MSI Journal of
Multidisciplinary Research (MSIJMR)

Volume: 3, Issue: 9 (September-2026)
Published by *MSI Publishers*
ISSN 3049-0669 (Online)

Received: 13-06-2026
Accepted: 27-08-2026
Published: 01-09-2026

Hydrochemical Characterization and Multivariate Statistical Assessment of Institutional Groundwater Quality

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ABSTRACT: Groundwater quality evaluation in high-density institutional settings requires advanced analytical techniques to distinguish the dominant hydrochemical characteristics and potential anthropogenic influences. This study presents a comprehensive hydrochemical and multivariate statistical assessment of operational groundwater resources within Kaduna Polytechnic, Nigeria. Groundwater samples were collected from fifteen operational boreholes and analyzed for eight physicochemical and organic parameters: pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate ($\mathrm{NO_3^-}$), sulphate ($\mathrm{SO_4^{2-}}$), chemical oxygen demand (COD), and total organic carbon (TOC). While univariate comparisons confirm that all parameters comply with World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) permissible limits, descriptive statistics reveal localized enrichment at vulnerable assets (EC up to $324.67\ \mu\mathrm{S/cm}$ at BH27; TDS up to $168.0\ \mathrm{mg/l}$ at BH04).

 DOI: ***10.5281/zenodo.22226299***

Pearson correlation matrix analysis revealed strong positive associations between ionic solutes (EC, TDS, and turbidity; $r > 0.85, p < 0.01$) and a near-perfect positive correlation between COD and TOC ($r = 0.997, p < 0.01$). Furthermore, Principal Component Analysis (PCA) identified two principal components that collectively explained 81.35% of the total variance, representing groundwater mineralization and localized organic influences. These findings demonstrate that integrating hydrochemical characterization with multivariate statistical analysis provides a robust framework for interpreting groundwater quality variability and supporting evidence-based groundwater management in institutional environments.

Keywords: *Hydrochemical characterization; Multivariate statistics; Principal Component Analysis (PCA); Groundwater quality; Institutional water security.*

1. Introduction

Groundwater is one of the most dependable freshwater resources worldwide, supplying nearly half of the global population with drinking water and supporting domestic, agricultural, industrial, and institutional activities. In many developing countries, particularly across sub-Saharan Africa, groundwater abstraction through decentralized boreholes has become the primary source of potable water owing to the inadequacy and unreliability of municipal water supply systems (United Nations, 2023; WHO, 2022). Educational institutions are among the largest institutional consumers of groundwater, relying extensively on boreholes to meet the daily water requirements of students, staff, laboratories, hostels, cafeterias, and administrative facilities. Consequently, maintaining groundwater quality is essential for safeguarding public health, ensuring uninterrupted institutional operations, and achieving sustainable water resource management.

Unlike residential communities, tertiary institutions function as densely populated micro-urban environments characterized by intensive human activities, including wastewater generation, sanitation facilities, refuse disposal, vehicular movement, and localized drainage systems. These anthropogenic pressures increase the likelihood of introducing dissolved ions, nutrients, and organic contaminants into shallow groundwater through infiltration and recharge processes, thereby altering the natural hydrochemical characteristics of aquifers (Hyeroba & Kalin, 2024). Hydrochemical characterization

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therefore provides a scientific basis for evaluating groundwater quality by examining key physicochemical and organic parameters that reflect mineralization processes, nutrient enrichment, and possible contamination. Parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate (NO_3^-), sulphate (SO_4^{2-}), chemical oxygen demand (COD), and total organic carbon (TOC) are widely used to determine the suitability of groundwater for drinking and other domestic purposes (Barbulescu, 2020).

Conventional groundwater quality assessment generally involves comparing measured parameter concentrations with guideline values established by organizations such as the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ). While compliance with these standards is fundamental for evaluating drinking water safety, such univariate assessments provide limited understanding of the interactions among hydrochemical variables and the processes controlling groundwater chemistry. Groundwater quality is influenced by a combination of natural processes, including water–rock interaction and aquifer mineralogy, as well as anthropogenic activities that may alter its chemical composition (Goyal et al., 2021). Consequently, interpretation based solely on individual water quality parameters may not adequately explain the factors governing groundwater variability.

Multivariate statistical techniques have therefore become valuable tools for groundwater quality investigations because they enable simultaneous evaluation of multiple hydrochemical variables and reveal patterns that are difficult to identify using conventional descriptive analyses alone. Pearson correlation analysis is commonly used to quantify relationships among water quality parameters, whereas Principal Component Analysis (PCA) reduces complex datasets into a smaller number of independent components that explain the dominant sources of hydrochemical variation (Bakhtiarizadeh et al., 2024; Barbulescu, 2020). Despite the increasing application of these techniques in groundwater research, studies integrating hydrochemical characterization with multivariate statistical analysis for institutional groundwater systems in Nigeria remain scarce. This study therefore presents a comprehensive hydrochemical characterization and multivariate statistical assessment of groundwater quality within Kaduna Polytechnic, Nigeria, with the objectives of evaluating groundwater quality relative to WHO and NSDWQ standards, examining relationships among hydrochemical parameters using Pearson correlation

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analysis, and identifying the principal factors governing groundwater quality variability through PCA.

2. Materials and Methods

2.1 Study Area and Sampling Design

This study was conducted within Kaduna Polytechnic, Kaduna State, Nigeria. Kaduna Polytechnic is one of the largest tertiary institutions in northern Nigeria and depends largely on groundwater abstraction through boreholes for domestic, academic, commercial, and institutional water supply. The study focused on the Tudun Wada Campus, which accommodates academic buildings, student hostels, commercial areas, and administrative facilities. Rapid population growth, increasing waste generation, and expanding campus infrastructure have intensified anthropogenic pressures on the groundwater system, necessitating regular hydrochemical monitoring to ensure the safety and sustainability of institutional water supplies.

Groundwater samples were collected from 15 operational boreholes selected to provide representative coverage of the campus water supply system. The selected boreholes were identified from an earlier campus-wide groundwater inventory and vulnerability assessment and comprised only functional boreholes actively used for water supply. Restricting the analysis to operational boreholes ensured that the hydrochemical assessment reflected the quality of groundwater currently consumed by the campus community while providing a representative dataset for subsequent statistical analyses.

2.2 Groundwater Sampling and Laboratory Analysis

Prior to sample collection, each borehole was allowed to discharge for several minutes to flush stagnant water from the distribution system and obtain representative groundwater. At each borehole, three independent water samples were collected directly from the discharge outlet into clean polyethylene bottles pre-rinsed with the respective groundwater. The samples were assigned unique identification codes, appropriately labelled, and transported immediately to the laboratory for analysis. Standard sampling, handling, and transportation procedures were followed to preserve sample integrity and minimize physicochemical alterations prior to analysis.

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The groundwater samples were analysed for eight water quality parameters: pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate (NO_3^-), sulphate (SO_4^{2-}), chemical oxygen demand (COD), and total organic carbon (TOC), in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). Measurements of pH, EC, and TDS were performed using a Hanna HI 9813-6 multiparameter meter, whereas turbidity, nitrate, and sulphate were determined using a Hanna HI 83099 multiparameter photometer. COD was analysed using the standard colorimetric method, while TOC was measured using a Total Organic Carbon Analyzer. The three samples collected from each borehole were analysed independently, and the mean values were used for subsequent statistical analyses. Quality assurance and quality control (QA/QC) procedures, including instrument calibration, reagent blanks, replicate analyses, and verification using standard reference solutions, were implemented to ensure analytical accuracy and reliability.

2.3 Statistical Analysis

The hydrochemical dataset was processed and analysed using Python within the Jupyter Notebook environment utilizing the Pandas, NumPy, SciPy, and Scikit-learn libraries. Descriptive statistical measures, including the mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV), were computed to summarize the distribution and variability of the measured groundwater quality parameters across the sampled boreholes.

Prior to multivariate analysis, all hydrochemical variables were standardized using z-score normalization to transform the data to a common scale with a mean of zero and a standard deviation of one. Standardization eliminates scale-dependent bias arising from differences in measurement units and magnitudes, ensuring that each variable contributes equally to the multivariate analyses.

Pearson correlation analysis was employed to evaluate the strength and direction of linear relationships among the measured physicochemical and organic parameters. The Pearson correlation coefficient was computed as:

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

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where r is the Pearson correlation coefficient, x_i and y_i are the observed values of variables x and y, $\bar{x}$ and $\bar{y}$ are their respective means, and n is the number of observations. The analysis was used to identify significant associations, collinearity, and potential common hydrochemical controls among the measured parameters.

Principal Component Analysis (PCA) was subsequently applied to the standardized dataset to reduce data dimensionality and identify the dominant factors controlling groundwater quality. PCA transforms the original correlated variables into a smaller set of orthogonal principal components according to:

$$PC_i = a_{i1}X_1 + a_{i2}X_2 + \cdots + a_{in}X_n \qquad (2)$$

where PC_i is the ith principal component, a_{ij} is the loading of the jth variable on the ith component, and X_j represents the standardized hydrochemical variables. Components with eigenvalues greater than 1.0 were retained based on the Kaiser criterion, while the corresponding loading matrices were interpreted to identify the principal hydrochemical processes influencing groundwater composition. Factor loadings with absolute values ≥0.75 were considered strong, 0.50–0.74 moderate, and 0.30–0.49 weak, following commonly accepted guidelines for multivariate environmental data analysis.

3. Results and Discussion

3.1 Hydrochemical Characteristics of Groundwater

The descriptive statistics of the analysed groundwater quality parameters are presented in Table 1, while their distributions are illustrated using boxplots in Figure 1. The groundwater exhibited slightly acidic to neutral conditions, with pH values ranging from 6.12 to 7.48 (mean = 6.62 ± 0.43), indicating that the sampled boreholes generally complied with the recommended drinking water guideline of 6.5–8.5 established by both the World Health Organization (WHO, 2022) and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015). Although the minimum pH recorded was marginally below the recommended lower limit, the overall groundwater chemistry suggests favourable acid-base conditions for domestic use.

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Table 1: Descriptive Statistics

Parameter	Unit	Mean	Min	Maxi	SD	CV (%)	WHO (2022)	NSDWQ (2015)	Compliance
pH	-	6.62	6.12	7.48	0.43	6.54	6.5–8.5	6.5–8.5	Compliant
EC	µS/cm	149.1	45.5	324.67	88.53	59.38	No guideline	1000	Compliant
TDS	mg/L	78.4	26	168	44.37	56.59	1000	500	Compliant
Turbidity	NTU	3.34	1.21	5.94	1.29	38.69	5	5	Compliant
Nitrate	mg/L	3.62	1.1	10.98	3.08	85.25	50	50	Compliant
Sulphate	mg/L	6.22	1.34	8.99	2.37	38.18	250	100	Compliant
COD	mg/L	0.87	0.04	1.8	0.67	76.92	No guideline	No guideline	Not Applicable
TOC	mg/L	1.17	0.05	2.63	0.91	77.96	No guideline	No guideline	Not Applicable

Electrical conductivity (EC) and total dissolved solids (TDS) exhibited mean values of 149.10 µS/cm and 78.40 mg/L, respectively, which are substantially lower than the recommended guideline values. These low concentrations indicate weak mineralization and limit dissolved ionic content within the aquifer system. Similarly, the mean sulphate concentration (6.22 mg/L) and nitrate concentration (3.62 mg/L) were considerably below their respective guideline limits, suggesting minimal influence from fertilizer application, sewage infiltration, or industrial contamination. Turbidity averaged 3.34 NTU, remaining below the recommended maximum value of 5 NTU, although isolated boreholes approached this threshold, indicating localized particulate matter or suspended sediments.

Organic pollution indicators also remained relatively low. Chemical oxygen demand (COD) and total organic carbon (TOC) averaged 0.87 mg/L and 1.17 mg/L, respectively, indicating limited organic matter within the groundwater. Although no regulatory guideline values are specified for COD and TOC in drinking water standards, the observed concentrations suggest that organic contamination is generally insignificant across the sampled boreholes.

 DOI: 10.5281/zenodo.22226299

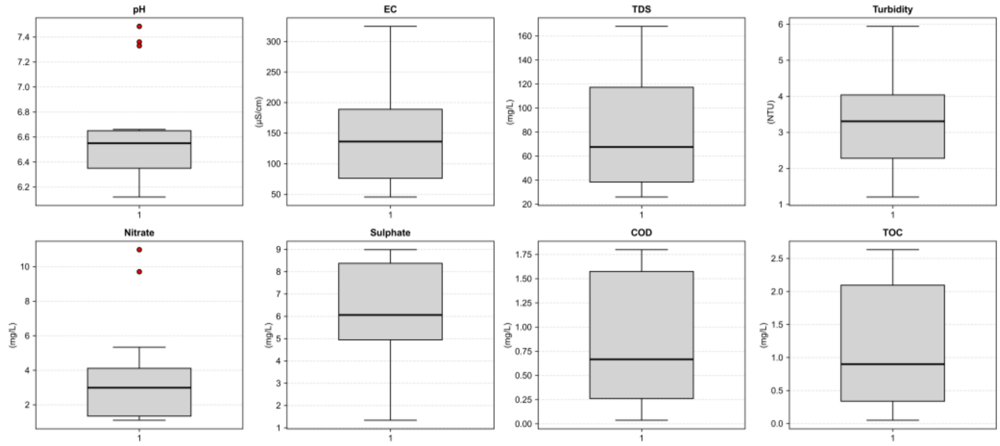

Figure 1: Distribution of Measured Groundwater Quality Parameters

The coefficients of variation (CV) reveal substantial differences in spatial variability among the measured parameters. According to commonly adopted classifications (CV < 15% = low variability; 15–35% = moderate variability; >35% = high variability), pH exhibited low spatial variability (6.54%), reflecting relatively stable groundwater buffering conditions across the study area. In contrast, EC (59.38%), TDS (56.59%), nitrate (85.25%), COD (76.92%), and TOC (77.96%) displayed high variability, indicating considerable heterogeneity in groundwater chemistry among boreholes. Such variability is characteristic of localized hydrogeological conditions and varying anthropogenic influences, including differences in aquifer mineral composition, groundwater residence time, and localized organic inputs. The boxplots (Figure 1) further demonstrate these variations by showing relatively narrow distributions for pH and sulphate but wider spreads for nitrate, COD, and TOC, confirming that groundwater quality is spatially heterogeneous despite overall compliance with drinking water standards.

3.2 Pearson Correlation Analysis

The Pearson correlation heatmap (Figure 2) reveals several significant relationships among the groundwater quality parameters, providing insight into the hydrochemical processes controlling groundwater composition.

A very strong positive correlation was observed between electrical conductivity (EC) and total dissolved solids (TDS) ($r = 0.92$), confirming that dissolved ionic constituents are the principal contributors to groundwater conductivity. Similarly, TDS exhibited a strong positive relationship with turbidity ($r = 0.90$), while EC also correlated strongly with turbidity ($r = 0.85$). These relationships suggest that boreholes containing elevated

DOI: 10.5281/zenodo.22226299

dissolved minerals also tended to exhibit higher suspended particulate concentrations, reflecting common hydrogeochemical controls or localized groundwater recharge characteristics.

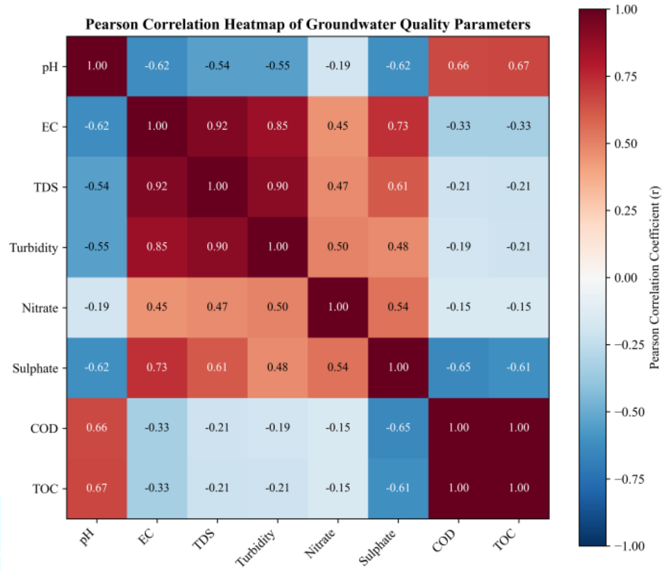

Figure 2: Pearson Correlation Analysis

Sulphate showed moderate to strong positive correlations with EC (r = 0.73) and TDS (r = 0.61), indicating that sulphate contributes to the overall ionic composition of groundwater. Nitrate demonstrated moderate positive associations with sulphate (r = 0.54), turbidity (r = 0.50), TDS (r = 0.47), and EC (r = 0.45), suggesting that nutrient enrichment may originate from diffuse anthropogenic activities such as wastewater infiltration or surface runoff rather than from a single dominant contamination source.

The strongest relationship observed in the dataset was between COD and TOC (r = 1.00), indicating that both parameters describe essentially the same organic matter characteristics within the sampled groundwater. This near-perfect correlation is expected because both variables quantify organic constituents through complementary analytical approaches. Their positive correlations with pH (COD: r = 0.66; TOC: r = 0.67) and negative correlations with sulphate (COD: r = −0.65; TOC: r = −0.61) suggest that groundwater enriched in organic matter exhibits a hydrochemical signature distinct from waters dominated by dissolved inorganic ions.

Conversely, pH displayed moderate negative correlations with EC (r = −0.62), sulphate (r = −0.62), turbidity (r = −0.55), and TDS (r = −0.54), indicating that groundwater with

 DOI: *10.5281/zenodo.22226299*

relatively higher ionic concentrations tended to exhibit slightly lower pH values. Overall, the correlation structure indicates the presence of two broad hydrochemical processes: one associated with inorganic mineral dissolution controlling EC, TDS, turbidity, and sulphate, and another associated with organic matter represented primarily by COD and TOC.

3.3 Principal Component Analysis (PCA) and Factor Identification

Principal Component Analysis (PCA) was performed to identify the dominant hydrochemical processes governing groundwater quality. The scree plot (Figure 3) and eigenvalue summary (Table 2) indicate that only the first two principal components possess eigenvalues greater than one, satisfying the Kaiser criterion for component retention. These two components explain 81.35% of the total variance, demonstrating that the multidimensional groundwater dataset can be adequately represented by two dominant hydrochemical factors.

Table 1: Eigenvalue Summary

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	5.003	58.37	58.37
PC2	1.97	22.98	81.35

The scree plot exhibits a pronounced decline in eigenvalues after the second component, followed by a relatively flat trend for subsequent components, indicating that additional components contribute only marginally to explaining groundwater variability. Consequently, only PC1 and PC2 were retained for interpretation.

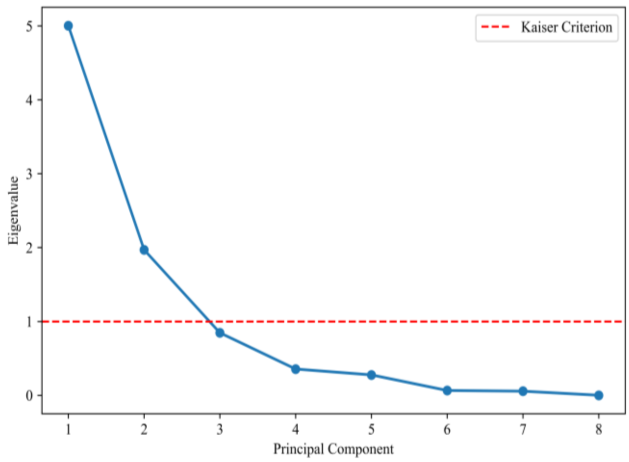

Figure 3: Scree Plot of Principal Component

DOI: *10.5281/zenodo.22226299*

The loading matrix (Table 4) shows that PC1, which explains 58.37% of the total variance, is characterized primarily by EC (−0.410), sulphate (−0.399), TDS (−0.383), pH (0.372), and turbidity (−0.364). Although no single loading exceeds ±0.50, these variables collectively describe the dominant physicochemical characteristics of the groundwater system. Accordingly, PC1 represents a general hydrochemical mineralization factor, reflecting variations in dissolved ionic constituents and overall groundwater chemistry across the study area.

The second principal component (PC2) accounts for 22.98% of the total variance and is dominated by COD (0.535) and TOC (0.529), with smaller positive contributions from turbidity (0.364), TDS (0.354), and nitrate (0.256). The dominance of COD and TOC indicates that this component primarily reflects organic matter and anthropogenic influence, distinguishing boreholes affected by relatively elevated organic constituents from those dominated by inorganic mineralization.

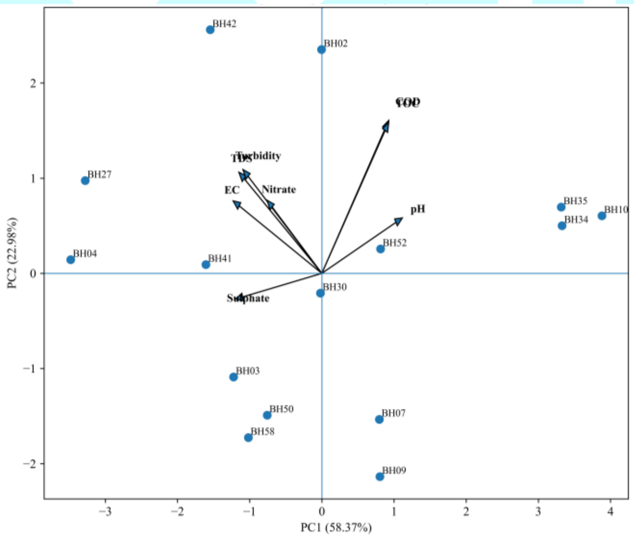

Figure 4: PCA Biplot

The PCA biplot (Figure 4) further illustrates the separation of groundwater quality variables into these two hydrochemical domains. EC, TDS, sulphate, and turbidity cluster closely along the first principal component, confirming their common geochemical origin, whereas COD and TOC align predominantly with the second principal component, reflecting their shared association with organic matter. The distribution of boreholes across the biplot demonstrates spatial heterogeneity in groundwater chemistry, with some boreholes influenced primarily by mineral dissolution processes and others exhibiting

 DOI: *10.5281/zenodo.22226299*

relatively stronger organic signatures. Overall, the PCA confirms that groundwater quality within Kaduna Polytechnic is controlled predominantly by two independent processes: natural hydrochemical mineralization and localized organic inputs.

Principal Component	pH	EC	TDS	Turbidity	Nitrate	Sulphate	COD	TOC
PC1	0.372	-0.410	-0.383	-0.364	-0.253	-0.399	0.309	0.309
PC2	0.194	0.254	0.354	0.364	0.256	-0.090	0.535	0.529

3.4 Study Limitations and Future Research

Although this study provides valuable insights into the hydrochemical characteristics of groundwater within Kaduna Polytechnic, several limitations should be acknowledged. The investigation was based on a single sampling campaign involving fifteen operational boreholes, representing groundwater conditions only during the sampling period. Consequently, seasonal variations in recharge, groundwater flow, and contaminant transport were not captured and may influence groundwater chemistry differently during the wet and dry seasons. Furthermore, the analysis focused on selected physicochemical parameters and did not include trace metals, microbiological indicators, or emerging contaminants, which could provide a more comprehensive assessment of groundwater quality and associated health risks. Although Pearson correlation and PCA effectively identified dominant hydrochemical relationships, these statistical techniques establish associations rather than direct cause-and-effect relationships. Future studies should incorporate seasonal monitoring, isotopic and geochemical fingerprinting, and geospatial groundwater vulnerability assessments to better distinguish natural hydrogeochemical processes from anthropogenic influences and strengthen long-term groundwater management.

4. Conclusion

This study evaluated the hydrochemical characteristics of groundwater from fifteen operational boreholes within Kaduna Polytechnic using descriptive statistics, Pearson correlation analysis, and PCA. The results indicate that all measured physicochemical parameters generally complied with the guideline limits of the World Health Organization

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(WHO, 2022) and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015), suggesting that the groundwater is suitable for domestic use with respect to the analysed parameters. However, the relatively high coefficients of variation observed for nitrate, electrical conductivity, total dissolved solids, chemical oxygen demand, and total organic carbon indicate considerable spatial heterogeneity in groundwater quality across the study area. Pearson correlation analysis revealed strong relationships among several hydrochemical parameters, particularly between electrical conductivity and total dissolved solids, confirming that dissolved ionic constituents largely control groundwater mineralization. PCA further simplified the dataset by identifying two dominant principal components that collectively explained 81.35% of the total variance. The first component represented the general hydrochemical mineralization and physicochemical characteristics of the groundwater system, whereas the second reflected variations associated with organic matter and localized anthropogenic influences.

Overall, the combined application of descriptive statistics, correlation analysis, and multivariate statistical techniques proved effective for characterizing groundwater quality and identifying the principal factors influencing groundwater chemistry within the study area. These findings provide a scientific basis for routine groundwater quality monitoring and evidence-based water resource management within higher educational institutions and similar urban environments.

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