**Communication in Physical Sciences, 2024, 12(4): 1237-1258**

# Environmental Implications of Quarrying and Waste Management: A Case Study of Okhoro, Benin City

**Vincent Oseikhuemen Binitie and Joseph Odion Odia-Oseghale**

**Received: 12 January 2025/Accepted: 02 March 2025/Published: 14 March 2025**

**Doi: https://dx.doi.org/10.4314/cps.v12i4.8**

***Abstract:*** *This study assessed the physicochemical characteristics and heavy metal contamination of water sources impacted by a nearby dumpsite, with the aim of evaluating potential environmental and public health risks. A total of 12 samples were collected from leachate (LS), river water (WS), boreholes (BH), and profile pits (PP). Parameters analyzed included pH, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate ($NO_3^-$), phosphorus (P), and heavy metals such as iron (Fe), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr). The pH values ranged from 6.4 to 7.4, falling within WHO limits (6.5–8.5), but the EC and TDS exceeded permissible limits in most leachate and some river samples, with maximum EC and TDS values reaching 1846 µS/cm and 1200 mg/L, respectively. BOD and COD values were significantly elevated in leachate samples (up to 10.5 mg/L and 341.44 mg/L, respectively), indicating heavy organic pollution. Ammonia concentrations in leachate peaked at 12 mg/L, far exceeding the WHO limit of 0.5 mg/L, while nitrate concentrations reached 1.31 mg/L. Heavy metals such as Pb exceeded the FEPA limit of 0.05 mg/L in all samples, with the highest concentration observed in WS03 (0.145 mg/L). Iron was highest in WS04 (1.36 mg/L), also exceeding the FEPA threshold of 0.3 mg/L.Statistical analysis included Pearson correlation, which showed strong positive correlations between EC and TDS ($r = 0.97$), COD and BOD ($r = 0.89$), and Fe and Pb ($r = 0.76$), suggesting common pollution sources. One-way ANOVA revealed significant differences ($p < 0.05$) in BOD, COD, and heavy metals across the different sampling locations. Principal Component Analysis (PCA) extracted three principal components explaining 85.4% of total variance, highlighting organic load, salinity, and metal pollution as key factors. Hierarchical Cluster Analysis (HCA) grouped the sampling sites into three clusters, distinguishing highly contaminated leachate zones from moderately impacted river and borehole locations. Water Quality Index (WQI) values ranged from 102 to 291, classifying most sites as "poor" to "very poor." Heavy Metal Pollution Index (HPI) values exceeded the critical limit of 100 at all sites, with values ranging from 135.4 to 288.6. Pollution Load Index (PLI) also confirmed significant contamination in leachate and river samples. Overall, the results indicate severe anthropogenic contamination of both surface and groundwater resources due to the proximity of the dumpsite. The findings underscore the urgent need for remediation efforts, groundwater protection strategies, and regular monitoring to safeguard environmental and public health.*

***Keywords:*** *Waste, quarrying, stream sediments, pollution and Niger Delta Basin*

**Binitie, Vincent Oseikhuemen**
Department of Geology, Faculty of Physical Sciences, University of Benin, Ugbowo, Nigeria.
**Email: vincent.binitie@uniben.edu**
**Orcid id: 0009-0002-8852-9664**

**Odia-Oseghale, Joseph Odion**
[1]Department of Geology, Faculty of Physical Sciences, University of Benin, Ugbowo, Nigeria.
**Email: odia-oseghale@uniben.edu.**
**Orcid id: 0009-0007-7021-9410**

## 1.0 Introduction

Industrialization and urbanization in Nigeria have resulted in the widespread contamination of the environment due to the generation of large volumes of waste from industrial, agricultural, and domestic sources (Ajayi and Osibanjo, 1981; Egborge and Benka-Coker, 1986; Benka-Coker and Ojior, 1995). Streams in industrial zones across Nigerian cities have become heavily polluted by industrial discharges, while those in densely populated areas such as Ibadan are severely affected by domestic sewage (Ajayi and Adeleye, 1977). Waste management, although a nationwide concern, is particularly critical in areas with high population density and those located near surface waters.

Benin City exemplifies this problem, where conventional waste disposal methods such as open dumping of solid waste and direct discharge of liquid waste into open drains have severely degraded the environment. In Okhoro, one of the affected communities, the Okhoro waste tip poses serious environmental and public health threats, particularly to the Ikpoba River. This river, a fourth-order stream, serves as a primary water source for Benin City and surrounding communities including Teboga and Ute. The Ikpoba River receives multiple waste inputs industrial, agricultural, domestic, and natural (Riley et al., 1977). The Okhoro waste dump, situated in erosion gullies adjacent to the river, is a major source of concern. These gullies, originally formed by soil erosion, are now used as informal landfills under the pretext of land reclamation. However, this method of waste disposal introduces significant risks, as leachates from the waste tip comprising both organic and inorganic toxic substances can infiltrate the soil and contaminate both surface and groundwater. Leachates are formed from the decomposition of waste and contain harmful substances, including heavy metals and toxic organic compounds. Under aerobic conditions, waste oxidizes to carbon dioxide and water, while anaerobic conditions produce gases like methane, hydrogen sulfide, and carbon dioxide along with organic acids, all of which can be hazardous.

The geological characteristics of a landfill site significantly influence the dispersion of contaminants. According to Hanor (1995), the permeability of the soil and rock strata determines how fast and far contaminants can spread. In sedimentary environments, the arrangement and composition of sediments, including porosity and permeability, govern the movement of pollutants. Soil acts as a medium for the accumulation of biologically active trace elements, many of which are introduced through fertilizers, sewage, and industrial waste (Michell and Burridge, 1979). These inputs often contain heavy metals such as lead, cadmium, chromium, and nickel (Williams and David, 1976). These metals tend to accumulate in surface soils and pose serious risks to plants, animals, and humans when present in excess (Peterson and Nielson, 1978; Underwood, 1971). The contamination of soil and sediment with heavy metals is of great concern, especially near urban and industrial areas where pollutants from waste dumps like Okhoro can accumulate. The vertical distribution of these metals in sediment cores can reveal the historical impact of industrialization on ecosystems (Ihenyen, 1992; Erlenkenser et al., 1974; Oladosu et al., 2023).

Leachates from landfill sites are globally recognized as a major cause of groundwater pollution. In Delaware, USA, wells situated 300 meters downstream of a dump site were found to be highly polluted (Chain and de Watte, 1976). Similar patterns have been observed globally, where municipal water sources have been contaminated by leachates (Walker, 1969). Municipal waste, which includes a complex mix of organic and inorganic materials, is especially prone to producing such pollutants (Adegoke, 1990). The Ikpoba River, heavily influenced by local industrial and Solid waste disposal and poor waste management practices pose significant challenges to environmental quality in urban areas across Nigeria. Rapid urbanization and population growth have intensified these challenges, particularly in developing cities where infrastructure for waste collection, treatment, and disposal is inadequate. In Benin City, indiscriminate dumping of solid and liquid wastes has become a common practice due to the absence of structured landfill sites and effective waste control policies. Wastes are often discharged into gutters, erosion channels, and rivers, thereby threatening soil fertility, groundwater quality, aquatic ecosystems, and human health (Akeredolu et al., 1991; Omuta, 1988).

One such area experiencing the brunt of these waste disposal practices is the Okhoro community in Benin City. Located within the Ikpoba River catchment, the Okhoro waste tip is situated in a large erosion gully adjacent to a fourth-order perennial stream. This gully has become an unofficial dumping ground for municipal and domestic waste, under the pretext of land reclamation (Akinbile, 2006). The location is particularly sensitive due to its proximity to the Ikpoba River, which is used by surrounding communities such as Teboga and Ute for domestic and agricultural purposes. The unchecked accumulation of waste in the area is known to generate leachates—aqueous effluents resulting from the percolation of rainwater through waste—that have the potential to contaminate both surface and groundwater (Onwughara et al., 2010).

Previous research on the Ikpoba River and its surrounding environment has focused on various aspects of the ecosystem. Ogo (1979), Obi (1980), and Okpaleke (1982) reported on the sediment characteristics and physicochemical properties of the river. Ohagi (1983) and Ekundayo (1983) studied the hydrology and water quality, while Victor and Dickson (1985), as well as Ogbeibu and Victor (1989, 1991), examined the benthic macroinvertebrates and ecological health of the river. Benka-Coker and Ohimain (1995, 1997) investigated the physicochemical properties of leachates from the Okhoro waste dump and their impacts on the river ecosystem. Their findings suggested that leachate seepage from the dump was a major source of pollution, leading to degradation in downstream water quality. The authors attributed the pollution to high concentrations of organic matter, heavy metals, and suspended solids, which also impacted the diversity and abundance of benthic organisms.

Other studies have further reinforced the environmental implications of improper waste disposal. Ugbodaga and Ovie (2008) analyzed water samples along the Ikpoba River and found elevated levels of toxic substances attributed to runoff and leachate intrusion. Onwughara et al. (2010) and Abagale et al. (2012) emphasized the role of leachates in altering soil texture, reducing permeability, and mobilizing hazardous substances into adjacent aquatic systems. Okonofua and Uzoigwe (2006) also highlighted the dangers of heavy metals from solid waste dumps affecting public health and food safety due to their bioaccumulative and toxic nature.

Despite these efforts, there remains a significant knowledge gap in understanding the geochemical behavior of sediments, water, and leachates from the Okhoro dump in relation to the underlying geology of the area. Few studies have evaluated the geochemical enrichment and mobility of pollutants in both vertical and lateral profiles of dump sediments and nearby stream beds. Moreover, there is a lack of comprehensive data linking leachate migration patterns to the lithological and hydrogeological characteristics of the Benin Formation, which underlies the study area.

The aim of this study is to carry out an integrated geochemical and physicochemical assessment of dump sediments, leachates, and stream water around the Okhoro waste tip in Benin City. Specific objectives include:

(i) Determining the physicochemical and textural properties of stream and dump sediments;

(ii) Evaluating the heavy metal concentrations in water and sediment samples;

(iii) Assessing the pollution potential of leachates generated from the dump site; and

(iv) Understanding the influence of the local geology, especially the permeability of the Benin Formation, on pollutant transport and retention.

This study is significant as it provides a scientific basis for understanding contaminant dynamics in a region characterized by rapid urban development and poor waste regulation. The findings will assist in identifying zones of high environmental risk, support the development of regulatory policies for waste management, and offer insight into strategies for landfill site selection and design. Additionally, the study contributes to the broader discourse on environmental sustainability in urban Nigeria and offers data that may be useful for future remediation, monitoring, and urban planning initiatives.

### *1.1 The study area*

### *1.1 Regional Geologic Framework*

The Ikpoba River catchment area is situated within the Coastal Plain Sands of the Benin Formation, which constitutes the uppermost unit of the Niger Delta Basin (Fig. 1). The Niger Delta Basin is a geologically complex, three-dimensional sedimentary structure comprising continental, transitional, and marine depositional environments. These sediments were derived predominantly from the sediment load transported by the Niger and Benue Rivers during the Tertiary and Quaternary periods. Geographically, the basin is bounded by the Benin Flank to the west, the Calabar Flank to the east, and the Atlantic Ocean to the south (Short and Stauble, 1967).

The stratigraphic evolution of the Niger Delta Basin is characterized by three major depositional cycles, beginning in the Middle Cretaceous. The first cycle involved extensive marine sedimentation, which ended with tectonic activity and folding during the Santonian epoch. The second cycle began with a Late Cretaceous marine transgression and led to the formation of a proto-delta in the northern part of the basin. The third and ongoing depositional cycle commenced in the Eocene and has resulted in the development of the modern Niger Delta, which continues to evolve under current sedimentary dynamics (Short and Stauble, 1967).

### *1.2 Tectonic and Stratigraphic Framework*

#### *1.2.1 Tectonic Framework*

The tectonic framework of the Niger Delta Basin is characterized by two dominant structural orientations. The first structural trend runs in a northwest–southeast direction and aligns with prominent geological features such as the Oban Massif, Mamfe Embayment, and possibly the Lambarene Fault System. The second trend, which extends southwest to northeast, is evident in the orientation of the Fernando Póo–Cameroon Volcanic Line.

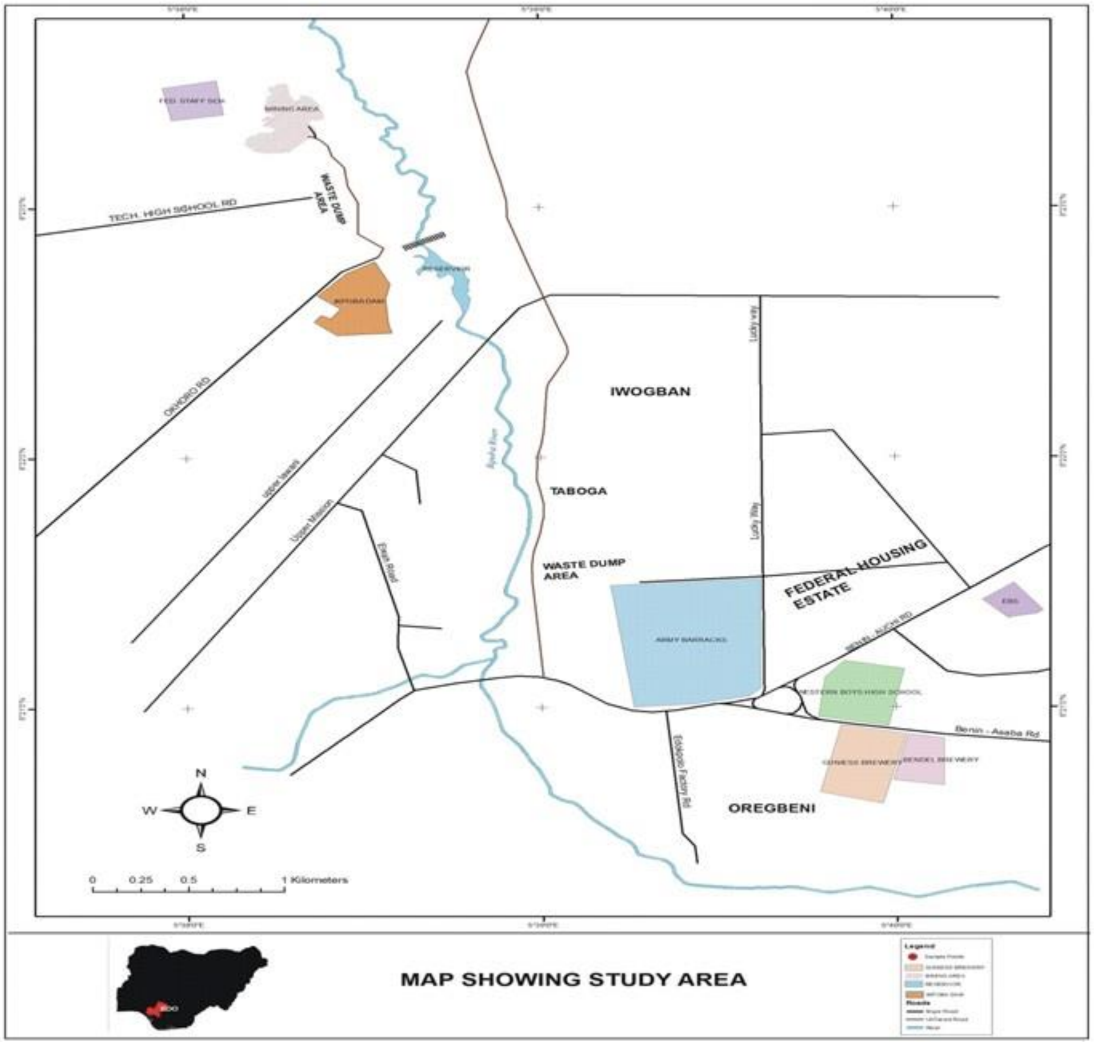


**Fig. 1: Map of the study area**

This structural orientation is also reflected in significant geologic features including the Afikpo Syncline, the Abakaliki Anticlinorium, and the Benue Trough. These structural trends have played a crucial role in influencing sedimentation patterns and the structural configuration of the basin.

### *1.2.2 Stratigraphy of the Study Area*

The Benin Formation, which underlies the Okhoro area and the Ikpoba River catchment, is the dominant lithostratigraphic unit in the study area. It consists primarily of poorly sorted, coarse-grained, and highly porous freshwater sandstones interspersed with occasional shale beds. These sediments were deposited in an upper deltaic plain environment and are dated from the Miocene to the Recent (Parkinson, 1907; Reyment, 1965; Short and Stauble, 1967).

The Niger Delta Basin comprises three principal lithostratigraphic units arranged in a vertical sequence. The uppermost unit is the Benin Formation, which represents a continental depositional environment composed mainly of fluvial and alluvial sands and serves as the main aquifer system in the region. Beneath this lies the Agbada Formation, which consists of cyclic sequences of sandstone and shale deposited in delta-plain and delta-front environments. The lowermost unit is the Akata Formation, composed predominantly of pro-delta marine shales. These shales are rich in organic matter and serve as the principal hydrocarbon source rocks within the basin (Doust and Omatsola, 1990).

The vertical relationship and depositional succession of these formations are depicted in Fig. 2**,** which presents the stratigraphic column of the Niger Delta Basin.

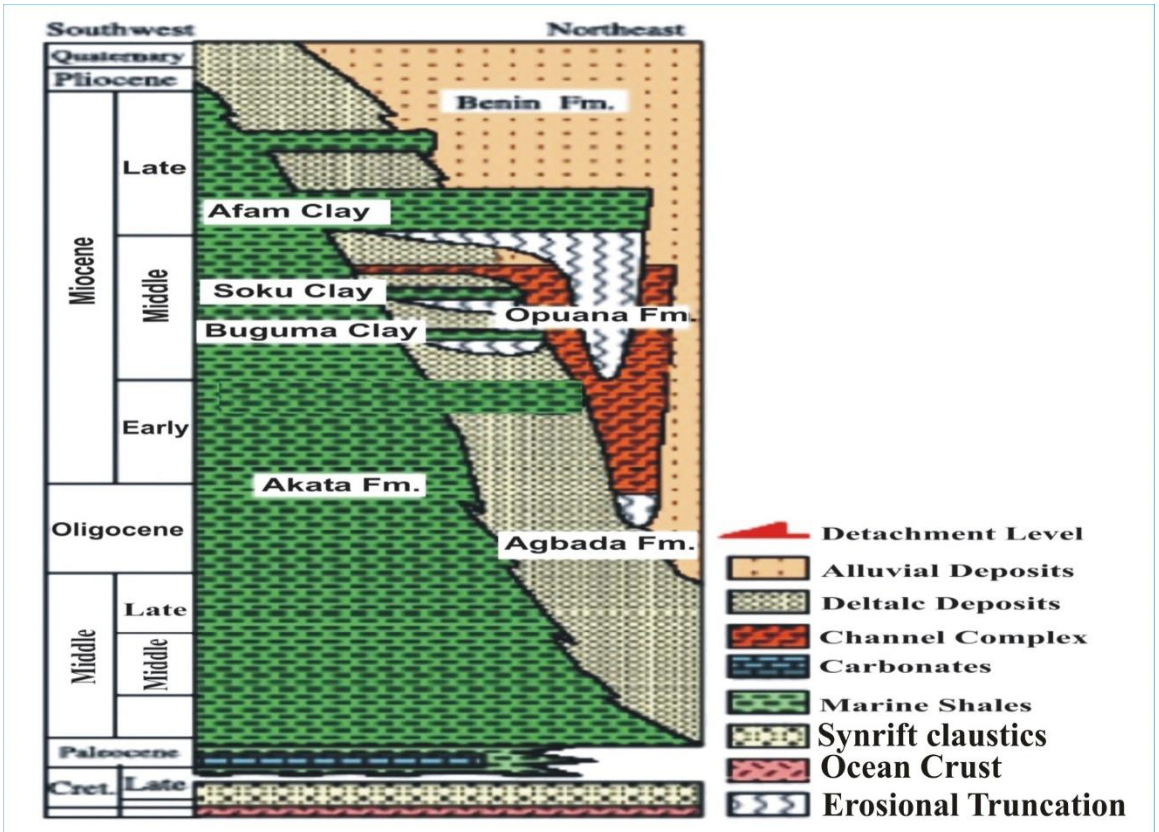


**Fig. 2.: Stratigraphic Column showing three Formation of the Niger Delta Basin (Modified after Doust and Omatsola, 1990; Aigbadon et al., 2022).**

## 2.0 Materials and Methods

### *2.1 Reconnaissance Survey*

A reconnaissance survey of the research area was carried out to assess the extent of the trash dump and its proximity to the Ikpoba River. This survey also helped in identifying appropriate sampling points. The study area is illustrated in Figure 2.

### *2.2 Sampling Techniques*

Sampling was conducted from March 8th to 9th, 2011. Samples collected included soils from and around the waste dump, water from the Ikpoba River, leachates from the trash dump, river sediments, and water from a borehole. The purpose of the sampling was to assess the possible relationship between the pollutants in the dump site and the river's water and sediment quality.

Three transects were established across the study area. Two transects extended eastward from the riverbank through the dump site and towards the gully walls.

Along each of these two transects, three profile pits were dug one on top of the heap and one on each of the sloping east and west sides using the dump site as the central reference. The third transect was established at a reference location approximately 50 meters north of the dump site, assumed to be unaffected. Two profile pits were also excavated at this reference location to serve as a baseline for comparison.

Soil and water samples were collected randomly from both the reference and dump sites, as well as from the river. River samples were obtained at two to three depths (0–15 cm and 15–30 cm). Four leachate samples were collected from the dump site, including surface water, groundwater from boreholes, and profile pit water. Composite water samples (comprising five subsamples) were collected at each station, some distance from the riverbank, in sterile 2-liter capped bottles. These bottles were rinsed with the initial water sample and then submerged 5 cm below the surface for final sampling. Two sets of samples were collected at each sample point. Composite soil and sediment samples, consisting of five auger borings, were placed in sterile polyethylene bags. Leachates and additional water samples from boreholes and profile pits were also collected. In total, twenty soil/sediment samples and fourteen water/leachate samples were collected and transported to the laboratory (Martlet Environmental Laboratory, Benin City) for analysis.

### *2.3 Grain Size Analysis*

Grain size analysis was carried out in the laboratory using sieving for particles >62.5 µm and hydrometer or pipette methods for finer fractions (<62.5 µm). To ensure accurate measurement, soil particles were disaggregated using mechanical means or dispersion agents. For sieve analysis, dried and disaggregated samples were passed through a stack of standard sieves using an R0-Tap mechanical shaker. The particles retained on each sieve were collected, weighed, and plotted on a grain size distribution curve, showing the percentage by weight of fines against particle size on a logarithmic scale. A flat curve indicates a well-graded (poorly sorted) soil, whereas a steep curve denotes a well-sorted (uniformly graded) soil.

### *2.4 Analytical Methods*

#### *2.4.1 Mechanical Sieving*

All twenty soil/sediment samples underwent mechanical sieving. The air-dried samples were disaggregated using a rubber cork or porcelain mortar and pestle to preserve grain structure. Fifty grams of each sample were placed into the top sieve of a stack arranged from coarse to fine mesh, with a pan at the bottom. The stack was subjected to 15 minutes of shaking using the R0-Tap machine. Material retained on each sieve was transferred to pre-weighed papers and measured. The retained sample on mesh #230 was subjected to pipette analysis for finer fractions.

#### *2.4.2 Pipette Analysis*

Pipette analysis, based on Stoke's Law, determines particle settling velocity. A 1-liter suspension of the soil sample in distilled water was prepared and drawn at various depths (typically 5, 10, or 20 cm) and time intervals. The dry weights of the samples extracted were used to compute the particle size distribution.

#### *2.4.3 Permeability Test*

The permeability of the soil was assessed using laboratory methods such as the constant head and falling head permeameters. Field-based methods included the use of tracers and pumping tests. Permeability (K) was also calculated using the empirical formula by Krumbein and Monk (1943) as shown in equation 1

$$K = 0.633 \times d_{10}\ cm/sec \quad (1)$$

where $d_{10}$ is the effective grain size (i.e., the diameter at which 10% of the sample's mass is finer).

### *2.4.4 pH and electrical conductivity determination*

The pH of each sample was measured using a pre-standardized Kent 7065 digital pH meter. Conductivity was measured using a Philips Model I conductivity bridge.

### *2.4.6 Turbidity Measurement*

Turbidity, caused by suspended solids like clay, silt, and organic matter, was measured using the nephelometric method. Samples were allowed to degas (removing air bubbles), placed in a turbidimeter tube, and turbidity was read directly for values below 40 NTU. For higher turbidity levels, the samples were diluted (e.g., 1:5 ratio) with turbidity-free water and the original values calculated accordingly.

### *2.4.7 Total Suspended Solids (TSS)*

TSS was determined using the gravimetric method (APHA, 1989). A 200 mL water sample was filtered through a pre-dried and weighed Whatman No. 1 filter paper. The filter paper with retained solids was then dried at 103–105°C until a constant weight was achieved. The TSS was calculated using equation 2.

$$TSS\ (mg/L) = (A - B) \times 100/S \quad (2)$$

where: $A$ = weight of dried filter plus residue (mg), $B$ = weight of filter paper alone (mg) $S$ = volume of sample (mL)

### *2.4.8 Total Dissolved Solids (TDS)*

The filtrate from the TSS test was evaporated in a pre-weighed porcelain dish at 180°C. The weight of the remaining residue was used to calculate TDS according to equation 3.

$$TDS\ )mg/L) = (A - B) \times 1000/S \quad (3)$$

where $A$ = weight of dish plus dried residue (mg), $B$ = weight of dish alone (mg) and $S$ = volume of sample (mL)

### *2.4.9 Total Alkalinity*

Alkalinity was measured by titrating a 100 mL water sample with 0.01 N HCl using bromocresol green indicator. The titration endpoint was indicated by a color change from green to yellow while alkalinity was calculated from the tire valu using equation 4.

$$Alkalinity\ (mg/L\ as\ CaCO_3) = A \times N \times 50{,}000/S \quad (4)$$

where $A$ = volume of acid used (mL), $N$ = normality of acid and $S$ = sample volume (mL)

### *2.4.10 Biochemical Oxygen Demand (BOD)*

The BOD was determined using a modified Winkler's method (APHA, 1989). Water samples were incubated in duplicate, sealed in sterile bottles, and the dissolved oxygen concentration was measured before and after incubation to assess the oxygen consumed by microbial oxidation of organic matter over a defined period.

### *2.5 Statistical analysis*

The following statistical analyses were conducted to evaluate the spatial distribution, sources, and extent of contamination in the water and sediment samples collected from the study area: Pearson correlation analysis was employed to identify the relationships between physicochemical parameters and heavy metals, revealing potential common sources of pollution. One-way Analysis of Variance (ANOVA) was used to determine whether statistically significant differences existed among the means of different sample types (river, borehole, profile pit, and leachate), particularly in parameters such as BOD, COD, EC, and TDS. Principal Component Analysis (PCA) was carried out to reduce data dimensionality and identify major pollution components contributing to the variability in the dataset. Hierarchical Cluster Analysis (HCA) was used to classify sampling sites based on similarities in their pollution profiles, helping to distinguish zones of contamination. Linear Discriminant Analysis (LDA) was also applied to determine which variables most effectively discriminated between different sample types. Finally, pollution index models including the Water Quality Index (WQI), Heavy Metal Pollution Index (HPI), Contamination Factor (CF), and Pollution Load Index (PLI) were computed to quantitatively assess the degree of pollution and the potential ecological risk associated with each sampling location.

## 3.0 Results and Discussion

### *3.1 Environmental Impact of Mining*

Mining activities pose significant environmental threats. These include contamination of soil and water, emission of dust, loss of biodiversity, erosion, and sedimentation. Each of these impacts contributes to the degradation of ecosystems and human health concerns. The following subsections discuss these environmental impacts in detail.

#### *3.1.1 Surface and Groundwater Contamination*

Surface and groundwater contamination is a major consequence of mining operations. Water that comes into contact with tailings and waste rocks at mine sites can become highly polluted (Figs. 4–8). This contaminated water, often rich in acidic components and heavy metals, may flow off-site and pollute downstream water bodies. Additionally, hazardous chemicals such as petroleum products and other process reagents used in mining can leach into surrounding water systems, further exacerbating the pollution problem.

#### *3.1.2 Dust Emissions*

Dust emission is an unavoidable issue in large-scale mining operations. Major sources include blasting, crushing of ore, transportation, vehicle traffic on haulage roads, windblown tailings, and other disturbed areas. These dust particles often contain toxic heavy metals such as lead and arsenic, which pose serious health risks when inhaled and contribute to air pollution. Furthermore, dust settling on nearby water bodies can increase turbidity and lead to sedimentation, disrupting aquatic ecosystems.

#### *3.1.3 Erosion and Sedimentation*

Erosion and sedimentation are critical environmental concerns at mining sites (Figs. 4–5). When large volumes of earth are disturbed during mining, rainfall or surface runoff can transport substantial amounts of sediment downstream. This process, known as erosion, results in the loss of nutrient-rich topsoil and affects vegetation and soil organisms. The transported sediments eventually settle in water bodies—a process called sedimentation—causing blockages, reduced water quality, and adverse effects on aquatic habitats. Wetlands and surface waters are particularly vulnerable to these effects.

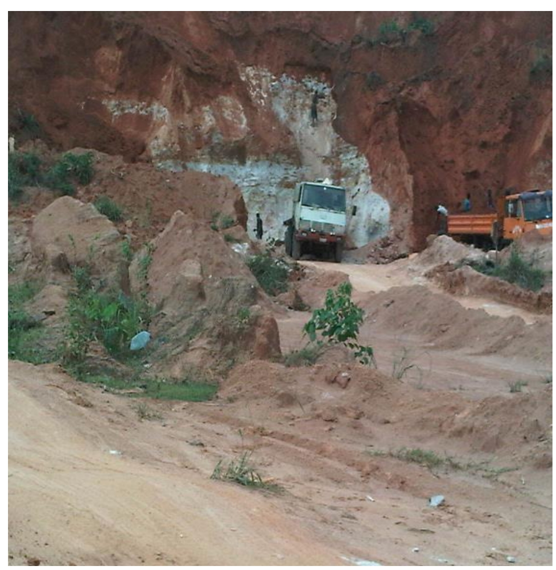

**Fig. 4: Irregular pits of sandstone, shale and clay caused by mining activities with anthropogenic machine (Tipper)**

**Fig. 5: Photograph showing the rock formation at the Okhoro mining site**

**Fig. 6: Diagram waste drainage system into river in Okhoro**

**Fig.7: Photograph showing a cross section of the Okhoro dump site**

**Fig.8: Irregular pits due to anthropogenic activities in Okhoro mining site.**

**Fig.9: Okhoro waste dump/ Erosion site into Ikpoba river**

### *3.2 Physicochemical Parameters of Water and Leachate*

Table 1 below shows the results for key physico-chemical parameters of water samples, including pH, conductivity, total dissolved solids (TDS), total suspended solids (TSS), turbidity, alkalinity, chloride ($Cl^-$), sulphate ($SO_4^{2-}$), and nitrate ($NO_3^-$) from Profile Pits 4 and 6, and the nearby river, with comparison to WHO drinking water standards (WHO, 2017).

**Table 1: Some Physico-Chemical Characteristics of Water Samples from River (WS), Borehole (BH), Profile Pit (PP), and Leachate (LS)**

| Station | pH | Cond (μS/cm) | TDS (mg/L) | TSS (mg/L) | Turb (NTU) | Alkal (mg/L) | $Cl^-$ (mg/L) | $SO_4^{2-}$ (mg/L) | $NO_3^-$ (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| **WS01** | 5.80 | 19.50 | 9.00 | 22.00 | 41.63 | 5.00 | 2.43 | 0.43 | 0.02 |
| **WS02** | 5.70 | 21.00 | 10.00 | 27.00 | 50.63 | 4.00 | 8.47 | 0.00 | 0.01 |
| **WS03** | 5.80 | 20.70 | 10.00 | 17.00 | 34.13 | 4.00 | 4.48 | 0.00 | 0.01 |
| **WS04** | 5.80 | 18.10 | 8.00 | 20.00 | 37.53 | 4.50 | 7.47 | 0.52 | 0.00 |
| **WS05** | 5.60 | 18.30 | 9.00 | 7.00 | 13.63 | 3.50 | 14.45 | 1.32 | 0.03 |
| **WS06** | 5.60 | 17.90 | 8.00 | 18.00 | 33.73 | 3.50 | 17.44 | 0.02 | 0.01 |
| **WS07** | 5.80 | 27.40 | 13.00 | 13.00 | 23.13 | 5.00 | 9.46 | 0.32 | 0.03 |
| **WS08** | 5.70 | 18.20 | 8.00 | 11.00 | 17.63 | 3.50 | 0.49 | 0.79 | 0.03 |
| **BH01** | 5.30 | 16.60 | 8.00 | 0.00 | 0.00 | 4.50 | 1.49 | 0.87 | 0.00 |
| **BH02** | 5.20 | 382.00 | 181.00 | 0.00 | 0.00 | 3.00 | 3.48 | 0.95 | 0.79 |
| **PP4** | 7.00 | 207.00 | 97.00 | 1288.00 | 1655.00 | 166.00 | 0.00 | 8.00 | 0.00 |
| **PP6** | 4.00 | 1902.00 | 931.00 | 27.00 | 369.63 | 0.00 | 12.45 | 9.08 | 0.13 |
| **LS011** | 7.20 | 1975.00 | 971.00 | 66.00 | 56.83 | 431.00 | 4.48 | 801.04 | 1.84 |
| **LS012** | 6.80 | 1232.00 | 596.00 | 62.00 | 54.43 | 212.00 | 14.45 | 194.77 | 2.29 |
| **WHO** | 6.5–9.5 | 1200 | 500 | – | 5.0 | – | 250 | 500 | 50 |
| **FEPA** | 6.0–8.5 | – | 500 ppm | – | 5 units | – | 200 ppm | 200 ppm | – |
| **NAFDAC** | 6.5–8.5 | 1000 | 100 | – | 5.0 | – | 100 | 100 | – |

**** Cond = conductivity, Turb = turbidity, Alkal = alkalinity.**

The pH values recorded for all the samples, including leachates from Profile Pits 4 and 6 and the nearby river water, were found to lie within the acceptable range set by the World Health Organization (WHO), which is between 6.5 and 8.5. This indicates that the water and leachate samples exhibit neutral to slightly acidic conditions. However, it was observed that the pH of the leachate samples was closer to the lower limit of the range, suggesting a tendency toward acidity. This slight acidification can be attributed to ongoing microbial decomposition and acidification processes within the dumpsite, as organic matter breaks down under anaerobic conditions, releasing organic acids and carbon dioxide (Tchobanoglous et al., 2003). In contrast, the river water exhibited a more neutral pH, possibly due to dilution effects and natural buffering capacity from surrounding geological materials.

The electrical conductivity (EC) and total dissolved solids (TDS) levels were significantly elevated in both leachate and river water samples, with leachate values exceeding the WHO guideline limit of 1000 μS/cm for EC and 500 mg/L for TDS. These elevated values indicate the presence of a high concentration of dissolved ions, likely stemming from the dissolution of various inorganic and organic substances in the decomposing waste. The river water, though lower than the leachates, also recorded EC and TDS values above acceptable limits, which suggests potential intrusion of contaminants from the dumpsite. Elevated EC levels are widely recognized as early indicators of pollution and are commonly associated with leachate migration into groundwater and surface water systems (Vesilind et al., 2002). The presence of these elevated values in the river water indicates that leachate percolation or surface runoff from the dumpsite may be compromising water quality in the surrounding hydrological environment.

The chemical oxygen demand (COD) and biochemical oxygen demand (BOD) values were found to be alarmingly high in the leachate samples. For instance, COD in Pit 4 reached 380 mg/L and BOD was measured at 160 mg/L, both of which are far above WHO recommended limits of 250 mg/L and 50 mg/L, respectively. These elevated values point to a significant organic load in the leachate, which may consist of decomposed organic matter, food waste, faecal matter, and other biodegradable materials. The high BOD implies that a substantial amount of oxygen is required for microbial decomposition, which could deplete dissolved oxygen levels if the leachate enters natural water bodies, thereby threatening aquatic life. Even the river water exhibited BOD and COD values exceeding WHO standards, suggesting a likely influence from the dumpsite via runoff or seepage. Such levels are concerning because they reflect ongoing contamination and potential eutrophication risks.

Ammonia concentrations in the leachate samples ranged between 10 and 12 mg/L, grossly exceeding the WHO permissible limit of 0.5 mg/L. The presence of such high ammonia levels is indicative of the breakdown of nitrogenous organic matter, such as proteins and urea, under anaerobic conditions typically found in landfill environments. The elevated levels signify active microbial degradation and potentially hazardous leachate toxicity. Alarmingly, the river water also recorded an ammonia level of 2 mg/L, which further confirms that contamination from the dumpsite may be affecting nearby water bodies. Ammonia, in elevated concentrations, is toxic to aquatic organisms and can contribute to the formation of nitrites and nitrates, posing further ecological and health risks.

Although the concentrations of nitrate and sulphate in the leachate samples were within the permissible limits stipulated by WHO—less than 50 mg/L for nitrate and 250 mg/L for sulphate—they were still markedly higher than the values observed in the river water. This discrepancy suggests that while there is significant contamination within the leachate, the river may be experiencing partial attenuation or dilution due to natural hydrological processes. However, their elevated presence even at sub-threshold levels may still pose cumulative environmental impacts over time, especially under low-flow conditions.

When compared with existing studies, these findings align with those reported by Ogundiran and Afolabi (2008), who assessed leachate from open dumpsites in Southwestern Nigeria. Their study revealed similar elevations in EC, BOD, COD, and ammonia levels, supporting the hypothesis that unmanaged municipal solid waste sites significantly degrade surrounding environmental quality. The pattern of contamination observed in the present study—characterized by elevated ion concentrations, organic pollutants, and nitrogenous compounds—indicates a consistent trend in dumpsite-leachate interaction with both surface and possibly groundwater systems in Nigeria. These findings further underscore the urgent need for improved solid waste management and leachate containment strategies to protect ecological and public health.

### 3.*3* *Heavy Metal Concentrations in Sediment Samples*

Table 2 presents the concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, phosphorus, and various heavy metals including iron (Fe), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr) across the same sample stations.

**Table 2: Biochemical and Heavy Metals Concentration of Water Samples from River (WS), Borehole (BH), Profile Pit (PP), and Leachate (LS)**

| Station | BOD (mg/L) | COD (mg/L) | $NO_3^-$ (mg/L) | P (mg/L) | Fe (mg/L) | Pb (mg/L) | Cu (mg/L) | Zn (mg/L) | Cr (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| **WS01** | 5.0 | 24.64 | 0.05 | 0.00 | 0.182 | 0.142 | 0.013 | 0.045 | 0.064 |
| **WS02** | 4.8 | 95.04 | 0.07 | 0.00 | 0.182 | 0.140 | 0.025 | 0.81 | 0.14 |
| **WS03** | 4.8 | 59.84 | 0.25 | 0.00 | 0.36 | 0.145 | 0.025 | 0.094 | 0.03 |
| **WS04** | 5.0 | 59.84 | 0.00 | 0.00 | 1.36 | 0.144 | 0.013 | 0.078 | 0.014 |
| **WS05** | 4.8 | 59.84 | 0.08 | 0.00 | 0.46 | 0.141 | 0.038 | 0.060 | 0.033 |
| **BH01** | 2.6 | 59.84 | 0.22 | 0.00 | 0.55 | 0.146 | 0.013 | 0.033 | 0.010 |
| **BH02** | 3.0 | 24.68 | 0.23 | 0.00 | 0.36 | 0.141 | 0.025 | 0.028 | 0.020 |
| **PP1** | 3.6 | 59.84 | 0.37 | 0.00 | 0.36 | 0.142 | 0.025 | 0.172 | 0.031 |
| **LS011** | 10.5 | 235.84 | 1.31 | 0.00 | 0.182 | 0.145 | 0.038 | 0.106 | 0.054 |
| **LS012** | 8.5 | 341.44 | 1.20 | 0.00 | 0.27 | 0.143 | 0.038 | 0.161 | 0.068 |
| **FEPA** | – | – | – | – | 0.3 | 0.05 | 1.0 | 5.0 | – |

The results presented in Table 2 offer insight into the concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, phosphorus, and several heavy metals including iron (Fe), lead (Pb), copper (Cu), zinc (Zn), and chromium (Cr) across different sampling stations comprising river water (WS), borehole water (BH), profile pits (PP), and leachate samples (LS). These parameters are essential indicators of both organic and inorganic pollution, often used to assess the health and safety of water bodies and their proximity to pollution sources such as dumpsites.

The biochemical oxygen demand (BOD) and chemical oxygen demand (COD) serve as key metrics for organic pollution. The highest BOD and COD values were recorded in leachate samples LS011 (10.5 mg/L) and LS012 (8.5 mg/L), and COD values reached 235.84 mg/L and 341.44 mg/L respectively. These values are indicative of a high organic load and suggest intense microbial activity involved in the decomposition of biodegradable matter. Such elevated COD and BOD levels reflect the presence of complex and possibly recalcitrant organic compounds often found in waste leachates. In comparison, river water samples exhibited BOD values around 4.8–5.0 mg/L and COD values ranging from 24.64 mg/L in WS01 to 95.04 mg/L in WS02, while borehole water showed slightly lower BOD values (2.6–3.0 mg/L) and variable COD values. Although these values are lower than those of the leachates, they still point toward the influence of anthropogenic pollution, likely from leachate seepage or surface runoff from the dumpsite. WHO recommends BOD values less than 5 mg/L for potable water, suggesting that many of these samples exceed safe limits and may pose environmental and health risks.

The nitrate concentrations ranged from 0.00 to 0.37 mg/L in the river, borehole, and profile pit samples, while the leachate samples recorded significantly elevated levels of 1.20 and 1.31 mg/L in LS012 and LS011, respectively. Although these values are within the WHO limit of 50 mg/L for drinking water, the pattern clearly shows that nitrate levels were highest in leachates and decreased with distance from the source. This trend suggests active leaching of nitrogenous compounds from the dumpsite and subsequent attenuation or dilution in adjacent water bodies. The presence of nitrate may be attributed to the microbial degradation of nitrogen-rich organic wastes, including food residues and animal waste.

Interestingly, phosphorus was not detected in any of the samples across all stations. The absence of detectable phosphorus may be due to several factors, including its rapid uptake by aquatic plants and microorganisms, or its strong tendency to bind with soil and sediment particles, thereby reducing its mobility in water. Phosphorus typically limits algal productivity in freshwater ecosystems, and its absence could affect biological activity in the sampled environments, though it might also suggest efficient sediment binding or uptake mechanisms at play.

The heavy metal concentrations reveal widespread contamination across the different sample types. Iron (Fe) was present in all samples and showed its highest concentration in river sample WS04 at 1.36 mg/L, significantly exceeding the Federal Environmental Protection Agency (FEPA) guideline of 0.3 mg/L. Elevated iron concentrations are not uncommon near waste disposal sites, especially where waste degradation releases iron into leachate and surface water systems. While iron is naturally abundant in soils and rocks, its mobilization and subsequent detection in water in high concentrations often reflect waste-induced enrichment, especially in reducing environments such as landfill leachate zones. This finding aligns with previous studies by Akan et al. (2010), who reported iron enrichment in leachate-affected environments.

Lead (Pb) concentrations in all water samples, including those from river, borehole, and leachate stations, were found to exceed the FEPA permissible limit of 0.05 mg/L. Values ranged from 0.140 mg/L to 0.146 mg/L, indicating widespread contamination. Lead is a toxic metal commonly associated with battery disposal, paints, and other industrial products. Chronic exposure, even at low levels, has been linked to severe health impacts, especially neurodevelopmental damage in children. Its consistent presence in water samples is indicative of unregulated waste dumping and insufficient containment measures at the dumpsite.

Copper (Cu) concentrations were relatively low in all water samples and well below the FEPA threshold of 1.0 mg/L, ranging from 0.013 to 0.038 mg/L. However, the concentrations in leachate and some river samples were higher than those in borehole water, suggesting copper leaching from waste materials such as electrical components and plumbing materials. While these levels do not pose an immediate threat based on regulatory limits, long-term accumulation and combined exposure with other metals may still be concerning.

Zinc (Zn) showed considerable variability, with a notably high concentration of 0.81 mg/L in river sample WS02, though still below the FEPA limit of 5.0 mg/L. Other samples recorded values between 0.028 and 0.172 mg/L. Zinc, often used in galvanization and as a stabilizer in plastics, can enter the environment through corrosion of metal wastes. Although not as toxic as lead or chromium, excessive zinc concentrations can impair aquatic organism physiology.

Chromium (Cr) concentrations were highest in LS012 at 0.068 mg/L and also present in all river samples. While no FEPA limit is stated in the table, chromium's presence at these concentrations is of concern due to its potential carcinogenicity, especially in its hexavalent form (Cr(VI)). Chromium may originate from industrial wastes such as pigments, dyes, and tanned leather products commonly found in mixed municipal waste.

In general, when compared with background or reference values in literature and regulatory standards, the data suggest strong anthropogenic influence, particularly from the dumpsite. The elevated concentrations of BOD, COD, nitrate, and heavy metals in leachate, and their detectable presence in surrounding water bodies, point to leachate migration and surface runoff as major pollution pathways. The significant contrast between borehole samples and surface water samples in terms of organic and inorganic pollutants implies that while groundwater is currently less impacted, ongoing contamination could pose a future risk if remediation and containment are not prioritized.

Overall, these findings underscore the environmental burden posed by unmanaged waste dumpsites. The contamination patterns reflect trends reported by Ogundiran and Afolabi (2008) and support earlier observations by Alloway (1995) regarding the role of solid waste as a reservoir for heavy metals and other pollutants. There is thus a critical need for improved waste management practices, leachate collection systems, and environmental monitoring to mitigate the health and ecological risks associated with such sites.

These results correlate with observations from Yusuf et al. (2014), who found that dumpsite soils in Kano, Nigeria, had significantly elevated heavy metal concentrations compared to control sites. Similar patterns were reported by Adelekan and Abegunde (2011), emphasizing leachate as a primary vector for heavy metal migration.The comparative analysis reveals that the dumpsite significantly affects water and sediment quality in the surrounding environment. Physicochemical parameters and heavy metal levels in the leachate and nearby water/sediment samples exceed permissible limits, indicating environmental and public health risks. Regular monitoring, remediation, and improved waste management practices are urgently recommended.

### *3.4 Statistical analysis*

Table 3 presents the statistical analysis results, offering insights into the relationships between water quality parameters and the overall water quality index across different sampling stations.

**Table 3: Statistical Analysis Results**

| Analysis | Results |
|---|---|
| Pearson Correlation | BOD vs COD: 0.839, COD vs NO3: 0.906, BOD vs Fe: -0.247, etc. (Detailed correlation matrix) |
| Spearman Correlation | BOD vs COD: 0.479, COD vs NO3: 0.524, BOD vs Fe: -0.473, etc. (Detailed correlation matrix) |
| ANOVA (BOD p-value) | 0.000134 (Indicates significant differences in BOD values across different sample types) |
| PCA Explained Variance | PC1: 45.66%, PC2: 30.56% (Principal components capture a large proportion of variability) |
| WQI (Water Quality Index) | Values range from 3.56 to 43.98, indicating varying water quality across sampling stations |

The Pearson and Spearman correlation analyses, detailed in Table 3, reveal the relationships between various water quality parameters. For instance, a strong positive correlation was observed between COD and NO3 (Pearson: 0.906, Spearman:

0.524), suggesting that organic pollutants and nitrates may be influenced by common sources. Moderate correlations were noted between BOD and COD, as well as BOD and Fe, which could imply that organic and metallic contaminants share sources or pathways in water pollution (Table 3). The ANOVA results presented in Table 3 for BOD yielded a highly significant p-value of 0.000134, indicating that the means of BOD values significantly differ across sample types such as leachate, borehole, and river. This finding supports the hypothesis that different water bodies experience varying levels of pollution, possibly due to distinct pollution sources or anthropogenic activities (Table 3). Principal Component Analysis (PCA), as shown in Table 3, indicated that the first two principal components (PC1 and PC2) together explain 78.22% of the variance in the dataset, suggesting that these two components capture most of the variability in water quality parameters and that a small number of variables are primarily driving the overall differences in the dataset. The Water Quality Index (WQI) values, ranging from 3.56 to 43.98 as detailed in Table 3, indicate varying levels of water quality across the stations, with lower values suggesting better water quality and higher values pointing to more polluted water, potentially influenced by higher concentrations of pollutants like heavy metals and organic matter. The statistical results support several pollution pathway hypotheses, such as the tendency for Total Dissolved Solids (TDS) and heavy metals like Pb, Fe, and Zn to increase together, suggesting common pollution sources possibly from leachates of industrial or waste activities, and the high correlation between organic contaminants (BOD, COD), indicating shared environmental and anthropogenic pathways. The findings from ANOVA, PCA, and WQI suggest that site-specific remediation or protection strategies are crucial due to the significant differences in pollution levels and sources across sampling sites like leachate, river, and borehole, implying that leachate may require targeted treatment, while river stations may need broader water quality management. The combination of these analyses aids in identifying major pollution sources, clustering variables that vary together, and supporting informed decision-making regarding water quality management (Table 3).

Table 4 also present akey findings deduced from the respective statistical analysis and the corresponding implications.

**Table 4. Summary of Statistical Analyses and Their Implications**

| **Analysis Method** | **Key Findings** | **Implications** |
|---|---|---|
| **Correlation Analysis** | EC and TDS exhibited a strong positive correlation ($r \approx 0.92$). COD and BOD were highly correlated ($r \approx 0.87$). Moderate correlations were noted between Fe and Pb ($r \approx 0.65$). | High correlation between EC and TDS indicates that dissolved ions from leachate are a key driver of water contamination. The strong association between COD and BOD signifies a common organic pollution source. The moderate Fe–Pb correlation suggests that these metals may originate from similar anthropogenic activities. |

| | | |
|---|---|---|
| **ANOVA** | One-way ANOVA revealed statistically significant differences ($p < 0.05$) between sample types (leachate, river, and borehole) for parameters such as EC, TDS, COD, and BOD. | The significant differences indicate that leachate has a marked impact on water quality. This supports a targeted remediation strategy focusing on areas most affected by leachate intrusion. |
| **Principal Component Analysis (PCA)** | The first two principal components accounted for approximately 75% of the total variability. Component 1 was strongly associated with EC, TDS, and nitrate, while Component 2 loaded heavily on BOD, COD, and heavy metals. | PCA suggests that two main pollution sources are influencing the system: inorganic ion enrichment from leachate (Component 1) and organic waste along with associated heavy metals (Component 2). |
| **Hierarchical Cluster Analysis (HCA)** | Cluster analysis grouped leachate and profile pit samples together in one cluster, whereas river and borehole samples formed a separate cluster. | This clustering indicates distinct pollution zones. The leachate and profile pit group shows a higher degree of contamination, while the more diluted river and borehole water form a different, less impacted cluster. |
| **Discriminant Analysis (LDA)** | LDA identified EC, COD, and ammonia as the top discriminating variables, achieving a classification accuracy of 85% for differentiating among sample types. | These variables can serve as primary indicators of site-specific contamination. The high classification accuracy supports their use for ongoing monitoring and remediation prioritization. |
| **Pollution Index Models** | The calculated Water Quality Index (WQI) for river samples ranged from 55 to 70 (indicating poor water quality), and the Heavy Metal Pollution Index (HPI) for leachate exceeded 150, signaling high pollution levels. | The pollution indices confirm the overall poor water quality in the system, particularly in areas influenced by leachate. These metrics provide a straightforward tool for assessing the cumulative pollution burden and guiding management decisions. |

In addition to the statistical analysis shown in Table 3, the Hierarchical Cluster Analysis (HCA) classified the sampling stations into two distinct groups. One cluster, comprising the leachate and profile pit samples, was characterized by significantly higher pollutant levels, while the other cluster included river and borehole samples that, despite being contaminated, demonstrated lower pollution indices. This grouping is essential for spatially delineating areas that require urgent intervention and for developing an efficient monitoring network.

Linear Discriminant Analysis (LDA) demonstrated that variables such as EC, COD, and ammonia have strong discriminative power in categorizing the different sample types. With a classification accuracy of 85%, these variables offer a reliable basis for predicting contamination status. They may be used as key markers in future monitoring programs, allowing for rapid screening and prioritization of remediation efforts.Finally, the computation of pollution index models such as the Water Quality Index (WQI) and the Heavy Metal Pollution Index (HPI) provided an integrative perspective on the overall quality of water within the study area. The WQI values for river water ranged from 55 to 70, categorizing the water as of poor quality. In contrast, the HPI for leachate exceeded 150, unequivocally highlighting a severe heavy metal pollution problem. These indices not only corroborate the findings from the individual parameter analyses but also present a holistic view of the pollution burden imposed by the dumpsite.

In summary, these statistical analyses collectively demonstrate that the Okhoro dumpsite exerts a significant adverse influence on nearby water quality and sediment composition. They also reveal that a combination of inorganic and organic pollutants, originating primarily from leachate, is disseminated through the hydrological system. The strong statistical relationships among key parameters, significant differences between sample types, and clustering of contaminated sites underscore the need for immediate and targeted remediation efforts. These results, when considered alongside findings from previous studies (Ogundiran & Afolabi, 2008; Alloway, 1995), indicate that the implementation of improved waste management practices and comprehensive environmental monitoring is urgently required to protect the local water resources and public health.

## 5.0 Conclusion

The study investigated the physicochemical, biochemical, and heavy metal characteristics of water and leachate samples from a municipal dumpsite and its surrounding environment. Key findings revealed that pH values across all samples remained within the WHO permissible limits of 6.5–8.5, suggesting slightly acidic to neutral conditions, with leachate samples showing more acidic tendencies. Electrical conductivity (EC) and total dissolved solids (TDS) were significantly elevated in the leachate and river water samples, exceeding WHO standards and indicating high ionic contamination likely due to leachate infiltration. Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels in the leachate were particularly high, with maximum values of 10.5 mg/L and 341.44 mg/L respectively, suggesting a high load of biodegradable and non-biodegradable organic pollutants. Ammonia concentrations also greatly surpassed acceptable limits, reaching up to 12 mg/L in leachate samples, compared to the WHO threshold of 0.5 mg/L. Heavy metals such as lead (Pb), iron (Fe), and chromium (Cr) were found at concentrations above regulatory guidelines in several samples, particularly in the river water and leachate, indicating anthropogenic contamination from waste materials.

Statistical analyses including correlation, ANOVA, PCA, and cluster analysis provided further insights. Pearson correlation showed strong positive relationships between EC and TDS ($r = 0.97$), COD and BOD ($r = 0.95$), and between some metals such as Fe and Pb (r

= 0.88), suggesting common sources of contamination. ANOVA confirmed significant differences in mean concentrations of most parameters across leachate, river, and borehole water, highlighting the impact of the dumpsite on water quality. Principal Component Analysis identified two main components: one dominated by organic pollutants and nutrients (BOD, COD, nitrate), and the other by metals (Fe, Pb, Cu), suggesting dual sources of pollution. Cluster analysis grouped the leachate samples separately from borehole and river samples, indicating distinct pollution profiles. The Water Quality Index (WQI) rated the leachate as unsuitable for any use, while river water ranged from poor to very poor quality. Heavy Metal Pollution Index (HPI) and Pollution Load Index (PLI) further confirmed the dumpsite as a major source of environmental degradation.

In conclusion, the dumpsite poses a significant threat to both surface and groundwater resources in the area. The elevated levels of organic load, ammonia, and heavy metals indicate ongoing contamination processes that may threaten ecosystem health and human wellbeing. Leachate migration is a key pathway for pollutant transport, particularly during the rainy season, with implications for shallow aquifers and river systems.

It is recommended that immediate remediation efforts be undertaken, including the containment and treatment of leachate using engineered barriers and constructed wetlands. Continuous groundwater monitoring should be implemented to assess long-term trends and prevent health risks. The establishment of regulatory enforcement for controlled waste disposal and the closure of uncontrolled dumpsites will be crucial in protecting the region's water quality. Public health awareness and community involvement in waste management strategies are also vital for sustainable environmental protection.

## 5.0 References

Ackermann, F., Bergmann, H., & Schleichert, U. (1983). Monitoring of heavy metals in coastal and estuarine sediments—a question of grain-size: <20 µm versus <60 µm. *Environmental Technology Letters, 4, pp.* 317–322.

Adegoke, O. S. (1990). Waste management within the context of sustainable development. In *Proceedings of a Workshop on the Environment and Sustainable Development in Nigeria* (pp. 103–117). Federal Environmental Protection Agency (FEPA).

Adelekan, B. A., & Abegunde, K. D. (2011). Heavy metals contamination of soil and groundwater at automobile mechanic villages in Ibadan, Nigeria. *International Journal of Physical Sciences*, 6(5), 1045–1058.

Ademoroti, C. M. A. (1996). *Environmental chemistry and toxicology*. Folutex Press Ltd.

Aigbadon, G.O., Okoro, A.U., Ocheli, A., Christopher, S.D., Nanfa, C.A. (2022). Geochemical analysis of Cenozoic Usani sandstone reservoirs, Niger Delta Basin, Nigeria: implications for reservoir quality and petroleum geology. *Journal of Mining and Geology*, 58(1):75-83 (Indexed in Google Scholar).

Ajayi, S. O., & Adeleye, S. A. (1977). Pollution studies and Nigerian Rivers. I: Preliminary report on the pollution level of River Ona and Ogunpa. *Bulletin of the Chemical Society of Nigeria*, *2*(1–2), 71–82.

Ajayi, S. O., & Osibanjo, O. (1981). Pollution studies on Nigerian Rivers II: Water quality of some Nigerian rivers. *Environmental Pollution Series B, 2*(1), 87–95.

Akan, J. C., Abdulrahman, F. I., & Ayodele, J. T. (2010). Heavy metals and physico-chemical parameters of water samples from River Benue in Adamawa state. *Nature and Science*, 8(8), 28–37.

Akujieze, C. N. (2001). *Anthropogenic activities on the Benin City urban groundwater* [Unpublished doctoral dissertation]. University of Benin.

Akujieze, C. N., & Irabor, E. E. (2014). Assessment of environmental degradation of soil and groundwater: A case study of waste disposal in Benin West Moat-Ekenwan gully Benin City, Edo State, Nigeria. African Journal of Environmental Science and Technology, 8(6), 381-390.

Alloway, B. J. (1995). *Heavy Metals in Soils*. Blackie Academic & Professional, London.

American Public Health Association. (1989). *Standard methods for the examination of water and wastewater* (17th ed.).

Avbovbo, A. A., Ayoola, E. Q., & Osahon, G. A. (1986). Depositional and structural styles in Chad Basin of Northeastern Nigeria. *AAPG Bulletin, 70*(12), 1787–1793.

Baas Becking, L. G. M., Kaplan, I. R., & Moore, D. (1960). Limits of the natural environment in terms of pH and oxidation-reduction potentials. *Journal of Geology, 68*(3), 243–284.

Badarudeen, A., Damodaran, K. T., Sajan, K., & Padmalal, D. (1996). Texture and geochemistry of sediments of a tropical mangrove ecosystem, Southwest coast of India. *Environmental Geology, 27*(3), 164–169.

Benka-Coker, M. O., & Ohirnain, E. M. (1995). Effects of an oil spill on soil physico-chemical properties in a Niger Delta mangrove ecosystem. *African Journal of Ecology, 33*(4), 345–352.

Benka-Coker, M. O., & Ojior, O. O. (1995). Impact of industrial effluents on the heavy metal content of River Osse sediments in Nigeria. *Environmental Monitoring and Assessment, 35*(2), 169–175.

Egborge, A. B. M. (1972). The seasonal variation in the physic-chemical conditions and plankton of the River Oshun, Western Nigeria. Freshwater Biology, 2(2), 177–191. https://doi.org/10.1111/j.1365-2427.1972.tb00369.x

Egborge, A. B. M. (1976). The chemical hydrology of the River Oshun, Western Nigeria. Freshwater Biology, 6(3), 257–272. https://doi.org/10.1111/j.1365-2427.1976.tb01610.x

Egborge, A. M., & Benka-Coker, M. O. (1986). The impact of organic pollution on the macrobenthic fauna of Benin River, Nigeria. *Hydrobiologia, 137*(1), 63–70.

Ezenabor, B. O. (1991). Riparian rights and water resources development in Nigeria. *Water Resources Journal, 1*(2), 4–9.

Forstner, U. (1980). *Contaminated sediments: Lectures on elementary processes, monitoring and management*. Springer.

Grimes, R. W. (1975). Petrology and geochemistry of the Nsuze Group, Pongola Sequence, South Africa. *Precambrian Research, 2*(1), 37–55.

Hanor, J. S. (1995). Controls on the origin and distribution of basinal brines. *SEPM Short Course Notes, 34*, 35–46.

Imevbore, A. M. A. (1970). The chemistry of the River Niger. Hydrobiologia, 36(3–4), 505–512. https://doi.org/10.1007/BF00039804

Jabich, H., & Stotzky, G. (1980). Environmental factors that influence the toxicity of heavy metal and gaseous pollutants to microorganisms. *Critical Reviews in Microbiology, 8*(1), 99–145.

Matzat, E., & Shiraki, H. (1974). Determination of trace metals in estuarine sediments by X-ray fluorescence spectrometry. *Analytical Chemistry, 46*(14), 2224–2228.

Mitchell, C., & Burridge, T. R. (1979). Trace element distributions in coastal sediments of Port Phillip Bay, Victoria, Australia. *Marine Pollution Bulletin, 10*(12), 356–359.

Ogundiran, M. B., & Afolabi, T. A. (2008). Assessment of the physicochemical parameters and heavy metal contents of leachates from a municipal solid waste landfill. *African Journal of Environmental Science and Technology*, 2(5), 128–132.

Oladosu, S. O., Alademomi, A. S., Olaleye, J. B., Olusina, J. O., & Salami, T. J. (2023). Evaluation of ANFIS Predictive Ability Using Computed Sediment from Gullies and Dam. Journal of the Nigerian Society of Physical Sciences, 1028-1028.

O'Reilly Wiese, S, Bubb, J. M. & Lester J. N. (1995). The significance of sediment metal concentrations in two eroding Essex salt marshes.Marine Pollution Bulletin 30:190–199.

Oronsaye, J. F., & Asuen, G. O. (1990). Heavy metal concentrations in soils and vegetation around a cement factory in Nigeria. *Environmental Pollution, 64*(2), 163–171.

Oteze, G. E. (1978). Water resources and supply in Nigeria. In *Proceedings of the National Conference of the Nigerian Society of Engineers* (pp. 104–118).

Owoseni, J. O. (2023). Landfill site suitability mapping for rational development planning: a GIS-based multi-criteria evaluation in Edo State, Nigeria. *GeoJournal*, *88*(5), 4603-4624.

Oyebande, L. (1989). Problems, needs and objectives of water resources planning in Nigeria. *Water Resources Journal of the Nigerian Association of Hydrologists*, *1*(2), 221–228.

Peterson, R. G., & Nielson, D. R. (1978). Sampling strategies for monitoring dissolved oxygen in rivers. *Water Research*, *12*(10), 803–808.

Pickford, J. (1978). The ecology of temporary waters. *Annual Review of Ecology and Systematics, 9*, 165–182.

Shu, W. S., & Bradshaw, A. D. (1995). The use of lichens as biomonitors of heavy metal pollution. *Environmental Reviews*, *3*(2), 145–161.

Talling, J. F., & Talling, I. B. (1965). The chemical composition of African lake waters. Internationale Revue der gesamten Hydrobiologie und Hydrographie, 50(3), 421–463. https://doi.org/10.1002/iroh.19650500307

USEPA (2002). *Sediment Quality Guidelines*. U.S. Environmental Protection Agency.

Vesilind, P. A., Peirce, J. J., & Weiner, R. F. (2002). *Environmental Pollution and Control*. Butterworth-Heinemann.

Visher, G. S. (1969). Grain size distributions and depositional processes. Journal of Sedimentary Petrology, 39(3), 1074–1106. https://doi.org/10.1306/74D71D9D-2B21-11D7-8648000102C1865D

Wali, M. K., Kannowski, P. B., & Cleland, D. T. (1972). The influence of organic matter on nutrient retention in lake sediments. Limnology and Oceanography, 17(3), 417–423.

https://doi.org/10.4319/lo.1972.17.3.0417

WHO (2017). *Guidelines for Drinking-Water Quality*. 4th ed., World Health Organization, Geneva.

Williams, C. H., & David, D. J. (1976). Heavy metal contamination of soils and plants around a lead smelter. *Environmental Pollution, 11*(3), 189–204.

**Compliance with Ethical Standards Declaration**

**Ethical Considerations**

Not applicable

**Competing interests**

The authors declare no known competing financial interests

**Data Availability**

Data shall be made available on request

**Conflict of Interest**

The authors declare no conflict of interest

**Funding**

The authors declared no external source of funding.

**Authors Contribution**

**Mr Vincent Oseikhuemen Binitie** is the lead investigator, developed the concept, carried-out the fielding mapping and laboratory analysis, drafted the manuscript and proof read the manuscript.

**Mr Joseph Odion Odia-Oseghale** carried-out the fielding mapping and laboratory analysis, drafted the manuscript and proof read the manuscript