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Principal Component Analysis of Seasonal Trends in Groundwater Contamination Around the Abule-Egba Dumpsite, Lagos, Nigeria

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Abstract- This study assessed seasonal variations in groundwater contamination around the Abule-Egba dumpsite in Lagos, Nigeria, using Principal Component Analysis (PCA). During the wet and dry seasons, groundwater samples were taken from five boreholes and one leachate spring. Physiochemical parameters such as pH, Turbidity, electrical conductivity etc., major ions (e.g., NO_2-, Cl^-, SO_4^{2-}) and heavy metals (Pb, Cd, Cr, and Fe). The PCA revealed distinct seasonal patterns in contaminant distribution. During the wet season, the first three principal components explained approximately 80.84% of the total variation in groundwater quality data. In contrast, the first three components in the dry season accounted for over 92% of the variance, PC1 alone contributing 66.16%. PC1 was influenced heavily by parameters linked to natural geochemical interactions, leachate infiltration and human activities. The concentration of nitrates and heavy metals recorded were observed to be higher during the wet season. The findings show that the Abule-Egba dumpsite has a significant impact on the groundwater quality within the vicinity of the dumpsite, as several locations had contaminants level exceeding the limit set by the World Health Organization and the Nigerian Standard of Drinking Water Quality.

Keyword- Groundwater Contamination, Municipal Solid Waste, Leachate, Dumpsite, Principal Component Analysis, Borehole Water Quality.

I. INTRODUCTION

Seasonal variations in groundwater recharge and storage can lead to groundwater-related hazards such as drought, floods, and water scarcity [32]. Therefore, knowing how seasonal variations affect the system is crucial for determining when pollution is most likely to affect it [13, 21]. The seasonal changes are an essential consideration in hydrodynamics and management of the environment, as they can significantly impact the quantity and quality of underground water available for industrial use, drinking, and food production [25]. Water chemistry exhibits fluctuations across various locations and temporal scales. Continuous monitoring of water quality helps countries to predict, assess and control the water pollution [43]. Nearly one-third of the world's population uses groundwater for their daily water needs, and it is critical to maintain the existence of communities across the globe, particularly in isolated or desert regions. Groundwater management has often been overlooked, mostly because it is not easily observed as it lies beneath the surface [5]. Groundwater becomes polluted when harmful chemicals or pathogens build up beyond safe limits [40]. In addition to severe illness that can be fatal, groundwater pollution can unbalance an ecosystem. It is therefore more beneficial to prevent groundwater pollution than to remediate it [44]. Degradation of groundwater is a global concern that significantly affects biodiversity and human health [29]. Once polluted, an aquifer could remain in that state for many years to come, restoring it back to its original form becomes very difficult, not only because of the complex nature of the pollutants involved but also due to the intricate structure of the aquifer's water-bearing formations [1]. The liquid that results from the breakdown of municipal solid waste through physical, chemical, and biological processes is called leachate. Waste transfer stations, incinerators, landfills, and composting facilities constitute some of the most common places where it is created, and it is often considered as highly toxic and polluted [46]. The contamination of groundwater due to leachate from landfills infiltration has been established in several Nigerian publications [33, 34, 36, 39]. Principal Component Analysis (PCA) is a common technique for reducing the number of dimensions, it simplifies the dataset by reducing its dimensionality while preserving as much of the original information as possible [15, 22]. The first procedure starts by calculating the average of the feature set, followed by building the covariance matrix, after which, eigenvalues and their matching eigenvectors are identified.

To simplify the dataset, PCA focuses on the eigenvectors linked to the highest eigenvalues, as these represent the directions where the data varies the most [22]. Previous research has demonstrated the use of principal component analysis (PCA) to detect heavy metal contaminants, analyze the physiochemical characteristics and microbial composition of groundwater, and evaluate the effect of seasonal fluctuations on groundwater contamination [9, 13, 18, 26, 31, 37, 41, 45]. PCA also offers valuable insights into changes in groundwater quality which helps to inform better strategies for managing groundwater resources [23]. Managing solid waste is still a major universal issue that both developing and developed nations must address [2, 3, 11, 17]. An array of issues are contributing to Africa's inefficient waste management, such as weak institutional frameworks, inadequate enforcement mechanisms, low public awareness, an absence of technical expertise, inadequate legal systems, and a shortage of investment [16]. Open solid waste dumping is still an important issue in Nigeria, with Lagos State dealing with some of the most serious challenges. Inadequate disposal methods, poor waste handling practices, extensive usage of illicit dumpsites amongst others worsen the problem and are a serious threat to both surface and groundwater resources [4, 6, 8, 10, 19, 20, 27]. The potential for open dumps to generate leachate, contribute to various health risks to the public, and serve as breeding grounds for the rats and insects makes them highly hazardous [7, 14, 27, 42]. Prior works on Abule-Egba dumpsite did not apply PCA or evaluate distance fluctuations; instead, it concentrated mostly on site delineation within a single season. By combining lateral gradients, wet and dry season tracking, and PCA, this work bridges that gap and reveals groundwater contamination patterns that haven't been investigated before for this region.

II. MATERIALS AND METHODS

Area of Study: This study was carried out at the Abule-Egba dumpsite which is situated in AbuleEgba in Agbado, Oke-Odo Local Council Development Area of Lagos State (Fig 2). It is located on a 10.2 hectare of land [38]. The dumpsite was opened in 1978 during the construction of the Lagos-Abeokuta expressway. The Lagos State Waste Management Authority presently disposes wastes of domestic, industrial, commercial, market and institutional origins at the site [12]. The wastes are of different types, ranging from organic to inorganic, hazardous and non- hazardous [35]. The Abule-Egba dumpsite contains approximately 1,256,363 metric tonnes with average waste depth of 12.5m [28]. It lies between longitudes 03°17′ E and 03°19′ E and latitudes 06°37′ N and 06°39′ N. The site is accessible by tarred road.

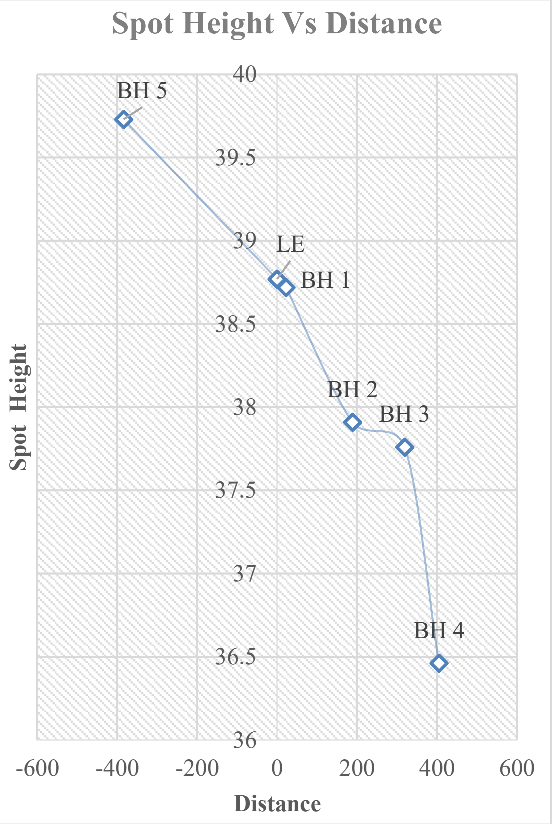

Fig 1: Plot of Spot Height vs Distance

Sampling Procedure and Quality Control: Prior to sample collection, a field survey was conducted to assess the topography of the study area and past technical reports on the dumpsites were reviewed. Groundwater samples were obtained from five boreholes, four located down-gradient (BH1–BH4) at distances ranging from 0 to 398 meters from the dumpsite, and one up-gradient borehole (UG-BH) positioned approximately 373 meters away (Fig 1). The water samples were collected within 500m of the dumpsite at varying distance to represent varying levels of potential leachate migration. They were determined considering local hydrogeological conditions, topography, and accessibility. Variations in concentrations of contaminants down gradient of the dump site were observed.

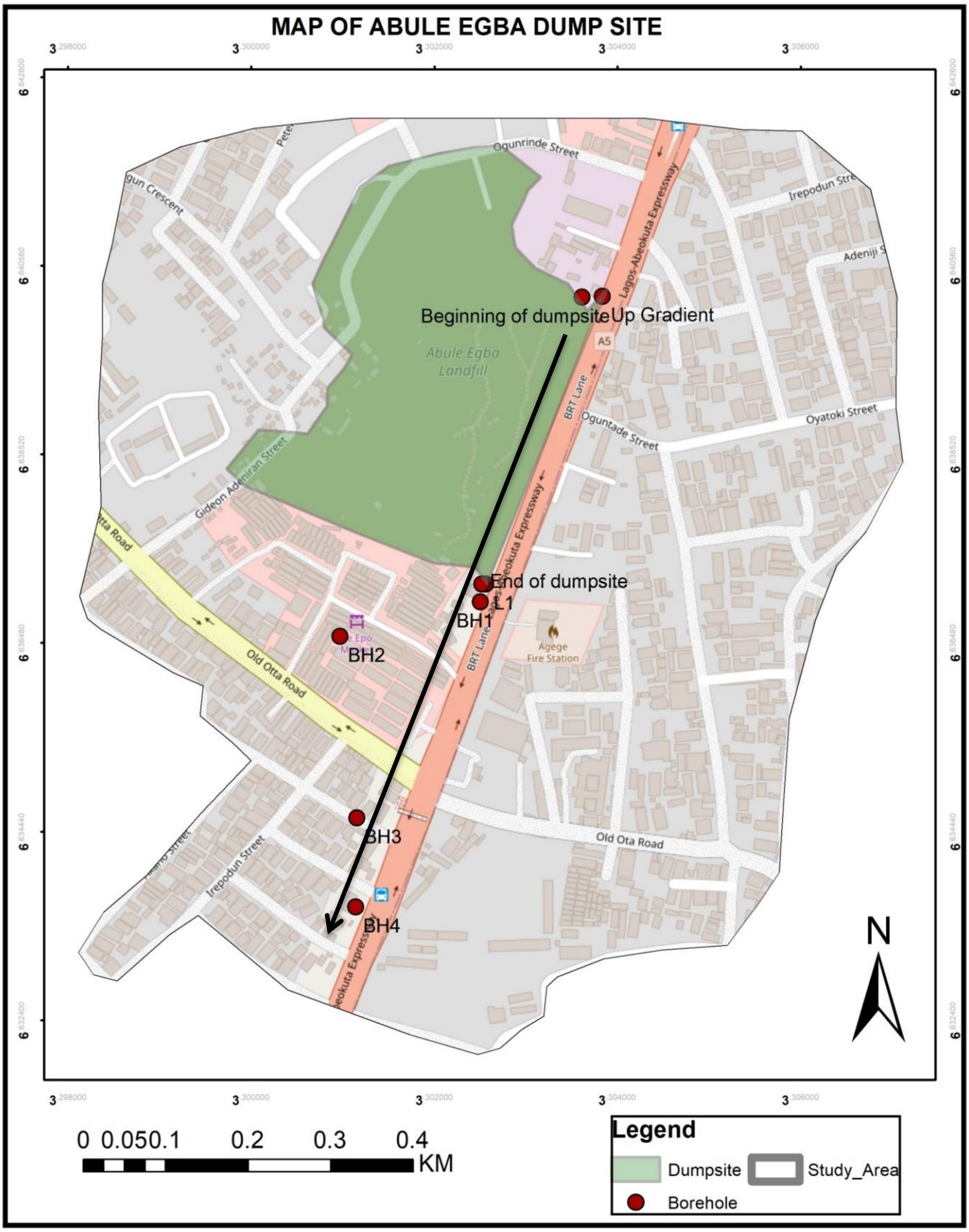

Fig 2: Map of Abule Egba Dumpsite with Sampling Location

Additionally, a leachate sample was collected directly from a spring emerging from the dumpsite. Sampling occurred during both the wet season (July 12, 2024) and the dry season (January 10, 2025), resulting in 12 total samples from six locations. A total of 26 parameters were analyzed, covering physicochemical properties, microbial content, and heavy metals. These included pH, temperature, TDS, electrical conductivity, alkalinity, turbidity, calcium hardness, chloride, dissolved oxygen, BOD, iron, *E. coli*, total coliforms, nitrite, chromium, manganese, sodium, lead, nickel, zinc, cadmium, copper, magnesium, and sulfate. For quality control, groundwater was sampled after purging the boreholes for five minutes to ensure representativeness.

Clean polyethylene bottles, pre-rinsed with deionized water and the site water were used for collection. Samples were sealed tightly and stored in ice-cooled containers at 4°C for same-day transport to the laboratory. All laboratory results were initially checked for consistency using descriptive statistics and visual tools such as scatter plots. Apparent extreme values were carefully examined by comparing them with field notes, replicate samples, and standard ranges for similar environments. Where confirmed as true reflections of site conditions, such as unusually high heavy metal or microbial counts in certain boreholes near the dumpsite, these values were retained in the dataset to represent actual contamination risks accurately.

Statistical Methods

Descriptive Statistics: The relationship between variables in a sample or population is described by descriptive statistics, which are used to organize and summarize data. Variable types (nominal, ordinal, interval, and ratio) as well as measurements of position, dispersion/variation, central tendency, and frequency are all included in descriptive statistics. The present research used descriptive statistics to give a broad picture of the characteristics pertaining to groundwater quality. By putting the raw data into a more comprehensible, practical, and clear style, these evaluations offered insights into the distribution pattern of each parameter under analysis.

Principal Component Analysis: The variable-reduction method known as principal components analysis is quite similar to exploratory factor analysis. In order to explain the majority of the variance in the original variables, it seeks to compress a larger number of variables into a smaller set of "artificial" variables known as "principal components." The dataset was made simpler while keeping the majority of its important information by using it as a multivariate statistical approach. Prior to conducting PCA, all groundwater quality parameters were standardized using z-score normalization (mean-centered and scaled to unit variance). This step ensured that variables with different units and scales contributed equally to the analysis and avoided bias toward parameters with larger absolute values. PCA was used in this study in contrast to other multivariate methods such as cluster analysis because PCA effectively evaluates correlations among numerous correlated parameters simultaneously by identifying the primary variables that account for the majority of the overall variation. In keeping with the study's goal of comprehending patterns of seasonal and spatial change close to the dumpsite, PCA also aids in the classification of sampling locations and the identification of contamination sources.

Pearson Correlation Coefficient: Pearson correlation quantifies if a linear relationship between two variables exists (as indicated by a p-value) and how strong it is (as indicated by the coefficient r between -1 and +1). Only when its fundamental assumptions are met may it be put to use. We determine that a correlation exists if the outcome is significant [24]. The direction and intensity of linear relationships between some groundwater quality measures were assessed using the Pearson correlation coefficient.

III. RESULTS AND DISCUSSION

Seasonal Variations and Implications

Physicochemical Parameters: Sulphate, TDS, and chloride levels were higher during the dry season, likely due to reduced rainfall and increased evaporation, which concentrate dissolved substances in the groundwater. Total Dissolved Solids (TDS) and Electrical Conductivity (EC) levels indicated significant contamination, with TDS values in leachate samples measuring 1024 mg/L in the wet season and escalating to 1751 mg/L in the dry season, reinforcing the strong impact of waste percolation. Additionally, turbidity values of 53 NTU (wet) and 75 NTU (dry) showed substantial particulate matter and organic contaminants in the leachate. Alkalinity and pH were also higher in the dry season, likely due to the increased decomposition of organic materials. Elevated turbidity and odor in leachate during the dry season suggest more concentrated pollutants accumulating in stagnant leachate pools.

Microbial Parameters: E. coli and coliform counts were higher in the wet season, likely due to surface runoff transporting contaminants into shallow groundwater. Both indicators were absent in the up-gradient borehole but detected in all down-gradient boreholes, with notably higher counts during the wet season, reaching up to 9.25 CFU/100 mL for E. coli and 5023 CFU/100 mL for coliforms. BOD levels rose in the dry season, indicating greater organic matter breakdown and increased oxygen demand. Leachate samples consistently showed extremely high bacterial loads across both seasons, confirming a persistent health risk from direct leachate migration.

Heavy Metals: Heavy metal analysis revealed that concentrations of Iron (Fe), Lead (Pb), Cadmium (Cd), Manganese (Mn), and Zinc (Zn) frequently exceeded WHO and NSDQW standards. Iron levels were consistently above the 0.3 mg/L limit, ranging from 0.44–1.26 mg/L in the wet season and increasing to 0.86–2.54 mg/L in the dry season, with BH2 recording the highest values. Lead exceeded safe limits in all boreholes, particularly in the dry season (up to 0.043 mg/L).

Table 1: Summary of Descriptive Statistics of Physicochemical Parameters and Microbial Counts in Groundwater Samples During the Rainy and Dry Seasons.

Parameter	**BH1-BH4 (Rainy season)**			**UG-BH**	**LE**	**BH1-BH4 (Dry season)**			**UG-BH**	**LE**	**% Change in concentration**		
	Mean	Range	Standard deviation			Mean	Range	Standard deviation			BH	UG	LE
pH	6.03	1.11	0.52	5.6	6.09	5.89	1.33	0.59	5.4	7.62	-2.38	-3.7	20.08
TDS	965.5	1009	878.7	90	1024	1165	1436	593.5	394	1751	17.12	77.16	41.52
Conductivity	1675	2745	1200	115	1970	2393	2713	1132.5	793	3518	30	85.5	44
Total alkalinity	201	434	198.3	38	578	280	744	353.4	56	976	28.21	32.14	40.78
Total Acidity	108	144	59.78	72	108	116	136	62.82	28	128	6.9	-157.14	15.63
Turbidity	2	5	2.49	0	53	4.5	13	6.14	0	75	55.6	0	29.33
T. hardness	83	56	25.58	26	108	196	232	108.5	440	96	57.6	94.09	-12.5
Cl	716.5	760	317.6	78	348	785.8	712	304.7	380	760	8.82	79.47	54.21
Na	78.81	67.65	28.81	10.79	25.18	92.05	21.8	10.62	51.2	171.3	14.38	78.93	85.3
Fe	0.78	0.82	0.33	1.9	0.83	1.44	1.68	0.75	1.06	5.81	45.83	-79.25	85.71
Pb	0.019	0.018	0.085	0.009	0.02	0.027	0.035	0.01	0.045	0.14	29.63	80	85.71
Cd	0.007	0.002	0.0008	0.006	0.006	0.0875	0.002	0	0.009	0.062	92	33.33	90.32
Mg	8.98	16.98	8.29	0.966	6.05	9.79	17.2	8.28	1.62	8.23	8.27	40.37	26.49
Mn	0.19	0.09	0.05	0.25	0.23	0.5	0.974	0.51	0.465	2.967	62	46.24	92.25
Zn	0.039	0.13	0.006	0.03	0.157	1.95	1.995	0.82	3.65	1.032	98	99.18	84.79
Ni	0.044	0.085	0.041	0.03	0.09	0.059	0.099	0.05	0.021	0.065	25.42	-42.86	-38.46
Cr	0.032	0.019	0.008	0.031	0.04	0.032	0.01	0	0.036	0.022	0	13.89	-81.82
2-So4	78.53	87.6	43.6	6.5	65.5	89.16	60.3	25.72	95.6	100.65	11.92	93.2	34.92
E.Coli	9.25	33	15.94	0	5800	0.25	1	0.5	0	30900	-3600	0	81.23
Coliform	4.75	15	7.08	0	21600	1.75	7	3.5	0	612000	-171.43	0	96.47
BOD	13.35	8.79	4.25	13.51	93.12	41.22	50.7	25.41	0	377.4	67.61	0	75.33

Cadmium was also present above permissible levels across seasons, with concentrations up to 0.010 mg/L. Manganese levels were elevated in both seasons, peaking at 1.02 mg/L in BH2 and BH3 during the dry season. Zinc remained within safe limits during the wet season but surpassed the WHO threshold (1.5 mg/L) in the dry season, with maximum values of 2.025 mg/L in BH1 and 2.95 mg/L in BH3. Leachate samples showed the highest levels of contamination, with iron rising from 1.90 mg/L (wet) to 5.805 mg/L (dry). Lead and cadmium also rose sharply, with cadmium reaching over 20 times the permissible limit in the dry season. Manganese and nickel showed a similar increasing trend, indicating intensified leachate concentration during the dry season and a heightened threat to groundwater quality. In comparison, the up-gradient borehole had lower contamination levels. Although iron, lead, and cadmium still exceeded limits, their lower presence is likely linked to regional geochemical factors or historic pollution rather than direct influence from the dumpsite.

Human Health and Ecological Risk Evaluation: The exceedance of drinking water standards for heavy metals, microbial indicators, and physicochemical parameters presents clear potential risks to human health, especially for residents relying on these boreholes for domestic use. Exposure to elevated lead and cadmium levels poses risks of neurological, kidney, and developmental effects, while the detection of E. coli and high BOD levels indicates significant fecal contamination and organic pollution, raising concerns for waterborne diseases.

Analysis of Groundwater Variation with Distance: The study of groundwater around the Abule-Egba dumpsite shows that contamination levels decrease with distance from the dumpsite. Boreholes located closer to the dumpsite, particularly BH_2 at 129 meters down-gradient, recorded the highest levels of total dissolved solids, electrical conductivity, heavy metals, and microbial counts, all exceeding WHO standards. This indicates strong leachate infiltration and lateral migration.

In contrast, the up-gradient borehole, located 373 meters away and outside the direct flow path, showed much lower levels of contaminants, confirming that the dumpsite is the primary source of pollution. Although exact depths to water tables were not fully measured, the consistent results suggest that shallow groundwater is most impacted by leachate percolation.

Overall, contamination reduces steadily beyond 300 meters down-gradient, indicating that distance acts as a natural buffer. Among all sites, BH2 is the most critical due to its proximity and highest pollutant levels.

Table 2: Summary of Groundwater Variation with Distance

Borehole	**Distance**	**Contamination Level**	**Risk**
BH$_1$	22m	High	High
BH$_2$	129m	Highest	Most critical
BH$_3$	313m	Moderate	Moderate
BH$_4$	398m	Low	Low
UG-BH	373m up-gradient	Lowest	Reference

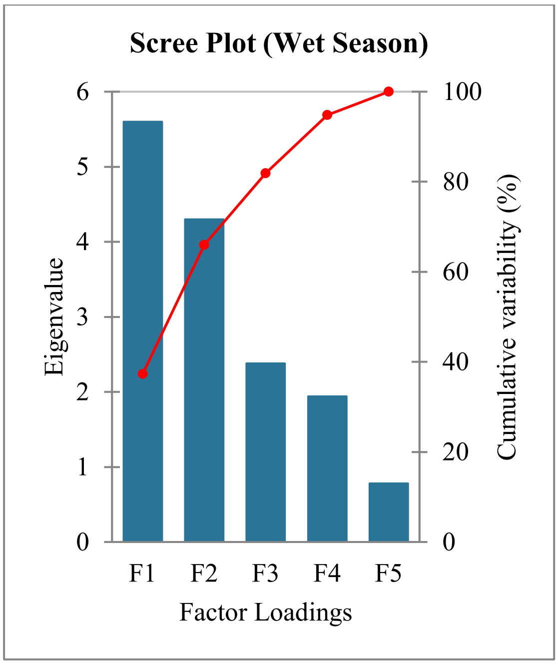

Fig 3: Scree Plot (wet season)

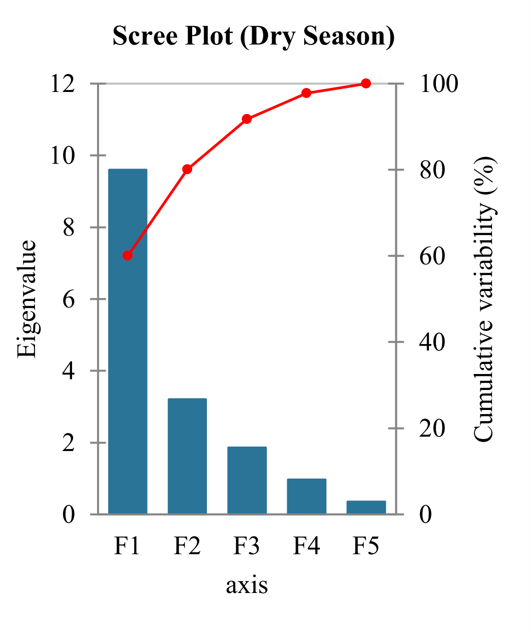

Fig 4: Scree Plot (dry season)

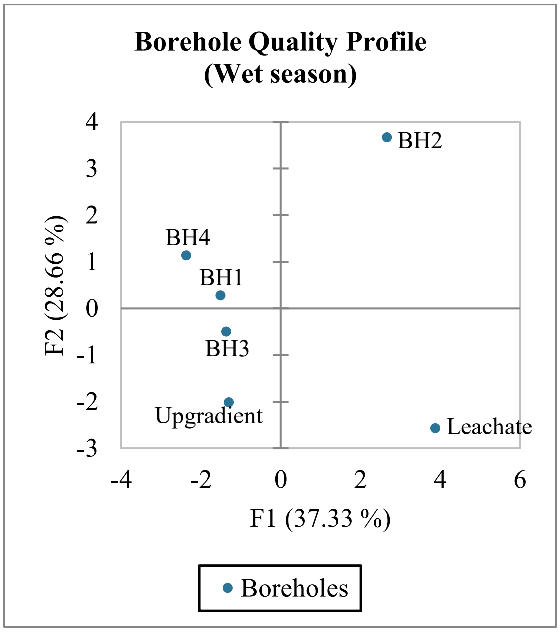

Fig 5: Borehole Quality Profile (wet season)

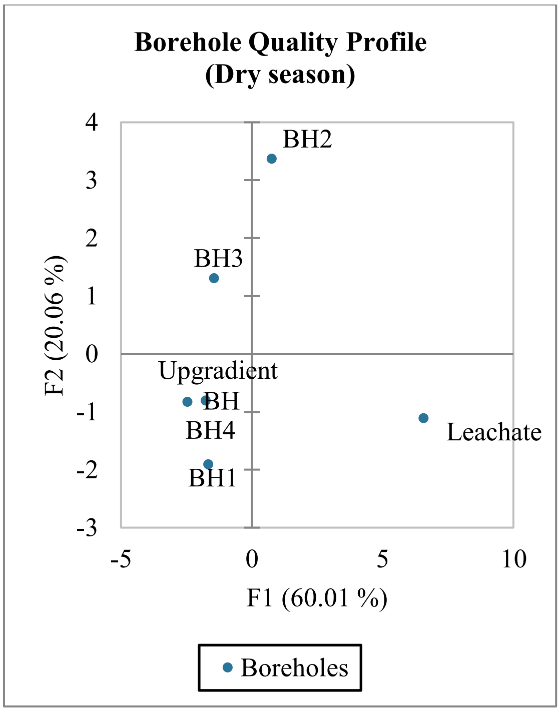

Fig 6: Borehole Quality Profile (dry season)

Principal Component Analysis for Groundwater Contamination in the Wet Season

This analysis uses PCA to identify key variables and trends influencing water quality. The first two principal components F1 and F2 (Fig 3) explain 64.83% of the total variance with F1 accounting for 36.75% and F2 for 28.08% indicating they capture most of the meaningful information. The scree plot shows a sharp drop in eigenvalues after F2, confirming that additional components contribute little to explaining the data's variability.

Biplot of boreholes and groundwater parameters wet vs dry season

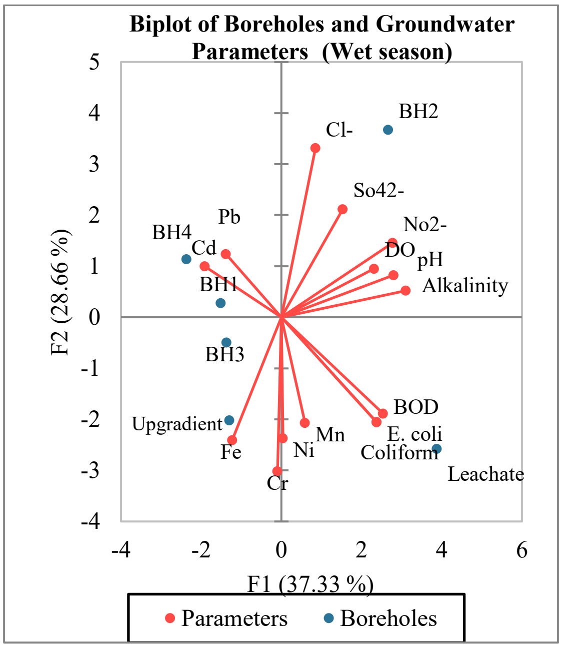

Fig 7: Biplot of Groundwater Parameters (Wet Season)

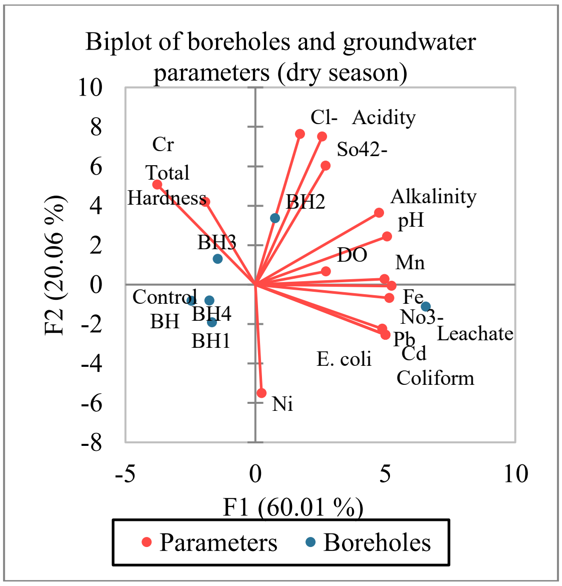

Fig 8: Biplot of Groundwater Parameters (wet season)

Scree Plot Interpretation: The scree plot visually represents the decline in eigenvalues across the principal components. According to Kaiser's Criterion, only components with eigenvalues greater than 1 should be retained, which further supports focusing on F1 and F2, possibly including F3 for additional insights into heavy metal pollution. This threshold is appropriate for our dataset because it ensures that each retained principal component explains at least as much variance as one original variable, which is essential when dealing with multiple correlated groundwater quality parameters measured in different units (physicochemical, microbial, and heavy metals).

Additionally, the scree plot shows a clear point of inflection after the main components with eigenvalues greater than one, indicating that retaining these components captures the dominant variation in the dataset while avoiding over interpretation of trivial factors. Together, these confirm that the eigenvalue > 1 cut-off is valid and statistically meaningful for this environmental multivariate analysis."

Analysis of Eigenvectors and Factor Loadings: The factor loadings (Table S1) indicate how strongly each original variable contributes to a given principal component (PC). In this study, loadings greater than 0.7 are interpreted as strong, meaning the variable has a significant influence on that component and helps define its meaning, while loadings below 0.4 would be considered weak and less relevant for interpretation. Eigenvectors as shown in (Table S2) indicate how strongly each parameter contributes to a given principal component. F1 is primarily influenced by pH (0.905), alkalinity (0.936), NO_2^- (0.937), and dissolved oxygen (0.771), indicating that it represents general water chemistry, particularly acidity, buffering capacity, and oxygenation levels. On the other hand, F2 is strongly associated with Cl^- (0.758), Cr (-0.729), Mn (-0.647), and *E. coli* (-0.697), suggesting that microbial contamination and heavy metal presence are key factors along this axis. F3, which explains 16.01% of variance, is dominated by Cd (0.618), Ni (0.670), and Mn (-0.607), indicating a strong presence of heavy metal contamination.

Correlation Matrix and Relationships between Parameters: The correlation matrix (Table S3) shows strong relationships among water quality parameters. High positive correlations between pH and DO (0.919) and pH and NO_2^- (0.853) suggest that alkaline conditions support oxygen retention and nitrate presence. Negative correlations with Pb (-0.524) and Cd (-0.560) indicate heavy metals are more soluble under acidic conditions. Distance also matters: DO decreases with distance from the dumpsite (-0.747) due to microbial activity, while Fe (0.599) and Mn (0.450) increase, pointing to natural groundwater interactions.

Biplot Interpretation: The biplot (Fig 7) reveals that pH, alkalinity, NO_2^-, and DO are aligned with F1, representing general water chemistry, while Cl^-, E. coli, and Coliform load heavily on F2, highlighting microbial contamination. Heavy metals (Fe, Pb, Cd, Ni) cluster separately, suggesting different sources. The leachate sample stands apart from boreholes, showing a distinct pollution profile. BH_2 is the most contaminated borehole with high loadings on both F1 and F2, while BH_1, BH_3, and BH_4 show similar but lower contamination. The up-gradient borehole remains the cleanest, serving as a reliable reference.

PCA Results for Groundwater Contamination (Dry Season)

Scree Plot Interpretation: The scree plot (Fig 4) shows that PC1 explains 66.16% of the variance, highlighting its key role in distinguishing contamination patterns, while PC2 adds 16.80% related to salinity variations. Together, the first three components account for over 92% of the total variance, justifying dimensionality reduction. The sharp drop after PC3 indicates that further components add little value, supporting the focus on the main principal components for analysis.

Factor Loadings and Eigenvalues: The factor loadings (Table S1) for the dry season show how strongly each parameter influences a given principal component (PC). Loadings above 0.7 are considered strong contributors, shaping the meaning of that component, while loadings below 0.4 are weak and less relevant for interpretation.

F1 is strongly influenced by pH (0.959), alkalinity (0.901), NO_2^- (0.975), E. coli (0.947), Fe (0.991), Pb (0.924), Cd (0.947), and Mn (0.94). This suggests that F1 represents the dominant water quality pattern during the dry season. *F2* is mainly defined by Cl^- (0.833) and SO_4^{2-} (0.657), indicating secondary salinity or mineral content influences. Other factors (F3–F5) show weaker or mixed loadings, capturing minor patterns and residual variability in the dataset. The eigenvectors (Table S2) confirm that these parameters contribute most strongly to the principal components in the dry season, highlighting the significant impact of concentration effects due to lower dilution and possible pollutant accumulation.

Correlation Matrix between Parameters: Strong positive correlations (Table S4) are observed between Pb and Cd (0.951), Na and Fe (0.586), and Cr and Mn (0.514), indicating similar sources or co-mobilization in the environment. Strong negative correlations include Fe and Mg (-0.680), Ni and Na (-0.837), and Mg and Cr (-0.691), suggesting opposing behaviors in the aquatic system.

Biplot Interpretation: The biplot (Fig 8) shows that pH, Fe, Pb, Cd, and E. coli align strongly with PC1, highlighting their role in overall contamination levels. Cl^- and SO_4^{2-} load heavily on PC2, representing salinity and dissolved ions. Heavy metals like Ni, Zn, and Cr form a separate cluster, suggesting different pollution sources. The leachate sample stands apart with high metal concentrations, while BH_2 is the most contaminated borehole, showing strong loadings on both PC1 and PC2. BH_1, BH_3, and BH_4 cluster together with moderate contamination, and the control sample remains distinct as a clean reference point.

Comparison of Results of Groundwater Contamination (Wet vs. Dry season)

This study also compared the results of the dry and wet season analyses using Principal Component Analysis (PCA) to identify key trends and factors influencing groundwater quality.

The scree plot and PCA results highlight clear seasonal differences in groundwater contamination. In the dry season, PCA shows PC1 alone explains 66.16% of the variance, dominated by contamination indicators such as pH, alkalinity, NO_2^-, E. coli, Coliforms, Fe, Pb, and Cd, while PC2 (16.80%) captures salinity variations through Cl^- and SO_4^{2-}. In the wet season, variance is more evenly distributed: PC1 explains 36.75%, related to general water chemistry, and PC2 (28.08%) is driven by microbial indicators like E. coli and Coliforms. PC3 in both seasons highlights heavy metal contamination but shows greater pollutant dispersion during the wet season due to increased water movement.

The biplot shows that in the dry season, heavy metals and microbial contaminants align closely, indicating localized pollution near the dumpsite, with BH_2 identified as the most contaminated borehole. In the wet season, samples are more widely spread, confirming broader pollutant transport. The observation axis chart further shows that boreholes closest to the dumpsite have higher contamination, especially during the rainy season, while the up-gradient borehole remains the cleanest throughout.

The correlation matrix confirms strong links between heavy metals (Ni, Pb, Fe, Cd) in the dry season, pointing to a common landfill source. Distance analysis shows Ni and Fe decrease with distance, while Na, Cd, and Pb increase, indicating different mobility patterns. In the wet season, rainfall weakens correlations but increases heavy metal solubility under acidic conditions. Dissolved oxygen declines with distance, reflecting microbial activity and organic degradation near the dumpsite.

IV. LIMITATION OF THE STUDY

One of the limitations in this study is the inability to determine the depth to the water level of each borehole, which is crucial for understanding groundwater flow patterns and potential contaminants' migration pathways. Accessing the water level required opening certain parts of the boreholes, which borehole owners did not permit due to concerns about damage or contamination. The study was also restricted by its spatial scope, Systematic grid sampling was not done due to financial constraints and accessibility, and future studies should implement this for broader spatial coverage.

Additionally, logistical and resource constraints limited the number of water samples tested. However, despite these limitations, the study provided valuable insights into the impact of solid waste on groundwater quality and highlights the need for improved waste management practices, continuous groundwater monitoring, and more comprehensive research to safeguard public health and environmental sustainability.

V. CONCLUSION AND RECOMMENDATION

The study underscores the critical role of sustainable waste management in protecting groundwater resources. The findings confirm that leachate from the dumpsite has significantly degraded groundwater quality, with various parameters exceeding permissible limits. The study recommends immediate monitoring and intervention, also transition to engineered landfills, combined with stringent environmental regulations, regular groundwater monitoring, and public awareness, will play a vital role in mitigating pollution risks. Furthermore, adopting innovative waste management solutions such as waste-to-energy technologies and bioremediation will contribute to long-term sustainability. This study's originality lies in its combined use of multi-seasonal sampling, and distance profiling, using PCA, and providing the first comprehensive spatial-temporal assessment of groundwater contamination near the Abule-Egba dumpsite.

VI. ACKNOWLEDGEMENT

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REFERENCES

[1] O. S. Aboyeji and S. F. Eigbokhan, "Evaluations of groundwater contamination by leachates around Olusosun open dumpsite in Lagos metropolis, southwest Nigeria," J. Environ. Manag., vol. 183, pp. 333–341, 2016. doi: 10.1016/j.jenvman.2016.09.002.

[2] I. R. Abubakar, K. M. Maniruzzaman, U. L. Dano, F. S. AlShihri, M. S. AlShammari, S. M. S. Ahmed, W. A. G. Al-Gehlani, and T. I. Alrawaf, "Environmental Sustainability Impacts of Solid Waste Management Practices in the Global South," Int. J. Environ. Res. Public Health, vol. 19, no. 19, p. 12717, 2022. doi: 10.3390/IJERPH191912717.

[3] I. Bello and M. N. bin Ismail, "Solid Waste Management in Africa: A Review," Int. J. Waste Resources, vol. 6, no. 2, 2016. doi: 10.4172/2252-5211.1000216.

[4] A. O. Aderemi and T. C. Falade, "Environmental and Health Concerns Associated with the Open Dumping of Municipal Solid Waste: A Lagos, Nigeria Experience," Am. J. Environ. Eng., vol. 2, no. 6, pp. 160–165, 2012. doi: 10.5923/J.AJEE.20120206.03.

[5] A. A. Ahmed, S. Sayed, A. Abdoulhalik, S. Moutari, and L. Oyedele, "Applications of machine learning to water resources management: A review of present status and future opportunities," J. Clean. Prod., vol. 441, p. 140715, 2024. doi: 10.1016/J.JCLEPRO.2024.140715.

[6] F. O. Ajibade, B. Adelodun, T. F. Ajibade, K. H. Lasisi, C. Abiola, J. R. Adewumi, and C. O. Akinbile, "The threatening effects of open dumping on soil at waste disposal sites of Akure City, Nigeria," Int. J. Environ. Waste Manag., vol. 27, no. 2, pp. 127–146, 2021. doi: 10.1504/IJEWM.2021.112947.

[7] M. I. Al-Wabel, M. Ahmad, H. Rasheed, M. I. Rafique, J. Ahmad, and A. R. A. Usman, "Environmental Issues Due to Open Dumping and Landfilling," in Environmental Issues and Management of Solid Waste, pp. 65–93, 2022. doi: 10.1007/978-3-031-07785-2_4.

[8] C. C. Aralu, P. A. C. Okoye, H. O. Abugu, K. E. Ochiagha, and J. C. Egbueri, "Evaluating the seasonal variations of risks associated with potentially toxic elements in underground water sources near a dumpsite in Awka, Nigeria," J. Hazard. Mater. Adv., vol. 15, p. 100440, 2024. doi: 10.1016/J.HAZADV.2024.100440.

[9] A. Barrie, S. K. Agodzo, R. Frazer-Williams, E. Awuah, and E. Bessah, "A multivariate statistical approach and water quality index for water quality assessment for the Rokel river in Sierra Leone," Heliyon, vol. 9, no. 6, e16196, 2023. doi: 10.1016/J.HELIYON.2023.E16196.

[10] O. Beatrice, B. Zainab, and J. Madukaihe, "Environmental and Health Risks of Selected Open Dumps in Lugbe, FCT Abuja, Nigeria," Int. J. Innov. Sci. Res. Technol., vol. 7, no. 11, 2022. [Online]. Available: www.ijisrt.com.

[11] Z. M. A. Bundhoo, "Solid waste management in least developed countries: current status and challenges faced," J. Mater. Cycles Waste Manag., vol. 20, no. 3, pp. 1867–1877, 2018. doi: 10.1007/S10163-018-0728-3.

[12] J. O. Fatoba, A. B. Eluwole, O. A. Sanuade, O. S. Hammed, W. N. Igboama, and J. O. Amosun, "Geophysical and geochemical assessments of the environmental impact of Abule-Egba landfill, southwestern Nigeria," Model. Earth Syst. Environ., vol. 7, no. 2, pp. 695–701, 2020. doi: 10.1007/S40808-020-00991-8.

[13] S. A. Ganiyu, B. S. Badmus, O. T. Olurin, and

Z. O. Ojekunle, "Evaluation of seasonal variation of water quality using multivariate statistical analysis and irrigation parameter indices in Ajakanga area, Ibadan, Nigeria," Appl. Water Sci., vol. 8, no. 1, pp. 1–15, 2018. doi: 10.1007/S13201-018-0677-Y/TABLES/11.

[14] T. K. Gebrekidan, N. G. Weldemariam, H. D. Hidru, G. G. Gebremedhin, and A. K. Weldemariam, "Impact of improper municipal solid waste management on fostering One Health approach in Ethiopia — challenges and opportunities: a systematic review," Sci. in One Health, vol. 3, p. 100081, 2024. doi: 10.1016/J.SOH.2024.100081.

[15] D. Groth, S. Hartmann, S. Klie, and J. Selbig, "Principal components analysis," Methods Mol. Biol., vol. 930, pp. 527–547, 2013. doi: 10.1007/978-1-62703-059-5_22.

[16] J. L. Guelfo, S. Korzeniowski, M. A. Mills, J. Anderson, R. H. Anderson, J. Arblaster, J. A. Conder, I. T. Cousins, K. Dasu, B. J. Henry, L. S. Lee, J. Liu, E. R. McKenzie, and J. Willey, "Environmental Sources, Chemistry, Fate, and Transport of Per- and Polyfluoroalkyl Substances: State of the Science, Key Knowledge Gaps, and Recommendations Presented at the August 2019 SETAC Focus Topic Meeting," Environ. Toxicol. Chem., vol. 40, no. 12, pp. 3234, 2021. doi: 10.1002/ETC.5182.

[17] P. Gupta, A. Sharma, and L. K. Bhardwaj, "Solid Waste Management (SWM) And Its Effect On Environment & Human Health," in Futuristic Trends in Agriculture Engineering & Food Sciences, vol. 3, no. 4, pp. 91–101, 2024. doi: 10.58532/V3BCAG4P1CH7.

[18] D. Hammoumi, H. S. Al-Aizari, I. A. Alaraidh, M. K. Okla, M. E. Assal, A. R. Al-Aizari, M. S. Moshab, S. Chakiri, Z. Bejjaji, "Seasonal Variations and Assessment of Surface Water Quality Using Water Quality Index (WQI) and Principal Component Analysis (PCA): A Case Study," Sustainability, vol. 16, p. 5644, 2024. doi: 10.3390/SU16135644.

[19] E. B. Ichipi and M. F. Senekane, "An Evaluation of the Impact of Illegal Dumping of Solid Waste on Public Health in Nigeria: A Case Study of Lagos State," Int. J. Environ. Res. Public Health, vol. 20, no. 22, p. 7069, 2023. doi: 10.3390/IJERPH20227069.

[20] O. O. Ige, A. T. Owolabi, O. F. Olabode, and D. O. Obasaju, "Groundwater quality evaluation: a case study of Igando waste dumpsite, southwestern Nigeria," Appl. Water Sci., vol. 12, no. 4, pp. 1–14, 2022. doi: 10.1007/S13201-022-01601-X/FIGURES/8.

[21] J. M. Ishaku, "Investigation of seasonal variation of groundwater quality in Jimeta-Yola area northeastern Nigeria," G. J. Geol. Sci., vol. 10, no. 1, pp. 15–36, 2012. doi: 10.4314/GJGS.V10I1.

[22] R. Jahangir, Y. W. Teh, H. F. Nweke, G. Mujtaba, M. A. Al-Garadi, and I. Ali, "Speaker identification through artificial intelligence techniques: A comprehensive review and research challenges," Expert Syst. Appl., vol. 171, 2021. doi: 10.1016/j.eswa.2021.114591.

[23] L. Kaur and P. Godara, "Application of Principal Component Analysis (PCA) in groundwater quality evaluation: A case study of arid region," Energy & Environ. Manage., vol. 1, no. 2, pp. 1–12, 2025. doi: 10.63333/EEM.V1N21.

[24] P. Kaur, J. Stoltzfus, and V. Yellapu, "Descriptive statistics," Int. J. Acad. Med., vol. 4, no. 1, 2018. doi: 10.4103/IJAM.IJAM_7_18.

[25] M. O. Kayode, W. B. Tomori, E. A. Okoronkwo, and K. A. N. Adiat, "Seasonal variation of groundwater quality in a basement complex geology of Ado Ekiti Nigeria using water quality index model," J. Umm Al-Qura Univ. For Appl. Sci., pp. 1–26, 2024. doi: 10.1007/S43994-024-00195-1/FIGURES/5.

[26] P. Kumari, N. C. Gupta, A. Kaur, and K. Singh, "Application of Principal Component Analysis and Correlation for Assessing Groundwater Contamination in and around Municipal Solid Waste Landfill of Ghazipur, Delhi," J. Geol. Soc. India, vol. 94, no. 6, pp. 595–604, 2019. doi: 10.1007/S12594-019-1366-7.

[27] W. Perla, "Landfills and Dumps," [Online]. Available: https://scalar.usc.edu/works/whats-in-a-name/landfills-and-dump?path=index.

[28] Lagos Waste Management Authority (LAWMA), "MSW Project Opportunity Olusosun, Abule Egbe and Solous Lagos, Lagos State, Nigeria," 2023. [Online]. Available: https://www.globalmethane.org/expo-docs/posters/msw/msw_ni_project_lagos-lfg_final.pdf.

[29] P. Li, D. Karunanidhi, T. Subramani, and K. Srinivasamoorthy, "Sources and Consequences of Groundwater Contamination," Arch. Environ. Contam. Toxicol., vol. 80, no. 1, p. 1, 2021. doi: 10.1007/S00244-020-00805-Z.

[30] E. O. Longe and R. M. Balogun, "Groundwater Quality Assessment near a Municipal Landfill, Lagos, Nigeria," Res. J. Appl. Sci. Eng. Technol., vol. 2, no. 1, pp. 39–44, 2010.

[31] G. T. Nguyen and N. T. H. Huynh, "Seasonal

Variations in Groundwater Quality under Different Impacts Using Statistical Approaches," Civil Eng. J. (Iran), vol. 9, no. 3, pp. 497–511, 2023. doi: 10.28991/CEJ-2023-09-03-01.

[32] M. A. Nguyen, K. Norström, W. Wiberg, J. Gustavsson, S. Josefsson, and L. Ahrens, "Seasonal trends of per- and polyfluoroalkyl substances in river water affected by fire training sites and wastewater treatment plants," Chemosphere, vol. 308, 2022. doi: 10.1016/J.CHEMOSPHERE.2022.136467.

[33] R. C. Nwankwo and A. A. Udo, "Investigation of Groundwater Aquifer Contamination due to Leachate Intrusion Using a High Resolution Real-Time Resistivity Technique at a Dumpsite around the University of Port Harcourt Environs, Choba, Rivers State, South-South, Nigeria," Seahipaj, 2025. [Online]. Available: www.seahipaj.org.

[34] O. Obiora and T. O. Theresa, "Investigating the impact of solid waste dumpsites on groundwater quality: A case study of the Mkpuka Obosi Landfill," G. J. Earth Environ. Sci., vol. 9, no. 1, pp. 15–27, 2024. doi: 10.31248/GJEES2024.146.

[35] A. S. Ogungbe, E. O. Onori, and Olaoye, "Application of electrical resistivity techniques in the investigation of groundwater contamination: A case study of lie -Epo Dumpsite, Lagos, Nigeria," Int. J. Geomatics Geosci., vol. 3, pp. 30–41, 2012.

[36] S. O. Ojoawo, O. A. Agbede, A. Y. Sangodoyin, S. O. Ojoawo, O. A. Agbede, and A. Y. Sangodoyin, "Characterization of Dumpsite Leachate: Case Study of Ogbomosoland, South-Western Nigeria," Open J. Civ. Eng., vol. 2, no. 1, pp. 33–41, 2012. doi: 10.4236/OJCE.2012.21006.

[37] A. A. Oketola, S. M. Adekolurejo, O. Osibanjo, A. A. Oketola, S. M. Adekolurejo, and O. Osibanjo, "Water Quality Assessment of River Ogun Using Multivariate Statistical Techniques," J. Environ. Prot., vol. 4, no. 5, pp. 466–479, 2013. doi: 10.4236/JEP.2013.45055.

[38] O. O. Okunowo, O. Y. Adeogun, K. S. Ishola, and S. Alli, "Delineation of leachate at a dumpsite using geo-electrical resistivity method: a case study of Abule Egba, Lagos, Nigeria," SN Appl. Sci., vol. 2, no. 12, pp. 1–12, 2020. doi: 10.1007/S42452-020-03573-6/FIGURES/4.

[39] L. Olubanji, A. A. Ayoade, O. Olukemi, and A. Adebola, "Determination and Delineation of Groundwater pollution from leachate generated from dumpsite, Ijagun community Odogbolu southwestern Nigeria," Aca. & Scholarly Res. J., vol. 5, no. 1, 2013. [Online]. Available: www.aasrc.org/aasrj.

[40] I. Oyiboka, "Effects Of Landfill Sites On Groundwater Quality In Igando," 2014, pp. 1–117.

[41] N. Sharma, P. Kumari, and A. Kaur, "Multivariate Statistical Interpretation and Seasonal Variation of Groundwater Quality for Southwestern Region of NCT Delhi, India," A. E. & Environ. Sci., vol. 10, 2022, pp. 540–550. doi: 10.12691/AEES-10-8-7.

[42] A. Siddiqua, J. N. Hahladakis, and W. A. K. A. Al-Attiya, "An overview of the environmental pollution and health effects associated with waste landfilling and open dumping," Environ. Sci. Pollut. Res., vol. 29, no. 39, pp. 58514–58536, 2022. doi: 10.1007/S11356-022-21578-Z.

[43] M. M. M. Syeed, M. S. Hossain, M. R. Karim, M. F. Uddin, M. Hasan, and R. H. Khan, "Surface water quality profiling using the water quality index, pollution index and statistical methods: A critical review," Environ. Sust. Indicat., vol. 18, p. 100247, 2023. doi: 10.1016/J.INDIC.2023.100247.

[44] A. O. Talabi, T. J. Kayode, A. O. Talabi, and T. J. Kayode, "Groundwater Pollution and Remediation," J. Water Resour. Prot., vol. 11, no. 1, pp. 1–19, 2019. doi: 10.4236/JWARP.2019.111001.

[45] A. Bolarinwa and A. T. Bolarinwa, "Seasonal Variations of Groundwater Chemistry in the Basement and Sedimentary Rocks of Ibadan and Lagos Areas, Southwestern Nigeria," Earth Sci. Res., vol. 7, no. 1, p. 55, 2017. doi: 10.5539/ESR.V7N1P55.

[46] Z. Youcai, "Pollution control technology for leachate from municipal solid waste: landfills, incineration plants, and transfer stations," 2018. [Online]. Available: https://lib.ugent.be/catalog/ebk01:4100000005388446.