



GROUNDWATER CONTAMINATION RISK ASSESSMENT: PAHS POLLUTION FROM CRUDE OIL LEACHING IN OGBIA, BAYELSA STATE

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ABSTRACT

Groundwater is the largest reservoir of drinkable water, accounting for approximately 22% of the world's freshwater. However, regular crude oil spills have resulted in severe groundwater contamination by Polycyclic Aromatic Hydrocarbons (PAHs), which harm human health and the environment. This investigated the presence and concentration of PAHs in groundwater in Ibelebiri in Ogbia, Bayelsa State, Nigeria, following an oil spill, to determine contamination pathways and potential consequences. Soil samples were taken from three locations (L_1 , L_2 , L_3) and three depths (topsoil, subsoil, and aquifer) and examined for PAHs such as Naphthalene, Acenaphthene, Fluorene, Pyrene, Anthracene, and Benzo(a)anthracene. Laboratory results found that Naphthalene had the highest concentration in all samples, particularly topsoil, whereas heavier PAHs such as Pyrene and Anthracene had lower quantities, notably in aquifer samples. The Leach Pollution Index (LPI) ranged from 81,199.25 to 83,374.10, indicating a high level of contamination potential. Statistical analysis using ANOVA revealed significant variation in the concentrations of lighter PAHs such as Naphthalene (P -value = 0.00059193) and Fluorene (P -value = 0.002376112) between soil layers, while heavier PAHs such as Pyrene (P -value = 0.969122843), Anthracene (P -value = 0.984906863), and Benzo(a)anthracene (P -value = 0.358155023) showed no significant differences across the samples. The findings underline the necessity for focused remediation measures to mitigate groundwater contamination while safeguarding public health and environmental quality.

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1.0 Introduction

Water is a basic necessity and is the most vital resource of survival for all God's creations so it must be made available as fresh, clean and pure water to keep people alive and healthy when consumed, meaning that fresh and clean water is a critical issue globally, as the population increases (Ijaola, et al., 2013; Oyinloye and Jegede, 2004; Sanda et al., 2022). The groundwater is the largest reservoir of drinkable water and due to the natural filtration, which is less contaminated as compared to surface water. Groundwater being a vital component of the global water cycle, accounting for approximately 22% of the world's freshwater resources (World Health Organization, 2018), it serves as a primary source of water for human consumption, agriculture, industry, and ecosystems, supporting human health, economic development, and environmental sustainability due to its long retention time and natural filtration capacity of aquifers. (National Research Council, 2015). However, groundwater quality is threatened by various contaminants which are both inorganic and organic. Some of the organic contaminants according to Ijaola and Sangodoying, (2020) are generated from the Petroleum and Pharmaceutical industries are seen among others as major contributors of organic contaminants because of continuous usage. The petroleum industrial effluents, namely the Produced water and crude oil spills, are the major sources of pollutants generated by the petroleum industry (Ijaola and Sangodoying, 2020; Ijaola and Sangodoying 2021). The crude oil spill generates an organic contaminant like Polycyclic Aromatic Hydrocarbons (PAHs), which pose significant risks to human health and the environment (Agency for Toxic Substances and Disease Registry, 2019) among many other contaminants. PAHs are a group of organic compounds consisting of two or more fused aromatic rings, formed during incomplete combustion of organic matter, such as fossil fuels, wood, and tobacco (Smith, 2020). (PAHs) are ubiquitous environmental pollutants

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that pose significant risks to human health and the ecosystem (WHO, 2019; Ijaola and Sangodoying, 2020; Ijaola and Sangodoying; 2021). PAHs can contaminate groundwater through various pathways, including industrial activities, agricultural runoff, and crude oil spills (Doe & Amadi, 2019). Among the myriad contaminants of concern, PAHs stand out as particularly nefarious due to their persistence, toxicity, and carcinogenic potential (Osuji *et al.*, 2015). Resistant to natural degradation, they readily accumulate in organisms, posing a significant threat to aquatic life and potentially entering the food chain, impacting human health indirectly (Ogwo *et al.*, 2019; Ijaola and Sangodoying, 2020). They are known to be carcinogenic, mutagenic, and teratogenic, causing harmful health effects, including cancer, reproductive issues, and developmental problems (World Health Organization, 2018, Boonpragob *et al.*, 2019; Ijaola and Sangodoying, 2020). Crude oil spillage, a common occurrence in oil-producing regions like Ogbia, Nigeria, can lead to PAHs contamination of groundwater (Osuji, 2015). Leached crude oil can migrate into groundwater, releasing PAHs and other toxic compounds (Adeniyi, 2018) which can infiltrate soil and aquifers, releasing PAHs into groundwater.

Nigeria, with its rich oil reserves, faces severe environmental challenges due to oil spillage (NNPC, 2020). The Niger Delta region, where Ogbia is located, has experienced frequent crude oil spills due to oil exploration and production activities (Nwankwoala *et al.*, 2017). This has resulted in widespread environmental degradation and health concerns including groundwater pollution (Amadi & Smith, 2017; Kumar, 2017). Frequent oil spills, a chronic issue plaguing the Niger Delta, originate from a multitude of sources including pipelines, storage facilities, and exploration activities. These spills unleash a toxic cocktail of contaminants, ranging from hydrocarbons and heavy metals to Polycyclic Aromatic Hydrocarbons (PAHs). The immediate damage is such serious that it affects both plants and animals. However, the true cost goes far beyond the initial impact, leaving a legacy of polluted soil and groundwater that jeopardizes the environment and its people's long-term well-being (Abdel-Shafy & Mansour, 2016). Polluted water does not impair people's health immediately, but it can be deadly over time. (Sanda *et al.*, 2022). Water pollution affects drinking water, rivers, lakes, and oceans all around the world, putting human health and the ecology at danger. (Gambhir *et al.*, 2012). Shallow water tables and permeable aquifers characterize the region's hydrogeology, increases the vulnerability of groundwater to contamination (Doe Amadi, 2019). Despite efforts to clean up oil spills, PAHs persist in the environment, posing long-term risks to human health and ecosystems (Agency for Toxic Substances and Disease Registry, 2019). PAHs persistence is in line with the scholars who have indicated that the recent problems in water treatment originate primarily from the increasing pollution of water by an organic compound that is difficult to decompose biologically because these substances resist the self-purification capabilities of the rivers as well as decomposition in conventional wastewater treatment plants (Ademiluyi *et al.*, 2009; Olafadehan and Aribike, 2000; Ogunlowo and Sakwe, 2023). Therefore, PAHs persistence with carcinogenic properties consequence has raised alarming concerns about the direct risks associated with long-term exposure through contaminated groundwater sources (Boonpragob *et al.*, 2019, Ogunlowo, 2022). While complete prevention remains the ultimate goal, in the face of existing spills, remediation efforts play a crucial role in mitigating the damage. A diverse range of techniques, from bioremediation to pump-and-treat methods, are employed to remove or contain spilled oil and its associated contaminants. However, the effectiveness of these interventions varies greatly depending on factors like the nature of the spill, environmental conditions, and implementation strategies (Osuji, 2015). Understanding their true impact on PAH leaching is critical for optimizing remediation strategies and safeguarding groundwater quality.

Previous studies have investigated PAHs contamination in soil and water like PAHs in the drinking water of counties along the Huai River in China which reveals PAHs associations with high cancer incidence (Enchun *et al.*, 2015), their epidemiological studies revealed that when professional are exposed to PAHs they are associated with many kinds of cancers (Eom, *et al.*, 2013, Mastrangelo *et al.*, 1996; Tsay *et al.*, 2013), and PAHs are listed as priority pollutants by the United States Environmental Protection Agency (US EPA) due to crude oil spillage in the Niger Delta region (Osuji, 2015; Nwankwoala *et al.*, 2017). Despite the risks, limited studies have investigated PAHs contamination in groundwater with leached crude oil in Ogbia, Nigeria. So, understanding the extent and impact of PAHs contamination in groundwater is crucial for developing effective mitigation strategies, protecting human health, and preserving environmental quality. This study will contribute to the existing body of knowledge on groundwater contamination by PAHs, providing valuable insights for policymakers, researchers, and stakeholders with the aims of assessing the pathways, the presence and concentration of leached Polycyclic Aromatic Hydrocarbons (PAHs), a contaminant from oil spills into the groundwater; the potential environmental and health impacts, with PAHs by comparing with USEPA standards and comparing the risk level of samples taking from polluted site with control using (a) statistical inferences such as ANOVA and Leached Pollution Index (LPI).

2. Materials and Methods

2.1 Study Area

The study was conducted in Ibelebiri, Bayelsa state. Ibelebiri is a small community located in Ogbia Local Government Area of Bayelsa State; between latitude $4^{\circ}55'51.457''\text{N}$ and Longitude $6^{\circ}24'54.80352''\text{E}$, Nigeria. Historically, the area is part of the larger Ijaw ethnic group, which is indigenous to the Niger Delta region. The community, like many others in Bayelsa, has a rich cultural heritage tied to fishing, farming, and trading, with a strong reliance on the natural environment for sustenance. Bayelsa State, created in 1996, was part of the old Rivers State before the restructuring. Ibelebiri has been significantly impacted by oil exploration, which began in the Niger Delta in the 1950s. This led to environmental challenges, including oil spills and pollution, affecting the local ecosystem and traditional livelihoods. Despite these challenges, Ibelebiri remains a close-knit community with deep cultural roots, actively involved in preserving its traditions and seeking sustainable development amidst the complexities of modern industrial activities.



Plate 1: Sub-Surface sampled area

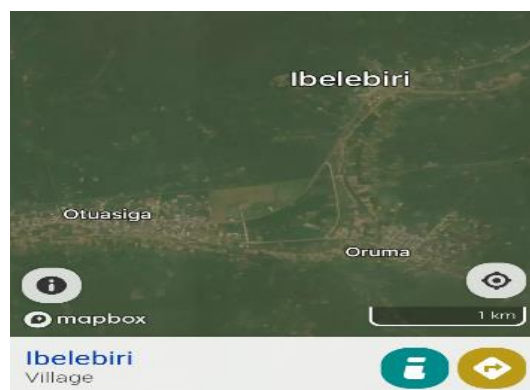


Plate 2: GPS Coordinate of Ibelebiri Twon



Plate 3: Crude Oil Spill Site

2.2 Sample collection

Within the research area, a network of three bore holes provided samples for collection. Using a hand shovel and a trowel, soil samples were taken from three locations surrounding the spill area. The first sample in the spill area, locations 1 and 2 were taken from the spill site across the river in the direction of latitude $4^{\circ}56' \text{N}$ and longitude $6^{\circ}25' \text{E}$. Latitude $4^{\circ}57' \text{N}$, longitude $6^{\circ}25' \text{E}$, in the direction of the second sample in the spill area. The control was taken within the residents of the community with the direction of latitude $4^{\circ}55' \text{N}$ and longitude $6^{\circ}25' \text{E}$. In order to comprehend the vertical distribution of contaminants, samples were obtained at three different depths. Three levels of soil were sampled at each location. The top soil, which was gathered at each location using a hand trowel. A second sample was obtained at each location at a depth of 0.3 meters through hand auger. The third sample was taken at 0.9 meters through hand auger in each location. Materials utilized in this research include: hand auger, shovel, trowel, polythene bag, amber bottles, personal protective equipment's, cooler and ice packs. 2g of sample was weighed into a clean extraction container. 20ml of extraction solvent (hexane) was added into the sample, mixed thoroughly and allowed to settle. The mixture was carefully filtered into solvent-rinsed extraction bottles using filter paper fitted into Buchner funnels. The extracts were concentrated to 2ml and then transferred for clean- up/separation

2.3 Laboratory Procedure for PAH Analysis

The laboratory procedure for Polycyclic Aromatic Hydrocarbon (PAH) analysis involves the extraction of PAHs from soil and water samples, followed by clean-up/separation, and finally gas chromatographic analysis to identify and quantify the PAH compounds, as previously described (Ijaola and Sangodoyin, 2020).

2.4 Statistical Analysis

To further determine the differences among the mean variation of tested contaminants by PAHs. The ANOVA analysis for each PAH was conducted to determine whether there were statistically significant differences between the concentrations of PAHs at different depths (S₁, S₂, and S₃) across locations. For most PAHs, significant variations were observed between locations but not always between soil layers, indicating that spatial variability is a more significant factor than depth.

2.5 Leach Pollution Index (LPI)

The LPI measures the possibility of leachate contamination in a specific area. It is a single number ranging from 5 to 100 (Simeon and Ayotamuno, 2022) that provides critical insight into the contamination potential of the soil to leach poisonous substances into groundwater. It is an increasing scale index; the higher value means a poor environmental condition, with a standard LPI value of 7.37 (Kumar and Alappat, 2003, Churchill and Ogunlowo, 2022). The Leach Pollution Index (LPI) is calculated using equation 1 and equation 2 as the LPI (leaching pollution index) using WHO's Standard values for groundwater quality.

$$LPI = \frac{\sum(wi \times pi)}{\sum wi} \tag{1}$$

where *W_i* is the weight assigned to *i*-th parameter

P_i is the sub-index for the *i*-th parameter, calculated as:

$$P_i = \frac{\text{observed value}}{\text{standard value}} \times 100 \tag{2}$$

The *W_i* should be Sum to 1.

3. Results and Discussion

3.1 Comparison of PAHs concentrations between sample Locations and Pathways

Table I: PAHs concentration between soil samples

Location	Naphthalene PPM	Acenaphthene PPM	Fluorene PPM	Pyrene PPM	Anthracene PPM	Benzo(a)anthracene PPM
L ₁ S ₁	1.265	0.0543	0.0368	0.041	0.0325	0.0027
L ₁ S ₂	1.245	0.0469	0.0376	0.026	0.071	0.0387
L ₁ S ₃	1.0502	0.0371	0.0048	0.0056	0.0037	0.0052
L ₂ S ₁	1.342	0.0288	0.0236	0.012	0.064	0.048
L ₂ S ₂	1.289	0.0385	0.0397	0.045	0.034	0.028
L ₂ S ₃	1.05	0.0382	0.005	0.0082	0.017	0.0074
L ₃ S ₁	1.258	0.0384	0.0397	0.024	0.062	0.061
L ₃ S ₂	1.267	0.0369	0.0397	0.034	0.045	0.055
L ₃ S ₃	1.056	0.0176	0.0065	0.0095	0.0068	0.0042

Note: L₁S₁ – Location A sample 1, L₁S₂ – Location A sample 2, L₁S₃ - Location A sample 3 L₂S₁ – Location B sample 1, L₂S₂ – Location B sample 2, L₂S₃- Location B sample 3, L₃S₁ – Location C sample 1, L₃S₂ – Location C sample 2, L₃S₃- Location C sample 3.: Where S₁= TOP SOIL, S₂ = SUB-SOIL, S₃= WATER. L₃= Control, L₁= first site of pollution, L₂= second site of pollution

In Table I and Figs (1-3), the concentrations of various PAHs, including Naphthalene, Acenaphthene, Fluorene, Pyrene, Anthracene, and Benzo(a)anthracene, measured in parts per million (PPM) is presented. Naphthalene consistently showed the highest concentrations across all samples, while Benzo(a)anthracene had the lowest concentrations. Naphthalene levels were highest in the topsoil at all locations, with Location 1 (L₁S₁) at 1.265 PPM and Location 2 (L₂S₁) at 1.342 PPM. These quantities indicate significant pollution, most likely owing to surface oil spills, whereas aquifer samples had the lowest Naphthalene concentrations, with L₁S₃ at 1.0502 PPM. Acenaphthene levels followed a similar trend, with the highest concentrations found in topsoil (L₁S₁: 0.0543 PPM) and a steady reduction from topsoil to an aquifer. Fluorene levels varied, with the subsoil in Location 2 having a higher concentration (0.0397 PPM) than the other strata, indicating a potential accumulating effect in this layer. The other PAHs, Pyrene, Anthracene, and Benzo(a)anthracene generally showed lower concentrations, though Pyrene and Benzo(a)anthracene were somewhat more prevalent in the subsoil. Overall, the data indicate that the topsoil is the most contaminated layer for PAHs, followed by the subsoil, with the aquifer displaying the least contamination. The data acquired from the study of PAH concentrations in soil samples gives useful information about the behavior of these pollutants in various soil

layers. PAH concentrations are higher in topsoil (S1) than in subsoil (S2) and aquifer (S3) layers, indicating that PAHs are more likely to accumulate near the surface due to limited vertical mobility. This can be attributed to the hydrophobic nature of PAHs, which often leads to their adsorption onto organic matter in the soil, particularly in the upper layers where organic content is higher, which agrees with (Patel et al.,2020)that found that the PAHs deposition is accelerated in the soil/sediments because of their higher hydrophobicity and low aqueous solubility, further, buttressed by the discovery of (Jesus et al., 2020) that PAHs tend to accumulate in the sediment due to higher hydrophobicity. This then account for the lower PAH concentrations in the aquifer layer indicate that PAH migration to groundwater may be limited, due to high filtration capacity of the soil, though some contamination is still present, which agrees with (Chen et al., 2022). Naphthalene, the lightest PAH analyzed in this study, showed consistently higher concentrations across all samples, particularly in the topsoil. This also shows that the lighter the contaminants the higher the mobility, it then reveled the lighter PAHs like Naphthalene leach more easily compared to heavier PAHs, explaining their greater prevalence in the samples.

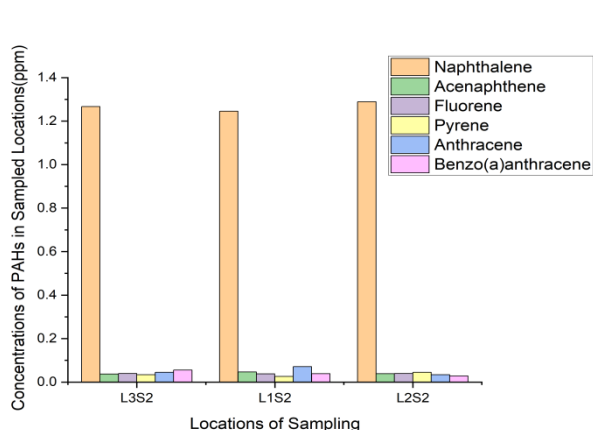


Figure 1: Comparison of PAHs Pollutant Between the Crude Oil Spills Polluted Area and Control at the Top-soil

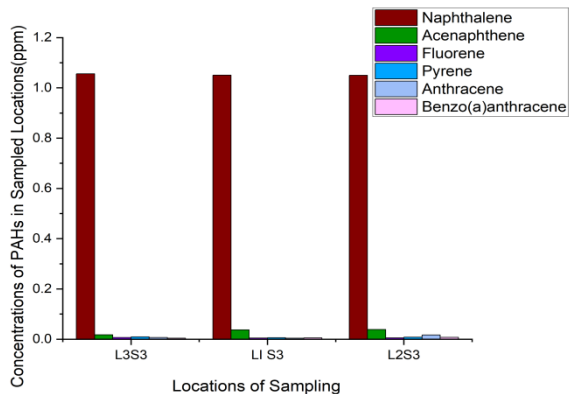


Figure 2: Comparison of PAHs Pollutant Between the Crude Oil Spills Polluted Area and Control at the Sub-soil

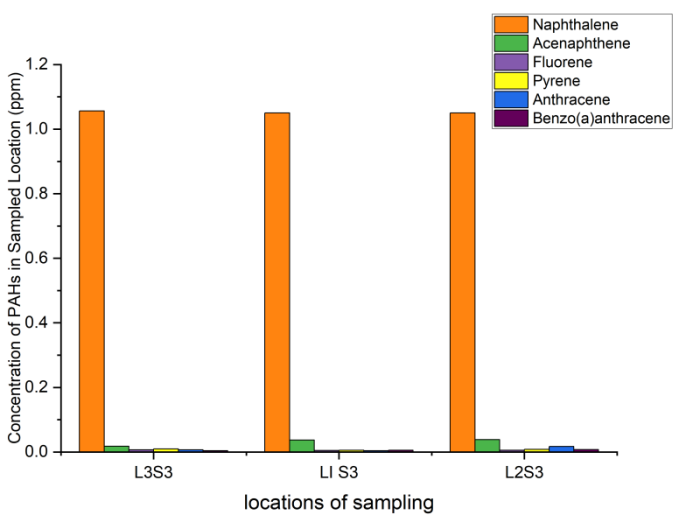


Figure 3: Comparison of PAHs Pollutant Between the Crude Oil Spills Polluted Area and Control at the aquifer

3.2 Comparison analysis of PAHs pathway within each sampled location with USEPA and Statistical Deductions

Table 2: Mean Values of PAHs concentration within each sampled Locations compared with USEPA Standard and Statistical inferences

Contaminants	L1	L2	L3	USEPA	P-value (soils)	P-value (water)
Naphthalene	1.187	1.227	1.194	0.0001	0.229335759	0.00059193
Acenaphthene	0.046	0.0352	0.031	0.0001	0.196707245	0.371481776
Fluorene	0.026	0.023	0.029	0.0002	0.427450803	0.002376112
Pyrene	0.024	0.022	0.023	0.0002	0.969122843	0.118947763
Anthracene	0.036	0.038	0.038	0.0002	0.984906863	0.080976903
Benzo(a)anthracene	0.016	0.028	0.040	0.0002	0.358155023	0.141269761

Table 2 shows the mean concentrations of each PAHs considered within the pathway of each location in comparison to United State Environmental Protection Agency (USEPA) guidelines for PAHs in groundwater. The monitored values were also compared using statistical inferences. From the table 2 all tested PAHs in comparison with standards revealed multiple acceptable limit violations, Naphthalene has the highest concentration levels of (1.187-1.227) ppm when compared to the others PAHs compounds indicating potential petroleum-related contamination. Acenaphthene, Fluorene, and Pyrene have relatively low concentration levels ranging from (0.046-0.031,0.029-0.023 and 0.022-0.024) ppm respectively suggesting minimal impact from these compounds, while Anthracene and Benzo(a)anthracene show varying concentration levels across sampling locations, indicating potential multiple contamination sources.

The ANOVA results in table 2 (P-value = 0.229335759, P-value > 0.05) confirm that significant differences exist in Naphthalene concentrations between soil layers, with topsoil samples exhibiting the highest levels. For heavier PAHs such as Pyrene, Anthracene, and Benzo(a)anthracene, the concentrations were much lower across all samples, particularly in the aquifer layers. These PAHs have lower solubility and higher affinity for adsorption onto soil particles, which explains their limited vertical migration. The relatively low concentrations of these compounds in the subsoil and aquifer indicate that they pose less risk of groundwater contamination compared to lighter PAHs like Naphthalene. Also, the ANOVA results for these compounds; Pyrene (P-value = 0.969122843 which is >0.05), Anthracene (P-value = 0.984906863 which is >0.05), and Benzo(a)anthracene (P-value = 0.358155023 which is > 0.05) showed a significant difference (P-value ≥ 0.05) between the samples, though their concentration indicating consistent low levels in water samples but higher values across the different soils layers as indicated in Table 2. Fluorene concentrations varied between samples, with the subsoil showing particularly high levels in Location 2, the ANOVA results for Fluorene (P-value = 0.002376112 which is < 0.05) indicated significant differences between the samples, suggesting that Fluorene concentrations vary notably across soil layers. The highest concentrations of Acenaphthene were again found in the topsoil. However, the ANOVA results indicated no significant differences between samples (P-value = 0.371481776, P-value ≥ 0.05), suggesting that while Acenaphthene levels are elevated, the variation between layers is not statistically significant. The ANOVA analysis indicated significant differences in contamination levels for several PAHs across different locations, suggesting notable spatial variability in contamination. This finding means; the sources of contamination may be localized, with certain areas experiencing higher concentrations of specific PAHs. In contrast, the differences between soil layers were less pronounced for most PAHs, indicating that the depth of soil has a limited impact on the variation in PAH concentrations. This suggests that while the topsoil is generally more contaminated, other factors, such as local environmental conditions or historical contamination events, may play a more significant role in influencing PAH levels than soil depth alone.

3.3 Leach Pollution Index and Contamination Assessment

The Leach Pollution Index (LPI) provides critical insight into the contamination potential of the soil to leach hazardous substances into groundwater. The LPI values of the samples for the three locations ranged from 81,199.25 to 83,374.10 as shown in Table 3, with the highest value at Location 1 and the lowest in Location 3. This index reflects the potential risk of PAH contaminants being leached from the soil into the aquifer and eventually affecting groundwater quality. This was achieved using the USEPA standard values for groundwater quality.

Table 3: Leach pollution index

Location	Leach Pollution Index (LPI)
A	83374.10
B	81460.87
C (Control)	81199.25

To evaluate the significance of these LPI values, it is essential to compare them to standard threshold values established for soil contamination assessments. According to environmental standards, the acceptable LPI threshold for hazardous leachates is 7,500. Any value above this indicates a potential risk for contaminant migration into groundwater sources (Ogbozor *et al.*, 2015). In this study, all recorded LPI values significantly exceed the standard threshold, with the lowest being 81,199.25 and the highest reaching 83,374.10. These values are higher than the standard, implying a severe contamination risk across all locations. The high LPI values suggest that the soil in the studied locations, particularly the topsoil and subsoil, has a high potential for contaminant migration, primarily driven by the presence of PAHs. This poses a significant risk of groundwater pollution, especially in areas where crude oil spills have heavily impacted the environment. The highest LPI value at Location 1 (83,374.10) suggests that this area has the greatest leaching potential, likely because of higher concentrations of PAHs in the topsoil and subsoil that may be as a result to closer proximity to the spill site or other factors such as soil type and permeability. Conversely, while Location 3 has the lowest LPI (81,199.25), it still presents a considerable risk as the value remains far above the standard threshold.

3.4 Implications for Groundwater Quality

The presence of PAHs in aquifer samples, even at lower amounts than in topsoil, raises concerns about groundwater quality. While the data demonstrate limited vertical migration, the presence of PAHs in groundwater samples suggests that there is still a possibility of PAH contamination in drinking water sources, which will definitely have negative effect on human health over time when consumed. This emphasizes the need for ongoing monitoring, and possibly remediation activities to prevent future contamination.

4. Conclusion

This study found considerable contamination by Polycyclic Aromatic Hydrocarbons (PAHs) in the topsoil (S1) and moderate in the subsoil (S2) and aquifer layers (S3). Naphthalene had the highest quantities, indicating mobility, whereas heavier PAHs such as pyrene and anthracene had lower concentrations due to their low solubility and stronger affinity for soil. The Leach Pollution Index confirmed significant pollution in all areas. Despite the comparatively low PAH concentrations in groundwater, there is a current concern that warrants additional investigation.

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References

- Ademiluyi FT., Amadi SA. And Amakama NJ. 2009. Adsorption and treatment of organic contaminants using activated carbon from Waste Nigerian Bamboo. *Journal Application Science Environment Management*.13(3):39-47
- Adeniyi, AA. 2018. Heavy metal contamination of groundwater due to crude oil spillage. *Journal of Environmental Science and Health*, 53(1): 42-53.
- Agency for Toxic Substances and Disease Registry (ATSDR). (2019). Toxicological Profile for Polycyclic Aromatic Hydrocarbons (PAHs). U.S. Department of Health and Human Services.
- Amadi, E. and Smith, J. 2017. Leaching of PAHs from Crude Oil into Groundwater in the Region. *Environmental Monitoring and Assessment*, 191(10): 1-15.
- ATSDR 2020. Toxicological Profile for Polycyclic Aromatic Hydrocarbons (PAHs). Agency for Toxic Substances and Disease Registry.

Chen , L., Zhang, Z., Ying, Z., Wang, X., Wang L., Junwu, X., Qian, Z., Xiong, S., Ruichao Zhao, Wei-LiuQiuke, Zhou, J., Hong, Z. and Kevin, C. 2022. Jones Distribution, sources and transport of polycyclic aromatic hydrocarbons (PAHs) in karst spring systems from Western Hubei, Central China, [Chemosphere](#), **300**: 134502

Churchill ES. and Ogunlowo OO., 2022. Assessment of Leachate Pollution Potential of Unlined Landfill Using Leachate Pollution Index (LPI), Nigeria. *Engineering and Technology*, **3(2)**: 67-76

Doe, J. and Amadi, E. 2019. Assessment of PAHs in Soil and Groundwater in the Niger Delta Region. *Environmental Monitoring and Assessment*, **191(10)**: 1-15.

En chun P., Hong S., Qiu JX., Zhang Q. Lin fei L., Xiao dong C. and Yan X. 2015. Polycyclic Aromatic Hydrocarbons Concentrations in Drinking Water in Villages along the Huai River in China and Their Association with High Cancer Incidence in Local Population, *BioMed Research International* **1:10**

Eom, SY., Yim, D. and Moon SI. 2013. Polycyclic aromatic hydrocarbon-induced oxidative stress, antioxidant capacity, and the risk of lung cancer: a pilot nested case-control study. *Anticancer Research*, **33 (8)**: 3089–3097.

Gambhir, RS., Kapoor, V., Nirola, A., Sohi, R. and Bansal, V. 2012. Water Pollution: Impact of Pollutants and New Promising Techniques in Purification Process. *Journal of Human Ecology*, **37(2)**: 103–109.

Ijaola OO., Sangodoyin, AY. 2021. Remediation of emerging pollutants in industrial contaminated water using *Oxytenanthera abyssinica* and *Bambusa vulgaris* in a treatment media. *IOP Conference Series: Materials Science and Engineering*.036(01).

Ijaola OO., Ogedengbe, K., Sangodoyin AY. 2013. On the efficacy of activated carbon derived from bamboo in the adsorption of water contaminants. *International Journal of Engineering Inventions*. **2(4)**: 29-34

Ijaola, OO. and Sangodoyin, AY. 2020. Determination and Remediation of Selected Polycyclic Aromatic Hydrocarbons in Petroleum Contaminated Water. *J. Appl. Sci. Environ. Manage.* **24 (3)** 459- 465.

Jesus, F., Joana, LP., Isabel, C., Martha, S., Ana, R., Keizer, J., António, N., Fernando JM., Nelson, A., and Serpa D. 2022. A review on polycyclic aromatic hydrocarbons distribution in freshwater ecosystems and their toxicity to benthic fauna, [Science of The Total Environment](#), **820**:153282

Kumar, P. 2017. Groundwater quality assessment using physiochemical parameters. *Journal of Water Resources and Hydraulic Engineering*, **6(2)**: 123-133.

Mastrangelo, G., Fadda, E. and Marzia, V. 1996. Polycyclic aromatic hydrocarbons and cancer in man,” *Environmental Health Perspectives*, **104(11)**:1166–1170.

National Research Council 2015. Petroleum in the Marine Environment. National Niger Delta Region. *Journal of Petroleum Science and Engineering*, **157**: 1-9.

Nwankwoala, HO., Udom., GT., Ugwu SA 2017. Physiochemical characterization of groundwater in oil-producing areas. *Journal of Environmental Science and Health, Part B*, **52(4)**: 236-246.

Ogbonnaya, U.O., Oyelami, A.O., Umego, M.O., Okere, U.V., David,O.A., Fasina, S.A., Semple, K.T., Assessment of PAH contaminated land: Implementing a risk-based approach. *Environmental Technology & Innovation* (2017), <http://dx.doi.org/10.1016/j.eti.2017.06.001>

Ogunlowo, OO. 2022. Adsorption Technique Alternative Treatment for Polycyclic Aromatic Hydrocarbon (PAHs) and Pharmaceutical Active Compounds (PhACs) Book Chapter in Book title: Wastewater Treatment ISBN 978-1-80355-847-9.Publisher: Intechopen, London <http://www.intechopen.com/book/wastewater-treatment>.

Ogunlowo, OO. and Sakwe, A. 2023. Evaluation of Lead and Iron Content in Different Stages of Water Treatment Facilities within Otuoke and Yenagoa Metropolis, Bayelsa State, Nigeria. *Journal of Applied Sciences and Environmental Management* **27(11)**: 2415-2420.

Olafadehan OA. and Aribike DS. 2000. Treatment of industrial wastewater effluent. Journal of Nigerian Society of Chemical Engineers. 19:50-53

Oluwadare, AD., Sunday AF. and Kirk TS. 2017. Assessment of PAH contaminated land: Implementing a risk-based approach. *Environmental Technology & Innovation*. Volume 8, 84-95

Opololaoluwa, OI. and Abimbola, YS. (2020). Adsorption Mechanism of Paracetamol, Salbutamol, Chlorpheniramine Maleate onto Locally Produced Nigeria Bamboo Activated Carbon. *Science & Technology*, 2020, 6(22): 93-106

Osuji, LC. 2015. Environmental pollution by crude oil. *Journal of Environmental Science and Health, Part B*, 50(6), 419-428.

Patel, AB., Shaikh, S., Jain, KR., Desai, C. and Madamwar, D. 2020. Polycyclic Aromatic Hydrocarbons: Sources, Toxicity, and Remediation Approaches. *Front Microbiol.* 5(11): 562813

Sanda, BY., Bah, AU. and Ibrahim, A. 2022. Involvement of the General Public in the Management of Water Pollution in Johor Bahru Malaysia. *Arid Zone Journal of Engineering, Technology and Environment* 18(1):79-96.

Smith, J. 2020. Groundwater Contamination by Polycyclic Aromatic Hydrocarbons (PAHs): A Review. *Journal of Environmental Science and Health*, 55: 1-12.

Tsay, JJ., Tchou-Wong, KM., Greenberg, AK. Pass, H. and Rom, WN. 2013. Aryl hydrocarbon receptor and lung cancer, *Anticancer Research*, 33(4): 1247–1256.

World Health Organization 2022. Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Geneva: World Health Organization. World Health Organization. Guidelines for drinking-water quality.

World Health Organization 2018 Guidelines on sanitation and health. Geneva, World Health Organization (<https://www.who.int/publications/i/item/9789241514705>). World Health Organization 2018. Guidelines for Drinking-water Quality: 4th Edition.