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Spatial Hotspots and Seasonal Fluxes of Heavy Metals in Soils Affected by Artisanal Refining in Bayelsa State, Nigeria

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ABSTRACT **Original research paper**

This study assessed the inter-spatial and seasonal variability of heavy metals in the soils of five artisanal refinery sites and a control site from Bayelsa State, Nigeria. Analysis of the samples was carried out for the following: mercury, arsenic, cadmium, chromium, copper, and lead. On all the studied sites, less than 0.001 mg/kg of mercury was recorded at the detection level, and since it was the determination level, mercury was said to be uncontaminated or minimally contaminated. Arsenic was present only in low levels in all the studied soils except for site L2, where 0.07 mg/kg concentration was higher than the highest acceptable level of 0.05 mg/kg by either WHO standard or EGASPIN. Cadmium was present between 0.02 to 0.035 mg/kg; chromium between 0.08 to 0.17 mg/kg; and copper from 2.79 to 4.45 mg/kg, all of which fall within permissible limits. Lead levels tended to increase from 2.52 mg/kg to 5.01 mg/kg, again well below such permissible levels. With changes across the seasons, concentrations of these metals indicate slight increases in arsenic pollution with the maximum value of as seen in March of 0.04 mg/kg, a similar situation also was observed in the case of cadmium and chromium; it was the highest during that dry season. For both copper and lead, the highest concentrations are recorded in the wet season (May). Most levels were well below permissible limits, although there will probably be occasional surges for all different metal levels and exposure arising from arsenic contamination brings localized challenges calling for continuing monitoring and regulation in order to mitigate possible long-term environmental and health risks.

Keywords: Heavy metal, Spatial, Soil, Seasonal fluxes, Artisanal.

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1. Introduction

There are many environmental and public health hazards caused by artisanal refining of crude oil as a pervasive informal economic activity in the region of Niger Delta. There are issues of unauthorized discharge of petroleum products as well as contaminants into the environment. Through this illicit practice, degradation of land, air, and water happens, enacting the elevation of heavy metals in addition to total petroleum hydrocarbons, which are actually considered to be quite functional, toxic, and bioaccumulative (Anyanwu *et al*., 2023; Suku *et al*., 2024).

The contaminants are primarily from crude oil and in addition to distillation processes, the pollutants are usually released into an ecosystem by spills, poor waste management, and atmospheric deposition (Anyanwu *et al*., 2023).Thus, there remains an increased pressure on the environment such as the existence of ecologically inharmonious environment and a disturbance in human well-being with heightened risks of respiratory, cancerous, and reproductive diseases among the local community (Suku *et al*., 2024). It has informed the accumulation of these elements, such as heavy metals and hydrocarbons in soil, surface water, and groundwater, making it a serious concern on potentially human and wildlife bioaccumulation in the food chain (Sharafi & Salehi, 2025). Also, its unique hydrogeological settings and biodiversity highlights in the Niger Delta will escalate the ecological side of this contamination and in the extreme event result in disruption to the ecosystem, as well as, the loss of habitats (Anyanwu *et al*., 2023).

Despite increasing pollution complaints from artisanal refinery processes in locations such as the Niger Delta, a comprehensive evaluation of contamination patterns and sources is missing, and very limited research exists regarding knowledge of the dynamics of these metals (Isah *et al*., 2025). Without detailed spatial analysis alongside multivariate analysis, effective localization of pollution hotspots and knowledge of seasonal variability in heavy metal concentrations-the kind of knowledge necessary for targeting to inform the process of site remediation strategies and public health interventions-has been made impossible (Isah *et al*., 2025). This work seeks to fill this cave by characterizing the spatial distribution and seasonal variation of heavy metals in soils impacted by artisanal refining in Bayelsa State, Nigeria, thereby giving significant insights into environmental management and policy formulation.

2. Materials and Methods

2.1 Study Area

The study was conducted within the confines of the Bayelsa State. This state was located within the Niger Delta region of Nigeria whereas it was known to have a high community engagement in oil bunkering activities. Artisanal refining, acknowledged to be relatively simple, is a widely practiced but substantially unregulated activity involving individual processing - outside the legal frame probably set by the oil companies, or group processing of crude into refined petroleum products without treatment of contaminants before disposed into surrounding environment. Bayelsa was chosen as the case study area for this research effort because of the highest density of artisanal refining sites in Nigeria, which were seen holding serious environmental and health risks.

2.2 Sampling sites

Key to the study was an attempt to capture field evidence of artisanal refining activities from the proximities of the sites located in five different areas in Bayelsa state. These areas include one L1 site located in Ogbia Local Government Area (LGA), two L2 and L3 sites in Ekeremor LGA, and two L4 and L5 sites in Southern Ijaw LGA. These areas were marked as the significant hotspots for artisanal refining, exposing them to the contamination of heavy metals reporting to the environment of their surrounding grounded surfaces. One control site (LX), which did not have historical knowledge about artisanal refining activities, was selected next to the study refining sites. This control site was important for the determination of baseline heavy metal concentrations for soils that were not affected by artisanal refining, thereby facilitating a comparative analysis of soil impacted against non-impacted areas.

2.3 Sampling Plan

Thus, the methodology used in the study employs a sampling approach that encompasses altogether all designated locations to ensure that the research findings will be representative of and reliable. The primary sampling points were just five along the line (L1 to L5), whereas one control site was established nearby (LX) that had been uninfluenced by crude refining. Essentially, the primary sampling points were selected according to their proximities to the known points of artisanal refining activities so as to ensure that the full extent of pollution resulting from such activities was covered by this investigation. The sites were divided into triples, so that they could cover spatial variability in sequence, and the results ensured that the data was consistent. The five primary sampling points were identified at each site within a preset radius so that the site was sampled in each different section, and a holistic evaluation of contamination of soil was ensured. Sampling for the control site (LX) was conducted this way for the concentrations of heavy metals in greater refinery-impacted sites.

2.4 Sample Collection and Field Procedures

Soil sampling is done with a depth of 0-30 cm (Aichberger & Back, 2001) which is considered a top arable layer mostly visited by pollutants due to atmospheric deposition and surface runoff (Yu *et al*., 2022a; Angon *et al*., 2024). Its procedures were adopted from well-detailed protocols as per the standard soil sampling to avoid cross-contaminations (Bach *et al*., 2022) as well as assure the integrity of the samples. Subsequent collection process was structured for a monthly post program, identifying six collection terms per year. Dry weather sampling was collected during the months of November, January, and March, while wet season samples were obtained in July, September, and November. This collection program allows the evaluation of seasonal changes in heavy metal concentrations, and concurrently records the potential effects of seasons like rainfall and temperature changes on soil burden. Before storage, each soil sample was well mixed or homogenized and placed in a clean, labeled polythene bag for the prevention of contamination. The samples were transported to laboratory conditions that were controlled to maintain the integrity of the samples until they were analyzed.

2.5 Analytical Procedures

Air-dried samples were sieved with a 2mm mesh to filter out large organic debris, after they arrived at the laboratory soil was air dried and sieved with a 2mm mesh to remove coarse debris. Air-dried samples were subsequently subjected to a two-step digestion process using a mixture of nitric acid and hydrochloric acid (Haq *et al*., 2022; Wang *et al*., 2023; Wang el al., 2024).This digestion process has fully extracted heavy metals from soil for instrumental analysis (El-Hamad *et al*., 2023; Igelle *et al*., 2024).Heavy metals, including lead, cadmium, arsenic, mercury, and chromium, were subjected to

Atomic Absorption Spectroscopy for most metals. The researchers conducted a number of studies on the average content of metals such as gypsum for example, Huang *et al*., 2024; Igelle *et al*., 2024; Abdelmonem *et al*., 2025. Calibration curves were plotted with certified standard reference materials to enhance the accuracy of their measurements. The standard materials were used at different concentrations to create a series of calibration standards.

2.6 Spatial Distribution and Hotspot Analysis

The geographic distribution of heavy metals in the study area was first put together statistically using software like Geographic Information System (GIS). GIS was employed here to produce maps that plotted out the prevailing concentrations of each heavy metal all around the study sites in order to pinpoint contamination hotspots. These maps of spatial distribution effectively relate the distance between residential lots and sites of artisanal refining processes to the heavy metal contamination levels present in the soil just under that surface level.

2.7 Data Analysis and Seasonal Pattern

Soil samples were analyzed to compare the seasonal variation in heavy metal levels in the dry and wet seasons. Soil samples were analyzed for metals at different sites as mentioned in the respective works (Yu *et al*., 2022b; Nana *et al*., 2023). Using ANOVA, significant differences in metal concentrations between rainy and dry seasons or within the respective seasons were analyzed. This analysis was sought to provide information regarding the impact of factors like temperature and rainfall on the fluxes of heavy metals in the selected soils (Nana *et al*., 2023).

2.8 Quality Control and Assurance

Strict quality control processes observed in all stages of sampling, preparation, and analysis ensured reliability and accuracy of the results (Cairns *et al*., 2024; Ray *et al*., 2025). Analysts used blank samples, replicates, and spike samples to evaluate method precision and accuracy (Adugna *et al*., 2023). Regular calibration of the instruments using certified reference materials was imperative to ensure the accuracy and consistency of the results (Bacon *et al*., 2023; Carrasco-Puig *et al*., 2023; Savoca *et al*., 2025).

3. Results and Discussion

This study assessed both spatial and seasonal variations in the heavy metal contamination of soils in artisanal-refinery sites in Bayelsa State. Soil samples from five artisanal-refinery sites (L1-L5) and a control site (LX) were analyzed for mercury, arsenic, cadmium, chromium, copper, and lead. Mercury levels, relative to detection limits, were consistent across all sites, with contamination deemed non-existent from artisanal refining activities (Table 1). Arsenic concentration levels were below detection at all sites except for L2, where a concentration of 0.07 mg/kg was registered, violating WHO and EGASPIN standards set at 0.05 mg/kg (Table 1).Cadmium levels ranged from 0.02 to 0.035 mg/kg, while chromium concentrations varied between 0.08 and 0.17 mg/kg, both of which were below the safety limits of 0.05 mg/kg and 0.5 mg/kg, respectively.

Table 1: Results on the spatial levels of heavy in soil

	Mercury (mg/kg)	Arsenic (mg/kg)	Cadmium (mg/kg)	Chromium (mg/kg)	Copper (mg/kg)	Lead (mg/kg)
L1	<0.001±0.00[a]	<0.001±0.00[a]	0.04±0.08[a]	0.17±0.04[a]	4.54±0.67[c]	2.52±0.58[b]
L2	<0.001±0.00[a]	0.07±0.02[b]	0.02±0.04[a]	0.15±0.03[a]	4.14±1.35[b]	2.85±0.42[b]
L3	<0.001±0.00[a]	<0.001±0.00[a]	0.02±0.05[a]	0.14±0.03[b]	2.79±0.93[b]	3.88±0.73[c]
L4	<0.001±0.00[a]	<0.001±0.00[a]	0.34±0.08[b]	0.15±0.04[b]	3.24±1.19[b]	5.01±0.69[d]
L5	<0.001±0.00[a]	<0.001±0.00[a]	0.35±0.08[b]	0.08±0.02[b]	2.84±0.45[b]	3.63±0.52c
LX	<0.001±0.00[a]	<0.001±0.00[a]	0.01±0.00[a]	0.04±0.03[a]	0.09±0.25[a]	0.01±0.00[a]

Key: Data expressed as Mean value ± Standard Deviation, difference in the alphabets indicate the degree of significant difference

Copper levels ranged from 2.79 to 4.45 mg/kg, and lead levels ranged from 2.52 to 5.01 mg/kg, all within the permissible limits of 10 mg/kg. While there were no significant variations in most metals across sites ($p>0.05$), higher concentrations of cadmium, chromium, and copper were observed at site L1, indicating potential hotspots linked to refining intensity (Table 1).

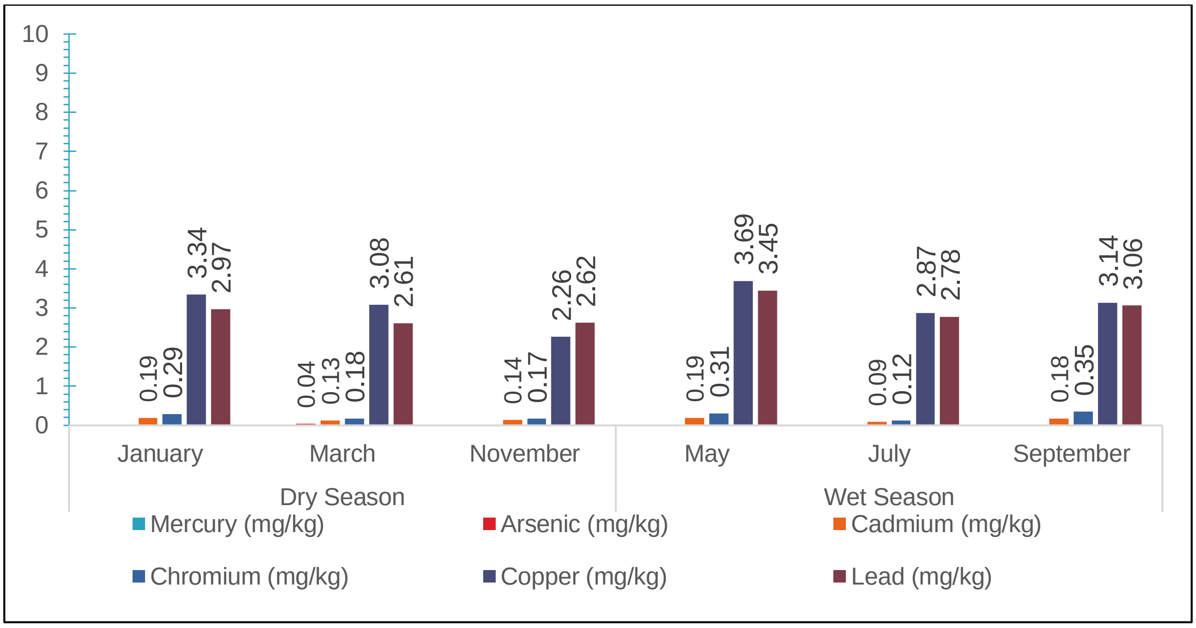

Figure 1: Seasonal variation of heavy metals in soil

Seasonal fluctuations in heavy metal level concentrations were noticed, especially during the dry months. Arsenic concentration reached a maximum of 0.04 mg/kg in the month of March, with the safe limit being 0.01 mg/kg (Figure 1). Cadmium levels ranged between 0.09 and 0.19 mg/kg, being highest in January and May. Chromium ranged between 0.12 and 0.35 mg/kg, with the maximum recorded in May. Copper and lead ranged between 2.26 and 3.69 mg/kg and were higher in the wet season in the month of May (Figure 1). Such seasonal variations may be suggesting that environmental parameters, such as rainfall and runoff, may dictate the heavy metal distribution, especially during the wet season when contamination from nearby mining sites or runoff is more evident.

In comparison with other works, one finds patterns in the accumulation of heavy metals in soils subjected to anthropogenic interference in Nigeria, with the metals lead, arsenic, and cadmium mostly exceeding regulatory limits (Igelle*et al.*, 2024) (Barde *et al.*, 2024). There have been instances of aggressive levels of lead, cadmium, and arsenic in the soils of gold mineralization areas of Nigeria that are well above the regulation limits and present environmental and human health risks (Adekiya *et al.*, 2024) (Barde *et al.*, 2024). The high levels, especially of cadmium, become alarming if one looks into the health effects that include carcinogenicity and kidney damage (Olalekan *et al.*, 2022; Okoro *et al.*, 2020) and are usually heightened by other industrial activities, such as drilling for oil wells.

Beyond this, the outcomes somehow conciliate: seasonal geoaccumulation index for heavy metals, especially chromium, indicates the greater risk during the dry seasons; hence rainfall could be a factor affecting metal mobility and distribution (Okoro *et al.*, 2020). This phenomenon further gained traction due to the observations of high concentrations of some metals, notably lead, barium, manganese, and aluminum, in the dry season; however, boron, chromium, iron, mercury, nickel, zinc, cadmium, cobalt, molybdenum, and copper revealed higher concentrations in the wet and early dry season, hence positing complex relationships between hydrological cycles and contaminant behaviors (Anyanwu *et al*., 2023).

Though this study did not find lead and cadmium always to be severe contaminants, there exists overwhelming proof in literature of the enrichment of these metals, along with zinc, by anthropogenic sources in similar environments (Ahmed *et al*., 2024). These alterations of metal concentration may largely be attributed to an unnatural disruption of the baseline levels of metals in sediments and aquatic ecosystems due to urban and industrial activities, which alter the geochemical processes to mobilize, transport, and disperse hazardous metals (Aciol*yet al.*, 2024). This mobilization is often stronger during the wet season due to the runoff and dissolution of rocks, which increases the concentrations of metals in surface water and soil (Norvivor *et al*., 2024). Meanwhile, some measured concentrations in the dry season may be partly explained by evaporation concentration and diminished dilution capacity, thereby exacerbating the pollutant load on surface soils (Sholanke *et al*., 2021).

While most heavy metals in the study site were within safe limits, arsenic concentration recorded at site L2 and seasonal enhancements of metals like arsenic and cadmium indicated possible localized contamination. These observations emphasize continuous monitoring, especially during the wet season when runoff may increase contamination. The study also highlights the necessity to regulate artisanal refining activities to prevent further environmental damages. In the long run, heavy metal contamination may pose a huge threat, and these can only be contained through continual monitoring and improvement of waste management methods, thereby protecting human health and ecological systems.

4. Conclusion

In conclusion, this study highlights both spatial and seasonal variations in heavy metal contamination in soils impacted by artisanal refining in Bayelsa State, Nigeria. While most heavy metals remained within safe regulatory limits, arsenic concentrations at site L2 exceeded the recommended threshold, indicating localized contamination. Seasonal fluctuations were significant, particularly for arsenic, cadmium, chromium, copper, and lead, with higher concentrations observed during the dry season, and copper and lead concentrations increasing during the wet season. These findings suggest that environmental factors, such as rainfall and runoff, influence the distribution and intensity of contamination. Although immediate health risks appear minimal, the potential for bioaccumulation and long-term ecological impacts, especially from arsenic and mercury, underscores the need for continuous monitoring. The study emphasizes the importance of regulating artisanal refining practices, implementing improved waste management strategies, and ensuring long-term environmental protection to safeguard public health and ecosystem stability.

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