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Rural–Urban Differences in Groundwater Quality in Lafia, Nigeria: Implications for Drinking Water Safety

Abubakar Sadiq Usman[a,c*], Ahmad Ibrahim Aliyu[b], Adamu Umar Ismail[a], Lukmon Olakunle Jimoh[c]

[a]Department of Civil Engineering Technology, Isa Mustapha Agwai I Polytechnic, Lafia. Nasarawa State, Nigeria
[b]Department of Geology, Federal University of Lafia, Nasarawa State, Nigeria
[c]Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia

[*]Correspondence: Abubakar Sadiq Usman (usman.sadiq.abubakar@imap.edu.ng).

Abstract

Groundwater is a primary source of drinking water for many communities in Nigeria, yet rapid urbanisation and unregulated human activities increasingly threaten its quality. This study compares the physicochemical characteristics of groundwater in urban Lafia and the rural community of Agunji in Nasarawa State, Nigeria. Ten samples were collected from boreholes and shallow hand-dug wells, with five from each location. Parameters analysed included temperature, pH, electrical conductivity, total dissolved solids (TDS), turbidity, hardness, alkalinity, acidity, and mineral content using standard laboratory methods. Welch's two-sample t-test at a 95% confidence level was used to assess differences between sites. Most parameters complied with the limits set by the Nigerian Standards for Drinking Water Quality and the World Health Organization. Significant differences were observed in temperature ($t = -2.578$, $p = 0.033$), turbidity ($t = -3.141$, $p = 0.014$), and acidity ($t = 5.444$, $p = 0.001$). Rural groundwater showed higher turbidity (3.02 ± 2.12 NTU) and temperature (31.70 ± 2.09°C), while urban groundwater had higher acidity (678.80 ± 62.99 mg/L), with large effect sizes ($d = 1.63$–3.44). No significant differences ($p > 0.05$) were found for pH, electrical conductivity, TDS, hardness, alkalinity, or mineral content. However, pH values in both locations were slightly acidic (5.96–6.22), below recommended limits. Although turbidity remained within permissible levels, higher rural values may increase the risk of microbial contamination. The consistently low pH suggests regional hydrogeochemical control, while elevated urban acidity may reflect anthropogenic or subsurface processes. Generally, groundwater quality in both areas is suitable for domestic use, but targeted treatment particularly pH adjustment and turbidity reduction and continuous monitoring are recommended to protect public health and ensure sustainable water management.

Keywords: Groundwater quality, Urban–rural comparison, Physicochemical parameters, Drinking water standards

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1. Introduction

Groundwater is one of the most important sources of potable water in Nigeria, particularly in urban and peri-urban areas where access to a centralised municipal water supply remains inadequate or unreliable (Danert & Healy, 2021). In many Nigerian cities, households depend largely on boreholes and hand-dug wells to meet domestic and commercial water demands (Olalemi et al., 2023). However, rapid urbanisation, population growth, and unregulated land use practices have increasingly placed pressure on groundwater systems, leading to concerns about water quality degradation (Ighalo & Adeniyi, 2020; Ojo et al., 2024). Urban development can introduce contaminants into the groundwater through domestic sewage, industrial discharges, solid waste dumps, fuel storage facilities, and surface runoff while also modifying natural groundwater recharge processes (Siddiqua et al., 2022).

Numerous studies conducted throughout Nigeria have demonstrated that groundwater quality in urban settings is affected by both natural geological factors and human activities, such as waste disposal methods and insufficient sanitation infrastructure (Lawal et al., 2023). Due to land-use intensity and pollution sources, urban groundwater is often more susceptible to chemical and physical degradation compared to groundwater in surrounding rural areas (Tegegne et al., 2023). Comparative studies have shown that urban groundwater usually has higher levels of electrical conductivity, total dissolved solids, turbidity, and acidity compared to nearby rural sources, which indicates the impact of human activities (Ahmad et al., 2021).

Evaluation of groundwater quality is commonly based on key physicochemical parameters such as temperature, pH, electrical conductivity, mineral content, total dissolved solids, turbidity, hardness, alkalinity, and acidity. These parameters provide essential information on groundwater suitability for domestic use. For instance, high pH values can adversely affect human health and cause corrosion of water distribution systems; elevated electrical conductivity and total dissolved solids indicate increased salinity; high turbidity can interfere with disinfection processes and protect pathogenic microorganisms; while excessive hardness affects taste and leads to scaling in pipes and household appliances (Ahmad et al., 2021). To protect public health, international and national drinking water guidelines specify permissible limits for these parameters, including pH values of 6.5–8.5, total dissolved solids not exceeding 500 mg/L, electrical conductivity below 1000 µS/cm, hardness less than 150 mg/L as $CaCO_3$ and turbidity below 5 turbidity (NTU) (Yohanna et al., 2021).

Despite the growing number of groundwater quality studies in Nigeria, many investigations remain largely descriptive, with limited application of inferential statistical techniques to quantitatively assess differences between groundwater conditions in rural and urban settings. In Lafia, the capital of Nasarawa State, groundwater remains the main source of drinking water for both urban residents and surrounding rural communities; however, systematic statistical comparison of groundwater quality between these settings is still lacking. Consequently, there is insufficient quantitative evidence to clearly establish the extent to which urbanisation has influenced groundwater quality in the area.

In response to this gap, the current study assesses the physicochemical quality of groundwater in specific urban areas of Lafia and rural communities in Agunji utilising a two-sample t-test methodology. The objective is to ascertain the presence of statistically significant differences between rural and urban groundwater quality parameters and to evaluate the groundwater's suitability for domestic use in compliance with World Health Organization and Nigerian Standards for Drinking Water Quality guidelines.

2. Methodology

2.1. Description of the Study Area

This study was carried out in Lafia and its surrounding rural settlements, specifically Agungi, located in Nasarawa State, North-Central Nigeria. Lafia is situated in the Guinea savannah ecological zone and has a tropical climate marked by pronounced rainy and dry seasons. The average temperature over the course of a year is between 26°C and 34°C, and the average amount of rain is between 1,100 and 1,500 mm.

The area mainly consists of sedimentary rocks from the Lafia formation in the Middle Benue Trough, which usually contain both shallow and deep aquifers that people can reach by hand-dug wells and boreholes (Umar et al., 2019). Groundwater constitutes a major source of potable water for both urban and rural residents due to the limited piped water supply. Urban Lafia is characterised by a higher population density, commercial activities, and waste generation, while Agungi is a predominantly agrarian rural setting with minimal industrial influence.

2.2. Sampling Design and Sample Collection

A comparative sampling design was adopted to evaluate groundwater quality differences between urban and rural environments. Ten groundwater sampling locations were selected, comprising five urban locations within Lafia town and five rural locations in Agungi. The selection was based on accessibility, frequency of use, and spatial representation of the study areas. Groundwater samples were collected from boreholes and hand-dug wells that people utilize for domestic purposes.

Existing hydrogeological studies in Lafia indicate that borehole depths typically range between approximately 10 m and 85 m, depending on the underlying lithology and aquifer characteristics, while hand-dug wells commonly range between 5 m and 20 m depth. Deeper boreholes are generally associated with sedimentary formations such as sandstone aquifers, whereas shallower wells occur within basement complex formations (Ifediegwu, 2022). These variations in well depth may partly influence groundwater temperature, turbidity, and mineral characteristics observed in this study.

Before sampling, wells were purged for several minutes to obtain fresh aquifer water. Clean, pre-washed plastic bottles were used to collect samples, and they were appropriately labelled. Field measurements were conducted immediately, and laboratory analyses were performed within 24 hours of collection to minimise physicochemical changes.

Sampling was conducted during the dry season to minimise the influence of seasonal recharge, rainfall variability, and surface runoff effects on groundwater quality. Conducting sampling within the same hydrological period ensured consistency in the comparison between rural and urban groundwater conditions.

2.3. Physicochemical Parameters Analyzed

The groundwater samples were analysed for temperature (°C), pH, Electrical Conductivity (µS/cm), Mineral Content (mg/L) representing the total concentration of dissolved inorganic constituents in groundwater, was assessed as an indicator of overall water mineralisation, Total Dissolved Solids (TDS, mg/L), Turbidity (NTU), Total Hardness (mg/L as $CaCO_3$), Alkalinity (mg/L as $CaCO_3$), Acidity (mg/L as $CaCO_3$. These parameters were selected due to their relevance in assessing groundwater suitability for domestic use and their sensitivity to geological and anthropogenic influences.

2.4. Field and Laboratory Analytical Procedures

Measurement of temperature, pH, electrical conductivity, and turbidity were carried out in situ using calibrated portable meters to avoid sample alteration during transportation. Total dissolved solids were determined using gravimetric methods, while mineral content was assessed based on standard analytical procedures. Total hardness was quantified with the ethylenediaminetetraacetic acid (EDTA) titrimetric technique. Alkalinity and acidity were determined using standard titrimetric methods and expressed as mg/L $CaCO_3$ equivalent. Acidity in this study represents the acid neutralising capacity of the water, including contributions from dissolved carbon dioxide, mineral acids, and weak organic acids, rather than direct hydrogen ion concentration (pH).

All analyses were performed in accordance with the standard protocols established by the American Public Health Association (APHA) and relevant drinking water quality guidelines. Instrument calibration and quality control checks were performed to ensure accuracy and reliability of results.

2.5. Data Processing and Statistical Analysis

2.5.1. Descriptive Statistical Analysis

Descriptive statistics, comprising the mean, standard deviation, minimum, and maximum values, were evaluated for each groundwater quality metric separately for urban and rural datasets. These statistics provided an initial assessment of central tendency and variability within each group.

2.5.2. Two-Sample t-Test Analysis

A two-sample statistical analysis was conducted to determine whether significant differences existed between groundwater quality parameters in rural and urban areas. Given the relatively small sample size ($n = 5$ per group) and the potential inequality of variances, Welch's two-sample t-test (unequal variances assumed) was adopted as it is more robust under such conditions.

The null hypothesis (H_0) assumed no significant difference between rural and urban groundwater quality means, while the alternative hypothesis (H_1) assumed a significant difference. All statistical analyses were performed at a 95% confidence level ($\alpha = 0.05$), and parameters with p-values less than 0.05 were considered statistically significant. In addition to p-values, degrees of freedom, and 95% confidence intervals were determined for each parameter, and effect sizes (Cohen's d) were calculated to assess the magnitude of differences between groups.

The normality of the datasets was evaluated using the Shapiro–Wilk test. Furthermore, a non-parametric Mann–Whitney U test was conducted to validate the robustness of the results. Effect sizes (Cohen's d) were calculated to evaluate the magnitude of differences between groups, with interpretation based on Cohen (1988), where values of 0.2, 0.5, and 0.8 represent small, medium, and large effects, respectively.

2.6. Comparison with Drinking Water Standards

The assessed groundwater quality parameters were compared with permissible limits established by the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ). This comparison was used to assess the suitability of groundwater from both rural and urban areas for domestic consumption.

3. Results

Table 1 presents a summary of descriptive statistics (mean ± SD) for each water-quality parameter in urban (Lafia town) and rural (Agunji village) samples, along with the t-test results (unequal variances assumed). Significant differences ($p<0.05$) between sites are marked. Notably, turbidity and acidity (mg/L) were significantly higher in the rural and urban sites, respectively, and water temperature was also higher in rural (Agunji village) than urban (Lafia town). Most other parameters (pH, electrical conductivity, mineral content, TDS, hardness, alkalinity) showed no statistically significant difference ($p>0.05$) between locations. The observed pH values were slightly acidic in both sites (6.0 - 6.2), below the NSDWQ recommended range of 6.5 - 8.5. Both sites' TDS and conductivity means were well below NSDWQ and WHO limits (NSDWQ: TDS $\leq$ 500 mg/L; WHO: TDS 600 mg/L), and turbidity means were also below the 5 NTU guideline.

The application of Welch's t-test ensured robustness against unequal variances, while the supplementary Mann–Whitney U test produced consistent results, confirming the reliability of the statistical findings. Normality assessment using the Shapiro–Wilk test indicated no significant deviation from normality for most parameters.

Table 1: Mean (±SD) values of groundwater parameters in Lafia (urban) and Agunji (rural) with Welch's t-test results (unequal variances assumed)

Parameter	**Urban (mean ± SD)**	**Rural (mean ± SD)**	**t-statistic**	**df**	**p-value**	**95% CI of mean difference**	**Cohen's d**	**NSDWQ**	**WHO**
Temperature (°C)	28.74 ± 1.49	31.70 ± 2.09	–2.578	7.23	0.033	-5.67 to -0.25	1.63		
pH	5.96 ± 0.98	6.22 ± 1.01	–0.412	7.99	0.691	-1.71 to 1.19	0.26	6.5 - 8.5	6.5 – 9.2
Electrical Conductivity (µS/cm)	388.60 ± 427.31	165.00 ± 68.87	1.155	4.21	0.281	-312.56 to 759.76	0.73	500	600
Mineral content (mg/L as CaCO3)	185.40 ± 206.45	80.00 ± 33.17	1.127	4.21	0.292	-147.05 to 357.85	0.71	-	-
TDS (mg/L)	149.60 ± 141.22	74.80 ± 24.17	1.167	4.23	0.277	-94.66 to 244.26	0.74	≤500	≤600
Turbidity (NTU)	0.04 ± 0.04	3.02 ± 2.12	–3.141	4.00	0.014	-5.62 to -0.34	1.99	5	
Hardness (mg/L as CaCO3)	240.00 ± 74.62	271.20 ± 277.16	–0.243	4.58	0.814	-377.80 to 315.40	0.15	150	>200
Alkalinity (mg/L as CaCO3)	193.56 ± 52.47	350.40 ± 179.09	–1.879	4.68	0.097	-368.41 to 54.73	1.19	-	-
Acidity (mg/L as CaCO3)	678.80 ± 62.99	324.40 ± 131.23	5.444	5.75	0.001	197.41 to 511.39	3.44	-	-

Note: df = Welch degrees of freedom; CI = confidence interval; Cohen's d indicates effect size where 0.2 = small, 0.5 = medium, and 0.8 = large effect.

The expanded statistical analysis presented in Table 1 includes degrees of freedom, 95% confidence intervals, and Cohen's d effect sizes to provide a more complete interpretation of the statistical results. Large effect sizes were observed for turbidity (d = 1.99), acidity (d = 3.44), and temperature (d = 1.63), confirming substantial differences between rural and urban groundwater conditions for these parameters.

The mean water temperature was significantly higher in the rural (Agunji) samples (31.7°C) than in urban Lafia (28.7°C) (t=–2.578, p=0.033). Both values are warm for groundwater, but the difference (3°C) is statistically robust. This may reflect environmental or hydrogeologic differences (such as shallower wells or less shading in rural areas) affecting warming. Such variation in ambient water temperature can influence chemistry and microbial activity, although both sites remain within expected tropical groundwater ranges.

Mean pH did not differ significantly (p=0.691) between sites (Lafia 5.96 vs Agunji 6.22). Both means are slightly acidic, below the NSDWQ and WHO guideline minimum of 6.5. Low pH in groundwater may arise from naturally acidic aquifer materials or anthropogenic acids (industrial/sewage inputs) (Saalidong et al., 2022). The lack of significant urban–rural difference suggests a regional influence on pH. Given the slight acidity, pH adjustment such as lime addition, may be advisable before consumption (Yehia & Said, 2021).

Urban samples had higher mean EC (389 µS/cm) and TDS (149.6 mg/L) than rural (165 µS/cm; 74.8 mg/L), but differences were not significant (p>0.27). Both sets of values are well below NSDWQ and WHO limits. These results suggest that groundwater in both areas is generally fresh (Emmanuel et al., 2020). The relatively higher EC and TDS values observed in urban samples may be associated with increased dissolved solids; however, both anthropogenic inputs and natural mineral dissolution processes may contribute to this trend (Asingbi et al., 2020).

Similarly, mean "mineral content" (assumed here as total dissolved minerals, mg/L) was higher in Lafia (185.4 mg/L) than Agunji (80.0 mg/L) but with no significant difference (p=0.292). Both are modest and well under WHO thresholds for minerals. No hazard is indicated, and consistent with EC and TDS data, both sources supply mineral levels typical of safe groundwater (Houria et al., 2020).

Turbidity showed a highly significant difference (t=–3.141, p=0.014). Rural water with a mean value of 3.02 NTU was much more turbid than urban water with a mean value of 0.04 NTU. Although both means are below the NSDWQ limit of 5 NTU, the rural turbidity is elevated. This evidence suggests the Agunji sources carry more suspended solids or organic matter (perhaps from soil erosion or inadequate well sealing) (Ghimire et al., 2025). In contrast, the water sources in Lafia appear well-maintained. Elevated turbidity can shield pathogens from disinfection, so even moderate turbidity warrants attention (Huang et al., 2021).

Both Lafia and Agunji exhibited moderately high hardness mean values of 240 mg/L and 271 mg/L, respectively, with no significant difference (p=0.814). These values fall in the "hard" category (WHO classifies >200 mg/L as hard) but below any health-based guideline (Umar et al., 2019). Hardness differences are nonsignificant, implying similar aquifer mineralisation. Hard water is not a health hazard, but it can affect taste and scaling; both sources may be perceived as hard.

Rural water was more alkaline with a mean value of 350.4 mg/L, while urban water was more "acidic" with a mean value of 678.8 mg/L, though the alkalinity difference was not significant (p=0.097). Acidity was dramatically higher in Lafia (t=5.444, p=0.001). These apparently contradictory results (higher alkalinity vs acidity) may reflect complex carbonate chemistry in the aquifer (Ifediegwu et al., 2019). The relatively high acidity values observed, particularly in urban groundwater, reflect elevated acid neutralisation capacity rather than extreme acidic conditions. This may be attributed to increased concentrations of dissolved carbon dioxide, organic acids, and other weak acid-forming constituents commonly associated with urban runoff and subsurface biogeochemical processes (Esquivel-Hernández et al., 2023).

Groundwater acidity values typically range between approximately 10–500 mg/L as $CaCO_3$, depending on dissolved carbon dioxide concentration, organic matter decomposition, and aquifer geochemistry (World Health Organisation (WHO), 2017). The relatively higher values observed in urban Lafia, therefore, suggest increased acid neutralisation capacity rather than harmful acidic conditions. Similar acidity ranges have been reported in tropical groundwater systems influenced by carbonate buffering processes (Saalidong et al., 2022).

The concurrent presence of high alkalinity, especially in rural samples, suggests an active carbonate buffering system within the aquifer, where bicarbonate and carbonate ions help stabilise pH despite variations in acidity. Such behaviour is typical in groundwater systems influenced by carbonate mineral dissolution and organic matter interactions (Winnick & Saccardi, 2024).

The comparison of Lafia and Agunji water samples shows higher acidity, TDS, and electrical conductivity in Lafia water samples (fig. 1A). This trend may be partially influenced by anthropogenic activities; however, the contribution of natural geochemical processes cannot be ruled out, and further investigation is required to establish definitive causation. Natural geochemical processes, such as carbonate mineral dissolution and extended water–rock interaction, primarily control the elevated hardness and alkalinity in the rural area. However, through organic matter decomposition and increased bicarbonate formation, particularly in shallow groundwater systems, secondary contributions from cassava processing activities may enhance alkalinity.

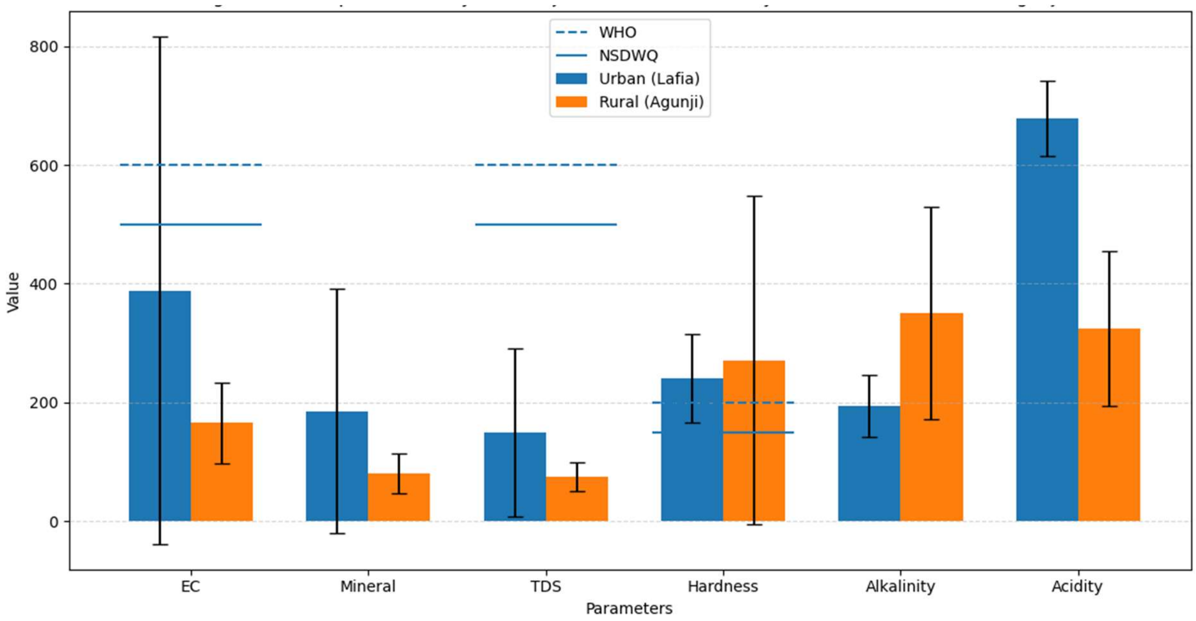

Figure 1A: Comparative analysis of major groundwater physicochemical parameters between Lafia (urban) and Agunji (rural) relative to WHO and NSDWQ permissible limits.

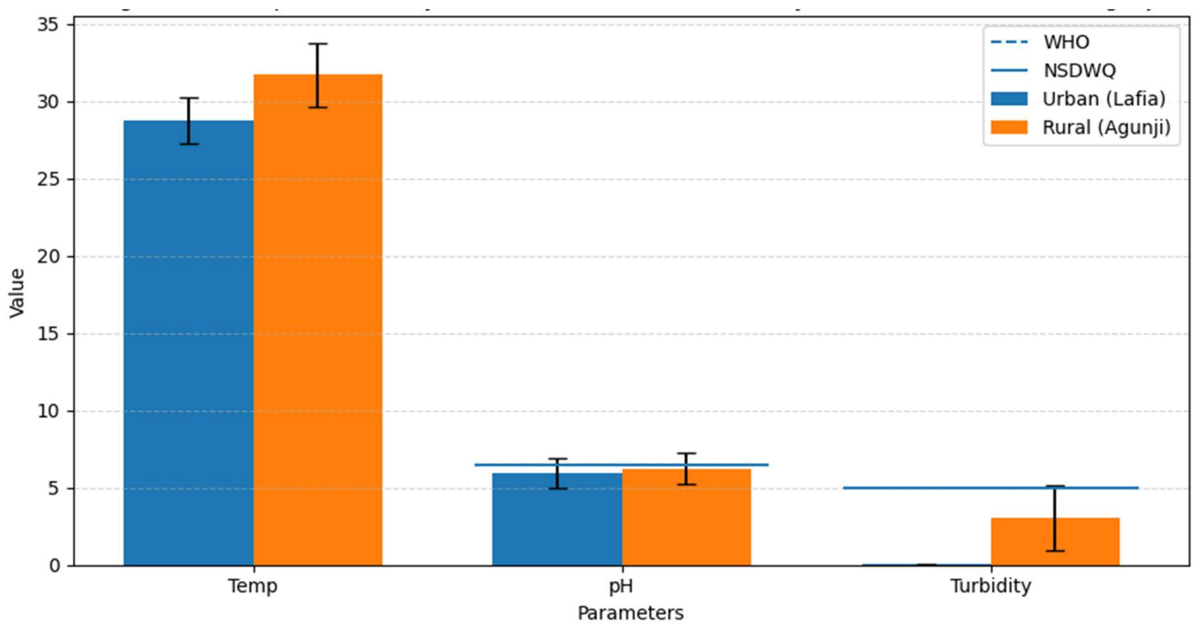

Figure 1B: Comparative analysis of minor groundwater physicochemical parameters between Lafia (urban) and Agunji (rural) relative to WHO and NSDWQ permissible limits.

To improve clarity and interpretation, the groundwater parameters were grouped according to magnitude into two graphical representations. Figure 1A presents major concentration parameters such as electrical conductivity, hardness, alkalinity, total dissolved solids, mineral content and acidity, while Figure 1B presents lower magnitude parameters including temperature, pH and turbidity. The graphical trends support the statistical results presented in Table 1, particularly for turbidity and acidity where clear differences between rural and urban groundwater are evident. Most parameters remain within WHO and NSDWQ permissible limits.

Generally, most water-quality parameters were comparable between urban and rural wells and within safe limits. Significant urban–rural differences were limited to temperature, turbidity, and measured acidity. Elevated rural turbidity suggests more suspended particulates in village water; elevated urban acidity suggests possible contamination or geochemical source differences. The generally safe chemical levels align with WHO and NSDWQ standards, although the slightly low pH in both areas indicates a potential acidity issue that should be mitigated. These findings are consistent with nationwide assessments noting both natural and anthropogenic influences on groundwater in Nigeria (Nnorom et al., 2019). The significant parameters identified by the t-tests highlight specific concerns: for example, WHO prioritises turbidity (<1–5 NTU) to prevent microbial survival, and our results show rural wells approach the upper limit.

4. Conclusion

This comparative analysis of Lafia (urban) and Agunji (rural) groundwater reveals that most physicochemical qualities are similar and largely within safe standards. However, statistically significant differences were limited to temperature, turbidity, and acidity, while other parameters (pH, EC, TDS, hardness, and alkalinity) showed no significant variation between urban and rural locations. Both sources are moderately hard and slightly acidic, which is below recommended ranges and may require treatment. Importantly, all mean values of TDS, EC, and turbidity are below NSDWQ and WHO limits, indicating overall potability. The results imply that, while neither source currently poses acute water-quality problems, targeted interventions may be warranted, such as turbidity reduction at rural wells and acid buffering in urban supply. The results indicate that while some differences exist between urban and rural groundwater quality, these variations cannot be solely attributed to urbanisation and are likely influenced by a combination of natural and anthropogenic factors. In summary, Lafia's urban groundwater and Agunji's rural groundwater are broadly comparable, but the identified differences highlight areas (temperature, turbidity, acid content) for focused management. This study underlines the necessity for continual monitoring and adherence to standards to ensure safe drinking water for both communities.

It is important to note that the relatively small sample size (n = 5 per group) may limit the statistical power of the analysis and the generalisability of the findings. Although robust statistical methods, including Welch's t-test and the Mann–Whitney U test, were applied, the results should be interpreted with caution. Future studies should incorporate larger sample sizes and seasonal sampling for more comprehensive assessment.

5. Recommendations

Routine groundwater quality monitoring should be maintained in both urban and rural areas, with particular attention to parameters that showed statistically significant variation, namely temperature, turbidity, and acidity. Continuous monitoring will help detect changes in water quality and support timely intervention.

Given the significantly higher turbidity observed in rural groundwater, the implementation of simple and cost-effective treatment methods such as sand filtration, settling tanks, and proper wellhead protection is recommended to reduce suspended particles and prevent surface contamination. Community awareness on proper well maintenance should also be encouraged.

The elevated acidity observed in urban groundwater suggests the need for periodic monitoring and, where necessary, corrective treatment measures such as lime dosing or neutralising filtration systems to improve water quality and ensure compliance with drinking water standards.

Compliance with the Nigerian Standard for Drinking Water Quality (NSDWQ) and World Health Organization (WHO) guidelines should be ensured, particularly for parameters approaching critical thresholds such as turbidity and pH. Regulatory bodies and local authorities should strengthen monitoring frameworks to support safe water supply.

Potential sources of groundwater contamination, including poor sanitation practices and improper waste disposal, should be effectively managed. However, it is important to recognise that both natural hydrogeochemical processes and anthropogenic activities may influence groundwater quality, and these factors should be considered in water management strategies.

The recommendations provided are based on the specific findings of this study and should be implemented in a site-specific manner. Further studies incorporating larger sample sizes and seasonal variations are recommended to provide more comprehensive insight into groundwater quality dynamics

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Abubakar Sadiq Usman: Conceptualization, Methodology, Investigation design, Supervision, Formal analysis guidance, Writing – review & editing, Validation.

Ahmad Ibrahim Aliyu: Investigation, Laboratory analysis, Data collection, Geological analysis, Literature review, Writing – review & editing.

Adamu Umar Ismail: Data curation, Formal analysis, Statistical analysis (Welch's two-sample t-test), Visualization, Writing – original draft, Results interpretation.

Lukmon Olakunle Jimoh: Literature contextualization, Writing – review & editing, Validation.

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Ethical Statements

This research did not involve human participants, animals, or confidential data requiring ethical approval. All research activities were conducted in accordance with relevant institutional practices and internationally accepted standards for academic research. The authors confirm that this work adheres to ethical guidelines for scholarly publication.

Data and Code Availability

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

Supplementary Materials

All relevant information supporting this study is included within the manuscript. No additional supplementary materials are associated with this article.

References

Ahmad, W., Iqbal, J., Nasir, M. J., Ahmad, B., Khan, M. T., Khan, S. N., & Adnan, S. (2021). Impact of land use/land cover changes on water quality and human health in district Peshawar Pakistan. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-96075-3

Asingbi, T., Durowoju, O., Olusola, A., & Obateru, R. (2020). Variations in Physico-Chemical Properties of Shallow Groundwater Aquifers Across Rural-Urban Differentials. *Analele Universităţii Din Oradea, Seria Geografie*, *30*(1), 53–64. https://doi.org/10.30892/auog.301107-814

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences (2nd ed.). Abingdon:

Routledge.

Danert, K., & Healy, A. (2021). Monitoring groundwater use as a domestic water source by urban households: Analysis of data from lagos state, nigeria and sub-saharan africa with implications for policy and practice. *Water (Switzerland)*, *13*(4), 1–18. https://doi.org/10.3390/w13040568

Emmanuel F., A., Veronica M., A., & Udeme U., I. (2020). Geoelectrical Investigation of Groundwater Quality Through Estimates of Total Dissolved Solids and Electrical Conductivity in Parts of Akwa Ibom State, Southern Nigeria. *Malaysian Journal of Geosciences*, *4*(1), 32–37. https://doi.org/10.26480/mjg.01.2020.32.37

Esquivel-Hernández, G., Sánchez-Murillo, R., Villalobos-Córdoba, D., Monteiro, L. R., Villalobos-Forbes, M., Sánchez-Gutiérrez, R., Cotrim, M. E. B., & Matiatos, I. (2023). Exploring the acid neutralizing effect in rainwater collected at a tropical urban area: Central Valley, Costa Rica. *Atmospheric Pollution Research*, *14*(9). https://doi.org/10.1016/j.apr.2023.101845

Ghimire, M., Byanjankar, N., Regmi, T., Jha, R., Joshi, D. R., & Prasai Joshi, T. (2025). Hydrogeochemical characterization of shallow and deep groundwater for drinking and irrigation water quality index of Kathmandu Valley, Nepal. *Environmental Geochemistry and Health*, *47*(3). https://doi.org/10.1007/s10653-025-02372-5

Houria, B., Mahdi, K., & Zohra, T. F. (2020). Hydrochemical characterisation of groundwater quality: Merdja plain (Tebessa town, Algeria). *Civil Engineering Journal (Iran)*, *6*(2), 318–325. https://doi.org/10.28991/cej-2020-03091473

Huang, J., Chen, S., Ma, X., Yu, P., Zuo, P., Shi, B., Wang, H., & Alvarez, P. J. J. (2021). Opportunistic pathogens and their health risk in four full-scale drinking water treatment and distribution systems. *Ecological Engineering*, *160*. https://doi.org/10.1016/j.ecoleng.2020.106134

Ifediegwu, I. S., Onyeabor, C. F., & Nnamani, C. M. (2019). Geochemical evaluation of carbonate aquifers in Ngbo and environs, Ebonyi State, southeastern, Nigeria. *Modeling Earth Systems and Environment*, *5*(4), 1893–1909. https://doi.org/10.1007/s40808-019-00646-3

Ifediegwu, S. I. (2022). Assessment of groundwater potential zones using GIS and AHP techniques: a case study of the Lafia district, Nasarawa State, Nigeria. *Applied Water Science*, *12*(1). https://doi.org/10.1007/s13201-021-01556-5

Ighalo, J. O., & Adeniyi, A. G. (2020). A comprehensive review of water quality monitoring and assessment in Nigeria. *Chemosphere*, *260*. https://doi.org/10.1016/j.chemosphere.2020.127569

Lawal, A., Tijani, M. N., Snow, D., & D'Alessio, M. (2023). Quality and hydrochemical assessment of groundwater in geological transition zones: a case study from N.E. Nigeria. *Environmental Science and Pollution Research*, *30*(4), 10643–10663. https://doi.org/10.1007/s11356-022-22762-x

Nnorom, I. C., Ewuzie, U., & Eze, S. O. (2019). Multivariate statistical approach and water quality assessment of natural springs and other drinking water sources in Southeastern Nigeria. *Heliyon*, *5*(1). https://doi.org/10.1016/j.heliyon.2019.e01123

Ojo, J. T., Ojo, O. M., Olabanji, T. O., & Aluko, R. T. (2024). Urbanization impact on groundwater quality of selected rural and urban areas in Ondo State, Nigeria using Water Quality Index. *Discover Water*, *4*(1). https://doi.org/10.1007/s43832-024-00061-5

Olalemi, A. O., Atiba, R., Weston, S., & Howard, G. (2023). Sanitary inspectionãnd microbial health risksãssociated with enteric bacteria in groundwater sources in Ilara-Mokinãnd Ibule-Soro, Nigeria. *Journal of Water and Health*, *21*(12), 1784–1794. https://doi.org/10.2166/wh.2023.111

Saalidong, B. M., Aram, S. A., Otu, S., & Lartey, P. O. (2022). Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems. *PLoS ONE*, *17*(1 1). https://doi.org/10.1371/journal.pone.0262117

Siddiqua, A., Hahladakis, J. N., & Al-Attiya, W. A. K. A. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. *Environmental Science and Pollution Research*, *29*(39), 58514–58536. https://doi.org/10.1007/s11356-022-21578-z

Tegegne, A. M., Lohani, T. K., & Eshete, A. A. (2023). Evaluation of groundwater quality for drinking and irrigation purposes using proxy indices in the Gunabay watershed, Upper Blue Nile Basin, Ethiopia. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e15263

Umar, N. D., Igwe, O., & Idris, I. G. (2019). Evaluation and characterization of groundwater of the Maastrichtian Lafia formation, Central Benue trough, Nigeria. *Journal of Earth System Science*, *128*(6). https://doi.org/10.1007/s12040-019-1199-1

WHO (2017). *Guidelines for drinking-water quality* (4th ed. in). World Health Organization.

Winnick, M. J., & Saccardi, B. (2024). Impacts of Carbonate Buffering on Atmospheric Equilibration of CO2, δ13CDIC, and Δ14CDIC in Rivers and Streams. *Global Biogeochemical Cycles*, *38*(2). https://doi.org/10.1029/2023GB007860

Yehia, H. M. A.-S., & Said, S. M. (2021). Drinking Water Treatment: pH Adjustment Using

Natural Physical Field. *Journal of Biosciences and Medicines*, *09*(06), 55–66. https://doi.org/10.4236/jbm.2021.96005

Yohanna, P., Apeh, O. V., & Lawuyi, T. (2021). Analyzing the Quality of Ground Water in Kaduna South Local Government Area, Kaduna State, Nigeria. *Fudma Journal of Sciences*, *5*(2), 413–418. https://doi.org/10.33003/fjs-2021-0502-631