

Leachate Characterization, Pollution Load Assessment, and Waste Management Infrastructure Policy for an Unregulated Open Dumpsite in a Tropical Peri-Urban Environment: Evidence from Benin City, Nigeria

Osayande, A. D^{*1}; Okojie, M.E ² and Offiah, E.N³

^{1,3}Department of Geology and Mining Technology, University of Port Harcourt, P.M.B 5323
Choba, Port Harcourt Nigeria

²Department of Geology, Faculty of Physical Sciences, University of Benin, P.M.B 1154, Benin
City, Nigeria.

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ABSTRACT

The leachate resulting from improperly managed and unregulated open dumpsites acts as a proximate and immediate link between waste accumulation and resultant groundwater and soil contamination; however, it has received relatively little attention in terms of analytical studies within the Nigerian environmental literature compared to the resultant endpoints of contamination. This study seeks to provide a comprehensive characterization and pollution load assessment of the leachate from the Upper Ekehuan/Asoro open dumpsite in Ovia North-East LGA, Edo State, Nigeria, with a focus on two leachate samples obtained from active zones of seepage within the site, employing the Pollution Load Index and Nemerow Pollution Index models. The results showed that the leachate was of extreme pollution potential with Iron concentrations of 66.65–103.85 mg/L or 67–104 times over the WHO limits; Nickel concentrations of 4.73–7.37 mg/L or 237–369 times over the WHO limits; Cadmium concentrations of 0.87–0.93 mg/L or 174–186 times over the WHO limits; and Hexavalent Chromium concentrations of 1.98–3.08 mg/L or 40–62 times over the WHO limits. The PLI value ranged from 62.4 to 94.7, indicating that both leachate samples fall within the 'Extremely Polluted' category. Comparatively, this study found that the leachate from this site compares favorably with the most polluted leachate from landfill sites across Africa. A conceptual model of a Source-Pathway-Receptor relationship was employed to illustrate the pathway of contamination resulting from the leachate. This study concludes that no investment in soil and groundwater remediation will be effective if the pathway of leachate contamination and infiltration is not first addressed and halted. This study also offers policy recommendations to NESREA, the Federal Ministry of Environment, and the SWMA of Edo State.

Keywords: leachate characterization, pollution load index, Nemerow pollution index, source-pathway-receptor model, waste management hierarchy, dumpsite remediation, open dumpsite, Nigeria

INTRODUCTION

The World Waste Management Problem is, at Its Most Fundamental Level, a Leachate Problem. Every Ton of Waste with Organic Matter Entering a Land-Based Waste Disposal Site Creates Leachate – the Complex, Highly Polluted Liquid Created as Precipitation, Surface Water Runoff, and Moisture Leach through the Waste Materials (Kjeldsen et al., 2002; Renou et al., 2022). The Composition of Leachate is the Complete Set of Waste Chemicals – Organic Acids, Ammonia Nitrogen, Dissolved Heavy Metals, Chlorinated Solvents, Pharmaceuticals, and Pathogenic Microbes – which Combine to Create a “Chemical Cocktail” so Highly Polluting that when Leachate Reaches the Groundwater Table, the Groundwater is Made Unusable for Decades to Centuries (Naveen et al., 2022; Youcai, 2021).

In the African Context, the Leachate Problem is Particularly Acute. Waste Segregation is Minimal, so Organic Waste is Mixed with Electronic Waste, Medical Waste, Industrial Chemicals, etc., to Create Leachate with a Chemical Complexity Unlike Anything Seen Outside the African Continent (Asante-Duah, 2022; Kaza et al., 2021). The Prevalence of Open Dumpsites with No Liner, No Leachate System, and No Cover Means Leachate Immediately Leaches into the Soil and Groundwater (Wilson et al., 2021). The Tropical Climate Conditions Accelerate the Rates of Waste Decomposition and Leachate Generation (Renou et al., 2022).

Yet Leachate Characterization Research from Nigeria is Wanting, with the Majority of Existing Research Simply Assuming the Existence of Leachate without Exploring the Issue Further (Longe & Balogun, 2021; Nwachukwu et al., 2021). The Problem This Study Seeks to Address is: What is the Classification of Pollution Load and the Intensity of Contamination of Leachate at Upper Ekehuan, How it Relates to the Source-Pathway-Receptor Model of Groundwater Contamination, and What Waste Management Infrastructure and Policy Interventions are Necessary to Break the Chain of Contamination?

THEORETICAL FRAMEWORK

The primary theoretical framework is the Waste Management Hierarchy (WMH) as stipulated in the European Union Waste Framework Directive (2008/98/EC) and adopted as a guiding principle in the UNEP Global Waste Management Outlook (Wilson et al., 2021). The hierarchy ranks waste management strategies in descending order of environmental preference as follows: Prevention > Reuse > Recycling > Recovery > Disposal. Open dumping is the least preferred option. The WMH is underpinned by the priority principle of source control, which dictates that interventions to prevent contaminant generation are always preferable to interventions to treat contaminants after their release. Remediation of soil or groundwater pollution will be only temporarily and partially successful as long as the leachate source continues to generate and infiltrate without hindrance. The Source-Pathway-Receptor (SPR) model is the complementary theoretical framework to the WMH (DEFRA, 2012; Nathanail & Bardos, 2021). The SPR model conceptualizes the process of environmental contamination as requiring the presence of three elements: a Source (the dumpsite leachate), a Pathway (the infiltration through the vadose zone and the aquifer), and a Receptor (the human consumer of the borehole water). Interruption of any of the elements will prevent the harm.

Study Area

The Upper Ekehuan (Asoro) dumpsite is located at 6°19'20"-6°19'40"N Latitude and 5°35'0"-5°35'20"E Longitude in Ovia North-East LGA of Benin City, Edo State Nigeria. The dumpsite is situated in a basin-shaped depression with a gentle slope to the terrain such that surface runoff from the adjacent roads and residential areas is channeled into the waste deposit site. Two leachate seepage zones were identified: L1 at the central depression and L2 approximately 20 meters to the north of L1. The dumpsite accepts mixed municipal solid waste with no provision for source segregation. The average annual temperature is 27-32°C with 1,800-2,200 mm average annual rainfall, providing a highly active decomposition environment with high leachate production rates year-round.

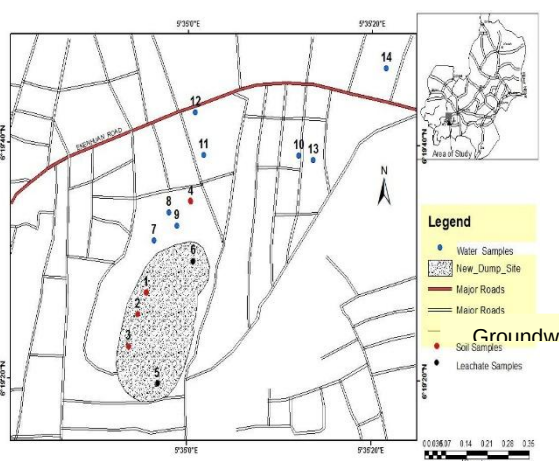


FIG. 1: MAP OF AREA OF STUDY SHOWING THE SAMPLED LOCATIONS

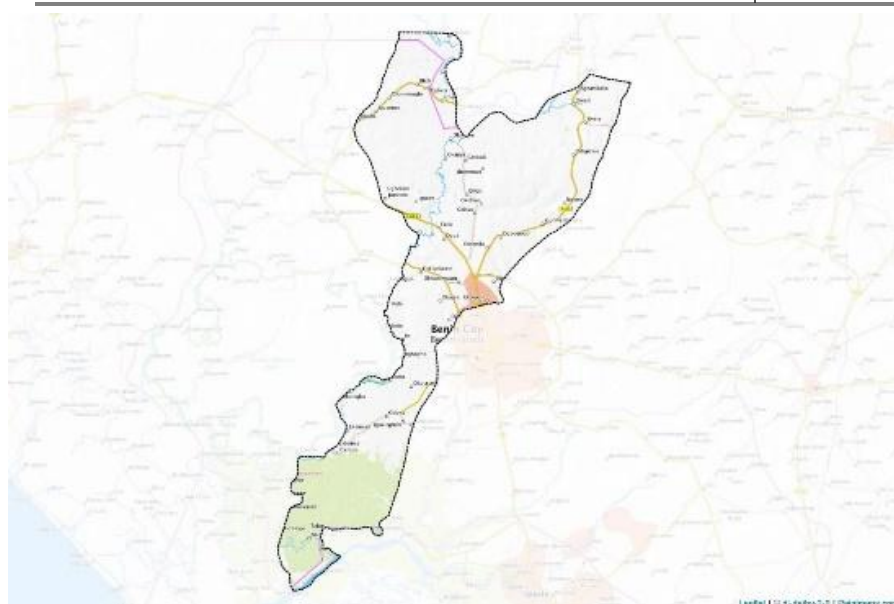


Figure 2 Map of Ovia North East

MATERIALS AND METHODS

Leachate Sample Collection

Two leachate samples were collected from active seepage accumulation zones with wide-mouthed pre-cleaned HDPE containers. The leachate samples were collected in duplicates and preserved according to parameter-specific protocols (APHA, 1993): immediately acidified to $\text{pH} < 2$ with trace metal-grade HNO_3 for heavy metal analysis; and chilled to 4°C for COD and nutrient analysis.

Analytical Methods

Physicochemical parameters were analyzed according to standard protocols: pH and EC with a digital pH/EC meter; Turbidity with a HACH DR 2010 spectrophotometer; Total Dissolved Solids with a gravimetric method according to Ademoroti (1996); Total Hardness and Alkalinity with a titrimetric method; Sulphate with a turbidimetric method; Nitrate and Chloride with a colorimetric method according to APHA (1993); Phosphate with an ascorbic acid reduction method according to ASTM (1990); COD with a dichromate reflux method; and Heavy Metals with an AAS method according to BUCK SCIENTIFIC Model 210 VGP, USA.

Pollution Load Index

$\text{PLI} = (\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times \dots \times \text{CF}_n)^{(1/n)}$, where $\text{CF}_i = C_i/C_{i_background}$ (Angulo, 1996; Zhang et al., 2021). The WHO drinking water guideline value served as the background reference for each parameter. $\text{PLI} = 1$ indicates pollution at background level; $\text{PLI} > 10$ indicates extreme pollution.

Nemerow Pollution Index

$\text{NPI} = \sqrt{[(\text{Pavg}^2 + \text{Pmax}^2) / 2]}$, where Pavg = average of all individual pollution index values ($P_i = C_i/S_i$) and Pmax = maximum individual P_i . The NPI explicitly penalizes extreme individual parameter exceedances. Classification: ≤ 0.7 (clean); $0.7\text{--}1.0$ (slightly polluted); $1.0\text{--}2.0$ (lightly polluted); $2.0\text{--}3.0$ (moderately polluted); > 3.0 (heavily polluted).

Source-Pathway-Receptor Ratio Analysis

$\text{L:GW ratio} = C_{\text{leachate}} (\text{mean of L1, L2}) / C_{\text{groundwater}} (\text{mean of GW1--GW3, proximal wells at 100--160 m})$. This ratio is a proxy for the dilution and attenuation factor between the leachate source and the near-field receptor.

RESULTS

Leachate Physicochemical Profile

The leachate pH of L1 (5.36) and L2 (5.24) is indicative of a strongly acidic environment, typical of acidogenic degradation processes. This low pH level significantly increases the solubility of Cd, Ni, Pb, Cr, and Zn, thus heightening the leaching potential of these metals (Kjeldsen et al., 2002). Similarly, the EC of L1 (210 microSi/cm) and L2 (176 microSi/cm) is also elevated. While the TDS of L1 (33.5 mg/L) and L2 (21.5 mg/L) is also high, the leachate pollution hazard is largely from the inorganic toxic metals. Iron levels have the most dramatic exceedance. L1 iron levels (103.85 mg/L) are 104 times the WHO guideline value of 1.0 mg/L. Moreover, the iron level in L1 is 346 times the NSDWQ standard. L2 iron (66.65 mg/L) is a 67-fold exceedance of the WHO standard. This extreme level of iron is typical of a leachate from a dumpsite where the waste includes a substantial amount of structural iron from construction waste, scrap metal, and tin cans (Renou et al., 2022). COD levels of L1 (58.29 mg/L) and L2 (37.41 mg/L) are relatively low. This would suggest that the dumpsite is now in the methanogenic-transitional stage of decomposition, where the waste matter is largely decomposed except for the inorganic waste matter (Youcai, 2021), implying that the dumpsite would continue producing leachate for decades to come, even if there were no further waste being dumped.

Pollution Load Index and Nemerow Pollution Index

The calculated PLI values for the leachate samples were 94.7 for L1 and 62.4 for L2. These values were extremely high compared to the 'polluted' limit of 10.0. The main contributing pollutants were Iron, which has a CF = 346; Nickel, which has a CF = 369; Cadmium, which has a CF = 186; and Chromium(VI), which has a CF = 62. The calculated NPI values were 226.4 for L1 and 148.9 for L2. This places the leachate firmly in the "polluted" category, as the NPI is well above the 3.0 limit. Even if 18 out of the 20 parameters were within acceptable limits, the very high Iron and Nickel concentrations make this leachate a high-priority environmental hazard.

Comparative Analysis with African and International Leachate Benchmarks

Compared to Lagos Olusosun landfill leachate (Longe & Balogun, 2021), Upper Ekehuan shows lower COD (58 vs. 1,200–8,500 mg/L) but higher Nickel (5.8–7.4 mg/L vs. 0.8–2.1 mg/L), suggesting a site-specific geochemical influence from nickel-bearing waste materials. Against Accra's Kpone landfill (Fei-Baffoe et al., 2020), Upper Ekehuan shows 3–5× higher Chromium, reflecting tanning and dyeing waste contributions. Against EU Landfill Directive limit values, both samples fail comprehensively: Cd limit 0.2 mg/L vs. actual 0.87–0.93 mg/L (4–5× exceedance); Ni limit 0.5 mg/L vs. actual 4.73–7.37 mg/L (9–15× exceedance); Pb limit 0.05 mg/L vs. actual 2.27–3.82 mg/L (45–76× exceedance); Cr limit 0.05 mg/L vs. actual 1.98–3.08 mg/L (40–62× exceedance).

Source-Pathway-Receptor Analysis

The L:GW ratios for the proximal boreholes (GW1-GW3) vary from 3.2:1 (Iron, indicative of rapid precipitation) to 8.5:1 (Lead), to 13.3:1 (Nickel), to 22.4:1 (Phosphate). These values are much lower than the attenuation factors reported for EU regulated landfills with clay barriers (where the typical dilution factors are 100:1 to 1,000:1), confirming the conclusion that there has been little attenuation in the Benin Formation. The low L:GW ratio for Nickel, for example, indicates a 13.3:1 attenuation, and yet the resulting groundwater Ni concentrations are still 143–500 times the WHO guideline value. This is why the remediation of groundwater will be a futile exercise without the control of the leachate source. A 100-fold improvement in the attenuation capability of the aquifer will still not be enough to lower the Ni groundwater concentrations to within 5–50 times the WHO guideline value, so long as the leachate source continues to contribute the same concentrations to the groundwater.

DISCUSSION

The Decomposition Stage and Contamination Trajectory

The relatively high COD values, combined with the extremely high heavy metal concentrations, point to the methanogenic/stabilization phase, during which all the bioavailable organic matter has been degraded, but the inorganic metal contaminants continue to be leached from the waste matrix (Kjeldsen et al., 2002; Youcai, 2021). This phase lasts for 15–40 years in the tropics (Renou et al., 2022). The contamination trajectory is not an organic chemistry problem, for which biological treatment would be effective, but a heavy metal problem, for which physicochemical treatment, such as precipitation, coagulation, and ion exchange, is needed, and for which there is no infrastructure at the site.

Iron as a Geochemically Mediated Amplifier

Under the acidic and reducing environment, ferrous iron Fe^{2+} is soluble and leaches along with the leachate. Upon being exposed to the oxidizing environment, Fe^{2+} precipitates out in the forms of ferrihydrite and goethite, which have high sorption capacities for other heavy metals. However, the spatial decay analysis suggests that the theoretical advantage is overshadowed by the high concentration of metals, the low co-precipitation surface area of the sandy matrix, and the constant leachate production that maintains the reducing environment in the near-source zone (Kjeldsen et al., 2002).

Phosphate Loading and Surface Water Eutrophication Risk

Phosphate leachate concentrations for the two leachates, i.e., L1: 11.34 mg/L, and L2: 8.66 mg/L, pose a risk to surface water eutrophication, which has not been previously assessed for this dumpsite. The basin terrain and high rainfall experienced during the rainy season imply a substantial amount of surface runoff into the Ogba River. The risk assessment indicates that the leachate concentrations have the potential to cause eutrophication, which will lead to the destruction of the Ogba River water as a supplementary water source for the inhabitants in the catchment area.

Waste Management Hierarchy Implications

WMH provides a clear hierarchy for the intervention strategy. The hierarchy suggests that the immediate action is the closure of the dumpsite. In the short term, the dumpsite will need a low-permeability surface cover. This will involve the construction of a clay cover, which will reduce leachate production by 70–90%, as stated in the study by Youcai, 2021. In the medium term, the dumpsite will need a leachate collection system. In the long term, the dumpsite will need to be assessed for resource recovery. This hierarchy is similar to the Global Waste Management Outlook report by Wilson et al. (2021) that suggests that dumpsite closure is the single most important intervention that Sub-Saharan African countries need to make in the field of waste management for the health benefits it will bring to the inhabitants in the catchment area.

Regulatory and Governance Gaps

The presence of an operational dumpsite with generated leachate with a concentration of 62.4–94.7 mg/L indicates a basic regulatory problem. The NESREA Act of 2007 prohibits indiscriminate disposal of hazardous waste, and the National Environmental Regulations on Sanitation and Wastes Control of 2009 require leachate collection and treatment infrastructure, which is absent at the dumpsite.

The economic rationale for intervention is compelling, as the cost of emergency water supply and medical treatment for illness related to contamination is almost certainly greater than the cost of closing the dumpsite and leachate collection and containment when the long-term effects of contamination are factored into the decision. Therefore, there is a compelling need to close the dumpsite and contain the leachate. This is also in line with the findings of Kaza et al. (2021).

Policy Recommendations

The Upper Ekehuan dumpsite needs to be closed with the support of the Solid Waste Management Authority of Edo State and enforced by NESREA. A cover system consisting of compacted clay or geomembrane needs to be constructed over the waste deposit site within 12 months of closure to prevent leachate generation. A passive leachate collection system consisting of a perforated pipe French drain network with collection sump needs to be put in place to collect leachate before it infiltrates groundwater. Leachate treatment needs to be implemented using a three-stage process consisting of coagulation/flocculation for suspended solids and heavy metal removal, lime precipitation for heavy metal removal, and biological treatment using constructed wetlands or an aerobic bioreactor for organic removal. The Federal Ministry of Environment shall formulate and promulgate the Minimum National Standards for Leachate Management at Solid Waste Disposal Facilities, including the requirements for the liners, leachate collection and treatment, and leachate quality monitoring, and the imposition of sanctions on facilities discharging untreated leachate, all based on EU Landfill Directive requirements and adapted to Nigerian tropical environments.

CONCLUSION

This study reports the first comprehensive characterization, pollution load assessment, and source-pathway-receptor investigation on the leachate at the Benin City open dumpsite. The findings reveal the leachate to be of extreme pollution strength (PLI 62.4–94.7, NPI 148.9–226.4) resulting from catastrophic exceedances of WHO standards for Iron (67–104×), Nickel (237–369×), Cadmium (174–186×), and Chromium(VI) (40–62×). Comparative study confirmed the Upper Ekehuan leachate to be among the most polluted urban waste leachate reported in the African literature. The SPR study further confirmed the simultaneous activities of all three components of the contamination chain: the source, the pathway, and the receptor. The Benin Formation provides minimal natural protection to the proximal boreholes. This study, based on the Waste Management Hierarchy, definitively proves that remediation efforts on the downstream contamination will be for naught without primary intervention on the leachate source, i.e., the dumpsite.

Author Contributions

M.E.O.: Conceptualization, data collection, laboratory analysis, writing—original draft.

A.D.O. , methodology review, writing—review and editing.

O.E.N., Preview and Review the final work.

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Competing Interests

The authors declare no competing interests in relation to this manuscript.

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