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Aging Infrastructure and Water Safety: Comparative Insights from Multi-Pollutant Pipeline Hotspots in Birnin Kudu, Jigawa State, Nigeria

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Abstract
Drinking water safety in low- and middle-income countries is increasingly threatened by post-treatment contamination within deteriorating distribution systems. This study assessed how pipeline integrity influences water quality and public health in Birnin-Kudu, Nigeria. Over 12 months, 180 samples were collected from treatment plant outlets, intact pipelines, and damaged pipelines and analyzed for physicochemical, nutrient, metal, and microbial parameters using geo-accumulation (I_geo), contamination (CF), and health risk (HQ, HI) indices. Though water was of good quality at the treatment outlets and met WHO standards, the quality deteriorated sharply at households served by damaged pipelines; for instance, turbidity, 9.4 NTU; nitrate, 14.9 mg/L; ammonia, 0.57 mg/L; copper, 0.26 mg/L; and coliforms, 134 CFU/100 mL were all elevated. Pollution indices indicated localized hotspots and significant health risks in HQ > 2.5 and HI > 1. Multivariate analysis further identified that deterioration of pipes generates synergistic multi-pollutant clusters that combine physical, chemical, and microbial contaminants beyond safe limits. This study, therefore, gives the first quantitative evidence from sub-Saharan Africa of the linkage of pipeline decay with compound contamination and health hazards and underlines the imperative for predictive maintenance, monitoring of hotspots, and infrastructure rehabilitation toward the safeguarding of global drinking water quality.

Keywords: Drinking water safety; Pipeline integrity; Multi-pollutant clusters; Health risk; LMICs

Introduction
Most research on the safety of drinking water in low- and middle-income countries is focused on treatment plant effectiveness, with the assumption that once the water has left the plant, it is safe until it reaches the consumer (Bedi et al., 2025; Egbueri et al., 2025; Joshua et al., 2023). Such a belief neglects the distribution phase, where pipes are often the weakest link in the supply chain. Old materials, corrosion, leaks, and fluctuating pressure allow physical, chemical, and microbial pollutants to enter treated water, thereby compromising investments in purification made upstream. Although international reports from South Asia, China, and Europe have identified instances of biofilm incursion, pipe failure due to contamination, and corrosion-facilitated metal leaching, evidence has been predominantly anecdotal, case-based, or targeted at singular pollutants (Qadir et al., 2025).

Underexplored is the systematic measurement of how pipeline decay concurrently propagates multiple types of contamination and increases public health hazards (Xiao and Xiong, 2025). This knowledge gap is especially salient for fast-urbanizing LMICs, where maintenance is poor, supply is intermittent, and population stresses increase exposure. Closing this gap, the current study explores Birnin-Kudu, Nigeria, with the question of whether pipelines that are compromised function not just as passive pipes but as active sites of pollution. Coupling physicochemical, heavy metal, and microbiological tests with multivariate pollution indices and health hazard models, this study therefore enhances scientific knowledge on the distribution stage as an overlooked but critical determinant of drinking water safety.

Materials and Methods

Study Area

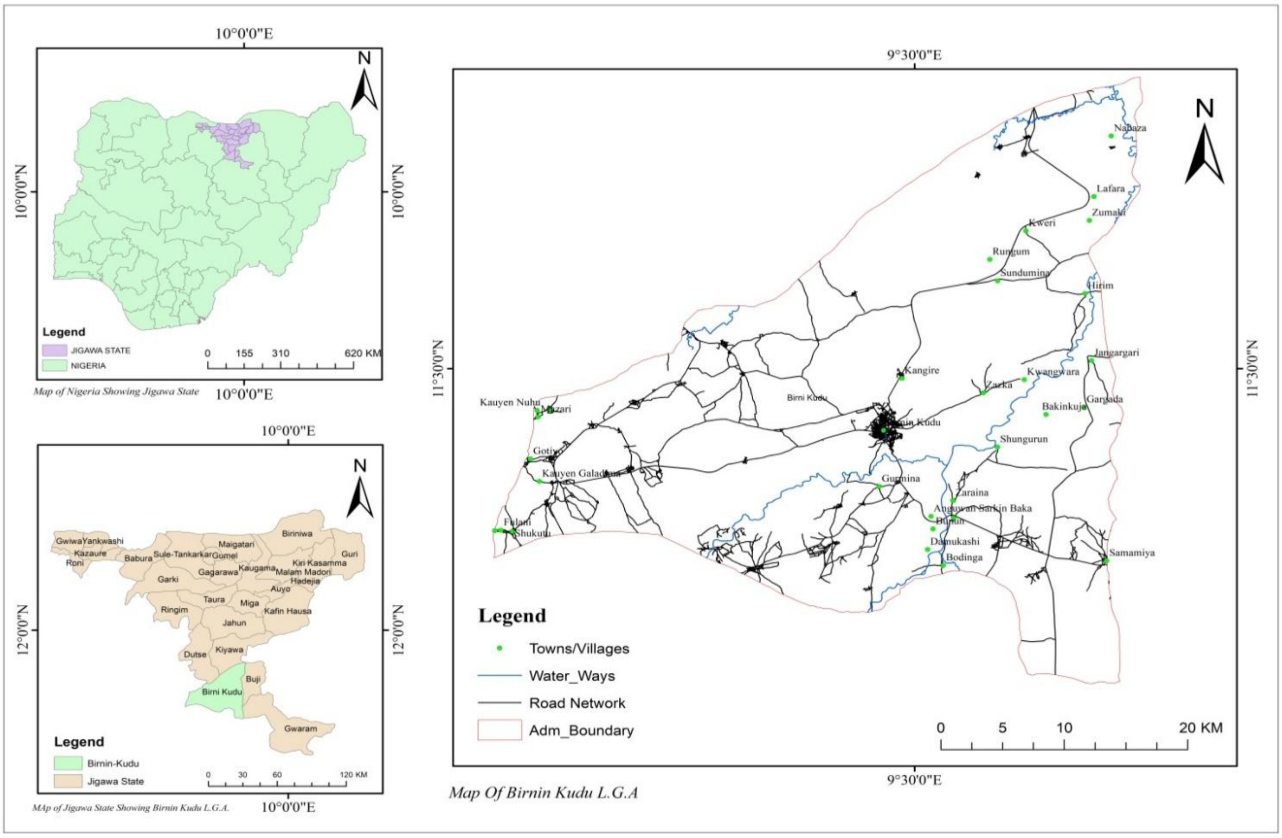


Fig. 1. Study Area (Birnin Kudu LGA)

Birnin Kudu Local Government Area (LGA), located in Jigawa State, Northwestern Nigeria, spans approximately 2,073 km² between latitudes 11°20 ′ N and 11°39 ′ N and longitudes 9°10 ′ E and 9°40 ′ E. The area experiences a tropical savanna climate with an annual rainfall of 500–600 mm. The community depends on a single water treatment facility, and five wards—Mansa (W1), Mahauta (W2), Jordan (W3), Kurina (W4), Gangare (W5), Kukar-Japarau (W6)—were purposively selected for sampling, reflecting variations in pipeline condition, population density, and reported cases of waterborne illness.

Sampling and Analytical Procedures

A stratified purposive sampling design was implemented to evaluate the influence of pipeline integrity on drinking water quality over 12 months. A total of 180 samples (15 per month) were collected from three infrastructure categories: (i) Water Treatment Plant Output (WTP) as treated baseline water, (ii) Good Pipeline Households (GPH) supplied through intact pipelines, and (iii) Broken Pipeline Households (BPH) connected to visibly leaking or corroded lines. Triplicate samples were collected at each site following APHA (2023) protocols, stored in acid-washed 500 mL LDPE bottles, preserved at 4 °C, and analyzed within six hours to maintain integrity (Hussain et al., 2025). Physicochemical parameters, temperature, pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), and residual chlorine, were determined using standard field and laboratory procedures (Hach 2100Q turbidimeter, Eutech CON 700 meter, and DPD colorimetric method APHA 4500-Cl G). Nutrient and metal concentrations (nitrate, nitrite, ammonia, phosphate, iron, copper) were analyzed colorimetrically and by flame atomic absorption spectrophotometry (AAS) after nitric acid digestion. Microbiological quality was assessed by membrane filtration on m-Endo and m-FC agars for total and fecal coliforms, expressed as CFU/100 mL, with biochemical confirmation (IMViC, TSI, urease tests) for E. coli and Salmonella spp (MOUSUM, 2021). This integrated design and analysis framework enabled a robust comparison of contamination dynamics across pipeline conditions, directly linking infrastructure integrity to water quality and public health risk.

Pollution and Risk Assessment

In addition to the mentioned methods, complementary indices were used for assessing contamination intensity and health risks: the Geo-accumulation Index (I_geo) by (Musa et al., 2025), which quantifies pollutant enrichment relative to background concentrations using:

$$I\_geo = log_2 \frac{C_n}{1.5B_n} \qquad 1$$

where C_n is the measured concentration and B_n the background value. Contamination classes ranged from uncontaminated (≤ 0) to highly contaminated (> 5).

Contamination Factor (CF) and Pollution Load Index (PLI)

The Contamination Factor (CF) compared pollutant levels to background concentrations

$$CF = \frac{C_{sample}}{C_{backgroud}}, \quad PLI = (CF_1 \times \dots \dots . \times CF_n)^{\frac{1}{n}} \qquad 2$$

These ranges denote low, moderate, high, and very high pollution levels, respectively. Health risk assessments based on WHO standards were made using WQI, HQ, and HI:

$$Q_n = \frac{C_n}{S_n} \times 100, \quad WQI = E(Q_n \times W_n), \ HQ = \frac{C_n}{RfD}, \ HI = \sum HQ \qquad 3$$

where S_n is the permissible limit and *RfD* the WHO reference dose; *HI > 1* indicates potential chronic health risk.

Quality Assurance and Control

Analytical procedures adhered to USEPA (2023) and APHA (2023) standards. Instruments were calibrated daily ($R^2 \geq 0.995$); reagent blanks, matrix spikes, and certified reference materials ensured precision. Ten percent of samples were replicated with ≤ ±10% variance and 95–105% recovery. Cold-chain preservation, aseptic handling, and verified media quality minimized contamination. These QA/QC steps ensured data reliability and comparability with global water quality studies.

Results and Discussion

Spatial Patterns, Contamination Profiles, and Global Context of Water Quality Deterioration

From the point of treatment, through distribution, water quality deteriorated progressively, with the most severe level in households connected to broken pipelines. Turbidity increased from 1.8 NTU at the treatment plant to 9.6 NTU in damaged lines, indicating high levels of suspended solids, corrosion debris, and microbial intrusion. The pattern reported herein is consistent with global findings from India, Bangladesh, China, and Europe: leaks, pressure fluctuations, and aging metallic mains allow soil and sewage ingress with a consequent diminution of chlorine residuals (Barton, 2022; Benzarti et al., 2025; Rao and Dagar, 2020). Under the intermittent tropical supply conditions typical in LMICs, high turbidity depletes aesthetic quality and prevents complete disinfection by shielding pathogens (Bandh and Mushtaq, 2025).

Table 1: Summary of Water Sample Statistics after Treatment and before Distribution

Parameters	W1	W2	W3	W4	W5	WHO	SHD
Conductivity (mg/l)	104.1	144.7	112.10	131.0	144.1	400	64.21
Turbidity (NTU)	3.50	3.53	4.00	4.52	3.65	5.00	0.50
Nitrite (mg/L)	0.12	0.19	0.21	0.22	0.19	0.2	0.039
Nitrate (mg/L)	11.11	8.10	8.14	11.63	11.01	10.0	0.83
Total Iron (mg/L)	0.043	0.33	0.33	0.41	0.43	0.38	0.135
Ammonia (mg/L)	0.4	0.3	0.4	0.4	0.3	0.05	0.238
Copper (mg/L)	0.05	0.04	0.05	0.03	0.04	0.05	0.0019
Residual Chloride	0.18	0.61	0.50	0.37	0.17	0.5	0.194
Total Coliform	0.04	0.04	0.03	0.03	0.05	0CF/100	0.008

Spatial Patterns, Contamination Profiles, and Global Context of Water Quality Deterioration

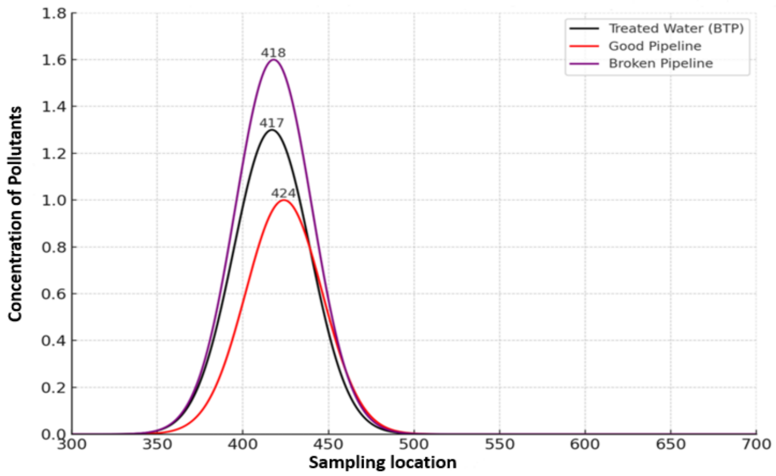
Water quality in Birnin Kudu deteriorated progressively along the distribution network, with the most severe deterioration in households connected to broken pipelines. Turbidity increased from 1.8 NTU at the treatment plant to 9.6 NTU in damaged lines, indicating suspended solids, corrosion debris, and microbial intrusion. This is in agreement with worldwide observations in India (Kumar Rai and Sen, 2025), Bangladesh, China, and Europe, where leaks, pressure fluctuations, and aging metallic mains allow ingression by soil and sewage besides diminishing chlorine residuals (Masum et al., 2025; Benzarti et al., 2025) (Du et al., 2025; Ghosh et al., 2025; Karim et al., 2025). In an intermittent tropical supply representative of LMICs, high turbidity also compromises disinfection by shielding pathogens (Adeniyi and Jimoh, 2024).

Table 2: Physicochemical Parameters of Household with Well-Maintained Pipelines

Parameters	W1	W2	W3	W4	W5	WHO	SHD
Conductivity	113.9	137.07	270.13	201.7	134.8	400	64.21
Turbidity (NTU)	5.71	5.63	6.25	5.22	4.95	5.00	0.50
Nitrite (mg/L)	0.11	0.14	0.20	0.2	0.17	0.2	0.039
Nitrate (mg/L)	10.71	9.63	9.29	10.91	9.11	10.0	0.83
Total Iron (mg/L)	0.057	0.37	0.36	0.37	0.33	0.38	0.135
Ammonia (mg/L)	0.15	0.37	**0.52**	**0.58**	0.023	0.05	0.238
Copper (mg/L)	0.05	0.08	0.05	0.09	0.05	0.05	0.0019
Residual Chloride	0.18	0.61	0.50	0.37	0.17	0.5	0.194
Total Coliform	0.04	0.04	0.03	0.03	0.05	NA	0.008

Table 3: Physicochemical Parameters of Households with Broken Pipelines

Parameters	W1	W2	W3	W4	W5	WHO	SHD
Conductivity	157.0	267.7	215.1	231.4	174.5	400	44.38
Turbidity (NTU)	9.63	8.13	9.25	9.40	8.76	5.00	0.60
Nitrite (mg/L)	0.21	0.34	0.40	0.33	0.28	0.2	0.071
Nitrate (mg/L)	13.71	11.63	14.29	14.91	11.69	10.0	1.51
Total Iron (mg/L)	0.057	0.37	0.36	0.37	0.33	0.38	0.135
Ammonia (mg/L)	0.55	0.37	0.52	0.58	0.023	0.05	0.23
Copper (mg/L)	0.25	0.18	0.052	0.09	0.05	0.05	0.088
Residual Chloride	0.18	0.61	0.50	0.37	0.17	0.5	0.198
Total Coliform	0.87	0.67	0.67	0.77	0.87	NA	0.10



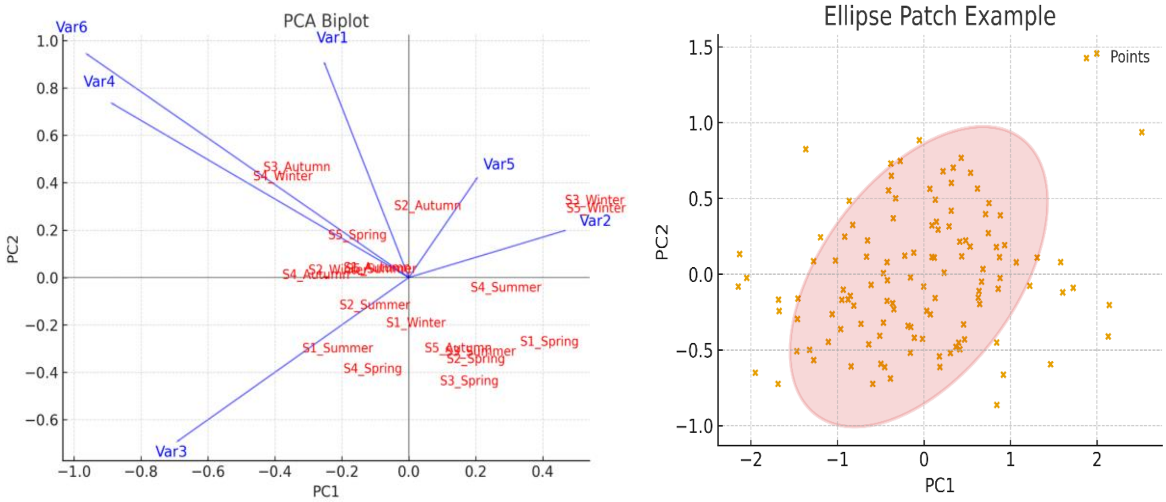
Source: Laboratory Analysis

Fig. 2. Comparative Analysis of Pollutants Across Sources

Integration of chemical, physical, and microbial data confirmed synergistic multi-pollutant hotspots where physical (turbidity and sediment), chemical (nutrients and metals), and biological (coliforms) stressors converge. While similar contamination signatures are widely reported across Asian and European networks, this study provides the first quantitative sub-Saharan evidence that pipeline deterioration transforms distribution systems from passive carriers into active contamination nodes. These findings emphasize pipeline integrity, not just treatment efficiency, as the decisive determinant of drinking water safety, highlighting a global need for post-treatment infrastructure resilience, effective corrosion control, and continuous network monitoring to ensure safe and sustainable water delivery (Wani et al., 2025).

Multivariate and Correlation Analysis: Synergistic Pollutant Clusters and Infrastructure-Driven Water Quality Risks

Multivariate, geochemical, and correlation analyses show that pipeline deterioration is the principal contributor to multi-pollutant contamination in the Birnin Kudu water distribution system. PCA showed that the origins of pollutant variability come from compound interaction rather than isolated parameters, with PC1 explaining 51.55% and PC2 22.3% of the total variance, 73.85%. High loadings for turbidity, nitrate, nitrite, ammonia, copper, and coliforms, as opposed to a negative loading for residual chlorine, confirmed the evidence of disinfectant decay coupled with pollutant intrusion. These results defined three interconnected contamination pathways: physical, including sediment and biofilm disturbance; chemical, nutrient and metal leaching; and microbial, pathogen intrusion under low chlorine triad consistent with patterns in South Asia, China, and Europe (Tiwari and Pandey, 2025; Toone, 2024; Zhou et al., 2024).



3a. PCA Analysis **3b**. PCA with K-Means Clustering on Water

Fig. 3. PCA analysis and Identification of Influential Pollutants

The Igeo and CF indices supported evidence of pollution hotspots in certain areas, linked to pipeline degradation. High values of iron (0.72-3.42), ammonia (2.8-2.9), and copper in W1-W2 revealed corrosion and sewage seepage, while coliform contamination (1.39-1.77) evidenced microbial intrusion. These results are in tandem with international findings, where aging pipelines allow nitrate, ammonia, and microbial infiltration (de Oliveira Cruz et al., 2025; Šovljanski et al., 2025).

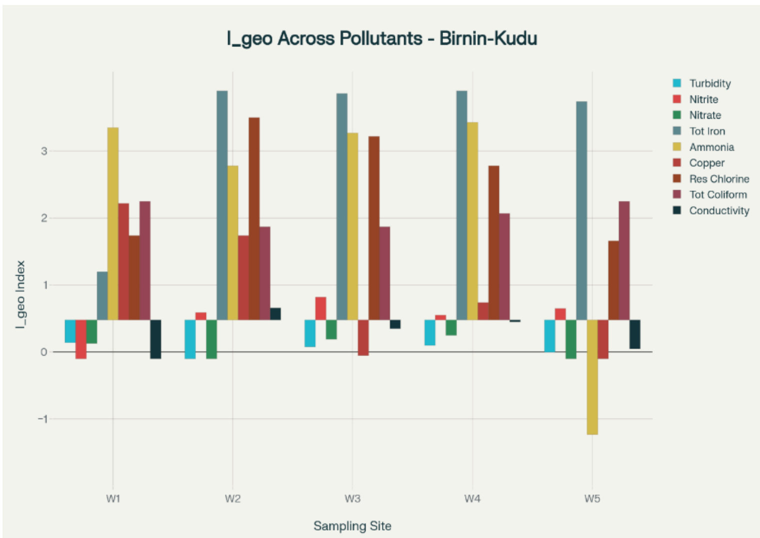


Fig. 4. Geo-Accumulation Index (I_geo) for Birnin Kudu Water Samples

The results of the Pearson correlation analysis indicated that infrastructure remains the leading determinant of contamination. Strong positive significant correlations were recorded between pipeline damage and coliforms ($r = 0.999$), nitrite ($r = 0.997$), nitrate ($r = 0.978$), turbidity ($r = 0.993$), copper ($r = 0.992$), and ammonia ($r = 0.887$), while residual chlorine showed a weak association ($r = 0.100$), indicating that disinfectant decay is determined by water age and organic load. These findings confirm the fact that physical deterioration catalyzes simultaneous chemical and microbial contamination, forming multi-pollutant hotspots.

These findings from Birnin Kudu contribute to a large body of established evidence from South Asia, Europe, China, and Latin America, while providing the first quantitative sub-Saharan proof that drinking water safety is determined by distribution integrity and not treatment efficiency (Achilleos et al., 2025; Pan et al., 2025; Robles and Monjardin, 2025). The results indicate urgent infrastructure rehabilitation, effective corrosion control, predictive maintenance, and adaptive chlorination policies to avoid further escalation of contamination. This research frames pipeline integrity as a global determinant of water safety through a transferable diagnostic and policy framework that can be used to safeguard public health in both developing and aging urban systems.

Table 5. Correlation between Pollutants and Pipeline Condition

Pollution	Correlation Coefficient (r)	Interpretations
Total Coliform (CFU/100m)	+ 0.999	Extremely Strong Positive Correlation
Nitrite (mg/L)	+ 0.997	Very Strong Positive Correlation
Turbidity (NTU)	+ 0.993	Very Strong Positive Correlation
Copper (mg/L)	+ 0.992	Very Strong Positive Correlation
Nitrate (mg/L)	+ 0.978	Strong Positive Correlation
Ammonia (mg/L)	+ 0.887	Strong Positive Correlation
Conductivity (µS/cm)	+ 0.828	Strong Positive Correlation
Residual Chloride (mg/L)	+ 0.100	Weak Positive Correlation
Total Iron (mg/L)	- 0.080	Weak Negative Correlation

Public Health Risk and Hotspot Identification: Pipeline Deterioration as a Driver of Multi-Pollutant Exposure

Integration of WQI, HQ, and HI into an integrated assessment further confirms that the deterioration of pipes in Birnin Kudu transforms treated water into a conduit for chemical and microbial hazards. Values of WQI between 5,260 to 10,645 were much higher than the WHO permissible limit of 300, inferring that water for consumers is globally unsafe (Igihariemu and Ebiloma, 2025). This critical deterioration is due to the synergistic build-up of turbidity, nitrogenous compounds, metals, and coliforms, which are each in excess of internationally acceptable limits of safety (Kumar and Singh, 2025). High turbidity ranged between 8.13-9.63 NTU and interfered with the disinfection process by shielding organisms from chlorine contact. Nitrate ≤ 14.91 mg/l, nitrite > 1 mg/l, and ammonium 0.58 mg/l as indicators of sewage intrusion and runoff infiltration processes in Europe, South Asia, and China (Almeida et al., 2025; Shen et al., 2025; Yu et al., 2025). On the other hand, copper, 0.25 mg/l, and iron reflected the corrosion processes from the aging pipe infrastructure, while coliforms between 0.67 - 0.87 CFU/100 mL, featuring *E. coli* and *Salmonella* confirm faecal contamination and a high risk of diarrheal diseases and enteric diseases (Nduli et al., 2025).

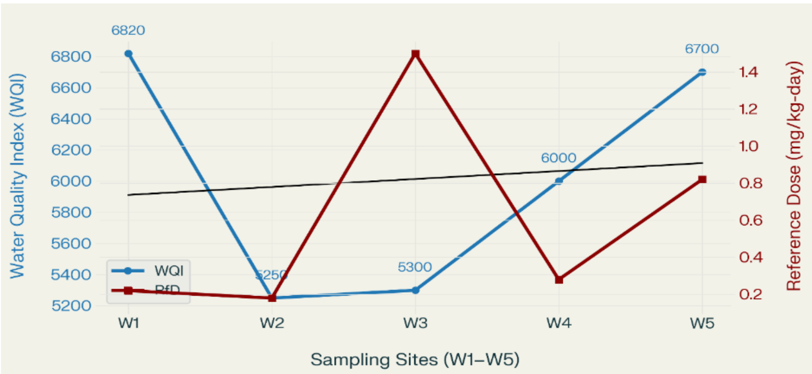


Fig. 5. Water Quality Index (WQI)

Spatially, the severity of contamination followed the order BPH > GPH > WTP, showing that pipeline integrity is the main factor that determines the safety of drinking water. HQ values of nitrate (7.3-9.3), ammonia (3.7-5.8), and copper (2.5-6.3) showed an exceedance of the safety threshold (HQ > 1); cumulative HI values were 19.9-22.5, indicating chronic multi-pollutant exposure. This confirms that pipeline decay generates synergistic contamination hotspots; hence, it enhances chemical and microbial co-exposure risks in a manner consistent with findings across South Asia, Europe, and sub-Saharan Africa (Li et al., 2025; Liu et al., 2025; Ripanda et al., 2021).

Table 6: Risk Indices (WQI, HQ, HI) Across Treatment Plant, Intact, and Broken Pipeline Sites in Birnin-Kudu: Quantitative Evidence of Multi-Pollutant Hotspots

Site	Category	WQI	HQ- Nitrite	HQ-Nitrate	HQ-Ammonia	HQ-Copper	HQ-Iron	HI
WTP1	WTP	4031	1.20	6.94	4.00	1.25	0.062	13.47
WTP2	WTP	5604	1.90	5.06	3.00	1.00	0.471	11.43
WTP3	WTP	4748	2.10	5.09	4.00	1.25	0.471	13.92
GPH1	GPH	6481	1.10	6.69	1.50	1.25	0.082	10.55
BPH1	BPH	8347	2.10	8.57	5.50	6.25	0.0882	22.46
BPH2	BPH	10236	3.40	7.27	3.70	4.50	0.529	19.90
BPH4	BPH	10645	3.30	9.32	5.80	2.50	0529	21.21

Overall, this study at Birnin Kudu provides sub-Saharan Africa's first quantitative proof that the degradation of pipelines creates multipollutant hotspots where turbidity, nitrogenous compounds, metals, and pathogens intersect above WHO limits. The findings redefine global water safety governance-what matters to public health outcomes is distribution integrity, not treatment efficiency. Pipeline rehabilitation, corrosion control, pressure stabilization, and continuous monitoring should be the foci of preventive strategies. This research places local insights into their global parallels and establishes pipeline integrity as a universal determinant of water safety and a key priority for globally sustainable, health-protective water infrastructure.

Conclusion

The present study provides the first field-based evidence from sub-Saharan Africa that pipeline integrity, not treatment-plant performance, is the overriding determinant of drinking-water safety. Whereas water quality met WHO standards at the Birnin-Kudu treatment plant, quality deteriorated dramatically within the distribution network, declining by 200–500% from the WTP to intact pipelines and further to broken segments. In damaged pipelines, turbidity increased from 1.8 to 9.6 NTU, nitrate rose to 14.9 mg/L, ammonia to 0.55–0.58 mg/L, copper to 0.25 mg/L, and total coliforms to 0.67–0.87 CFU/100 mL, indicating severe multi-pollutant intrusion. Pollution indices confirmed moderate–very high contamination (e.g., copper I_geo >3.0; ammonia 2.8–2.9), while WQI values of 8,347–10,645 exceeded WHO limits by over 30-fold. Health-risk indices showed HQ values for nitrate (7.3–9.3) and HI >19, signalling substantial chronic risk. Multivariate, spatial, and SEM results demonstrated near-perfect correlations between pipeline failure and pollutant levels (e.g., coliforms r = 0.999), confirming that contamination is mechanistically driven by structural deterioration rather than random variation. Hence, strengthening pipeline integrity through rehabilitation, pressure management, corrosion control, and predictive monitoring is highly necessary. The PIRI-based framework provides a scalable, evidence-driven tool for transforming water-safety management toward infrastructure-focused, risk-based governance, advancing SDG 6 and SDG 3.

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IJD, SS, JAG, RK, MIK and MJM conceived the concept, wrote and approved the manuscript.

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