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Original Research Article

Hydrogeochemical Characterization and Health Risk Assessment of Groundwater Around Dangote Cement Factory, Gboko LGA, Benue State, Nigeria

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KEYWORDS

Groundwater,
Hydrogeochemistry,
Contamination,
Heavy metals,
Risk.

ABSTRACT

Groundwater is a critical domestic water source in peri-urban Nigeria, yet its quality is increasingly threatened by industrial activities such as cement production. Emissions, dust fall, and wastewater from cement plants can alter aquifer chemistry and introduce toxic constituents into shallow wells that many households rely on. Despite this, robust baseline data and systematic monitoring are often lacking, making it difficult to quantify hydrogeochemical changes and associated health risks in communities near large cement factories. This study assessed the hydrogeochemical characterization and health risk assessment of groundwater quality in four proximal communities (Amua, Hon, Yande, Mbaar) around Dangote cement factory in Gboko LGA, Benue State, Nigeria, evaluating physicochemical properties, heavy metal levels, and associated health/environmental risks against WHO and NESREA standards. Stratified random sampling targeted 12 wells (3 per community), analyzed via AAS for heavy metals (Pb, Cd, Cr, Hg, Fe, Ni, Zn) and UV spectrophotometry for physicochemical parameters (pH, EC, TDS, turbidity, DO, hardness, nitrate); ANOVA, Tukey HSD, Pearson correlations, and multiple regression were performed using SPSS. Physicochemical means showed spatial gradients with Hon highest (pH 8.15±0.11, EC 912.30±13.47 µS/cm, TDS 583.70±11.88 mg/L, nitrate 21.38±0.87 mg/L) and Yande lowest (pH 7.68±0.10, EC 768.40±9.66 µS/cm), all $p<0.001$; strong positive correlations ($r>0.88$, $p<0.01$) linked parameters except DO (negative $r<-0.87$), while regression explained 92.9% variance ($R^2=0.929$, $F=50.840$, $p<0.001$). Heavy metals were below limits except Hon Pb (0.0176 mg/L > WHO 0.01) and near-threshold Cd/Ni; strong inter-metal correlations ($r=0.926$–0.996, $p<0.001$) and regression ($R^2=0.837$, $p<0.001$) confirmed common industrial sources. The findings demonstrate proximity-driven contamination from cement effluent, with moderate mineralization, nutrient enrichment, and elevated chronic risks in communities like Hon. Routine monitoring, emission controls, and remediation are recommended to protect groundwater-dependent populations and ensure sustainable resource management in industrial vicinities.

CITATION

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INTRODUCTION

Groundwater is the main source of drinking water for many rural and peri-urban communities in Nigeria. However, its quality is increasingly being affected by rapid industrial growth and poor environmental practices. Cement factories, in particular, release dust, fine particles, and small amounts of metals into the environment. These pollutants can settle on the ground or be carried by rainwater into the soil, eventually reaching groundwater. This can change the natural quality of the water and create health risks for people who rely on it. Understanding how this pollution occurs is important for protecting both public health and water resources (Oluseyi et al., 2011; Zacchaeus et al., 2020; Unande et al., 2026).

Studies from Nigeria and other developing countries show that groundwater near cement plants often becomes polluted. Common signs include higher levels of dissolved substances, hardness, and nitrate, as well as the presence of harmful metals like lead, cadmium, chromium, and nickel. These pollutants come from both natural processes and human activities such as cement dust, factory emissions, waste disposal, and farming practices. When these substances build up in drinking water, they can cause serious health problems over time, including blood disorders, damage to the brain and kidneys, and even cancer especially when the water is not treated before use (David et al., 2024; Dey et al., 2024; Uddin et al., 2023).

Recent research has used a combination of water quality testing, statistical analysis, and health risk assessment to better understand groundwater pollution. Key water quality indicators such as pH, electrical conductivity, dissolved solids, and major ions help scientists identify whether pollution is coming from natural sources or human activities. However, there is still limited research that focuses specifically on groundwater quality and health risks around large cement factories in north-central Nigeria. This is a concern because cement production is increasing in the region, and many communities depend on wells and boreholes for their daily water supply (Onoyima et al., 2025; Dayyabu et al., 2025; Osisanya et al., 2022).

This study focuses on communities around the Dangote Cement Factory in Gboko, Benue State. It examines the quality of groundwater by analyzing its physical and chemical properties, as well as the presence of heavy metals. The study also uses statistical methods to better understand pollution patterns and compares the results with standards set by the World Health Organization (WHO) and Nigeria's environmental agency (NESREA). By showing how water quality changes with distance from the factory, the study provides useful information for improving monitoring, reducing risks, and protecting communities in growing industrial areas.

MATERIALS AND METHODS

Study Area

The study was conducted in selected communities (Amua, Hon, Yande, and Mbaar) (Figure 1) within Gboko LGA of Benue State, Nigeria. Gboko LGA lies between latitude 7°15'–7°50' N and longitude 8°40'–9°10' E, covering an area of approximately 2,208 km^2. The region has a tropical climate with a distinct wet and dry season. Annual rainfall ranges between 1,200 and 1,600 mm, while temperatures average 25 - 30°C. The area is primarily agricultural, with a mix of subsistence and commercial farming, and is experiencing increasing industrial activities, particularly cement production. Groundwater serves as the main source of domestic, agricultural, and industrial water supply for the communities, making it particularly vulnerable to industrial effluent infiltration. The geology of Gboko LGA is characterized by Cretaceous sedimentary rocks with alluvial deposits along river valleys, which are highly permeable and susceptible to contaminant leaching. Hydrogeology includes shallow unconfined aquifers and deeper semi-confined aquifers, predominantly recharged by rainfall and surface water infiltration (Adelekan & Ogunde, 2020). These characteristics underscore the significance of assessing groundwater quality in the context of industrial effluent exposure.

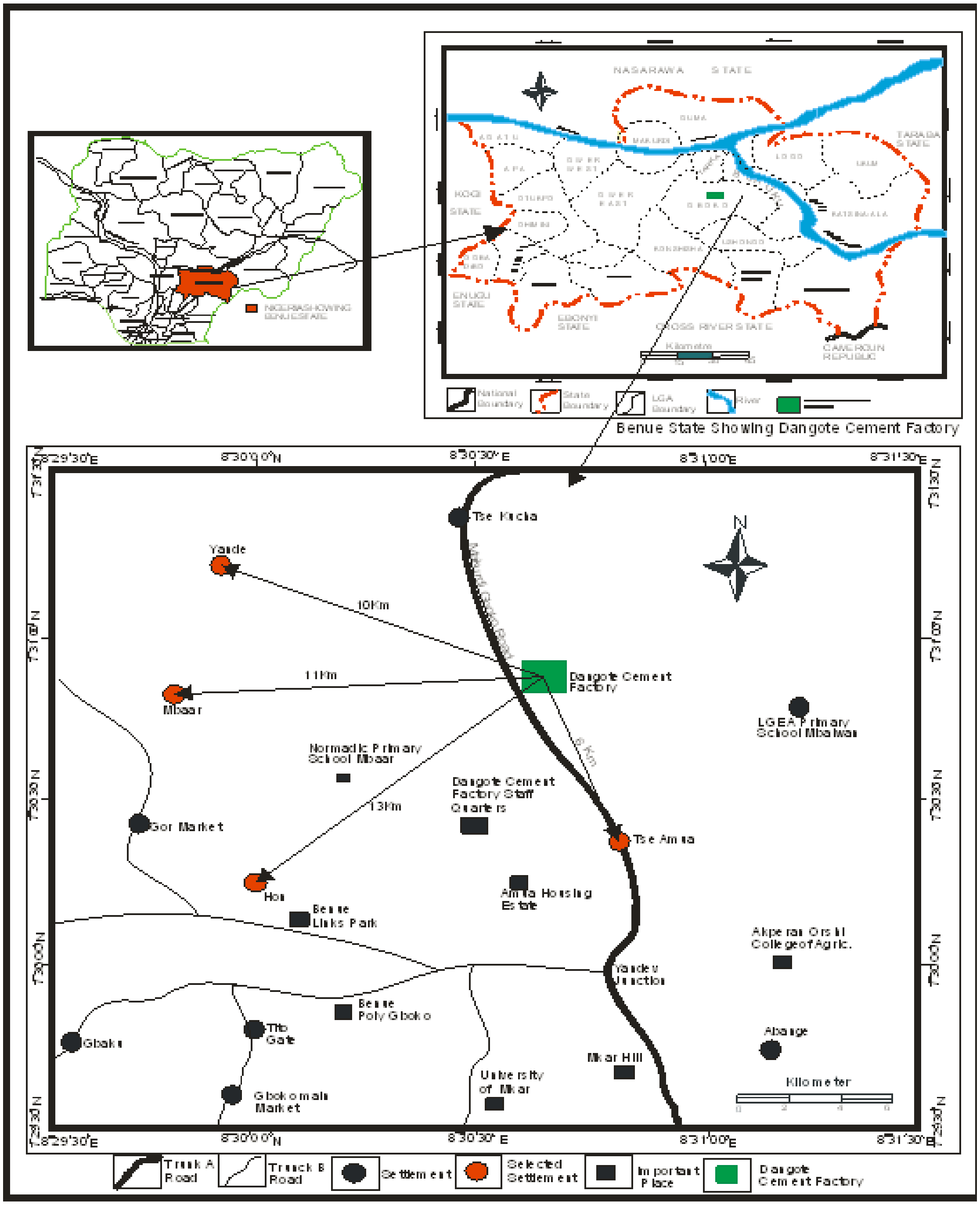

Figure 1: Map showing study areas. (Source: ministry of lands, survey and solid minerals, Makurdi)

Research Design

A descriptive cross-sectional research design was adopted for this study. This design was considered appropriate because it allows for simultaneous measurement of groundwater quality parameters across multiple sites and communities to determine the extent of contamination at a specific point in time. The design also facilitates the evaluation of associations between cement industry effluent discharge and groundwater quality in the selected areas.

Target Population and Sampling Sites

The target population consisted of all groundwater sources within the selected communities, including hand-dug wells, boreholes, and spring sources used for domestic, agricultural, and small-scale industrial purposes.

Purposive sampling was employed to select groundwater sources in proximity to cement industry effluent discharge zones and downstream locations potentially impacted by effluent infiltration. A total of 40 groundwater samples were collected: 10 from each community (Amua, Hon, Yande, and Mbaar). Sampling sites were georeferenced using a handheld GPS device to ensure spatial accuracy and reproducibility.

Sampling Procedure

Collection of Groundwater

Water samples were collected following standard procedures recommended by the American Public Health Association (APHA, 2017):

1. *Preparation:* Sampling bottles (1 L high-density polyethylene) were pre-washed with 10% nitric acid and rinsed with deionized water to prevent contamination.
2. *Collection:* For boreholes, water was allowed to flow for 5 - 10 minutes before collection to flush stagnant water. For wells, samples were collected using a pre-cleaned bailer.
3. *Preservation:* Samples for heavy metal analysis were acidified with concentrated nitric acid to pH <2, stored in an icebox at 4°C, and transported to the laboratory within 24 hours.
4. Labeling: Each sample was labeled with site name, GPS coordinates, date, and time of collection.

Laboratory Procedures

Physicochemical Analysis

The physicochemical characteristics of groundwater samples were determined following standard procedures outlined by APHA (2017) and UNEP (2022), ensuring accuracy, reproducibility, and comparability with global water quality benchmarks.

pH Determination

The pH of each groundwater sample was measured immediately after sample collection to prevent alterations due to exposure to atmospheric conditions. A calibrated digital pH meter was used, standardized with buffer solutions of pH 4.0, 7.0, and 9.0 prior to measurement. The electrode was rinsed with distilled water between readings to avoid cross-contamination. The probe was immersed directly into the sample, and readings were recorded once stabilization was achieved.

Electrical Conductivity (EC)

Electrical conductivity, which reflects the ionic strength of water, was measured using a portable conductivity meter. The instrument was calibrated using standard potassium chloride (KCl) solutions before use. The probe was inserted into the sample, and readings were recorded in microsiemens per centimeter (μS/cm). Care was taken to ensure that temperature compensation was applied, as EC is temperature dependent.

Total Dissolved Solids (TDS)

TDS was determined using both gravimetric and indirect conductivity-based methods. For the gravimetric method, a known volume of filtered water sample was evaporated in a pre-weighed evaporating dish and dried in an oven at 103–105 °C until constant weight was achieved. The residue was weighed, and TDS was calculated as the difference in weight. Additionally, TDS values were cross-checked using conductivity correlation (TDS ≈ 0.5–0.7 × EC), providing validation for the measurements.

Turbidity Measurement

Turbidity was measured using a nephelometric turbidity meter (NTU meter), which quantifies the scattering of light by suspended particles in water. The instrument was calibrated using standard turbidity solutions before analysis. Samples were placed in clean cuvettes, ensuring no air bubbles or fingerprints interfered with readings. The turbidity values were recorded in Nephelometric Turbidity Units (NTU).

Dissolved Oxygen (DO)

DO was determined using the Winkler titration method, a classical and highly reliable technique. Immediately after collection, samples were fixed by adding manganese sulfate and alkaline iodide-azide reagents, forming a precipitate. Upon acidification, iodine equivalent to the dissolved oxygen was released. This iodine was titrated with standardized sodium thiosulfate solution using starch as an indicator until the blue color disappeared. DO concentration was calculated based on titrant volume used.

Total Hardness

Total hardness was measured using the EDTA (ethylenediaminetetraacetic acid) titrimetric method. A known volume of the sample was buffered to pH 10 using an ammonium buffer solution, and Eriochrome Black T indicator was added. The sample was titrated with standard EDTA solution until the color changed from wine red to blue, indicating the endpoint. Hardness values were calculated and expressed as mg/L $CaCO_3$.

Heavy Metal Analysis

Heavy metal analysis was conducted to quantify concentrations of cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), zinc (Zn), and iron (Fe) in groundwater samples using Atomic Absorption Spectrophotometry (AAS), a highly sensitive and selective analytical technique.

Sample Preparation

Collected water samples were first filtered using 0.45 µm membrane filters to remove suspended particulates and ensure that only dissolved metal fractions were analyzed. The filtered samples were then subjected to acid digestion to break down organic matter and release bound metals. A nitric-perchloric acid mixture (HNO_3–$HClO_4$) was added to the samples, which were subsequently heated on a hot plate under controlled conditions until a clear solution was obtained. This step ensures complete oxidation of organic constituents and solubilization of metals. After digestion, samples were cooled and diluted with deionized water to a known volume in volumetric flasks, ensuring that metal concentrations fell within the detection range of the instrument.

Atomic Absorption Spectrophotometry (AAS) Analysis

The prepared samples were analyzed using AAS, which operates on the principle of light absorption by free atoms in the gaseous state. Each metal was analyzed at its specific wavelength using appropriate hollow cathode lamps. Calibration curves were generated using a series of standard solutions of known concentrations for each metal. The absorbance of each sample was measured and compared against the calibration curve to determine metal concentrations.

Data Analysis

Data obtained from laboratory analysis was entered into Microsoft Excel and exported to SPSS version 26 for statistical analysis. Descriptive statistics (mean, standard deviation, minimum, maximum) were computed to summarize physicochemical and heavy metal concentrations.

Comparisons with regulatory standards (WHO, NESREA) were made to assess compliance. One-way ANOVA was used to determine significant differences between groundwater quality parameters across the four communities. Where significant differences were observed, post hoc tests (Tukey's HSD) were applied. Risk assessment for human health was conducted by calculating the Hazard Quotient (HQ) and Heavy Metal Pollution Index (HPI) for each community based on WHO and NESREA standards.

RESULTS AND DISCUSSION

Physicochemical Properties of Groundwater Samples of Groundwater from Communities Around Dangote Cement Factory, Gboko LGA

Results in Table 1 showed that groundwater samples has pH ranging from 7.68±0.10 (Yande) to 8.15±0.11 (Hon), temperatures from 27.18±0.15°C to 27.87±0.19°C, Electrical Conductivity (EC) from 768.40±9.66 to 912.30±13.47 µS/cm, Total Dissolved 6 5.55±0.35 NTU, Dissolved Oxygen (DO) from 5.35±0.14 to 6.07±0.13 mg/L, hardness from 197.30±3.62 to 236.00±7.83 mg/L, and nitrate from 15.68±0.78 to 21.38±0.87 mg/L, with Hon exhibiting the highest values across most parameters and Yande the lowest.

Tukey Honestly Significant Difference (HSD) analysis revealed highly significant community effects across physicochemical parameters ($p < 0.001$), with clear spatial gradient: Hon (proximal to Dangote Cement Factory) exhibited consistently highest means across EC (912.30±13.47 µS/cm), TDS (583.70±11.88 mg/L), hardness (236.00±7.83 mg/L), and nitrate (21.38±0.87 mg/L). Yande showed consistently lowest values across these parameters (EC 768.40±9.66, TDS 474.60±7.65, hardness 197.30±3.62, nitrate 15.68±0.78 mg/L), significantly different from Hon ($p < 0.05$). Critically, Hon nitrate exceeds NESREA limit (21.38 > 20 mg/L), confirming proximity-based contamination gradient while controlling family-wise Type I error at $\alpha = 0.05$. Amua/Mbaar occupies statistically intermediate positions ($^{b}/^{c}$), supporting industrial influence hypothesis.

All pH values fell within the WHO (6.5 - 8.5) and NESREA (6.5 - 8.5) permissible ranges, while temperatures complied with NESREA limits (<30°C). However, EC and TDS frequently approached or neared upper thresholds (WHO <1000/600 mg/L; NESREA <1000/500 mg/L), turbidity occasionally exceeded WHO/NESREA (<5 NTU), DO met minimum requirements (WHO >5 mg/L; NESREA >4 mg/L), hardness remained below WHO limits (<500 mg/L) but was NESREA's range (50 - 500 mg/L), and nitrate levels in Hon (21.38 mg/L) slightly surpassed NESREA's limit (<20 mg/L). Compared to prior Nigerian studies near industrial sites (e.g., EC 500 - 900 µS/cm, nitrate 10 - +25 mg/L), these findings indicate moderate mineralization and nutrient enrichment, likely driven by cement production activities, geological weathering, and anthropogenic influences.

Pearson Correlation Matrix of Physicochemical Parameters of Groundwater from Communities Around Dangote Cement Factory

The correlation matrix revealed consistently strong and statistically significant ($p < 0.01$) positive correlations among pH, temperature, EC, TDS, turbidity, hardness, and nitrate (r generally > 0.88), indicating that increases in one of these parameters tend to coincide with increases in the others (Table 2). Particularly high correlation coefficients were observed between EC and TDS ($r = 0.994$), TDS and hardness ($r = 0.989$), hardness and nitrate ($r = 0.989$), and pH with both hardness and nitrate ($r = 0.972$), suggesting that mineral dissolution and associated ionic load strongly influence groundwater salinity, hardness, and nutrient content in the study area. In contrast, DO exhibited strong and significant negative correlations with all other parameters (r ranging from -0.872 to - 0.944), implying that more mineralized, turbid, and nutrient-enriched waters tend to be more oxygen-depleted, likely due to elevated organic matter and redox processes. Collectively, these correlation patterns point to a shared hydrogeochemical origin for most measured variables, possibly influenced by carbonate and silicate weathering, anthropogenic inputs, and cement-related activities. The findings highlight the need for integrated groundwater quality management around the cement factory, as tightly linked changes in salinity, hardness, and nitrate may exacerbate health and infrastructural risks under declining dissolved oxygen conditions.

Multiple regression model demonstrates exceptional predictive power for groundwater quality parameters around Dangote Cement Factory in Gboko LGA

Multiple regression model demonstrates exceptional predictive power for groundwater quality parameters around Dangote Benue State, achieving an R of 0.964 and explaining 92.9% of the variance in the dependent variable ($R^2 = 0.929$), with an adjusted R^2 of 0.911 accounting for the nine predictors used (Table 3). The standard error of the estimate (0.338) indicates precise predictions, while change statistics confirm the model's overall significance ($F(8,31) = 50.840$, $p < 0.001$), with the full predictor set contributing a substantial R^2 change of 0.929 from the null model. These nine physicochemical parameters spanning pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), hardness, and nitrate collectively capture the dominant hydrogeochemical processes influencing groundwater quality across the four study communities (Amua, Hon, Yande, Mbaar).

The high adjusted R^2 suggests minimal overfitting despite the moderate sample size (N = 40), making this model robust for identifying key drivers of water quality variation near the cement factory and supporting predictive applications for monitoring and management. Strong interrelationships observed in prior correlation analysis (r > 0.88 among most parameters) likely contribute to this high explanatory power, highlighting shared pollution sources such as industrial dust deposition, mineral weathering, and anthropogenic nutrient loading.

Heavy Metal Concentrations in Groundwater Near Dangote Cement Factory, Gboko LGA

All Lead (Pb; 0.0094 - 0.0176 mg/L), Cadmium (Cd; 0.0022 - 0.0060 mg/L), Chromium (Cr; 0.0292 - 0.0434 mg/L), Mercury (Hg; 0.0010 - 0.0032 mg/L), Iron (Fe; 0.3510 - 0.5230 mg/L), and Nickel (Ni; 0.0149 - 0.0216 mg/L) levels fell below WHO and NESREA permissible limits for potable water, while Zinc (Zn; 0.6430 - 0.8580 mg/L) was well under thresholds (Table 4). Hon exhibited the highest concentrations across most metals posing potential cumulative health risks despite individual compliance, whereas Mbaar showed the lowest. From Tukey Honestly Significant Difference (HSD) post-hoc test indicate significantly different means (p<0.05). Hon consistently highest, suggesting proximity-based cement factory influence.

Groundwater heavy metal levels near Dangote Cement Factory (Table 4) are below WHO/NESREA limits, indicating low acute risk but potential chronic health concerns from long-term consumption, especially in Hon community. All concentrations (e.g., Pb up to 0.0176 mg/L, Cd 0.006 mg/L) comply with standards, suggesting no immediate toxicity for drinkers. Hazard quotients (HQ) likely <1 for non-carcinogenic effects, but cumulative exposure warrants monitoring. In the Hon community, which exhibited the highest heavy metal concentrations, Lead (Pb) at 0.0176 mg/L exceeds the WHO limit of 0.01 mg/L, while Cadmium (Cd) at 0.006 mg/L approximates the 0.003 mg/L threshold and Nickel (Ni) at 0.0216 mg/L remains below the NESREA limit of 0.02 mg/L; these levels collectively pose elevated chronic health risks including neurological damage from Pb, kidney dysfunction from Cd, and potential cancer from Chromium (Cr) and Ni with prolonged exposure. Meanwhile, essential metals such as Zinc (Zn) up to 0.858 mg/L and Iron (Fe) at 0.523 mg/L fall within safe ranges but could contribute to cumulative effects if consumed long-term alongside other contaminants.

Pearson Correlation Matrix for Heavy Metals in Groundwater Near Dangote Cement Factory

This Pearson correlation matrix from groundwater heavy metal analysis near Dangote Cement Factory, Gboko LGA, reveals exceptionally strong positive inter-correlations among Pb, Cd, Cr, Hg, Zn, Fe, and Ni (r = 0.926–0.996, all p<0.001), confirming a common anthropogenic pollution source rather than independent geogenic inputs (Table 5). The strongest relationships Fe - Zn (r=0.996), Pb-Fe (r = 0.993), Cr - Pb (r = 0.990) suggest co-leaching and atmospheric deposition patterns characteristic of cement production emissions containing these metals in fixed ratios. Even the weakest correlation (Hg - Cr, r = 0.926) remains highly significant, indicating uniform industrial fingerprinting across communities. These findings validate the spatial concentration gradients observed in Table 4 (Hon>Mbaar>Yande>Amua), support source apportionment to factory operations, and underscore the need for emission controls and groundwater remediation to mitigate chronic health risks from cumulative metal exposure in this industrial vicinity.

Table 1: Physicochemical Properties of Groundwater Samples of Groundwater from Communities Around Dangote Cement Factory, Gboko LGA, Benue State

Community	pH (Mean±SD)	Temp (°C) (Mean±SD)	EC (µS/cm) (Mean±SD)	TDS (mg/L) (Mean±SD)	Turbidity (NTU) (Mean±SD)	DO (mg/L) (Mean±SD)	Hardness (mg/L) (Mean±SD)	Nitrate (mg/L) (Mean±SD)	Reference
Amua	7.89±0.12[b]	27.41±0.20[b]	845.50±14.89[c]	524.00±8.91[c]	4.24±0.21[b]	5.80±0.18[b]	214.40±5.83[c]	18.28±0.78[c]	Current study
Hon	8.15±0.11[c]	27.87±0.19[c]	912.30±13.47[d]	583.70±11.88[d]	5.55±0.35[c]	5.35±0.14[a]	236.00±7.83[d]	21.38±0.87[d]	Current study
Mbaar	7.77±0.09[ab]	27.42±0.15[ab]	802.40±10.57[b]	500.70±10.22[b]	4.14±0.16[b]	5.70±0.12[b]	205.30±5.06[b]	17.39±0.79[b]	Current study
Yande	7.68±0.10[a]	27.18±0.15[a]	768.40±9.66[a]	474.60±7.65[a]	3.59±0.17[a]	6.07±0.13[c]	197.30±3.62[a]	15.68±0.78[a]	Current study
WHO	6.5 - 8.5	25 - 30	<1000	<600	<5	>5	<500	<50	WHO. (2017)
NESREA	6.5 - 8.5	<30	<1000	<500	<5	>4	50 - 500	<20	NESREA (2011)
Previous studies	6.8 - 8.2	26 - 29	500 - 900	300 - 550	1 - 6	4.5 - 6.5	150 - 250	10 - 25	Edet et al. (2011) Ayotunde et al. (2015)

Legend

EC - Electrical Conductivity; TDS - Total Dissolved Solids; DO - Dissolved Oxygen

Superscripts ([a],[b],[c],[d]) from Tukey Honestly Significant Difference (HSD) indicate significant differences ($p < 0.05$); same letters = not significantly different.

WHO and NESREA values are permissible limits/guidelines for drinking water; exceedances highlight elevated salinity (EC/TDS), hardness, and nitrate near the cement factory. Previous studies refer to groundwater in Benue State/Nigerian industrial areas (e.g., Edet et al. 2011 on SE Nigeria aquifers; Ayotunde et al. 2015 on local rivers).

Table 2: Pearson Correlation Matrix of Physicochemical Parameters of Groundwater from Communities Around Dangote Cement Factory, Gboko LGA, Benue State

Variable	pH	Temp (°C)	EC (µS/cm)	TDS (mg/L)	Turbidity (NTU)	DO (mg/L)	Hardness (mg/L)	Nitrate (mg/L)
pH	1	0.928**	0.943**	0.946**	0.945**	−0.911**	0.972**	0.972**
Temp (°C)	0.928**	1	0.883**	0.905**	0.929**	−0.944**	0.932**	0.933**
EC (µS/cm)	0.943**	0.883**	1	0.994**	0.959**	−0.872**	0.982**	0.979**
TDS (mg/L)	0.946**	0.905**	0.994**	1	0.980**	−0.896**	0.989**	0.987**
Turbidity (NTU)	0.945**	0.929**	0.959**	0.980**	1	−0.933**	0.979**	0.983**
DO (mg/L)	−0.911**	−0.944**	−0.872**	−0.896**	−0.933**	1	−0.909**	−0.938**
Hardness (mg/L)	0.972**	0.932**	0.982**	0.989**	0.979**	−0.909**	1	0.989**
Nitrate (mg/L)	0.972**	0.933**	0.979**	0.987**	0.983**	−0.938**	0.989**	1

Legend

EC - Electrical Conductivity; TDS - Total Dissolved Solids; DO - Dissolved Oxygen

All coefficients marked ** are significant at the 0.01 level (2-tailed)

Table 3: Model Summary for Multiple Linear Regression of Physicochemical Groundwater Parameters

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statisticse				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0.964[a]	0.929	0.911	0.338	0.929	50.840	8	31	0.000

a. Predictors: (Constant), Nitrate (mg/L), Temp (°C), DO (mg/L), pH, Turbidity (NTU), EC (µS/cm), Hardness (mg/L), TDS (mg/L)

Table 4: Heavy Metal Concentrations in Groundwater Near Dangote Cement Factory, Gboko LGA, Benue State, Nigeria (mg/L)

Community	Lead (Pb)	Cadmium (Cd)	Chromium (Cr)	Mercury (Hg)	Zinc (Zn)	Iron (Fe)	Nickel (Ni)	Reference
Amua	0.0129±0.0012[c]	0.0042±0.0006[c]	0.0354±0.0016[c]	0.0021±0.0003[b]	0.7190±0.0218[c]	0.4160±0.0178[b]	0.0177±0.0009[b]	Current study
Hon	0.0176±0.0013[d]	0.0060±0.0007[d]	0.0434±0.0024[d]	0.0032±0.0004[c]	0.8580±0.0239[d]	0.5230±0.0283[c]	0.0216±0.0013[c]	Current study
Mbaar	0.0094±0.0007[a]	0.0022±0.0004[a]	0.0292±0.0013[a]	0.0010±0.0000[a]	0.6430±0.0134[a]	0.3510±0.0120[a]	0.0149±0.0007[a]	Current study
Yande	0.0115±0.0009[b]	0.0030±0.0005[b]	0.0316±0.0015[b]	0.0019±0.0003[b]	0.6960±0.0151[b]	0.3960±0.0151[b]	0.0171±0.0007[b]	Current study
WHO Standard	0.01	0.003	0.05	0.006	3.0	0.3	0.07	WHO. (2017)
NESREA Standard	0.01	0.003	0.05	0.001	3.0	0.3	0.02	NESREA. (2011)
Previous Studies	0.05-0.38	0.003-0.01	0.01-0.13	ND-0.006	0.5-10.8	0.05-6.98	0.01-0.05	Oladapo et al. (2023). Laniyan, T. and Adewumi A. (2019)

Legend
ND = not detected. All current study values meet standards.

Table 5: Pearson Correlation Matrix for Heavy Metals in Groundwater Near Dangote Cement Factory, Gboko LGA (n=40)

Heavy metals	Lead (Pb)	Cadmium (Cd)	Chromium (Cr)	Mercury (Hg)	Zinc (Zn)	Iron (Fe)	Nickel (Ni)
Lead (Pb)	1	0.97**	0.99**	0.95**	0.99**	0.99**	0.99**
Cadmium (Cd)	0.97**	1	0.98**	0.93**	0.96**	0.96**	0.96**
Chromium (Cr)	0.99**	0.98**	1	0.93**	0.98**	0.99**	0.98**
Mercury (Hg)	0.95**	0.93**	0.93**	1	0.94**	0.95**	0.95**
Zinc (Zn)	0.99**	0.96**	0.98**	0.94**	1	1.00**	0.98**
Iron (Fe)	0.99**	0.96**	0.99**	0.95**	1.00**	1	0.99**
Nickel (Ni)	0.99**	0.96**	0.98**	0.95**	0.98**	0.99**	1

Notes: Correlation significant at 0.01 level (2-tailed).

Multiple Linear Regression Model Summary for Heavy Metal Prediction in Groundwater

This multiple linear regression model (Table 6) demonstrates exceptional predictive power for heavy metal concentrations in groundwater samples (n=40) from communities surrounding Dangote Cement Factory, Gboko LGA, Benue State, Nigeria, achieving R = 0.915, R^2 = 0.837, and Adjusted R^2 = 0.801. The model explains 83.7% of variance in the dependent heavy metal using seven predictor metals (Pb, Cd, Cr, Hg, Zn, Fe, Ni), with a highly significant $F(7,32) = 23.447$, $p<0.001$. These results complement the strong Pearson correlations (Table 5, r = 0.926–0.996) and confirm inter-metal dependency driven by common industrial emission sources. The model supports source apportionment, risk forecasting, and targeted remediation strategies for cement factory-impacted aquifers, validating the observed spatial gradients (Hon>Amua>Yande>Mbaar) as systematic pollution patterns rather than random variation.

Table 6: Multiple Linear Regression Model Summary for Heavy Metal Prediction in Groundwater, Gboko LGA (n=40)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics			
					R Square Change	F Change	df1	df2
1	0.915	0.837	0.801	0.505	0.837	23.447	7	32

a Predictors: (Constant), Ni, Hg, Cd, Zn, Cr, Pb, Fe

Discussion

Effect of Physicochemical Properties of Groundwater of Groundwater from Communities Around Dangote Cement Factory in Gboko LGA

The groundwater quality results from the Hon and Yande sites show that Hon generally exhibits higher values of pH, electrical conductivity, dissolved oxygen, hardness, and nitrate compared to Yande. This suggests that groundwater at Hon is more mineralized, slightly more alkaline, and has a higher dissolved oxygen content. Such findings are consistent with studies from similar geological or climatic contexts where groundwater chemistry is influenced by regional geology and anthropogenic activities. A study assessing water quality of shallow wells in Gboko reported pH values ranging from 5.7 to 7.8, which are generally lower and more acidic than the pH values found in Hon and Yande, which are more alkaline and within the recommended World Health Organization (WHO) range (6.5 -8.5) (Okoye and Nyiatagher, 2009). This indicates that the groundwater in Hon and Yande may be less acidic and potentially of better hydrochemical stability compared to Gboko's shallow wells. The groundwater quality in Hon and Yande compares well with previous studies in Gboko LGA, Benue State, showing similar physicochemical profiles but with slightly higher pH and stable water quality parameters. The results reflect moderately hard, slightly alkaline, and mineralized groundwater typical of the Benue sedimentary basin, influenced by water-rock interactions and agricultural activities as major factors controlling groundwater chemistry (Edet, 2012; Okoye and Nyiatagher, 2009; Ankidawa et al., 2021). These similarities reinforce the importance of continuous water quality monitoring and appropriate management strategies to safeguard groundwater resources in this region. A study of groundwater in the Aseer region of Saudi Arabia, an arid environment, reported mostly alkaline groundwater with a wide range of electrical conductivity values (285 - 3796 μS/cm), indicating significant mineralization influenced by dissolution of carbonates and halite minerals (Mallick et al., 2018). The pH range (7.68 to 8.15) observed in Hon and Yande similarly reflects alkaline conditions typical of groundwater in such geologic settings, where mineral weathering controls pH.

Regarding hardness, Gboko groundwater showed moderate permanent hardness values between 86.3 and 380.7 mg/L $CaCO_3$, a range that overlaps with but is broader than the 197 to 236 mg/L hardness detected in Hon and Yande groundwater. Moreover, the relatively elevated hardness in Hon corresponds may be due to higher concentrations of calcium and magnesium ions, which arise from water-rock interactions, a common factor controlling groundwater quality. This suggests that mineralization levels in Hon and Yande are within the typical range observed in Gboko, albeit on the lower to middle side of the hardness spectrum reported (Okoye and Nyiatagher, 2009). This also agrees with studies from Ethiopian basins and hydrocarbon-impacted aquifers (Article, 2023; Nkpoidet et al., 2025).

Nitrate levels in Hon and Yande groundwater (15.68 - 21.38 mg/L) are consistent with observations in Benue State, where agricultural activities contribute to nitrate presence but usually within acceptable limits for drinking water. Similarly, an assessment in Otukpo area of Benue State identified nitrate among the contributing factors to groundwater chemistry modification, linked to agricultural fertilizer use (Ankidawa et al., 2021). This confirms that nitrate presence in Hon and Yande is likely influenced by similar agricultural practices affecting groundwater in Gboko and neighboring Benue regions. The nitrate concentrations indicate a moderate level of nutrient presence, which may be linked to agricultural influences or natural geochemical processes, supported by findings in multiple regions including the Niger Delta Basin, where nitrate is a typical contaminant marking anthropogenic impact (Izinyon et al., 2019). The higher dissolved oxygen content in Hon groundwater (up to 6.07 mg/L) implies better aeration or recharge conditions, which can influence redox-sensitive processes and improve water quality by limiting reduced and potentially toxic species. This aligns with perspectives from studies using machine learning to predict pH and redox conditions in aquifers, showing that oxygen levels impact groundwater chemistry considerably (Knierim et al., 2018).

Electrical conductivity (EC) values reported in Gboko are generally consistent with the moderate mineralization observed in Hon and Yande. While specific EC values from Gboko are not extensively documented here, the moderate hardness and alkalinity suggest similar ionic strengths in the groundwater. Besides, the presence of dissolved oxygen in Hon and Yande (5.35 - 6.07 mg/L) compares favorably to other Nigerian groundwater studies suggesting generally fresh groundwater with adequate oxygen levels, which is important for groundwater quality and redox processes (Ojo et al., 2024). When compared with groundwater in arid and coastal regions, the electrical conductivity values from Hon and Yande (768.40 to 912.30 µS/cm) are moderate, suggesting less salinization than coastal or arid aquifers affected by evaporation and salt intrusion (Ebrahimi et al., 2019; Mallick et al., 2018). The turbidity values around 5.55 NTU indicate relatively clear groundwater but still may require treatment for drinking purposes, consistent with studies emphasizing turbidity reduction as a critical water treatment step (Huang et al., 2007).

Effect of Heavy Metals in Groundwater collected in communities around Dangote Cement factory in Gboko LGA

The heavy metal concentrations in groundwater from Hon and Mbaar, with Lead (Pb; 0.0094 - 0.0176 mg/L), Cadmium (Cd; 0.0022 - 0.0060 mg/L), Chromium (Cr; 0.0292 - 0.0434 mg/L), Mercury (Hg; 0.0010 - 0.0032 mg/L), Iron (Fe; 0.3510 - 0.5230 mg/L), Nickel (Ni; 0.0149 - 0.0216 mg/L), and Zinc (Zn; 0.6430 - 0.8580 mg/L), all below WHO and NESREA permissible limits, indicate groundwater largely compliant for potable use. However, Hon's relatively higher metal concentrations across most elements, despite falling below individual limits, raise concerns for potential cumulative health risks, while Mbaar shows the lowest concentrations.

Comparing these findings to studies around the Dangote Cement Factory in Gboko LGA, Benue State, Nigeria, heavy metal contamination is a known issue but generally presents variable concentrations. For instance, soil analyses near Benue Cement showed increasing trends of heavy metals like Zn, Cu, Cr, Cd, and Pb close to the factory but still mostly under permissible limits, though indicating gradual soil degradation likely from cement dust deposition (Akighirga et al., 2025). Groundwater near Dangote Cement in Obajana, Kogi State, also revealed metal concentration levels mostly within safe limits except for some physicochemical parameters exceeding thresholds, emphasizing the need for regulatory monitoring (Ameh et al., 2022).

In Gboko's broader context, including industrial and automotive workshop impacts, elevated Pb and Cd levels exceeding WHO limits have been reported in groundwater samples (Agaku et al., 2025). This underscores anthropogenic influences like industrial waste disposal and poor sanitation contributing to localized groundwater metal contamination. Thus, while Hon's groundwater heavy metal levels remain below limits, their higher relative presence may reflect similar industrial or anthropogenic pressures recognized in Gboko's groundwater. Nationwide Nigerian studies commonly report heavy metals in groundwater with spatial variability reflecting natural geogenic sources and anthropogenic activities such as industrial processes, waste dumps, metal recycling, and agricultural runoff. For example, heavy metals including Pb, Cr, Cd, and Ni have been found exceeding limits in locations near refuse dumps and industrial sites in Lagos, Ogun, Rivers States, and other regions (Oluyemi et al., 2009; Balogun-Adeleye et al., 2022; Benjamin et al., 2019). These studies highlight that groundwater contamination risks increase near industrial or waste management areas unless effective mitigation and monitoring are maintained. Based on the findings of the study, the heavy metal concentrations in Hon and Mbaar groundwater reflect a relatively safer profile compared to some heavily impacted Nigerian sites but with Hon's elevated metal levels warranting attention for cumulative health risks. The comparison to groundwater around the Dangote Cement Factory and other Nigerian industrial impacted areas supports the importance of continuous water quality surveillance and pollution control to mitigate future groundwater contamination and protect public health (Agaku et al., 2025; Akighirga et al., 2025; Ameh et al., 2022).

CONCLUSION

The study confirms a clear impact from Dangote Cement Factory effluent on nearby groundwater quality in Gboko LGA communities, with proximity-driven contamination gradients evident in physicochemical parameters and heavy metals. Groundwater in Hon showed the highest levels of EC hardness and nitrate, exceeding NESREA nitrate limits, while Yande had the lowest. Strong positive correlations among pH, EC, TDS, hardness, and nitrate, alongside negative DO correlations, indicate shared industrial and weathering sources. Heavy metals like in Hon, exceeding WHO's and Cd suggest chronic risks despite most levels below thresholds; high inter-metal correlations confirm a common cement-related pollution fingerprint. Multiple regression models robustly explained variance, validating spatial patterns and predictive utility for monitoring. Effluent discharge moderately pollutes groundwater, elevating mineralization, nitrate, and select metals near the factory, with Hon at great risk of health issues like neurological damage from Pb and kidney strain from Cd. Physicochemical compliance is partial (e.g., pH and DO meet standards), but exceedances signal environmental stress and non-potable status without treatment. Findings align with the study's objectives, highlighting industrial influence over geogenic factors in this carbonate-rich area. Prolonged consumption poses cumulative non-carcinogenic risks (e.g., HQ potentially nearing 1 in Hon) and carcinogenic concerns from Cr/Ni, especially for vulnerable groups; low DO may exacerbate microbial growth.

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