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Assessment of Groundwater Quality, Contamination Risk, and Hydrogeochemical Characteristics Around Okitipupa Dumpsites, Southwestern Nigeria

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Abstract

Groundwater contamination from unmanaged dumpsites threatens water quality and public health in many developing countries. This study evaluated the physicochemical properties and contamination risk of groundwater around dumpsites in Okitipupa, Ondo State, Nigeria, during the dry season, January 2025. Sixteen samples were collected from Ayeka, Igodan, Market Area, and Irele Road as the reference site and analyzed for physicochemical parameters using standard methods. Data were analyzed with PCA, Water Quality Index (WQI), and health risk assessment in R and MicroCal Origin. The groundwater was generally acidic, with a pH below the WHO range of 6.5 to 8.5. The Market Area showed elevated electrical conductivity, total dissolved solids, and chloride, indicating strong leachate influence. After excluding phosphate and total suspended solids and verifying standards, WQI values ranged from 64.6 to 117.6. The Market Area had the poorest quality (WQI = 117.6; poor), while Ayeka, Igodan, and Irele Road were classified as good. The non-carcinogenic health-risk assessment, based on the stated reference doses for nitrate and phosphate, yielded HQ and HI values below 1 for adults and children at all locations. The Market Area remained the most impacted site overall, while contamination at the more distant locations suggests additional anthropogenic sources. A limitation is that sampling was limited to the dry season and to physicochemical parameters only.

Keywords: Groundwater contamination; dumpsite leachate; physicochemical analysis; water quality index; health risk assessment; SDG 6: Clean Water and Sanitation.

I. Introduction

Groundwater is a major source of drinking water in many regions experiencing water scarcity and is widely used for domestic, agricultural, and industrial purposes because of its accessibility and generally good quality [1–2]. However, population growth, rapid urbanization, industrial activities, agricultural practices, and indiscriminate waste disposal have contributed to groundwater quality deterioration worldwide. Contaminants from dumpsite leachate, rock weathering, atmospheric deposition, and other anthropogenic activities can alter groundwater chemistry and compromise its suitability for drinking and domestic use [3–6]. Recent studies in Nigeria have also reported groundwater contamination by persistent organic pollutants, petroleum hydrocarbons, and microorganisms associated with anthropogenic activities, emphasizing the need for continuous groundwater quality monitoring and risk assessment [7–8]. Groundwater contamination, therefore, remains an important environmental and public health concern.

Groundwater quality is controlled by both natural (geogenic) and human-induced (anthropogenic) processes. Its contamination can adversely affect soil quality, agricultural productivity, and human health [9], while excessive exploitation of this resource has been associated with increased acidity and elevated electrical conductivity [10], [11]. In Nigeria, the hydrochemistry of the Ogbaru area has been attributed to both geogenic and anthropogenic factors [12], while conditions in the Umunya district have similarly been linked to geological processes and human activities [13]. Studies in southwestern Nigeria have also reported polycyclic aromatic hydrocarbons and other anthropogenic contaminants in aquifers, highlighting their increasing vulnerability to human-induced pollution [14]. These findings underscore the importance of understanding local hydrogeological conditions and contamination sources when assessing water quality.

Okitipupa requires a detailed groundwater investigation because it is predominantly underlain by the Benin Formation, characterized by highly permeable sandy deposits, low clay content, and a shallow unconfined aquifer. These hydrogeological characteristics facilitate the infiltration and migration of surface contaminants into groundwater. In addition, open dumping remains the predominant method of municipal solid waste disposal in Okitipupa, with dumpsites lacking engineered liners and leachate collection systems. This increases the potential for leachate migration into the surrounding groundwater. Dumpsites in Ondo State have been identified as reservoirs of hazardous hydrocarbons capable of contaminating nearby soils and posing risks to environmental media and human health [15]. Open dumping has also been associated with the release of hazardous organic contaminants and persistent pollutants capable of infiltrating groundwater systems and increasing potential health risks [8], [15]. Given the reliance of residents on groundwater for domestic water supply, contamination of shallow aquifers could have significant environmental and public health consequences.

Although several groundwater quality studies have been conducted in southwestern Nigeria, no comprehensive study integrating hydrogeochemical facies analysis, multivariate statistical techniques, Water Quality Index (WQI), and quantitative human health risk assessment has been conducted around the Okitipupa municipal dumpsites. Consequently, the hydrogeochemical evolution, contamination sources, and potential health implications of groundwater in the area remain poorly understood. A comprehensive groundwater quality assessment is therefore necessary to support evidence-based environmental management, sustainable water resource protection, and public health protection.

This study provides a comprehensive baseline assessment of groundwater quality in Okitipupa by integrating physicochemical characterization, WQI evaluation, Piper and Gibbs hydrogeochemical diagrams, Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and quantitative health risk assessment to distinguish geogenic and anthropogenic controls. Specifically, the study aimed to: (i) assess the physicochemical characteristics of groundwater around selected municipal dumpsites in Okitipupa, Ondo State, Nigeria; (ii) evaluate groundwater quality using WQI; (iii) determine hydrogeochemical facies and controlling geochemical processes using Piper and Gibbs diagrams; (iv) identify major sources of groundwater contamination using PCA and HCA; and (v) evaluate the non-carcinogenic human health risks associated with groundwater consumption.

II. Materials and Methods

A. Description of the Study Area

Okitipupa is a town in southwestern Nigeria and the administrative headquarters of Okitipupa Local Government Area, Ondo State. It lies within the Niger Delta sedimentary basin between latitudes 6°28′ and 6°30′N and longitudes 4°45′ and 4°50′E. The area is predominantly underlain by the Benin Formation, characterized by poorly consolidated, highly permeable fine- to coarse-grained coastal plain sands intercalated with thin clay lenses. This geological setting hosts a shallow unconfined aquifer at a depth of 5 to 20 m, making it susceptible to surface-derived contamination [16–20].

The region has a warm tropical climate with distinct rainy and dry seasons. The porous soils and shallow water tables facilitate subsurface water movement and increase the vulnerability of the aquifer to contamination, particularly during heavy rainfall. Improper waste management further increases this risk, as household wastes, including batteries, plastics, and electronic materials, may release hazardous substances that infiltrate the soil and water sources. The town has an estimated population of about 316,100 [16].

Annual temperatures range from 26 to 28 °C, with the highest temperatures occurring from January to March and cooler conditions in August. Annual rainfall ranges from 1,800 to 2,000 mm, occurring mainly between March and

October and supporting groundwater recharge [21–22]. Relative humidity ranges from 70 to 90%, while wind speeds range from 2.0 to 3.5 m/s [17].

Fig. 1 shows the study locations, while Table I presents the geographical coordinates of the sampling sites. Ayeka, Market Road, Igodan, and Irele are designated A, M, I, and R, respectively.

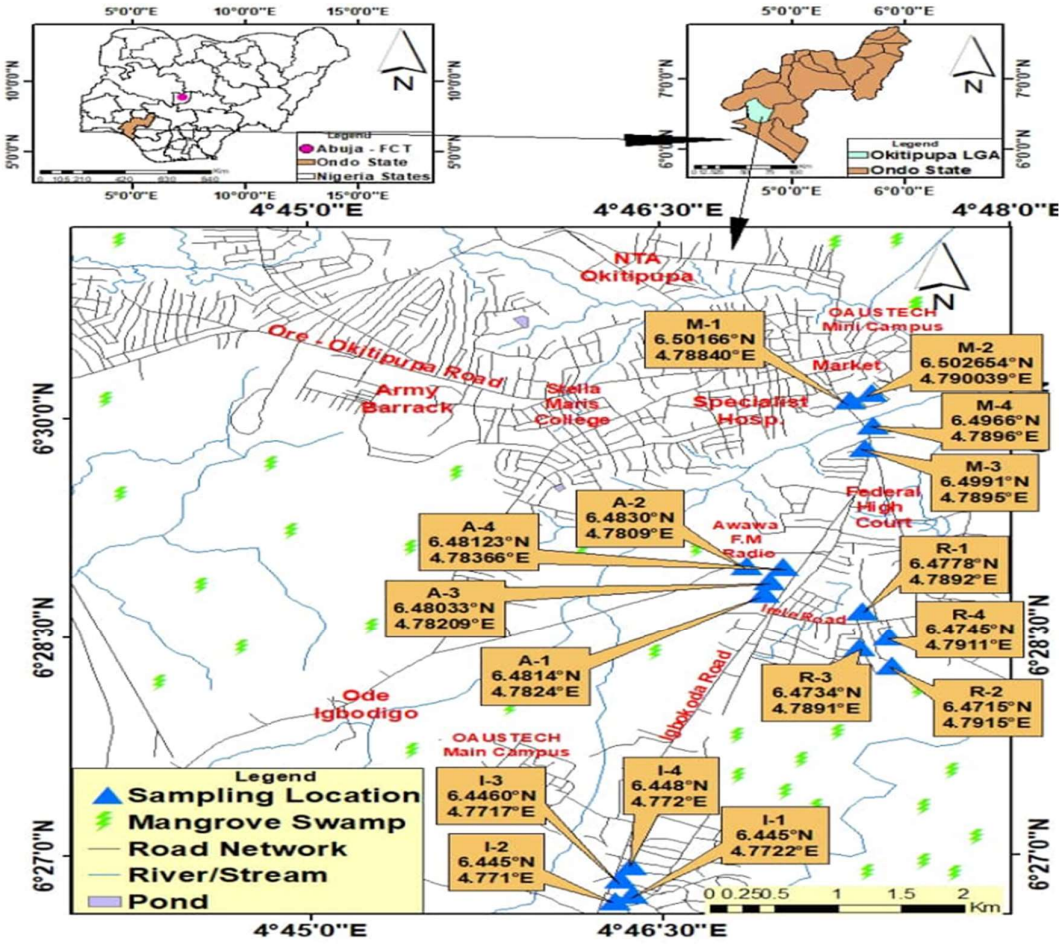

Fig. 1. Geographical map of the study locations in Okitipupa.

Table I. Geographical locations of sampling sites.

Sampling Locations	Coordinates (Decimal Degrees)	Distance from Nearest Dumpsite (m)
A_1	6.48143°N, 4.78240°E	~280 m (Ayeka dumpsite)
A_2	6.48300°N, 4.78097°E	~220 m
A_3	6.48033°N, 4.78209°E	~190 m
A_4	6.48123°N, 4.78367°E	~300 m
M_1	6.50166°N, 4.78840°E	~50 m (Market dumpsite)
M_2	6.50265°N, 4.79004°E	~80 m
M_3	6.49910°N, 4.78960°E	~120 m
M_4	6.49665°N, 4.78963°E	~150 m
I_1	6.44500°N, 4.77220°E	~160 m (Igodan dumpsite)
I_2	6.44500°N, 4.77100°E	~200 m
I_3	6.44600°N, 4.77170°E	~175 m
I_4	6.44800°N, 4.77200°E	~240 m
R_1	6.47780°N, 4.78920°E	>2,000 m (control)
R_2	6.47150°N, 4.79150°E	>2,000 m (control)
R_3	6.47340°N, 4.78910°E	>2,000 m (control)
R_4	6.47450°N, 4.79110°E	>2,000 m (control)

B. Sampling Design and Well Description

Sampling was conducted in January 2025, during the peak dry season. During this period, water levels are generally at their lowest seasonal levels, while dissolved-ion concentrations are elevated relative to wet-season conditions because of reduced dilution and enhanced evaporative concentration [18].

Sixteen groundwater samples were collected from the four locations using 1-L polyethylene bottles. Before sampling, the bottles were pre-cleaned with distilled water and rinsed five times with sample water. Twelve samples were collected within 50 to 300 m of three dumpsites at Okitipupa Market Area, Ayeka, and Igodan, with four samples obtained from each location. The remaining four samples were collected along Irele Road, more than 2 km from the studied dumpsites, and served as the reference site because direct influence from dumpsite leachate was assumed to be minimal. However, the site was not considered pristine, as diffuse anthropogenic activities, including roadside runoff, septic systems, and domestic activities, may influence water quality.

Samples were obtained from hand-dug wells, which are the primary water sources for residents. The wells are approximately 8 to 15 m deep, lined with PVC casing to prevent wall collapse, and were constructed approximately 5–10 years ago.

C. Sample Preservation and Quality Assurance

After collection, samples were transported in an ice chest and stored at 4 °C upon arrival at the laboratory, where they were analyzed within 24 h to minimize chemical and biological changes. For quality assurance and quality control, sample bottles were washed with detergent, rinsed with tap water, soaked in 10% nitric acid for 24 h, and finally rinsed with deionized water. All physicochemical parameters were measured in triplicate, with relative standard deviations maintained below 5%. Method and reagent blanks were analyzed alongside the samples to assess cross-contamination. Analytical instruments were calibrated with standard solutions before each batch of measurements, while standard reference materials were used to verify analytical accuracy.

D. Laboratory Analysis

Total dissolved solids (TDS), pH, and electrical conductivity (EC) were measured in situ [2]. Sulfate and nitrate were determined by spectrophotometry, while calcium, magnesium, potassium, and sodium were determined by titration and flame photometry. Chloride and phosphate were determined using a titrimetric method, while turbidity and total suspended solids (TSS) were measured using a nephelometer and a gravimetric method, respectively. Bicarbonate was determined by acid-base titration using 0.02 N hydrochloric acid with a bromocresol green-methyl orange indicator for evaluating hydrogeochemical facies and calcium-bicarbonate dominance.

Heavy metals and microbiological parameters were not analyzed due to budgetary and instrumentation constraints and are recommended for future research. Additionally, the low pH values observed across the study sites may enhance metal solubility [12], making heavy metal assessment a priority for future studies.

E. Statistical Analysis

The data were statistically analyzed using MicroCal OriginPro 8.5. Correlation plots of the physicochemical parameters were generated using the R package OpenAir to examine relationships among factors affecting water quality. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were performed using SPSS version 26 on log-transformed, z-score-standardized data to identify contamination sources and classify sampling sites according to hydrochemical similarity. Before PCA, the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were performed. Varimax rotation was used to improve component interpretability.

F. Water quality index

Groundwater quality was evaluated using the Water Quality Index (WQI), a single-value indicator for assessing the effects of natural and human-induced pollution on the suitability of water for drinking [4], [19], [23–24]. The WQI assigns weights to physicochemical parameters based on World Health Organization (WHO) standards and their relative importance. The calculation involved five steps: assigning a weight to each parameter based on its health significance; calculating the relative weight by dividing each assigned weight by the sum of all assigned weights; determining the quality rating from the measured concentration and corresponding guideline value; calculating the sub-index from the relative weight and quality rating; and obtaining the overall WQI by summing the sub-indices.

The initial parameter set included total suspended solids (TSS) because high concentrations of suspended particles can harbor pathogens, reduce light penetration, and indicate surface runoff or soil erosion, which are important factors in shallow aquifer vulnerability. The initial set was subsequently reviewed against the applicable WHO and NIS 554:2015 drinking-water standards. Because no numerical drinking-water limits are specified for phosphate or TSS, both parameters were excluded from the final standards-based composite WQI, and the relative weights of the remaining parameters were renormalized. Table II presents the initial assigned weight (w_i) and relative weight (W_i) scheme. The WQI was calculated using (1) [19].

$$WQI=\frac{\sum w_i \times q_i}{W_i} \quad (1)$$

where w_i is the weight assigned to each parameter, and W_i is the relative weight, calculated as given by (2).

$$W_i=\frac{w_i}{\sum w_i} \quad (2)$$

The quality rating (q_i) for each parameter was determined according to WHO standards, as outlined in (3).

$$q_i = \left(\frac{c_i}{s_i}\right) \times 100 \quad (3)$$

where c_i is the measured concentration and s_i is the corresponding WHO guideline value.

The sub-index (SI_i) for each parameter and the composite WQI were calculated using (4) and (5).

$$SI_i = W_i \times q_i \quad (4)$$

$$WQI = \sum SI_i \quad (5)$$

Table II. Initial Weight of Parameters (w_i) and Relative Weight (W_i)

Parameter	w_i	W_i
PO_4	1	0.022
Cl	5	0.114
TSS	3	0.068
Nitrate	5	0.114
pH	4	0.091
EC	4	0.091
TDS	5	0.114
Turbidity	3	0.068
SO_4	5	0.114
Ca	3	0.068
Mg	3	0.068
K	2	0.045
Na	2	0.045
Total	45	1.000

G. *Hydrogeochemical Analysis*

To evaluate groundwater chemistry and identify the dominant hydrogeochemical processes, Piper trilinear and Gibbs diagrams were generated using AquaChem software. Ion ratios were used to distinguish natural weathering from human-induced leachate inputs following established procedures [1], [12]. The sodium-to-chloride ratio (Na/Cl) was used to assess salinity sources, with values near unity indicating halite dissolution or seawater intrusion and deviations suggesting other weathering processes. The calcium-to-magnesium ratio (Ca/Mg) was used to identify sources of hardness, with higher values indicating calcite weathering and lower values suggesting dolomite dissolution. The (Ca+Mg)/(Na+K) ratio was used to assess the relative dominance of alkaline earth and alkali metals and the influence of carbonate weathering. The chloride-to-bicarbonate ratio (Cl/HCO_3) was used as an indicator of anthropogenic pollution, with higher values suggesting contamination from waste leachates or agricultural runoff.

H. *Health Risk Assessment*

Non-carcinogenic health risk was assessed using the United States Environmental Protection Agency Hazard Quotient model. Chronic daily intake through oral ingestion was estimated from contaminant concentration, ingestion rate, exposure frequency, exposure duration, body weight, and averaging time. Ingestion rates of 2.0 and 1.0 L/day were used for adults and children, respectively, with an exposure frequency of 365 days/year. Exposure durations were 30 years for adults and 6 years for children, while body weights were 70 and 15 kg, respectively. Averaging time was calculated as the exposure duration multiplied by 365 days.

The Hazard Quotient (HQ) was calculated by dividing chronic daily intake by the reference dose, while the Hazard Index (HI) was obtained as the sum of individual HQs. For the final risk calculation, nitrate and phosphate were retained because contaminant-specific oral reference doses are stated and cited in this study. Nitrate concentration was expressed as nitrate-nitrogen for comparison with the chronic oral reference dose of 1.6 mg nitrate-nitrogen/kg body weight/day [25]. Phosphate concentration was expressed as phosphorus for comparison with the chronic reference dose of 1 mg phosphorus/kg body weight/day for sodium and potassium salts of inorganic phosphate [26]. Although a subchronic phosphate reference dose of 4 mg phosphorus/kg body weight/day is also reported in [26], the chronic value was used for this assessment. Chloride was excluded because a chloride-specific oral reference dose was not provided in the cited methodology. HI values greater than 1 indicate a possible non-carcinogenic health risk.

III. Results and Discussion

A. *Physicochemical Parameters*

Table III presents the physicochemical properties of water samples from Ayeka, Igodan, Market Area, and Irele Road. Mean pH values were 5.59, 5.05, 3.90, and 4.66, respectively, with an overall range of 3.68–6.28. These values were below the WHO [27] recommended range of 6.5–8.5, indicating acidic conditions across the study sites. This agrees with findings from southern Nigeria, where low pH was attributed to pyrite oxidation and weathering of subsurface rocks [12]. Acidic conditions may enhance metal dissolution and increase ion concentrations.

Electrical conductivity (EC) ranged from 16.40 to 533.0 µS/cm and remained within the WHO [27] guideline of 1500 µS/cm. The Market Area recorded the highest mean EC (320.60 µS/cm), suggesting increased mineralization from ion leaching from soil and rock, consistent with [28]. Total dissolved solids (TDS) ranged from 16.35 to 355.32 mg/L and remained below the WHO [27] limit of 500 mg/L. The Market Area recorded the highest mean TDS (213.58 mg/L), followed by Igodan (180.35 mg/L), possibly reflecting anthropogenic inputs from waste disposal and agricultural runoff [29]. Although WHO [27] and NIS 554:2015 [35] do not specify a numerical drinking-water limit for TSS, the elevated values at the Market Area (264.60 mg/L) and Igodan (39.70 mg/L) indicate particulate contamination, surface runoff, or waste-derived inputs [30].

Chloride concentrations ranged from 23.36 to 127.62 mg/L across the study locations, with mean values of 31.60, 61.42, 56.50, and 30.26 mg/L at Ayeka, Igodan, Market Area, and Irele Road, respectively. Nitrate levels ranged from 2.07 to 3.94 mg/L. Both chloride and nitrate were below the WHO [27] limits of 250 and 50 mg/L, respectively. The relatively

higher chloride concentration in the Market Area may be linked to domestic waste discharge and soil salt leaching, while the low nitrate concentrations suggest a lower risk of contamination from fertilizers or organic waste [12], [31].

Table III. Physicochemical parameter values for all sites.

Parameter	Units	Sampling Location	Range	Mean	SD	Variance
PO_4^{3-}	mg/L	Ayeka	0.18–0.43	0.29	0.03	0.0009
		Igodan	0.15–0.43	0.28	0.04	0.0016
		Market Area	0.28–1.16	0.61	0.13	0.0169
		Irele Road	0.09–1.93	1.01	0.31	0.0961
Cl^-	mg/L	Ayeka	29.77–33.43	31.60	2.14	4.58
		Igodan	49.28–72.54	61.42	12.87	165.64
		Market Area	23.36–127.62	56.50	48.06	2309.76
		Irele Road	24.82–35.45	30.26	4.65	21.62
TSS	mg/L	Ayeka	13.00–24.00	18.70	5.61	31.47
		Igodan	6.00–130.00	39.70	60.29	3634.88
		Market Area	11.60–975.00	264.60	473.78	224467.49
		Irele Road	6.00–96.54	20.90	22.07	487.08
NO_3^-	mg/L	Ayeka	2.24–2.82	2.61	0.27	0.07
		Igodan	2.23–2.50	2.38	0.12	0.01
		Market Area	2.17–3.94	2.90	0.80	0.64
		Irele Road	2.07–3.07	2.41	0.32	0.10
pH	–	Ayeka	5.35–6.28	5.59	0.41	0.17
		Igodan	4.47–5.56	5.05	0.52	0.27
		Market Area	3.68–4.31	3.90	0.28	0.08
		Irele Road	4.03–5.15	4.66	0.53	0.28
EC	µS/cm	Ayeka	24.5–113.0	51.38	41.93	1758.12
		Igodan	16.40–103.00	46.20	38.78	1503.89
		Market Area	65.5–533.0	320.60	242.67	58888.73
		Irele Road	32.9–105.0	86.08	35.46	1257.41
TDS	mg/L	Ayeka	16.35–87.33	37.25	33.85	1145.82
		Igodan	19.14–319.79	180.35	158.87	25239.68
		Market Area	43.66–355.32	213.58	161.89	26208.37
		Irele Road	21.99–70.00	57.39	23.61	557.43
Turbidity	NTU	Ayeka	0.90–4.30	1.88	1.62	2.62
		Igodan	0.80–1.20	1.05	0.19	0.04
		Market Area	0.70–1.00	0.83	0.13	0.02
		Irele Road	0.50–1.90	1.08	0.60	0.36
SO_4^{2-}	mg/L	Ayeka	17.25–33.90	22.60	7.68	58.98
		Igodan	19.03–28.55	23.34	4.27	18.23
		Market Area	15.46–26.77	19.93	5.51	30.36
		Irele Road	11.30–30.93	23.20	8.39	70.39
Ca^{2+}	mg/L	Ayeka	0.08–0.59	0.39	0.22	0.05
		Igodan	0.06–0.88	0.43	0.39	0.15
		Market Area	1.65–23.15	12.37	12.25	150.06
		Irele Road	0.25–3.29	1.19	1.41	1.99
Mg^{2+}	mg/L	Ayeka	0.06–0.40	0.25	0.14	0.02
		Igodan	0.06–0.48	0.25	0.21	0.04
		Market Area	0.73–4.26	2.53	1.82	3.31
		Irele Road	0.05–0.60	0.36	0.24	0.06
K^+	mg/L	Ayeka	0.01–3.50	0.89	1.74	3.03
		Igodan	0.01–0.81	0.28	0.38	0.14
		Market Area	1.31–15.04	8.62	7.18	51.55
		Irele Road	0.00–0.81	0.45	0.42	0.18
Na^+	mg/L	Ayeka	0.82–1.50	1.31	0.33	0.11
		Igodan	1.40–5.44	2.91	1.78	3.17
		Market Area	4.23–35.00	21.13	16.19	262.12
		Irele Road	1.01–4.50	2.90	4.59	21.07
HCO_3^-	mg/L	Ayeka	20.0–45.0	32.5	10.2	104.04
		Igodan	25.0–55.0	40.0	12.5	156.25
		Market Area	30.0–85.0	55.0	22.0	484.00
		Irele Road	15.0–40.0	28.0	8.5	72.25

Phosphate and sulfate concentrations ranged from 0.09 to 1.93 mg/L and 11.30 to 33.90 mg/L, respectively, across all sites. Because WHO [27] and NIS 554:2015 [35] do not specify a numerical drinking-water limit for phosphate, the mean phosphate concentration of 0.54 ± 0.18 mg/L was considered in relation to possible inputs from agricultural runoff, domestic wastewater, and detergents. Turbidity values ranged from 0.50 to 4.30 NTU.

For the observed cations, calcium, magnesium, potassium, and sodium concentrations ranged from 0.06 to 23.15, 0.05 to 4.26, 0.00 to 15.04, and 0.82 to 35.00 mg/L, respectively, across the study locations. The average cation concentrations in Igodan, the Market Area, and Irele Road followed the decreasing order sodium > calcium > potassium > magnesium, while Ayeka followed sodium > potassium > calcium > magnesium. The anion dominance sequence across all sites was chloride > sulphate > nitrate > phosphate. The presence of calcium and magnesium in the groundwater samples may be due to dissolution of minerals within the local sedimentary formation [13], [32].

Overall, the consistently acidic pH remained the clearest standards-related concern. Elevated chloride, total dissolved solids, total suspended solids, phosphate, and sodium in parts of the study area were interpreted as indicators of anthropogenic influence [34]. However, the elevated phosphate concentration at Irele Road also indicates that water quality at the reference site may be influenced by other anthropogenic activities.

Fig. 2(a–c) illustrates the spatial variation of the measured physicochemical parameters across the four sampling locations. The plots show that the Market Area generally recorded higher values of EC, TDS, TSS, and major cations than the other locations, reflecting greater anthropogenic influence, while the acidic pH observed at all sites is also evident.

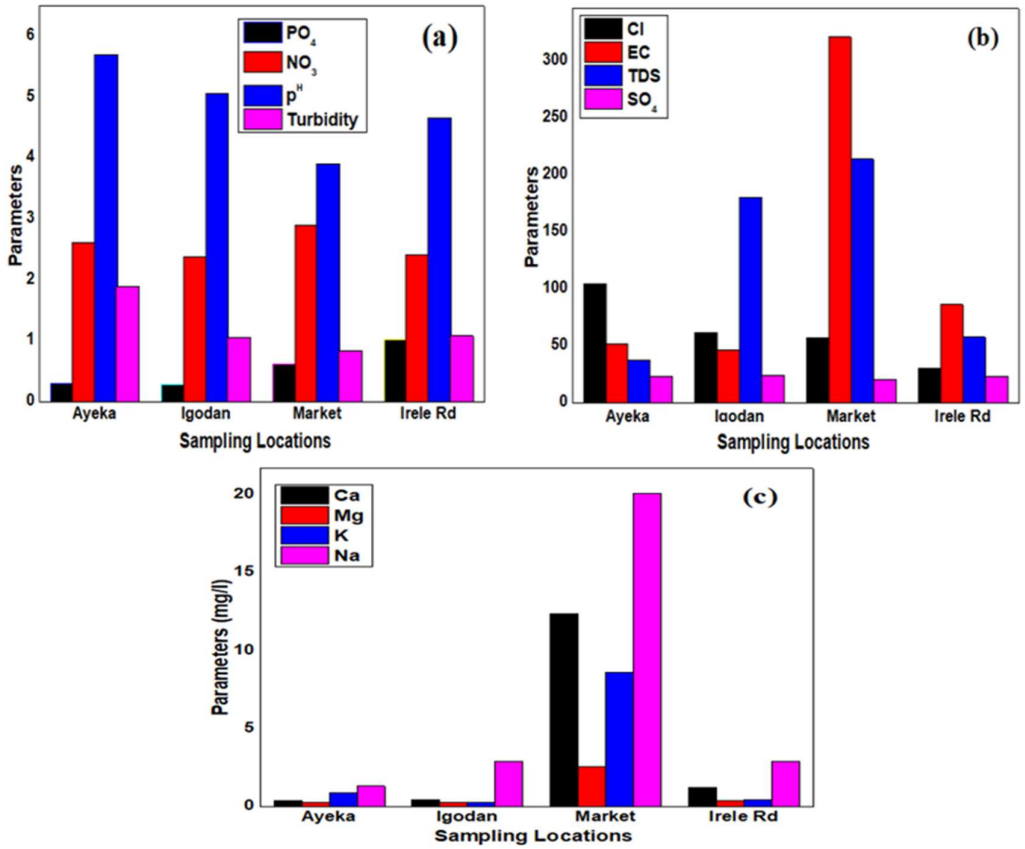

Fig. 2. Spatial variation of the physicochemical parameters of groundwater samples from the study locations: (a), (b), and (c).

Table IV presents the minimum, maximum, and mean ± standard deviation of the measured physicochemical parameters alongside their corresponding drinking-water standards. The overall mean concentrations were 0.54 mg/L for phosphate and 85.99 mg/L for TSS. Neither the WHO guidelines nor NIS 554:2015 [35] specifies numerical limits for phosphate or total suspended solids. Therefore, these two parameters are discussed only as environmental indicators of nutrient enrichment, particulate load, surface runoff, and possible anthropogenic influence. While pH values fell below the acceptable range, the remaining parameters were assessed against their applicable standards.

Table IV. Summary of physicochemical parameters for all sites combined.

Parameters	Units	Minimum	Maximum	Mean ± SD	WHO [27]	NIS 554:2015 [35]
PO_4^{3-}	mg/L	0.09	1.93	0.54 ± 0.18	Not specified	Not specified
Cl^-	mg/L	23.36	127.62	44.95 ± 26.71	250	250
TSS	mg/L	6.00	975.00	85.99 ± 239.04	Not specified	Not specified
NO_3^-	mg/L	2.07	3.94	2.57 ± 0.46	50	50
pH	–	3.68	6.28	4.82 ± 0.77	6.5–8.5	6.5–8.5
EC	µS/cm	16.40	533.00	126.06 ± 162.44	1500	1000
TDS	mg/L	16.35	355.32	122.14 ± 129.63	500	500
Turbidity	NTU	0.50	4.30	1.21 ± 0.88	5	5
SO_4^{2-}	mg/L	11.30	33.90	22.27 ± 6.14	250	100
Ca^{2+}	mg/L	0.06	23.15	3.59 ± 7.61	50	75
Mg^{2+}	mg/L	0.05	4.26	0.85 ± 1.30	No health-based guideline value	20
K^+	mg/L	0.00	15.04	2.56 ± 4.91	No health-based guideline value	Not specified
Na^+	mg/L	0.82	35.00	7.06 ± 11.16	200	20
HCO_3^-	mg/L	15.0	85.0	38.88 ± 18.50	No specific guideline value	Not specified

Bicarbonate concentrations ranged from 15.0 to 85.0 mg/L, with mean values of 32.5, 40.0, 55.0, and 28.0 mg/L at Ayeka, Igodan, Market Area, and Irele Road, respectively. As neither WHO [27] nor NIS 554:2015 [35] specifies a numerical guideline value for bicarbonate, the concentrations were interpreted hydrogeochemically and support the calcium-magnesium-bicarbonate facies associated with natural weathering.

B. Hydrogeochemical Facies and Source Attribution

Piper trilinear diagrams were used to classify the hydrogeochemical characteristics of the 16 groundwater samples (Fig. 3). Two water types were identified: calcium-magnesium-bicarbonate at Ayeka and Igodan, reflecting natural silicate and carbonate mineral weathering within the Benin Formation, and sodium-potassium-chloride at the Market Area, indicating anthropogenic inputs of sodium, potassium, and chloride from leachate. Irele Road samples plot within a transitional calcium-magnesium-bicarbonate to mixed calcium-magnesium-chloride-sulphate zone, attributable to slight contamination despite their distance from active dumpsites.

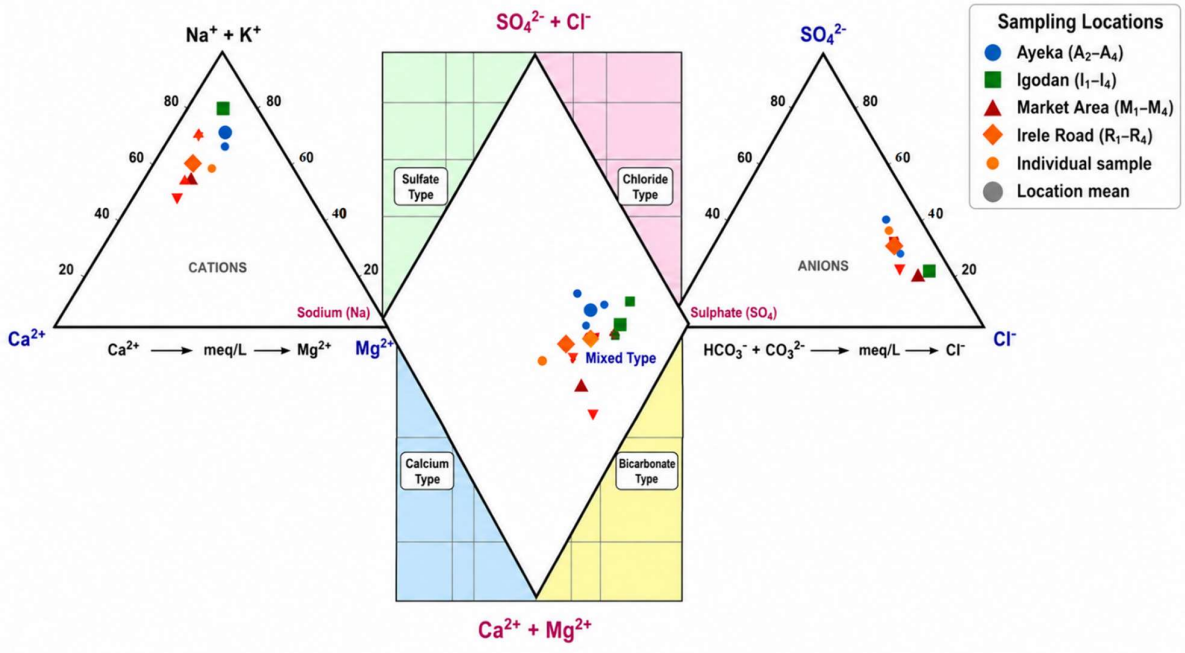

Fig. 3. Piper trilinear diagrams for groundwater around Okitipupa dumpsites.

Analysis of the Gibbs diagram in Fig. 4 shows that most samples lie within the rock-water interaction domain, confirming that geogenic mineral dissolution is the dominant control on background groundwater chemistry. However, samples from the Market Area fall within the evaporation-concentration domain with elevated sodium and chloride ratios, suggesting leachate contamination superimposed on the geogenic background.

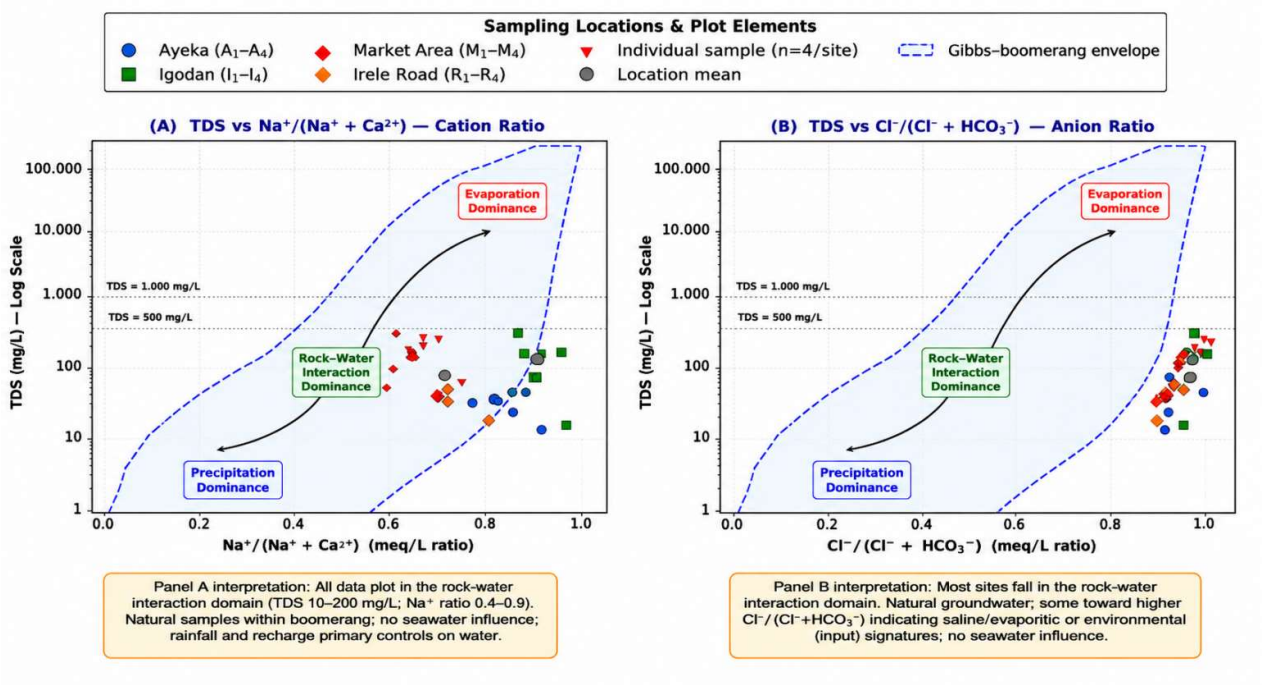

Fig. 4. Gibbs diagrams for groundwater around Okitipupa dumpsites.

Further evidence for source differentiation was obtained from the ion ratio analysis presented in Table V.

Table V. Ion ratios for groundwater samples across the study locations.

Site	Na/Cl	Ca/Mg	(Ca+Mg)/(Na+K)	Cl/HCO_3
Ayeka	0.85	1.56	2.10	0.98
Igodan	0.72	1.72	2.45	1.54
Market	0.27	4.89	1.15	1.03
Irele	0.95	3.31	2.80	1.08

The Na/Cl molar ratio at the Market Area was substantially lower than the seawater reference value of 0.86, suggesting that anthropogenic chloride contributions from dumpsite leachate are dominant over marine sources. Ca/Mg ratios greater than 1 indicate the dominance of calcite weathering over dolomite dissolution within the sedimentary lithology. Similarly, (Ca+Mg)/(Na+K) ratios greater than 1 indicate that alkaline earth metals exceed alkali metals, confirming carbonate weathering. Finally, Cl/HCO_3 ratios greater than 1 at most sites indicate anthropogenic pollution, with higher values suggesting significant contamination from waste leachates or domestic runoff.

C. Multivariate Statistical Analysis

Statistical evaluation of the groundwater data yielded a Kaiser-Meyer-Olkin (KMO) value of 0.71 and a significant Bartlett test, confirming the suitability of the data for principal component analysis (PCA). Three principal components were identified, explaining 78.3% of the total variance in groundwater chemistry. Table VI presents the principal component loadings for all groundwater quality parameters.

Table VI. Principal Component Analysis loadings for groundwater quality parameters

Variable	PC1	PC2	PC3
pH	-0.15	-0.10	-0.81
EC	0.91	0.12	0.05
TDS	0.89	0.15	0.08
TSS	0.20	0.10	0.72
Turbidity	0.15	0.08	0.76
Cl^-	0.82	0.25	0.10
SO_4^{2-}	0.30	0.79	0.15
NO_3^-	0.45	0.20	0.30
PO_4^{3-}	0.73	0.15	0.25
Ca^{2+}	0.40	0.87	0.10
Mg^{2+}	0.35	0.83	0.12
Na^+	0.88	0.18	0.05
K^+	0.85	0.10	0.08
HCO_3^-	0.50	0.65	0.20
Eigenvalue	5.38	3.44	2.14
Variance (%)	38.4	24.6	15.3
Cumulative (%)	38.4	63.0	78.3

The first principal component (PC1), which accounted for 38.4% of the total variance, showed strong positive loadings on EC, TDS, sodium, potassium, chloride, and phosphate. This component was interpreted as an anthropogenic leachate factor associated with contamination from open dumpsites. PC1 scores were consistently highest at the Market Area sites, suggesting that leachate infiltration is a major contributor to the observed contamination at these locations.

The second principal component (PC2) accounted for 24.6% of the total variance and showed strong positive loadings for calcium, magnesium, and sulfate. This component was interpreted as a geogenic mineral weathering factor, representing the dissolution of calcite, dolomite, and sulfide minerals within the Benin Formation. Contributions from all four sampling sites suggest a widespread natural influence.

The third principal component (PC3) accounted for 15.3% of the total variance and was strongly associated with pH, turbidity, and TSS. This component was interpreted as a surface runoff and soil leaching factor. The negative loading of pH suggests acidification caused by oxidative weathering and decomposition of organic matter, while increased turbidity and TSS are associated with erosion-related particle transport during rainstorm events.

Hierarchical Cluster Analysis (HCA), using Ward linkage and Euclidean distance, grouped the samples into two distinct clusters, as shown in Fig. 5.

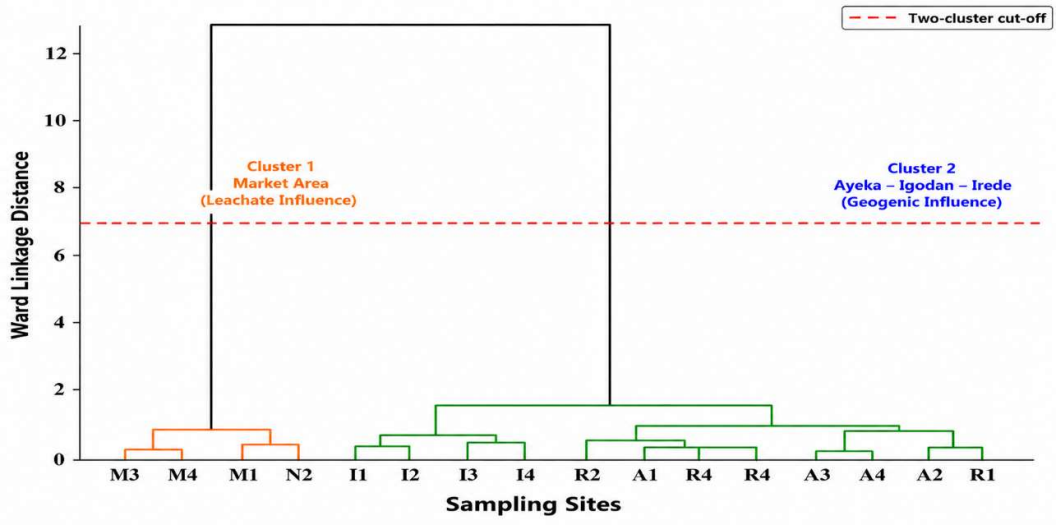

Fig. 5. Hierarchical cluster analysis dendrogram showing the grouping of sampling sites.

The dendrogram shows two distinct clusters. Cluster 1 comprises the Market Area sites, characterized by elevated EC, TDS, sodium, potassium, and chloride concentrations, consistent with strong leachate influence. Cluster 2 comprises the Ayeka, Igodan, and Irele Road sites, which exhibit lower overall mineralization and are dominated by geogenic weathering products.

D. Water Quality Index Results

Table VII presents the parameter quality ratings used in the revised WQI calculation. Phosphate and total suspended solids were excluded because neither WHO [27] nor NIS 554:2015 [35] provides a numerical drinking-water limit for these parameters. After their removal and renormalization of the relative weights, the composite WQI values were 88.3 for Ayeka, 87.0 for Igodan, 117.6 for the Market Area, and 64.6 for Irele Road. The Market Area remained the most impacted location and was classified as poor, while Ayeka, Igodan, and Irele Road were classified as good. The "good" WQI classification represents the overall composite water-quality status and does not necessarily indicate compliance with every individual drinking-water parameter.

The parameter-level ratings indicate that acidic pH remained an important concern across the four locations. Electrical conductivity and total dissolved solids were more elevated in the Market Area, supporting the interpretation of increased mineralization and waste-derived ionic inputs. Chloride, nitrate, turbidity, sulfate, and the measured cations showed spatial differences consistent with the hydrochemical and multivariate analyses. Total suspended solids continued to be considered descriptively as an indicator of erosion, runoff, and particulate contamination, but it was not assigned a WQI rating.

Phosphate was similarly retained as a descriptive nutrient indicator and was not assigned a guideline-compliance or WQI class. This distinction prevents unsupported numerical values from influencing the composite index while preserving the environmental relevance of the measured phosphate and TSS concentrations. The WQI results, therefore, identify the Market Area as the location with the poorest overall water quality.

Table VII. Water Quality Index (WQI) values for all sites.

Parameters	Ayeka	WQ Class	Igodan	WQ Class	Market Area	WQ Class	Irele Road	WQ Class
Cl	210.0	Unfit	125.0	Unfit	115.0	Unfit	60.0	Mod. poor
NO_3	25.0	Excellent	25.0	Excellent	30.0	Good	25.0	Excellent
pH	352.0	Unfit	312.0	Unfit	240.0	Unfit	288.0	Unfit
EC	40.0	Good	36.0	Good	256.0	Unfit	68.0	Mod. poor
TDS	35.0	Good	180.0	Unfit	215.0	Unfit	55.0	Mod. poor
Turbidity	114.0	Unfit	63.0	Mod. poor	51.0	Mod. poor	66.0	Mod. poor
SO_4	45.0	Good	45.0	Good	40.0	Good	45.0	Good
Ca	3.0	Excellent	3.0	Excellent	75.0	Very poor	6.0	Excellent
Mg	1.5	Excellent	1.5	Excellent	3.0	Excellent	0.2	Excellent
K	14.0	Excellent	4.0	Excellent	144.0	Unfit	8.0	Excellent
Na	2.0	Excellent	2.0	Excellent	22.0	Excellent	2.0	Excellent

Overall, the parameter-specific WQI results indicate that the Market Area and Irele Road were among the most impacted locations, with several standards-based parameters classified as moderately poor or unfit. Ayeka and Igodan generally showed better parameter-specific water quality, although acidic pH remained an important concern across all locations. Phosphate and TSS were excluded from these parameter-level WQI ratings and were retained only as descriptive environmental indicators.

The composite WQI values and corresponding water quality classifications are presented in Table VIII. Irele Road recorded the lowest composite WQI of 64.6 and was classified as good. Igodan and Ayeka recorded values of 87.0 and 88.3, respectively, and were also classified as good, while the Market Area recorded the highest composite WQI of 117.6 and was classified as poor.

Table VIII. Composite Water Quality Index and classification for the study locations.

Site	Composite WQI	Water Class
Ayeka	88.3	Good
Igodan	87.0	Good
Market Area	117.6	Poor
Irele Road	64.6	Good

E. *Correlation Between Water Quality Parameters*

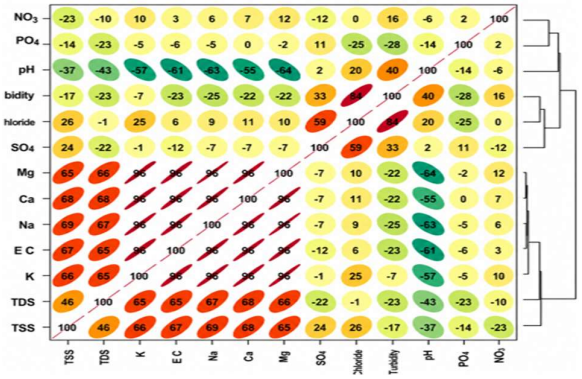

Fig. 6. Correlation plots of physicochemical parameters from sampling points in Okitipupa.

Fig. 6 is a correlation plot showing the correlation coefficients among various groundwater quality parameters. TSS exhibited weak positive correlations with TDS (0.46), SO_4^{2-} (0.24), and Cl^- (0.25), while K^+, EC, Na^+, and Ca^{2+} showed moderate positive correlations with TSS. In contrast, turbidity, pH, PO_4^{3-}, and NO_3^- displayed weak negative correlations with TSS. EC showed a strong positive correlation with TDS (r = 0.97), with the cations Na^+ (r = 0.89), K^+ (r = 0.86), and Ca^{2+} (r = 0.81), indicating that elevated ionic concentrations are the primary driver of conductivity.

The cations showed weak negative correlations with SO_4^{2-} and turbidity and weak positive correlations with Cl^- and NO_3^-. SO_4^{2-} showed weak negative correlations with most parameters, except pH, TSS, and PO_4^{3-}. Turbidity exhibited a strong positive correlation with Cl^- (r = 0.84), which may reflect colloidal transport of chloride-bearing particles from near-surface waste deposits. These correlation patterns agree with the PCA findings presented in Section III.C. The EC–TDS–Na^+–K^+–Cl^- cluster represents the anthropogenic leachate factor, while the relatively independent behavior of SO_4^{2-}, Ca^{2+}, and Mg^{2+} supports their geogenic origin from mineral weathering.

F. Discussion of Contamination Sources

1) Geogenic Influences

The natural geochemical evolution of the groundwater is primarily controlled by weathering of the Benin Formation. Dissolution of carbonate and silicate minerals within the coastal plain sands releases calcium, magnesium, and bicarbonate into the aquifer. This geogenic mineral dissolution is reflected in the hydrogeochemical facies, where the calcium-magnesium-bicarbonate water type dominates in areas distant from direct anthropogenic impacts.

2) Dumpsite Contributions

The dumpsites appear to be major contributors to the elevated chloride, sodium, EC, and TDS observed in the Market Area. Leachate from these open waste disposal sites introduces soluble salts and organic matter into the shallow aquifer, shifting the hydrogeochemical facies towards a

sodium-potassium-chloride type. Although the dumpsites appear to be a major contributor, other diffuse anthropogenic sources cannot be excluded.

3) Other Anthropogenic Sources

Beyond the direct influence of the dumpsites, other diffuse anthropogenic activities affect groundwater quality across the study area. Septic tanks, agricultural fertilizers, domestic wastewater, and roadside runoff contribute to elevated nutrient and suspended solid loads. This is particularly evident at Irele Road. Although selected as a reference site because of its distance from the dumpsites, Irele Road exhibited elevated phosphate and moderate WQI deterioration, suggesting additional local anthropogenic inputs unrelated to the studied dumpsites, including roadside runoff and domestic septic systems.

G. Human Health Risk Assessment

Table IX presents the revised non-carcinogenic Hazard Quotient (HQ) and Hazard Index (HI) values for nitrate and phosphate through oral ingestion for adults and children at each sampling location. Chloride was not included in the final HQ and HI calculation because a chloride-specific oral reference dose was not provided in the cited methodology.

Table IX. Revised analysis of non-carcinogenic health risk for adults and children across all study locations

Parameter	Adults, Ayeka	Children, Ayeka	Adults, Igodan	Children, Igodan	Adults, Market	Children, Market	Adults, Irele	Children, Irele
NO_3^-	0.011	0.025	0.010	0.022	0.012	0.027	0.010	0.023
PO_4^{3-}	0.003	0.006	0.003	0.006	0.006	0.013	0.009	0.022
HI (sum)	0.013	0.031	0.012	0.029	0.017	0.041	0.019	0.045

All revised HQ and HI values were below 1.0 for adults and children at the four sampling locations. The highest HI values occurred at Irele Road for both adults (0.019) and children (0.045), followed by the Market Area, with HI values of 0.017 for adults and 0.041 for children. These results do not indicate a non-carcinogenic risk from the nitrate and phosphate exposures assessed using the stated chronic reference doses. Children nevertheless had higher HQ and HI values than adults because of the exposure assumptions used in the assessment. Chloride was considered in the physicochemical interpretation but was not assigned an HQ in the final risk calculation because a corresponding oral reference dose was not provided in the cited methodology.

H. Seasonal Considerations and Study Limitations

Field sampling was conducted in January 2025, during the peak dry season, which has important implications for interpreting the groundwater results. During this period in southwestern Nigeria, groundwater levels are minimal, residence times increase, and dissolved-ion concentrations are generally higher than during the wet season due to reduced dilution and enhanced evaporative concentration [21], [37]. Consequently, the elevated total dissolved solids, electrical conductivity, and ion concentrations recorded at the Market Area are attributable to near-peak contamination levels. These concentrations are expected to decline during the wet season due to recharge-driven dilution, although turbidity and total suspended solids may increase because of surface runoff.

Dumpsite leachate generation also varies seasonally, as increased rainstorm events during the wet season enhance leachate production and may expand the extent of the contamination plume. Therefore, future studies should incorporate both wet- and dry-season sampling to better characterize seasonal variations.

The study was limited by the relatively small sample size resulting from limited research funding, which restricted the spatial accuracy of contamination mapping. Heavy metal and microbiological analyses were also not included, although these are recommended for future studies because the observed low pH conditions may increase metal solubility. Other limitations include the single-season sampling design and the absence of hydrogeological data required for accurate modelling of leachate movement. These limitations define the scope of this baseline investigation and highlight key areas for future research in the study locations.

IV. Conclusion

This study examined contamination risks and conducted physicochemical analysis of groundwater samples near Okitipupa dumpsites in southwestern Nigeria, providing the basic research-based baseline dataset for groundwater quality at this site. A total of 16 water samples were collected from four strategic locations in Okitipupa. The integrated analysis led to the following specific conclusions: pH values across the sampling locations were acidic (mean 3.90–5.59) and consistently fell below the WHO acceptable range of 6.5 to 8.5. This condition is potentially related to pyrite oxidation and breakdown of acid-generating minerals within the shallow Benin Formation aquifer, although anthropogenic organic acid production near the Market Area may also contribute.

In addition, Okitipupa Market Area recorded persistently elevated levels of EC, TDS, Na^+, K^+, Ca^{2+}, and Cl^-, with mean values of 320.60 µS/cm, 213.58 mg/L, 21.13 mg/L, 8.62 mg/L, 12.37 mg/L, and 56.50 mg/L, respectively. These

concentrations were generally higher than those observed at Ayeka, Igodan, and Irele Road. The spatial pattern indicates greater contamination at the Market Area, although the measured parameters did not show a strictly monotonic decline with distance from the dumpsites.

Hydrochemical facies from Piper diagram analysis classified Na–K–Cl water types as groundwater from Market Area sites and Ca–Mg–HCO_3 types at less-impacted sites. However, PCA extracted three components that explained 78.3% of the total variance, which were classified as an anthropogenic leachate factor (PC1), a geogenic mineral weathering factor (PC2), and a surface runoff factor (PC3). Hierarchical cluster analysis also supported the spatial distinction between the Market Area and the other sites.

The composite WQI values were 88.3, 87.0, 117.6, and 64.6 for Ayeka, Igodan, the Market Area, and Irele Road, respectively. The Market Area was classified as poor and remained the most impacted location, whereas Ayeka, Igodan, and Irele Road were classified as good. Phosphate and TSS were retained as descriptive indicators of nutrient and particulate contamination but were not interpreted as WHO or NIS 554:2015 compliance exceedances.

The non-carcinogenic health-risk assessment, using the stated chronic reference doses for nitrate and phosphate, produced HQ and HI values below 1 for adults and children at all four locations. Chloride was not assigned an HQ because a chloride-specific oral reference dose was not used in the study.

The study recommends urgent intervention by water safety agencies, the National Environmental Standards and Regulations Enforcement Agency (NESREA), and the Ondo State Environmental Protection Agency (OSEPA) to remediate and routinely monitor the Market Area dumpsite. The establishment of properly lined waste containment systems is also recommended to prevent further leachate infiltration and associated groundwater contamination. In addition, long-term groundwater quality monitoring programmes should be implemented, incorporating sampling during both wet and dry seasons. Future studies should further include heavy metal and microbiological analyses, as well as formal modelling of leachate transport to provide a more comprehensive assessment of contaminant migration and environmental risk.

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AVAILABILITY OF DATA

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

AUTHORS' CONTRIBUTIONS

Opeyemi R Omokungbe and Abiola O Ilori: conceptualization, data acquisition, statistical analysis, and writing of the original manuscript. Adetoyosi C Ariyo, Micheal R Olojugba, and Thompson F Ediagbonya: site selection, data acquisition, statistical analysis, and manuscript revision. All authors reviewed and approved the final version of the manuscript for publication.

DISCLOSURE STATEMENT

The authors declare no competing financial interests or potential conflicts of interest.

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