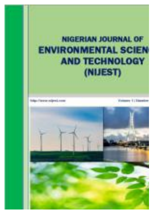
Nigerian Journal of Environmental Sciences and Technology (NIJEST)
www.nijest.com
ISSN (Print): 2734-259X | ISSN (electronic): 2734-2603
Vol 9, No. 2 October 2025, pp 21 - 32



Physicochemical and Microbial Assessment of Underground Water in Commercial Areas of Benin City, Edo State

Archibong U. D. [1]*, Osagie A. F. [2] and Agho T. I. [1]

[1] *Department of Applied Chemical Science Laboratory Technology, Faculty of Science Laboratory Technology, University of Benin, Benin City, Edo State, Nigeria*

[2] *Department of Chemistry, Faculty of Physical Science, University of Benin, Benin City, Edo State, Nigeria*

*Corresponding author's email: ukeme.archibong@uniben.edu

https://doi.org/10.36263/nijest.2025.02.41

ABSTRACT

This study investigates the groundwater's physicochemical and microbial quality from twelve commercial locations in Benin City, Edo State, Nigeria. Results reveal widespread deviations from WHO/SON standards, particularly in pH, mineral content, and microbial contamination. All the physicochemical water quality parameters were carried out following the regulatory standards. A Flame Atomic Absorption spectrophotometer was used to determine the concentrations of zinc, iron, sodium, calcium, magnesium, copper, chromium, and lead in the water samples. The Microbiological analysis involved the enumeration of total heterotrophic bacteria, coliforms, E. coli, and yeasts using standard culture-based techniques. Samples were incubated on selective media at appropriate temperatures, and results were expressed in CFU/mL. Physicochemical parameters of the groundwater samples revealed pH values ranging from 5.03 to 6.27, indicating slight acidity. Turbidity values were low (0.00–1.05 NTU), while electrical conductivity and total dissolved solids varied between 18.7–398.0 µS/cm and 10.26–218.9 mg/L, respectively, reflecting generally low mineralization. Total suspended solids (11.57–12.45 mg/L) and total solids (22.26–230.90 mg/L) were also within acceptable limits. Other key parameters included total alkalinity (24.00–72.00 mg/L), total hardness (0.29–19.33 mg/L), chloride (1.10–7.00 mg/L), nitrate (0.28–0.46 mg/L), bicarbonate (0.24–0.72 mg/L), sulphate (2.27–6.16 mg/L), calcium (0.10–7.00 mg/L), magnesium (0.02–20.50 mg/L), sodium (0.80–33.43 mg/L), and potassium (0.97–74.67 mg/L). Trace metal concentrations were generally low: zinc (0.01–0.34 mg/L), iron (0.01–0.13 mg/L), copper (0.01–0.04 mg/L), chromium (0.01–0.05 mg/L), and lead (constant at 0.01 mg/L). Microbiological analysis detected Escherichia coli (0–1 CFU/mL), coliforms (0–2 CFU/mL), and total bacteria (1–5 CFU/mL), whereas yeasts were absent in all samples, suggesting minimal fungal contamination.Multivariate statistical analyses, including Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), identified distinct spatial patterns and contamination sources. The findings underscore the urgent need for targeted water treatment and management strategies in commercial areas.

Keywords: Groundwater, Contamination, Parameter, Borehole samples, Benin City

1.0. Introduction

Groundwater serves as an indispensable source of potable and domestic water in many urban areas of Nigeria, where public water supply systems are often inadequate or unreliable. Consequently, households, industries, and commercial establishments increasingly depend on boreholes and hand-dug wells to meet their daily water needs (Ogbeifun *et al.*, 2019; Bassey & Archibong, 2023). However, the quality and safety of these underground water sources are being progressively compromised by the rapid pace of urbanization, population growth, and expansion of commercial and industrial activities (Onwordi *et al.*, 2022; Edokpayi *et al.*, 2018). The uncontrolled disposal of untreated effluents, industrial wastes, and solid refuse has intensified groundwater contamination risks, particularly in densely populated commercial districts where land-use activities exert significant stress on natural aquifers (Akpan & Udoh, 2016). The contamination of groundwater arises from multiple physicochemical and microbiological pathways. Physicochemical pollutants such as heavy metals, nitrates, phosphates, and chlorides often originate from industrial discharges, waste leachates, and agricultural runoff, while microbial contaminants typically result from the infiltration of sewage, animal waste, or decomposing organic matter (WHO, 2017; APHA, 2017). When present above permissible limits, these contaminants pose severe health hazards, including gastrointestinal disorders, neurological impairment, and carcinogenic effects (Edokpayi *et al.,* 2017; Sharma & Bhattacharya, 2016). Water quality indicators such as pH, electrical conductivity, total dissolved solids (TDS), turbidity, and nutrient content provide critical diagnostic information for assessing contamination status and determining water suitability for domestic and industrial use (Olasoji *et al.,* 2019; Bassey & Archibong, 2023). Microbial markers, notably total coliforms and Escherichia coli, serve as direct evidence of fecal contamination and the possible presence of pathogenic microorganisms responsible for waterborne diseases such as cholera, typhoid fever, and dysentery (Edokpayi *et al.,* 2017; WHO, 2017). Seasonal variation further complicates this dynamic, as the onset of the rainy season often enhances pollutant mobility through surface runoff and leachate infiltration, while the dry season may concentrate certain dissolved ions through evaporation (Kumar *et al.,* 2019). Understanding these spatiotemporal trends is crucial for evaluating pollution risks and implementing preventive water management strategies.

Despite growing awareness of these threats, studies addressing the spatial distribution, seasonal variability, and interrelationships of physicochemical and microbial contaminants in Benin City's groundwater remain scarce. Most available assessments provide isolated parameter evaluations without comprehensive statistical interpretation or source identification. Hence, this study aims to bridge this knowledge gap by systematically assessing the physicochemical and microbial quality of groundwater from selected commercial areas of Benin City, Edo State. Advanced multivariate statistical techniques, including Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), were employed to discern dominant contamination sources, classify water quality patterns, and reveal spatial heterogeneity across sampling sites. These methods have proven valuable in global hydrogeochemical studies for identifying pollution drivers and delineating water quality clusters (Kumar *et al.,* 2019; Onwordi *et al.,* 2022). The findings of this study are expected to enhance understanding of groundwater quality dynamics in urban environments and support the formulation of effective water resource management policies and public health protection strategies in Nigeria and comparable developing regions

2.0. Materials and Methods

2.1. Study Area

This study was conducted in Benin City, the capital of Edo State, Nigeria. The city lies between latitudes 6°19'N and 6°23'N and longitudes 5°36'E and 5°44'E. Twelve commercial locations, decoded as follows: SAKP, AGPA, IKPS, EKEW, MISS, SAPE, USEL, AKPA, UNIB, IKPH, OREG, APRT were systematically sampled in 2025. Each site is characterized by varying commercial activity density and land use. Figure 1 shows the map of the study area, and the coordinates, elevation, and names of the specific sampling locations are presented in Table 1.

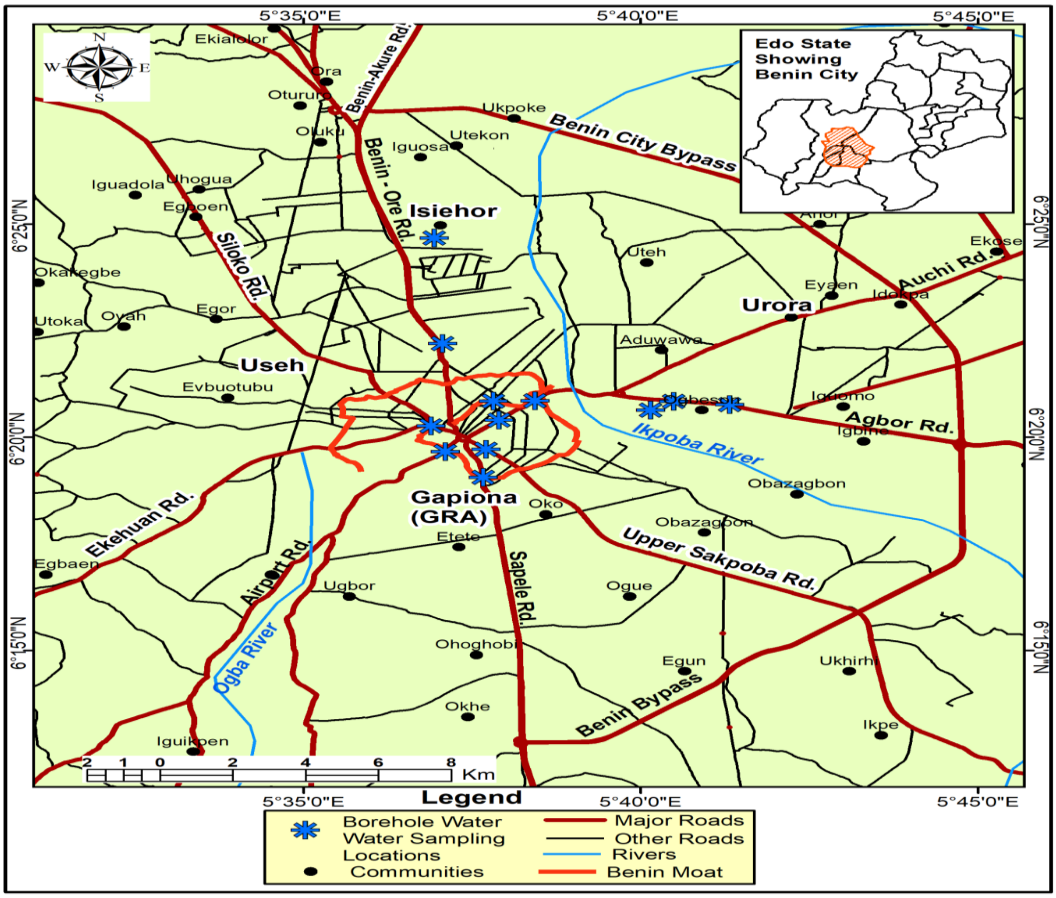


Figure 1: Benin City Showing Borehole Water Sampling Locations
Source: Fieldwork using Global Navigation Satellite System receiver

Table 1: Geographic Coordinates of Borehole Water Sampling Locations

S/No	Location	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)	Elevation (Meters)
1	Isiehor	6.41127	5.615673	113
2	Near Firm Foundation, Ikpoba Hill	6.347374	5.674824	82
3	Near NPC Office, Ikpoba Slope	6.347684	5.640513	56
4	Near Firm Agbor Park, Ikpoba Hill	6.346158	5.688617	88
5	Akpakpaava by James Watt Road	6.340143	5.631682	87
6	Upper Sakpoba by Hausa Quarters	6.328653	5.628489	83
7	Airport Road by Chief Osuan Ave.	6.327742	5.618456	82
8	Ekenwan Road by Zabayor Street	6.337798	5.614851	84
9	Mission Road by Oguola Road	6.347481	5.630286	90
10	Sapele Road by 2nd East Circular Road	6.317742	5.627781	81
11	Oregbeni Quarters	6.343924	5.669063	67
12	Near Ediake Pri. Sch. Road by Okiri Street	6.370072	5.617757	94

Source: Fieldwork using Garmin GPSMAP 64sx with ±3–5 m accuracy

2.2. Sample Collection and Analytical Procedure

Groundwater sampling was conducted between March and July 2025, targeting 12 functional borehole sources using a random sampling technique facilitated by a table of random numbers. Samples were collected daily between 9:00 am and 11:00 am in triplicate. Samples were analyzed for 25 parameters (see Table 2), including pH, turbidity, EC, TDS, major ions, heavy metals, and microbial counts (E. coli, coliform, yeast, bacteria) using standard methods as described by APHA (2017) and Ogbeifun et al. (2019). Physicochemical analyses were performed at the Department of Applied Chemical Science Laboratory Technology, while microbial assessments were conducted at the Department of Natural Science Laboratory Technology, both within the Faculty of Science Laboratory Technology, University of Benin.

2.3. Physicochemical Analysis

The following parameters, namely pH, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) were determined by measurement in situ using a multi-parameter water quality meter (Hanna HI 9829). Turbidity was determined using a turbidimeter, while temperature was recorded on-site with a mercury thermometer. Nitrate and Phosphate were quantified spectrophotometrically using UV-visible spectrophotometer (Shimadzu UV-1800) following standard colorimetric methods (APHA, 2012). Also, chloride was determined by argentometric titration. Total Hardness and Alkalinity were also assessed using EDTA titrimetric method. All measurements were taken in triplicate, and results expressed as mean ± standard deviation.

2.4. Microbiological Analysis

Microbiological assessments were conducted to enumerate total heterotrophic bacteria, total coliforms, E. coli and yeast counts. Total Heterotrophic Bacterial Count was determined using the pour plate method on nutrient agar incubated at 37°C for 24–48 hours. Determination of Coliform and E. coli Counts was obtained by the membrane filtration method using selective media (MacConkey agar and Eosin Methylene Blue agar). At the same time, the yeast count was incubated at 44°C for 24 hours to confirm thermotolerant strains. Colony counts were reported as colony-forming units per milliliter (CFU/mL).

2.5. Quality Control and Statistical Analysis

All reagents used were of analytical grade. Equipment calibration and method validation were carried out using standard reference materials. Descriptive statistics, independent *t*-tests, Pearson correlation, Principal Component Analysis (PCA) with varimax rotation, Hierarchical Cluster Analysis (HCA) based on Ward's linkage method, and Chi-square tests were conducted using SPSS software (v25.0). Independent t-test comparing the means of two groups was computed as

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (1)$$

where,

$\bar{x}_1$ and $\bar{x}_2$ are the group means, s_1^2 and s_2^2 are the variances, while n_1 and n_2 are the sample sizes of the respective groups.

Pearson's correlation Coefficient (r) quantifying the linear association between variable x and y was calculated as

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (2)$$

where,

x_i and y_i are paired observations, and $\bar{x}$ and $\bar{y}$ are their respective means.

PCA decomposed the data matrix **X** into scores (**T**), loadings (**P**), and residuals (**E**) as

$$\mathbf{X} = \mathbf{T}\mathbf{P}^T + \mathbf{E} \quad (3)$$

This transformation reduces dimensionality and identifies principal components representing major sources of water quality variability.

HCA applied Ward's linkage method, which minimizes within-cluster variance by merging clusters A and B that causes the smallest increase in the error sum of squares (ESS) was computed as

$$\Delta ESS = \frac{n_A n_B}{n_A + n_B} \parallel \bar{x}_A - \bar{x}_B \parallel^2 \quad (4)$$

where,
n_A and n_B are the sizes of clusters A and B , and $\bar{x}_A$ and $\bar{x}_B$ are their respective centroids.
The Chi-square test for categorical data evaluated goodness-of-fit using:

$$x^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \quad (5)$$

where,
O_i and E_i represent the observed and expected frequencies, respectively, across k categories.

Compliance of the water quality parameters with SON/WHO standards was evaluated. PCA biplots and dendrograms were subsequently generated to aid interpretation and classification of the sampling sites as shown in Figure 6, Figure 4 and Figure 5.

3.0 Results and Discussion

The descriptive statistics outlined in Table 2 provide valuable insights into the measured water quality parameters and their conformity with SON/WHO regulatory standards

Table 2: Descriptive Statistics Showing the Mean, Range, and Compliance Rates for Each Parameter

Parameter	Unit	Mean	Min	Max	Count	SON/WHO STANDARD
pH@25°C	–	5.50±0.36	5.03	6.27	12	6.50 - 8.50
Turbidity	NTU	0.39±0.43	0.00	1.05	12	5.0
Electrical Conductivity	µS/cm	143.67±124.97	18.70	398.00	12	900 – 1200
Total Dissolved Solids	mg/L	78.98±68.67	10.26	218.90	12	500 – 1500
Total Suspended Solids	mg/L	12.02±0.18	11.57	12.45	12	-
Total Solids	mg/L	91.00±68.73	22.26	230.90	12	-
Total Alkalinity	mg/L	49.67±12.91	24.00	72.00	12	100
Total Hardness	mg/L	7.96±6.08	0.29	19.33	12	100 – 250
Chloride	mg/L	3.71±1.85	1.10	7.00	12	10.00 - 50.00
Nitrate	mg/L	0.38±0.05	0.28	0.46	12	45.00-50.00
Bicarbonate	mg/L	0.51±0.14	0.24	0.72	12	0.01 - 0.05
Zinc	mg/L	0.07±0.09	0.01	0.34	12	100 – 500
Iron	mg/L	0.06±0.03	0.01	0.13	12	0.3 - 3.0
Copper	mg/L	0.02±0.01	0.01	0.04	7	0.00 - 2.00
Chromium	mg/L	0.03±0.01	0.01	0.05	10	0.00 - 0.05
Sulphate	mg/L	3.96±1.19	2.27	6.16	12	0.00 – 100
Lead	mg/L	0.01±0.00	0.01	0.01	7	0.00 - 0.01
Sodium	mg/L	13.79±9.50	0.80	33.43	12	10.00 - 25.00
Potassium	mg/L	32.34±29.14	0.97	74.67	12	NS
Calcium	mg/L	2.11±2.27	0.10	7.00	12	NS
Magnesium	mg/L	2.15±5.55	0.02	20.50	12	0.00 - 20.00
E. coli Count	CFU/mL	0.08±0.28	0.00	1.00	12	0
Coliform Count	CFU/mL	0.75±0.72	0.00	2.00	12	0
Yeast Count	CFU/mL	0.00±0.00	0.00	0.00	12	0
Bacteria Count	CFU/mL	2.17±1.28	1.00	5.00	12	0

NOTE- NS: calcium and potassium levels are more focused on aesthetic qualities and potential health impacts at higher concentrations

3.1. Physicochemical Parameters

3.1.1. pH

The mean pH of the groundwater samples was 5.50 ± 0.36, with values ranging from 5.03 to 6.27 falling below the SON/WHO recommended range of 6.5 to 8.5. This indicates a slightly acidic nature of the borehole water. Similar trends have been reported by Ogbeifun *et al*. (2019), who noted persistent low pH levels across the mangrove swamp zones of the Niger Delta. One plausible contributor to this acidity is gas flaring, a common industrial activity in the region (Edokpayi *et al*., 2017). The combustion of fossil fuels releases carbon dioxide, which dissolves in atmospheric moisture to form carbonic acid ($CO_2 + H_2O \rightarrow H_2CO_3$). This weak acid infiltrates the subsurface environment, subsequently lowering the pH of groundwater. Although pH itself does not have a direct toxicological impact on human health, it significantly influences biochemical reactions, many of which are pH-dependent (WHO, 2017). The acidic nature of the water makes it suboptimal for human consumption and may contribute to a variety of issues. Naturally acidic groundwater can arise from geological processes, such as volcanic emissions or geothermal alterations, and is often associated with adverse health outcomes, including eye, skin, and mucous membrane irritation. Moreover, acidic water has corrosive properties that can degrade plumbing infrastructure and enhance the leaching of toxic metals like lead and copper into the water supply (WHO, 2017). This pose both chemical and health risks, including potential gastrointestinal irritation in consumers (Edokpayi *et al*., 2017).

3.1.2. Turbidity

The mean turbidity value recorded was 0.39 NTU, significantly below the WHO-recommended limit of 5 NTU, indicating excellent water clarity. As noted by APHA (2012), low turbidity suggests a minimal presence of suspended particulate matter, an indicator of good water quality and reduced potential for microbial contamination. Similar low turbidity levels have been reported in Dutsin-Ma (Ibrahim and Nuraddeen, 2014), where values also fell below acceptable thresholds. This has been attributed to the geologic composition of the area, which appears to be relatively stable and free from materials that typically elevate turbidity levels. These conditions suggest that the aquifer system is largely unaffected by sediments, microscopic organisms, pigmented organic matter, silt, or clay, indicating a naturally filtered and geologically stable groundwater environment. The low presence of finely divided organic and inorganic matter suspended in the groundwater suggests limited disturbance and good natural filtration, both of which contribute to the safety and clarity of the water.

3.1.3. Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

The mean electrical conductivity (EC) and total dissolved solids (TDS) were 143.67 μS/cm and 78.98 mg/L, respectively, both well below the SON/WHO permissible limits of 900–1200 μS/cm for EC and 500–1500 mg/L for TDS. Electrical conductivity reflects the water's ability to conduct current, which depends on the temperature, types, and concentrations of dissolved ions. It is widely used as an indirect measure of total ionic concentration or mineral content in water. At elevated levels, high conductivity is often associated with excessive salinity, which can impart an unpleasant taste or odour and may even lead to gastrointestinal discomfort in consumers. The low EC and TDS values observed in this study suggest minimal mineralization and low salinity, characteristics typical of fresh, unpolluted groundwater. This implies that the water is unlikely to pose health risks related to excessive intake of dissolved salts (Kumar *et al.*, 2019). Furthermore, the low conductivity values may reflect limited solute dissolution within the aquifer, possibly due to the presence of relatively insoluble geological formations or minimal geochemical weathering. Alternatively, it may indicate rapid ion exchange processes between soil and water, which prevent the accumulation of dissolved constituents, pointing to a geochemically stable and uncontaminated groundwater system.

3.1.4. Total Suspended Solids (TSS) and Total Solids (TS)

TSS and TS values were 12.02 mg/L and 91.00 mg/L, respectively, with no specific standards provided. The relatively low TSS indicates low particulate contamination, which is beneficial for aesthetic quality and reduces microbial habitats (Sillanpää *et al.*, 2018). Elevated levels of Total Suspended Solids (TSS) contribute to increased turbidity, often serving as an indicator of pollution. TSS typically consists of carbonates, bicarbonates, chlorides, phosphates, nitrates of calcium, sodium, potassium, and manganese, as well as organic matter, silt, and other particulate materials. High TSS concentrations are generally considered aesthetically unsuitable for bathing and other domestic uses. However, the TSS and Total Solids (TS) levels recorded in the analyzed water samples were well below the World Health Organization (WHO) recommended thresholds, indicating that the water is safe for drinking and other household applications.

3.1.5. Alkalinity and Hardness

Total alkalinity exhibited a mean concentration of 49.67 mg/L, remaining well below the established standard limit of 100 mg/L, indicating limited buffering capacity and increased vulnerability to pH fluctuations. Such instability can harm aquatic life and accelerate corrosion in water infrastructure. Total hardness was very low at 7.96 mg/L, far beneath the 100–250 mg/L recommended range, signifying very soft water. The observed low hardness levels align with findings by Kumar *et al.* (2019), who reported soft water in rural areas due to geological factors. While soft water reduces scaling, excessively low hardness can increase corrosivity, causing metals like lead and copper to leach from pipes, posing health risks and damaging distribution systems (WHO, 2017). Together, the low alkalinity and hardness reflect a water source with limited ability to neutralize acids and maintain chemical balance, making it prone to acidification from environmental pollutants.

3.1.6. Chloride and Sulphate

The average concentration of chlorides and sulphates at all locations was 3.71 and 3.96 mg/L, respectively. Both concentrations were within safe limits, indicating minimal risk of taste issues or purgative effects associated with higher concentrations (Edokpayi *et al*., 2017). However, while the human body requires essential nutrients for proper physiological function, excessive intake can pose significant health risks notably, all nutrient concentrations measured during the study remained within the World Health Organization (WHO) guidelines for potable water. Consequently, the water samples from all locations can be considered safe for consumption, as none of the nutrient levels exceeded the recommended limits.

3.2. Trace Metals and Heavy Metals

The mean concentrations of zinc (0.07 mg/L), iron (0.06 mg/L), copper (0.02 mg/L), chromium (0.03 mg/L), and lead (0.01 mg/L) were all within or near the lower limits of WHO permissible standards. However, lead was detected at its maximum allowable limit (0.01 mg/L), raising concern due to its high toxicity and tendency to bioaccumulate. The presence of lead at permissible limits echoes concerns raised by Edokpayi *et al.* (2017) about metal contamination from corroded pipes and industrial pollution. Prolonged exposure to lead is particularly harmful to children, with established links to neurological impairment (Needleman, 2004). Chromium, though within acceptable limits, approached the upper threshold (0.05 mg/L), highlighting the need for ongoing monitoring due to the known carcinogenicity of its hexavalent form (ATSDR, 2012).

3.3. Nutrients and Electrolytes

Sodium (13.79 mg/L) and potassium (32.34 mg/L) showed variable concentrations, with sodium within recommended limits and potassium lacking a defined standard (NS). Elevated potassium levels, although not commonly regulated, can affect individuals with kidney disorders (Sharma and Bhattacharya, 2016). Calcium and magnesium levels were low, with magnesium averaging 2.15 mg/L, close to the upper limit of 20 mg/L. These minerals are essential for human health, and low concentrations may reduce the water's contribution to dietary intake (WHO, 2017).

3.4. Microbiological Parameters

The mean counts for *E. coli* (0.08 CFU/ml) and total coliforms (0.75 CFU/ml) indicate the presence of microbial contamination, exceeding the zero-tolerance standard for potable water. The presence of coliforms and *E. coli* suggests faecal contamination, posing significant health risks such as gastrointestinal infections, diarrhoea, and other waterborne diseases (Edokpayi et al., 2022; WHO, 2017). For instance, Olayinka *et al.* (2018) found detectable coliforms in well water, attributing contamination to poor sanitation practices. Yeast counts were zero, indicating no fungal contamination, while bacteria counts averaged 2.17 CFU/ml, which should ideally be zero in drinking water.

However, the overall distribution of groundwater quality parameters with SON/WHO standard ranges for commercial areas in Benin City is as revealed in Figure 2.

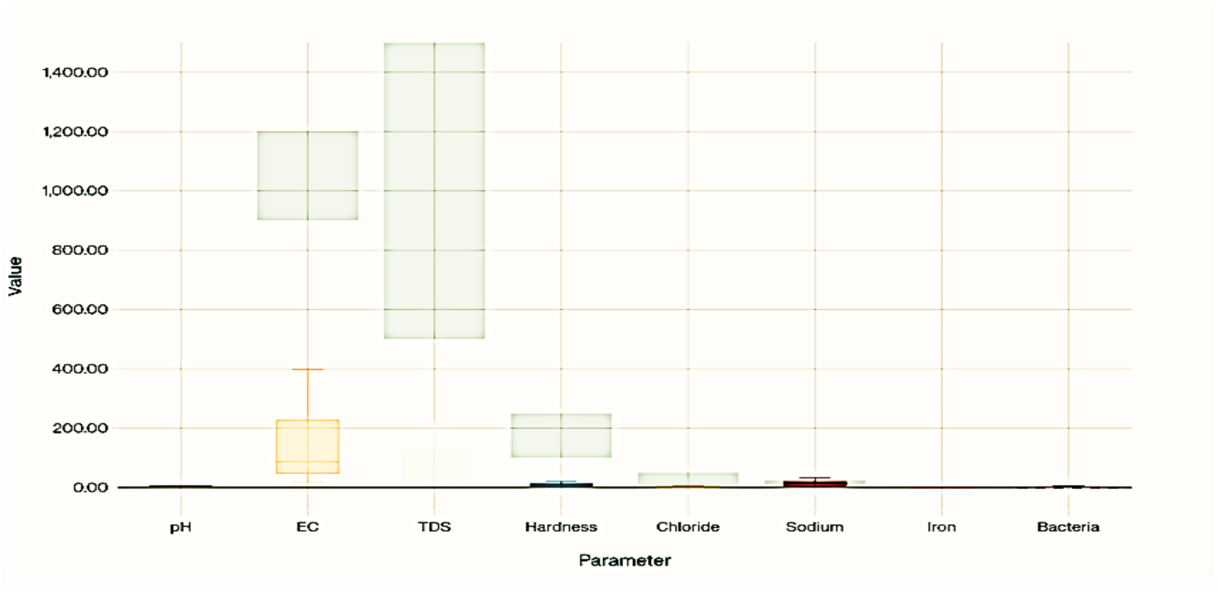


Figure 2: Box plots showing distribution of groundwater quality parameters with SON/WHO standard ranges for commercial areas in Benin City

The correlation matrix displayed in Figure 3 showed several significant relationships that provide insights into groundwater geochemistry and contamination sources. The perfect correlation between electrical conductivity and total dissolved solids ($r = 0.999$, $p < 0.001$) demonstrates the fundamental relationship between ionic strength and dissolved mineral content. The strong correlation between total hardness and sodium ($r = 0.871$, $p < 0.001$) suggests common geological sources, possibly from feldspar weathering or clay mineral interactions.

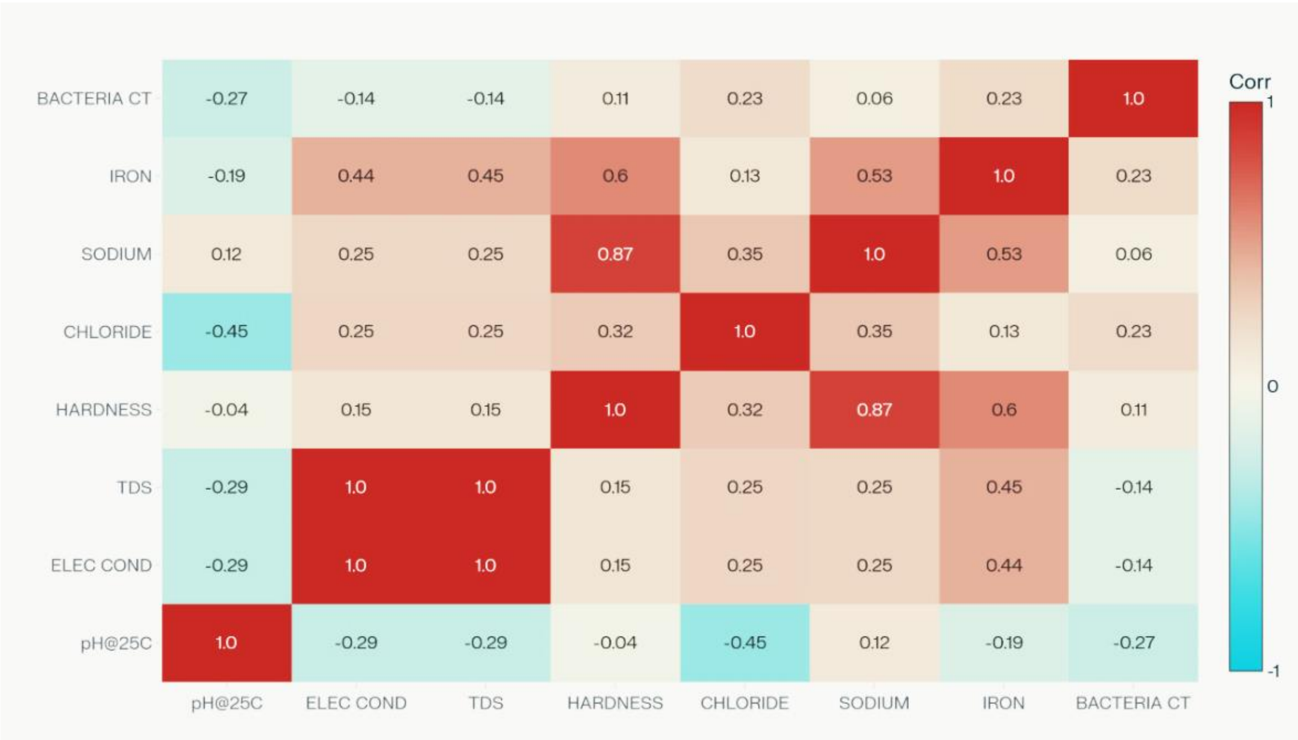


Figure 3: Correlation Heatmap of Groundwater Physicochemical and Microbiological Parameters

3.5. Principal Component Analysis and Hierarchical Clustering of Groundwater Quality Data

The multivariate statistical analysis of groundwater quality data from twelve commercial locations in Benin City revealed distinct patterns through Principal Component Analysis (PCA) and hierarchical clustering, providing deeper insights into the spatial distribution and relationships among water quality parameters.

3.5.1. Principal Component Analysis

The PCA analysis of 21 key physicochemical and microbiological parameters indicated that the first two principal components explained 49.4% of the total variance in the dataset. PC1 accounted for 29.1% of the variance, while PC2 contributed 20.3%. This substantial proportion of explained variance indicates that the first two components capture the most significant patterns in groundwater quality variation across the commercial areas, as shown in Figure 4.

Figure 4: PCA Biplot of Groundwater Quality at 12 Commercial Locations in Benin City

Component loadings analysis revealed that PC1 was primarily dominated by parameters related to mineral content and contamination indicators. The highest positive loadings on PC1 were observed for potassium (0.332), electrical conductivity (0.294), total dissolved solids (0.294), sodium (0.292), and turbidity (0.281). These parameters collectively represent the dissolved mineral content and overall contamination levels in groundwater. Conversely, sulphate showed a strong negative loading (-0.306), indicating an inverse relationship with the mineral content cluster. PC2 was characterized by parameters related to water hardness and specific contaminants. The highest positive loadings included copper (0.434), calcium (0.359), sodium (0.322), and total hardness (0.300). This component appears to capture the hardness-related chemistry and specific metal contamination patterns. The negative loadings were led by turbidity (-0.285) and electrical conductivity (-0.260), suggesting an inverse relationship between turbidity and the hardness-related parameters.

3.5.2. Hierarchical Clustering Analysis

The hierarchical clustering analysis using Ward's linkage method successfully identified three distinct clusters of groundwater quality characteristics across the commercial locations. The dendrogram analysis revealed clear separation patterns with distinct linkage distances, indicating meaningful groupings based on water quality similarity.

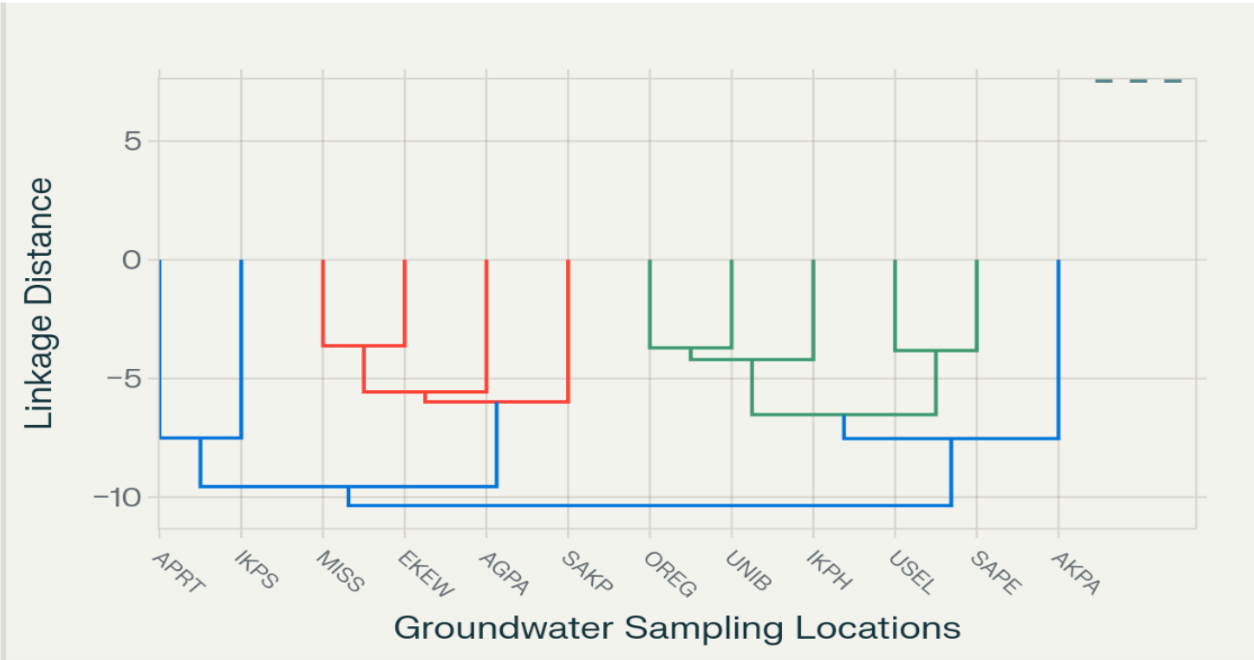


Figure 5: Hierarchical Clustering of Groundwater Quality at 12 Commercial Sites.

Hierarchical Cluster Analysis (HCA) grouped the twelve groundwater sampling sites into three distinct clusters based on similarities in their physicochemical and microbial characteristics. Cluster 1, comprising SAPE, USEL, AKPA, UNIB, IKPH, and OREG, represented locations with the best water quality, marked by low acidity, minimal mineral content, and the lowest bacterial counts. Cluster 2 (IKPS and APRT) exhibited elevated hardness and sodium levels despite low conductivity, suggesting localized geogenic influence. Cluster 3, which included SAKP, AGPA, EKEW, and MISS, demonstrated the poorest water quality, characterized by high electrical conductivity, increased acidity, and elevated microbial loads, indicative of anthropogenic contamination. These clustering patterns aligned closely with the results of the Principal Component Analysis (PCA), reinforcing the observed spatial trends and validating the grouping of locations based on shared water quality features. The strong agreement between PCA and HCA strengthens the robustness of the classification and supports the interpretation of underlying contamination sources and hydrogeochemical influences across the study area.

3.6. Compliance Analysis

The compliance assessment revealed concerning levels of non-conformity across several key water quality parameters. Chi-square analysis indicated a statistically significant variation in compliance rates among the parameters assessed ($\chi^2 = 32.73$, $p < 0.001$), underscoring the uneven distribution of regulatory adherence. Notably, certain parameters exhibited exceedances of regulatory thresholds at specific sampling points, indicating localized non-compliance with water quality standards. However, overall compliance was maintained for the majority of measured variables as observed for critical parameters, including pH, electrical conductivity, total dissolved solids (TDS), bicarbonate, and bacterial counts, all of which exceeded or fell short of the SON/WHO recommended standards across all sampling locations. In contrast, partial compliance was recorded for sodium and magnesium, with compliance rates of 50.0% and 91.7% respectively, suggesting variability in their distribution across the sampling sites. Conversely, parameters such as copper, chromium, sulphate, and lead remained within acceptable detection limits across all samples, indicating complete compliance and minimal risk associated with these elements. These findings highlight the need for urgent remedial action, particularly in addressing the widespread deviations observed in acidity, mineral load, and microbial contamination, which pose significant health and infrastructure risks.

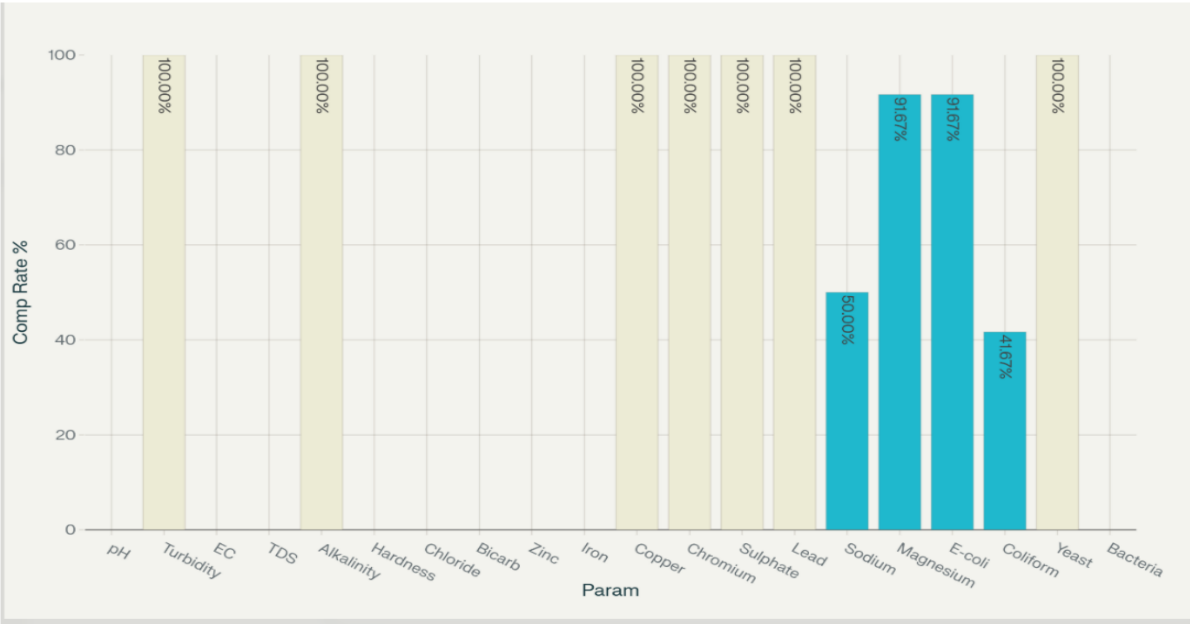


Figure 6: Compliance of Groundwater Quality with WHO/SON Standards in Benin City

4.0 Conclusions

Groundwater quality assessment in commercial zones of Benin City revealed significant departures from regulatory benchmarks, notably elevated acidity and pronounced microbial contamination. While most trace metals and nutrients fell within permissible thresholds, the detection of lead at its regulatory limit, alongside persistent faecal indicators, signals a clear and immediate threat to public health. Without decisive intervention, these conditions risk escalating into long-term environmental degradation, increased disease burden, and substantial socio-economic costs. Therefore, implementing advanced water treatment technologies, rigorous surveillance systems, and proactive management strategies is imperative to ensure sustainable access to safe groundwater and to protect the resilience of urban water infrastructure.

Acknowledgments

The authors acknowledge the Faculty of Science Laboratory Technology, University of Benin, for laboratory support and all field assistants involved in sample collection.

References

APHA (2017). Standard Methods for the Examination of Water and Wastewater, 23rd Edition.

ATSDR (2012). Toxicological Profile for Chromium. Agency for Toxic Substances and Disease Registry.

Bassey, P. and Archibong, U. D. (2023). Physiochemical Assessment for Groundwater Quality in Sakponba Community of Orhionmwon L.G.A. of Edo State, Southern Nigeria. *Nigerian Journal of Applied Science,* 41(1), 79-85.

Edokpayi, J. N., Enitan, A. M., Mutileni, N., and Odiyo, J. O. (2018). Evaluation of water quality and human risk assessment due to heavy metals in groundwater around Muledane area of Vhembe District, Limpopo Province, South Africa. *Chemistry Central Journal*, 12(1).

Edokpayi, J. N., Nkhumeleni, M., Enitan-Folami, A. M. and Olaniyi, F. C. (2022). Water quality assessment and potential ecological risk of trace metals in sediments of some selected rivers in Vhembe district, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 126, 103111.

Edokpayi, J. N., Odiyo, J. O., and Durowoju, O. S. (2017). Impact of contaminated water on the health of children in developing countries. *International Journal of Environmental Research and Public Health*, 14(2), 1-13.

Ibrahim, Y. E. and Nuraddeen, A. M. (2014). An assessment of some water quality properties of groundwater in Dutsin-Ma Metropolis, Nigeria. *International Journal of current microbiology and applied sciences*, 3(5):644-649.

Kumar, A., Singh, P., and Singh, R. (2019). Assessment of groundwater quality and its suitability for drinking and irrigation purposes. *Environmental Monitoring and Assessment*, 191(7), 1-15.

Needleman, H. (2004). Lead poisoning. Annual Review of Medicine, 55, 209-222.

Ogbeifun, D. E., Archibong, U. D., Chiedu, I. E. and Ikpe, E. E. (2019). Assessment of the Water Quality of Boreholes in selected Areas in Benin City, Edo State, Nigeria. *Chemical Science International Journal*, 28(2): 1-13.

Olasoji, S. O., Oyewole, N. O., Abiola, B., & Edokpayi, J. N. (2019). Water Quality Assessment of Surface and Groundwater Sources Using a Water Quality Index Method: A Case Study of a Peri-Urban Town in Southwest, Nigeria. *Environments*, *6*(2), 23.

Onwordi, C. T., Semako, M., Izunobi, J. U., Osifeko, O. L., Majolagbe, A. O., and Ojekale, A. B. (2022). Assessment of the groundwater quality, physicochemical composition, and human and ecological health risks in a coastal metropolitan: A case study of a residential estate in Lagos, Nigeria. *Environmental monitoring and assessment*, *194*(3), 148.

Sharma, S., and Bhattacharya, A. (2016). Drinking water contamination and treatment techniques. *Applied Water Science*, 7(3), 1043–1067.

Sillanpää, M., Ncibi, M. C., and Matilainen, A. (2018). Advanced oxidation processes for water treatment: advances and trends for R&D. *Water Research*, 147, 1-19.

WHO (2017). Guidelines for Drinking-water Quality, 4th Edition. Geneva: World Health Organization.

Cite this article as:

Archibong U. D., Osagie A. F. and Agho T. I. (2025). Physicochemical and Microbial Assessment of Underground Water in Commercial Areas of Benin City, Edo State. *Nigerian Journal of Environmental Sciences and Technology*, 9(2), pp. 21-32. https://doi.org/10.36263/nijest.2025.02.41