paucicostata for the Phytoremediation of Petroleum*

Hydrocarbons in Crude Oil-Contaminated Wetlands. Scientific reports. 2020a; 10:8489.

13. *Ekperusi, F., Sikoki, F. D., & Aigberua, A. O. Efficiency of aquatic plants in heavy metal removal. Environmental Technology Reviews. 2020b; 9(1): 11-20*
14. *Ekpo, I. O., Bassey, E. E., &Udoh, N. E. Assessment of groundwater quality around dumpsites in Nigeria. Groundwater for Sustainable Development. 2023; 22, 100668.*
15. *Idowu, O. A., Olayemi, J. O., &Oyebanjo, R. O. Climate impacts of open dumpsites. International Journal of Environmental Studies. 2022; 79(3): 562-578.*
16. *Ifon HT and P. E Asuquo. Tempo-spatial assessment of Calabar River, using crabs as bio-indicator of Pollution. International Journal of national and Applied Sciences. 2021; 14:23-31.*
17. *Igelle, E. I., & Ekwok, S. E. Assessment of spatial distribution of contaminants and their levels in soil and water resources of Calabar, Nigeria using geophysical and geological data. Journal of Geoscience and Environment Protection. 2017; 5(12): 1-15.*
18. *Igelle, E. I., Phil-Eze, P. O., Akim, O. O., Kanu, H. I., Ekowk, I. C., Atsa, J. W., Ojugbo, P. A., Okputu, J. S., Abdelrahman, K., Ekwok, S. E., Andráš, P., &Eldosouky, A. M. Spatial analysis of leachate penetration at Lemna dumpsite, Calabar: Implications for sustainable waste management in Cross River State. Heliyon. 2024; 10(9): e30097*
19. *Jadia, C. D., & Fulekar, M. H. Phytoremediation of heavy metals. Journal of Applied Biosciences. 2019; 11(4): 45-52*
20. *Li, Z., Shen, X., Huang, L., & Wang, J. Effectiveness of extended phytoremediation periods for metal-contaminated water treatment using duckweed species. Journal of Environmental Management. 2021; 287: 112271.*
21. *Linger, P., Ostwald, A., Haider, K., & Wursthorn, H. Chelating agents and their potential role in enhancing heavy metal uptake by duckweed species. Environmental Technology. 2002; 23: 349–356.*
22. *Liu, J., Wang, X., Zhang, J., Zhang, Z., & Zheng, Z. Effects of temperature on nutrient removal and growth of duckweed in pilot-scale wastewater treatment. Bioresource Technology. 2013; 143: 611–617.*
23. *Liu, X., Zhang, S., & Shan, X. Q. Effects of biochar on heavy metal stabilization and uptake by duckweed. Chemosphere. 2018; 191: 272–280.*
24. *Lyu, J., Zhang, L., Wang, Y., & Wu, C. Advances in genetic engineering of duckweed for phytoremediation applications. Plant Biotechnology Journal. 2019; 17(8), 1502–1512.*
25. *Ma, Y., Rajkumar, M., Zhang, C., & Freitas, H. Impacts of biomass density on metal sequestration and phytoremediation efficacy. Environmental Pollution. 2018; 233: 635–642.*
26. *NESREA (National Environmental Standards Regulations Enforcement Agency. Surface and Groundwater Quality Control. Federal Republic of*

Nigeria, Official Gazette. 2011a

27. *NESREA, (National Environmental Standards Regulations Enforcement Agency) Base Metals, Iron and Steel Manufacturing/ Recycling Industries Sector. Federal Republic Nigeria Official Gazette. 2011a; 98(40): 419-479.*
28. *Newell, G. E. and Newell, R. C. 1975. Marine plankton: a practical guide. 5th Ed. Hutchinson and Co. Publishers Ltd., London pp. 24.*
29. *NiMet (Nigerian Meteorological Agency). Climate & weather averages in Calabar, Nigeria. Retrieved November 15, 2024, from www.nimet.gov.ng.*
30. *Oliveira, H., Pinto, E., & Lopes, T. Heavy metal toxicity in ecosystems. Ecotoxicology and Environmental Safety. 2021. 194, 110-129.*
31. *Osang, J. E, Obi, E. O, Ewona, I. O., Udoimuk, A. B., and Nnwankukwu, N. Review of Gas flaring Activities in Nigeria Delta Area of Nigeria. International Journal of Scientific and Engineering Research. 2013; 4(9):23-32*
32. *Prasad, M. N. V., & Freitas, H. Metal hyper accumulation in plants: Biodiversity prospecting for phytoremediation technology. Electronic Journal of Biotechnology. 2003: 6(3); 285–321.*
33. *Pulford, I. D., & Watson, C. Phytoremediation of heavy metal-contaminated land by trees—A review. Environment Inte rnational. 2020; 69: 394-405.*
34. *Rajbhandari, A., Ghimire, M., & Bhattarai, S. Characterization and management of heavy metals in municipal solid waste landfill leachates. Journal of Environmental Management. 2022; 308, 114598.*
35. *Sanchez, A. M., Brown, R., & Taylor, D. Advances in green technology for environmental sustainability. Sustainable Development and Environmental Protection. 2022; 30(1): 76-83.*
36. *Sarwar, N., Malhi, S. S., Zia, M. H., Naeem, A., Bibi, S., &Farid, G. Role of mineral nutrition in minimizing cadmium accumulation by plants. Journal of the Science of Food and Agriculture. 2010. 90(6): 925–937.*
37. *Vymazal, J. Constructed wetlands for wastewater treatment: Five decades of experience. Environmental Science & Technology. 2014; 48(4): 2241–2245.*
38. *Xu, X., Liu, X., & He, Q. Sequential harvesting and replanting of duckweed for optimized phytoremediation of metal-contaminated water. Environmental Research. 2022. 206, 112373.*
39. *Yan, Y., Song, Z., Yang, Z., & He, Z. Role of pH in enhancing heavy metal uptake in duckweed-based phytoremediation. Journal of Hazardous Materials. 2020; 394: 122584.*