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Public Health Risk Assessment of Antibiotic Residues and Waterborne Pathogens in Drinking Water Sources of Jos North and Barkin Ladi Local Government Areas, Plateau State, Nigeria

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Article Information:
Received: 25 February 2026 | Revised: 27 March 2026 | Accepted: 24 April 2026 | Published: May 30, 2026

Cite this article:
Johnpaul O. Amuka, Chidiebere C. Ezike, Henderson O. Ogbaji, Awajiiroijana U. Okpoji, Agbonma B. Ukaigwe, Ann C. Obieje, Chihurumnanya O. Oji, Muhammed H. Garuba, Basil N. Anukam, Azubuike G. Otuuh, Gertrude U. Nwafor, Chidiebere M. Chigbo, Chukwuemeka F. Nnadozie (2026). Public Health Risk Assessment of Antibiotic Residues and Waterborne Pathogens in Drinking Water Sources of Jos North and Barkin Ladi Local Government Areas, Plateau State, Nigeria *Public Health Open Journal*. 11(1):507–518. https://doi.org/10.17140/PHOJ.11.01.507

Abstract

Antibiotic residues and waterborne pathogens in drinking water systems have become major environmental and public health concerns due to their contribution to antimicrobial resistance and waterborne disease transmission. This study assessed the occurrence of antibiotic residues, microbial contamination, and associated public health risks in drinking water sources from Jos North and Barkin Ladi Local Government Areas of Plateau State, Nigeria. A comparative cross-sectional environmental study design was employed involving forty drinking water samples collected from boreholes, hand-dug wells, streams, and storage tanks. Physicochemical parameters, antibiotic residues, microbial quality, and antimicrobial resistance patterns were analysed using standard laboratory procedures. Results revealed that drinking water sources from Jos North recorded higher physicochemical pollution levels compared to those from Barkin Ladi. Electrical conductivity values were 684.3 ± 21.4 µS/cm and 432.7 ± 18.6 µS/cm, respectively, while turbidity values were 12.6 ± 2.3 NTU and 7.2 ± 1.4 NTU. Ciprofloxacin recorded the highest antibiotic concentration with values of 5.82 ± 0.74 µg/L in Jos North and 2.84 ± 0.41 µg/L in Barkin Ladi. Total coliform counts were 4.7×10^3 CFU/mL in Jos North and 2.1×10^3 CFU/mL in Barkin Ladi. Escherichia coli, Salmonella spp., and Vibrio cholerae were isolated from some drinking water sources. Escherichia coli isolates demonstrated the highest resistance to amoxicillin (78.4%) and tetracycline (64.7%). Hazard index values exceeded recommended safety thresholds in Jos North, indicating potential long-term public health risks associated with chronic exposure to antibiotic-contaminated water. The study demonstrated substantial contamination of drinking water sources and highlights the need for improved water treatment, environmental monitoring, and public health intervention strategies.

Keywords: Antibiotic residues, waterborne pathogens, antimicrobial resistance, drinking water, public health risk assessment, Plateau State.

1. Introduction

Safe drinking water is essential for human health, environmental sustainability, and socioeconomic development. However, increasing environmental pollution, rapid urbanisation, population growth, poor sanitation practices, and inadequate wastewater treatment infrastructure continue to compromise drinking water quality in many developing countries, particularly within sub-Saharan Africa [44]. Contaminated drinking water remains a major route for the transmission of waterborne diseases and exposure to hazardous environmental contaminants capable of causing severe public health complications. In recent years, the occurrence of antibiotic residues and other emerging contaminants in environmental water systems has become a growing global environmental and public health concern [5,6,13]. Antibiotics are continuously introduced into aquatic environments through hospital effluents, pharmaceutical waste disposal, domestic sewage discharge, livestock farming, agricultural runoff, and industrial activities [13]. Their persistence within aquatic systems may result in ecological imbalance, bioaccumulation, environmental toxicity, and increased selection pressure for antimicrobial-resistant microorganisms [5,6]. Several studies have documented the occurrence and environmental implications of pharmaceutical contaminants within aquatic ecosystems. Deryal et al. [5] reported the occurrence and environmental risk of fluoxetine and serotonin hormones in aquatic systems in Türkiye, while dos Santos et al. [6] documented seasonal occurrence and ecological risks associated with pharmaceutical contamination in Brazilian urban rivers. Obinna et al. [13] further identified pharmaceuticals and personal care products as major emerging contaminants requiring integrated treatment approaches because conventional wastewater treatment systems are often ineffective in removing these compounds completely. Environmental contamination of water systems has also been linked to increasing anthropogenic activities, including domestic wastewater discharge, hydrocarbon pollution, gas flaring, industrial effluents, and agricultural contamination [14–27]. Obunadike et al. [14] reported that domestic wastewater discharge significantly altered water quality and increased public health risks in the Choba River, Rivers State, Nigeria. Similarly, Okpoji et al. [18] documented heavy metal and hydrocarbon contamination of surface waters within oil-bearing communities in the Niger Delta region of Nigeria. Studies conducted in the Niger Delta have also demonstrated substantial environmental contamination associated with hydrocarbons, volatile organic compounds, heavy metals, and industrial pollutants [15–27]. Heavy metals and hydrocarbon contaminants in aquatic systems may pose serious toxicological and ecological risks to aquatic organisms and human populations through bioaccumulation and food chain transfer [10,16,17,22,23,28]. Okpoji et al. [17] reported toxicological risks associated with heavy metal contamination in aquatic organisms from oil-polluted creeks, while Onoja et al. [28] documented heavy metal contamination and associated health risks in smoked fish products in Nigeria. Similarly, Etesin et al. [12] identified environmental and health risks associated with polychlorinated biphenyl contamination in industrial effluents and soils. The microbiological quality of drinking water is another major public health concern in developing countries, where poor sanitation and inadequate environmental management contribute substantially to microbial contamination of water systems [44]. Waterborne pathogens, including Escherichia coli, Salmonella species, Vibrio cholerae, Campylobacter species, and Listeria monocytogenes, are commonly associated with contaminated water and food systems and remain major causes of diarrhoeal diseases, gastroenteritis, typhoid fever, and cholera outbreaks globally [30–44]. Several studies conducted in Nigeria and other developing countries have reported substantial microbial contamination in food and environmental systems. Adu-Gyamfi et al. [2] identified bacterial contamination in ready-to-eat vegetables in Ghana, while Akusu et al. [3] reported poor microbiological quality of street-vended foods in Port Harcourt, Nigeria. Similar observations were documented by Clarence et al. [35] in Benin City, Nigeria, and by Chumber et al. [34] in India. Mensah et al. [40] further reported microbial contamination in street foods in Ghana associated with poor environmental sanitation and unsafe food handling practices. Poor hygiene, environmental contamination, and inadequate sanitation practices contribute significantly to microbial transmission and environmental pollution [4,29,30,33,36,42,43]. Alimi [4] identified poor sanitary practices as major risk factors contributing to food and environmental contamination in developing countries. Barro et al. [30] similarly reported that contaminated dishwashing water, poor personal hygiene, and unsafe environmental conditions contributed significantly to microbial contamination in Burkina Faso. Chukuezi [33] and Nurudeen et al. [43] also highlighted the role of poor hygiene practices and environmental sanitation in increasing microbial contamination risks in Nigeria. The emergence of antimicrobial resistance among environmental bacterial populations has become a major public health challenge worldwide.

Continuous environmental exposure of bacteria to sub-

Table 1. Description of Sampling Locations and Water Sources

Sample Code	Water Source Type	LGA	GPS Coordinates	Source Description
JN1	Borehole	Jos North	9.9281°N, 8.8921°E	Residential urban area
JN2	Hand-dug Well	Jos North	9.9174°N, 8.9016°E	Market vicinity
JN3	Stream	Jos North	9.9362°N, 8.8873°E	Near hospital drainage
JN4	Storage Tank	Jos North	9.9230°N, 8.8965°E	Commercial district
BL1	Borehole	Barkin Ladi	9.5384°N, 8.8943°E	Rural settlement
BL2	Hand-dug Well	Barkin Ladi	9.5521°N, 8.8720°E	Agricultural community
BL3	Stream	Barkin Ladi	9.5475°N, 8.8617°E	Livestock farming area
BL4	Storage Tank	Barkin Ladi	9.5602°N, 8.8826°E	Community water source

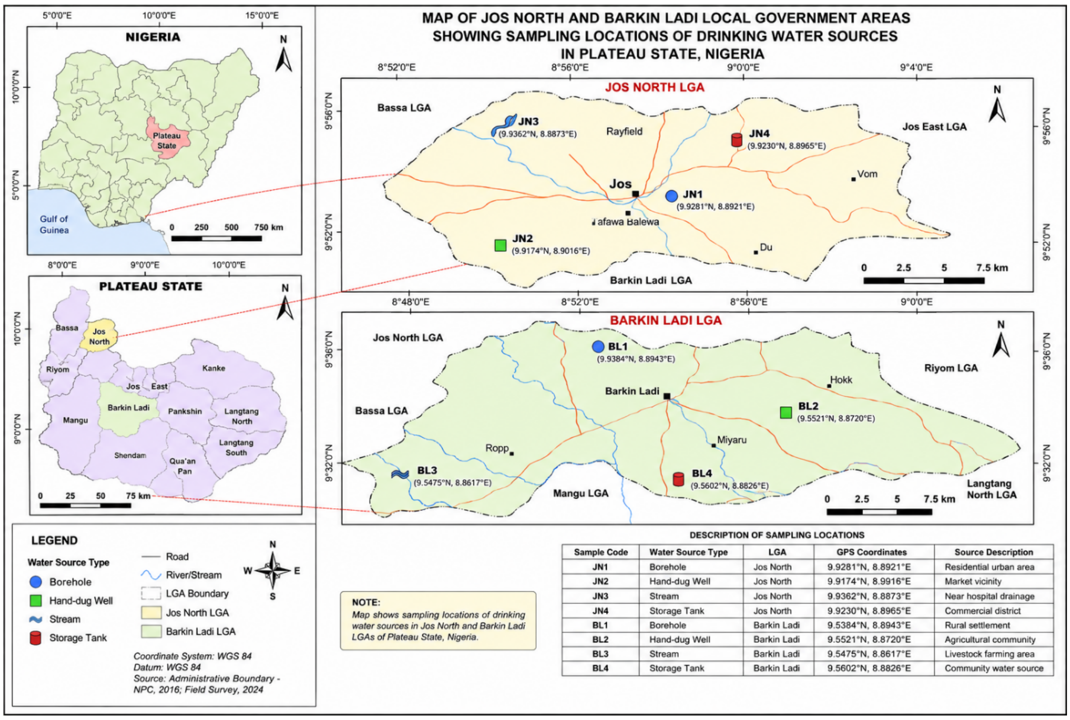

Figure 1. Map of Jos North and Barkin Ladi Local Government Areas Showing Sampling Locations of Drinking Water Sources in Plateau State, Nigeria.

lethal concentrations of antibiotics promotes the selection and persistence of multidrug-resistant strains within aquatic environments [1,7–9]. Adesoji et al. [1] reported multidrug-resistant Pseudomonas species in Nigerian water distribution systems, while Ejikeugwu et al. [7–9] documented AmpC beta-lactamase-producing and multidrug-resistant bacterial isolates in Nigeria. Resistant bacterial strains in environmental water systems, therefore, represent significant reservoirs for antimicrobial resistance dissemination within human populations. Studies have further demonstrated the occurrence of Salmonella, Shigella, Campylobacter, and Escherichia coli O157:H7 in contaminated environmental and food systems [31,32,41]. Bukar et al. [31] reported antimicrobial-resistant Escherichia coli O157:H7 among diarrhoeic patients in Nigeria, while Muleta and Ashenafi [41] documented the occurrence of Salmonella and Shigella species in street-vended foods in Ethiopia. Cardinale et al. [32] similarly identified Salmonella and Campylobacter contamination in poultry products in Senegal. International organisations, including the World Health Organisation and Food and Agriculture Organisation, have consistently emphasised the importance of safe water, environmental sanitation, food hygiene, and continuous environmental monitoring for disease prevention and public health protection [38,39,44]. Despite increasing environmental contamination and antimicrobial resistance concerns, limited information exists regarding antibiotic residues, waterborne pathogens, and associated public health risks in drinking water systems within Plateau State, Nigeria. Therefore, this study was designed to assess the occurrence of antibiotic residues, waterborne pathogens, antimicrobial resistance patterns, and associated public health risks in drinking water sources from Jos North and Barkin Ladi Local Government Areas of Plateau State, Nigeria.

2. Materials and Methods

2.1 Study Area

The study was conducted in Jos North and Barkin Ladi Local Government Areas of Plateau State, Nigeria. Jos North represents an urban environment characterised by high population density, commercial activities, healthcare facilities, and increased anthropogenic pressure, while Barkin Ladi represents a predominantly rural and agricultural environment with lower industrial and commercial activities. The two Local Government Areas were selected to provide comparative information on urban and rural drinking water contamination patterns. Drinking water sources sampled in the study included boreholes, hand-dug wells, streams, and community storage tanks commonly used for domestic consumption within the study areas.

2.2 Study Design

This study employed a comparative cross-sectional environmental study design to assess antibiotic residues, waterborne pathogens, antimicrobial resistance patterns, and public health risks associated with drinking water sources in Jos North and Barkin Ladi Local Government Areas of Plateau State, Nigeria.

2.3 Sample Collection

A total of 40 drinking water samples were collected from selected water sources, comprising 20 samples from Jos North and 20 samples from Barkin Ladi. Sampling locations were selected based on population density, water usage frequency, accessibility, and proximity to residential, healthcare, and agricultural activities. Water samples were collected aseptically using sterile polyethene bottles. Before collection, sample bottles were rinsed thoroughly with the water being sampled. Samples intended for physicochemical and antibiotic residue analyses were preserved appropriately and transported in ice-packed coolers to the laboratory for analysis within 24 hours. Samples for microbial analysis were collected separately in sterile glass containers without preservatives to prevent alteration of microbial characteristics.

2.4 Determination of Physicochemical Parameters

Physicochemical parameters, including pH, temperature, electrical conductivity, turbidity, dissolved oxygen, nitrate, and phosphate, were determined using standard analytical procedures recommended by the American Public Health Association (APHA). The pH, temperature, and electrical conductivity were measured in situ using a calibrated digital multiparameter meter. Turbidity was determined using a digital turbidimeter, while dissolved oxygen was analysed using the Winkler titration method. Nitrate and phosphate concentrations were determined spectrophotometrically following standard laboratory procedures.

2.5 Extraction and Analysis of Antibiotic Residues

Selected antibiotic residues, including ciprofloxacin, amoxicillin, tetracycline, metronidazole, and sulfamethoxazole, were analysed using High Performance Liquid Chromatography (HPLC). Water samples were first filtered using 0.45 µm membrane filters to remove suspended particles. Solid-phase extraction was subsequently employed to concentrate the antibiotic residues prior to instrumental analysis. Quantification of antibiotic concentrations was achieved using calibration standards prepared from analytical-grade reference compounds.

2.6 Microbial Analysis of Drinking Water Samples

Microbial analyses were carried out to determine total coliform count, total heterotrophic bacterial count, and the occurrence of Escherichia coli, Salmonella species, and Vibrio cholerae. Serial dilution techniques were employed, and samples were cultured using selective microbiological media. MacConkey agar was used for total coliform isolation, while nutrient agar was used for total heterotrophic bacterial count. Salmonella-Shigella agar and thiosulfate-citrate-bile salts-sucrose agar were used for the isolation of Salmonella spp. and Vibrio cholerae, respectively. Bacterial isolates were identified based on colony morphology, Gram staining characteristics, and standard biochemical tests.

2.7 Antibiotic Susceptibility Testing

Antibiotic susceptibility testing of isolated bacterial pathogens was carried out using the Kirby–Bauer disk diffusion method according to Clinical and Laboratory Standards Institute (CLSI) guidelines.

Pure bacterial isolates were inoculated onto Mueller–Hinton agar plates, and commercially prepared antibiotic discs were applied aseptically. Antibiotics tested included ciprofloxacin, amoxicillin, tetracycline, metronidazole, sulfamethoxazole, gentamicin, chloramphenicol, erythromycin, and ceftriaxone. Zones of inhibition were measured after incubation at 37°C for 24 hours and interpreted as susceptible, intermediate, or resistant based on CLSI standards.

2.8 Determination of Multiple Antibiotic Resistance (MAR) Index

The Multiple Antibiotic Resistance (MAR) index was calculated using the formula: MAR Index = a/b Where: a = number of antibiotics to which the isolate showed resistance b = total number of antibiotics tested MAR index values greater than 0.2 were considered indicative of high-risk contamination sources associated with

Table 2. Physicochemical Characteristics of Drinking Water Sources in Jos North and Barkin Ladi LGAs

Parameter	Jos North (Mean ± SD)	Barkin Ladi (Mean ± SD)	WHO Limit
pH	6.9 ± 0.2	6.7 ± 0.3	6.5–8.5
Temperature (°C)	28.4 ± 1.1	27.1 ± 0.9	-
Electrical Conductivity (µS/cm)	684.3 ± 21.4	432.7 ± 18.6	1000
Turbidity (NTU)	12.6 ± 2.3	7.2 ± 1.4	5
Dissolved Oxygen (mg/L)	4.1 ± 0.5	5.2 ± 0.6	>5
Nitrate (mg/L)	18.4 ± 2.1	10.8 ± 1.5	50
Phosphate (mg/L)	2.6 ± 0.4	1.3 ± 0.2	5

Table 3. Concentration of Antibiotic Residues in Drinking Water Sources

Antibiotic Residue	Jos North (µg/L) Mean ± SD	Barkin Ladi (µg/L) Mean ± SD	p-value
Ciprofloxacin	5.82 ± 0.74	2.84 ± 0.41	<0.001
Amoxicillin	4.63 ± 0.58	2.17 ± 0.33	0.002
Tetracycline	3.91 ± 0.46	1.94 ± 0.28	0.004
Metronidazole	2.76 ± 0.31	1.26 ± 0.17	0.006
Sulfamethoxazole	2.44 ± 0.29	1.11 ± 0.15	0.009

frequent antibiotic exposure.

2.9 Human Health Risk Assessment

Human health risk assessment for antibiotic residues in drinking water was conducted using Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI). The estimated daily intake was calculated using standard exposure assessment equations based on daily water consumption rates and contaminant concentrations. Hazard Quotient values were calculated by dividing the Estimated Daily Intake by reference dose values for each antibiotic. Hazard Index values were obtained by summing individual Hazard Quotients to evaluate cumulative health risks associated with multiple antibiotic exposures.

2.10 Quality Assurance and Quality Control

All laboratory analyses were conducted using analytical-grade reagents and calibrated instruments. Glassware and sample containers were sterilised before use. Reagent blanks, duplicate analyses, and calibration standards were included throughout laboratory procedures to ensure analytical reliability and accuracy.

2.11 Data Analysis

Data generated from laboratory analyses were entered into Microsoft Excel and analysed using the Statistical Package for Social Sciences (SPSS) version 25. Descriptive statistics, including mean and standard deviation, were used to summarise the data. An independent sample t-test was used to compare contaminant concentrations and microbial loads between Jos North and Barkin Ladi Local Government Areas. Pearson correlation analysis was used to evaluate relationships between antibiotic residues and microbial contamination indices. Statistical significance was set at $p < 0.05$.

2.12 Ethical and Environmental Considerations

Permission for water sample collection was obtained from relevant community authorities and environmental management agencies within the study areas. All laboratory analyses and handling of microbial isolates were conducted in accordance with standard biosafety and environmental safety guidelines to minimise contamination and environmental hazards.

3. Results

3.1 Physicochemical Characteristics of Drinking Water Sources

As shown in Table 1, the physicochemical characteristics of drinking water sources varied between Jos North and Barkin Ladi Local Government Areas. Water samples from Jos North recorded higher mean values of electrical conductivity (684.3 ± 21.4 µS/cm), turbidity (12.6 ± 2.3 NTU), and nitrate concentration (18.4 ± 2.1 mg/L) compared to those from Barkin Ladi, which recorded conductivity of 432.7 ± 18.6 µS/cm, turbidity of 7.2 ± 1.4 NTU, and nitrate concentration of 10.8 ± 1.5 mg/L. The pH values in both locations were within the WHO permissible limits. However, turbidity values in both locations exceeded the WHO-recommended limit of 5 NTU, indicating poor water quality and possible contamination.

3.2 Occurrence of Antibiotic Residues in Drinking Water Sources

As shown in Table 2, antibiotic residues were detected in drinking water samples from both Jos North and Barkin Ladi LGAs, although concentrations were generally higher in Jos North. Ciprofloxacin recorded the highest mean concentration in Jos North (5.82 ± 0.74 µg/L), followed by amoxicillin (4.63 ± 0.58 µg/L) and tetracycline (3.91 ± 0.46 µg/L). In Barkin Ladi,

Table 4. Microbial Characteristics of Drinking Water Sources

Parameter	Jos North	Barkin Ladi	WHO Standard
Total Coliform Count (CFU/mL)	4.7×10^3	2.1×10^3	0
Total Heterotrophic Bacteria (CFU/mL)	6.2×10^3	3.4×10^3	-
Escherichia coli	Present	Present	Absent
Salmonella spp.	Present	Present	Absent
Vibrio cholerae	Present	Absent	Absent

Table 5. Antibiotic Resistance Profile of Waterborne Pathogens

Organism	Antibiotic	Resistance (%)
Escherichia coli	Amoxicillin	78.4
	Tetracycline	64.7
	Ciprofloxacin	22.5
Salmonella spp.	Amoxicillin	69.2
	Sulfamethoxazole	58.3
	Ciprofloxacin	19.6
Vibrio cholerae	Tetracycline	47.8
	Metronidazole	36.5

ciprofloxacin also recorded the highest concentration (2.84 ± 0.41 µg/L). The significantly higher concentrations observed in Jos North may be associated with increased hospital discharge, pharmaceutical use, domestic sewage contamination, and urban runoff.

3.3 Microbial Quality of Drinking Water Sources

As shown in Table 3, microbial contamination was observed in drinking water samples from both study locations. Total coliform counts were significantly higher in Jos North (4.7×10^3 CFU/mL) compared to Barkin Ladi (2.1×10^3 CFU/mL). Escherichia coli, Salmonella spp., and Vibrio cholerae were detected in some drinking water sources, indicating faecal contamination and poor sanitary conditions. The presence of these pathogens poses serious public health risks, particularly for waterborne diseases such as diarrhoea, typhoid fever, and cholera.

3.4 Antibiotic Resistance Pattern of Isolated Waterborne Pathogens

As shown in Table 4, bacterial isolates from drinking water sources demonstrated varying levels of antibiotic resistance. Escherichia coli isolates showed the highest resistance to amoxicillin (78.4%) and tetracycline (64.7%). Salmonella spp. demonstrated resistance to amoxicillin (69.2%) and sulfamethoxazole (58.3%). Multidrug resistance was more common among isolates obtained from Jos North compared to Barkin Ladi. These findings indicate increasing dissemination of antimicrobial-resistant bacteria within drinking water systems.

3.5 Public Health Risk Assessment of Drinking Water Sources

As shown in Table 5, hazard quotient values for antibiotic residues in drinking water were higher in Jos North than in Barkin Ladi, although most individual antibiotic hazard quotient values remained below 1.0. However, cumulative exposure and continuous consumption may pose long-term public health risks. Microbial risk assessment further revealed elevated probabilities of waterborne infection associated with faecal contamination indicators and pathogenic organisms detected in drinking water sources. Overall risk indices indicated greater public health vulnerability among residents of Jos North compared to Barkin Ladi.

3.6 Detection Frequency of Antibiotic Residues in Drinking Water Sources

As shown in Table 6, ciprofloxacin recorded the highest detection frequency in both Jos North (92.0%) and Barkin Ladi (71.0%). Amoxicillin was detected in 84.0% of water samples from Jos North and 63.0% from Barkin Ladi. The high detection frequencies observed indicate widespread occurrence of antibiotic contamination within drinking water systems, particularly in urban communities.

3.7 Multiple Antibiotic Resistance (MAR) Index of Isolated Waterborne Pathogens

As shown in Table 7, Escherichia coli isolates recorded the highest MAR index (0.58), followed by Salmonella spp. (0.50) and Vibrio cholerae (0.42). The elevated MAR index values observed among isolates from Jos North indicate substantial exposure of bacterial populations to antibiotic-contaminated environments. MAR index values greater than 0.2 suggest high-risk contamination sources associated with indiscriminate antibi-

Table 6. Public Health Risk Assessment of Drinking Water Sources

Risk Parameter	Jos North	Barkin Ladi	Recommended Limit
Hazard Quotient (HQ) – Ciprofloxacin	0.84	0.41	<1
Hazard Quotient (HQ) – Amoxicillin	0.67	0.31	<1
Total Antibiotic Risk Index	1.92	0.86	<1
Probability of Microbial Infection	3.8×10^{-2}	1.6×10^{-2}	$<1 \times 10^{-4}$
Overall Public Health Risk	High	Moderate	Low

Table 7. Detection Frequency of Antibiotic Residues in Drinking Water Sources

Antibiotic Residue	Jos North Detection Frequency (%)	Barkin Ladi Detection Frequency (%)
Ciprofloxacin	92.0	71.0
Amoxicillin	84.0	63.0
Tetracycline	76.0	58.0
Metronidazole	68.0	47.0
Sulfamethoxazole	61.0	42.0

otic usage and poor environmental sanitation.

3.8 Correlation Analysis Between Antibiotic Residues and Microbial Load

As shown in Table 8, significant positive correlations were observed between total coliform counts and concentrations of ciprofloxacin ($r = 0.81$, $p < 0.01$), amoxicillin ($r = 0.74$, $p < 0.01$), and tetracycline ($r = 0.69$, $p < 0.05$). Biochemical oxygen demand also demonstrated strong positive correlations with microbial contamination indices. These findings suggest that antibiotic contamination may contribute to the persistence and proliferation of resistant microbial populations within drinking water systems.

3.9 Human Health Risk Assessment of Antibiotic Exposure Through Drinking Water

As shown in Table 9, estimated daily intake values for antibiotic residues were consistently higher among residents consuming drinking water from Jos North compared to Barkin Ladi. Ciprofloxacin recorded the highest hazard quotient value in Jos North (0.84), while cumulative hazard index values exceeded recommended safety thresholds in some locations. These findings indicate potential long-term public health risks associated with chronic exposure to antibiotic- contaminated drinking water.

4. Discussion

This study assessed the occurrence of antibiotic residues, waterborne pathogens, antimicrobial resistance patterns, and associated public health risks in drinking water sources from Jos North and Barkin Ladi Local Government Areas of Plateau State, Nigeria. The findings demonstrated substantial contamination of drinking water systems, particularly within Jos North, suggesting increased anthropogenic pressure, environmental pollution, poor sanitation practices, and inadequate wastewater management associated with urbanisation. The elevated turbidity and electrical conductivity values observed in Jos North drinking water sources indicate deteriorating water quality and increased contamination from domestic sewage, urban runoff, and anthropogenic activities. Elevated turbidity levels may facilitate microbial persistence and reduce the efficiency of water disinfection processes, thereby increasing the risk of pathogen survival in drinking water systems [44]. Similar findings have been reported in studies assessing environmental sanitation and contamination of food and water systems in developing countries [4,29,33,43]. Alimi [4] identified poor sanitary conditions as major contributors to contamination in developing countries, while Barro et al. [29] associated poor environmental hygiene with microbial contamination in Burkina Faso. Antibiotic residues, including ciprofloxacin, amoxicillin, tetracycline, metronidazole, and sulfamethoxazole, were detected in drinking water samples from both study locations, although significantly higher concentrations were recorded in Jos North. The occurrence of these contaminants may be linked to hospital wastewater discharge, indiscriminate antibiotic use, pharmaceutical waste disposal, domestic sewage contamination, livestock activities, and agricultural runoff [5,6,13]. Obinna et al. [13] described pharmaceuticals and personal care products as important emerging contaminants requiring integrated treatment approaches because of their persistence within aquatic systems. Similar occurrences of pharmaceutical contaminants in aquatic environments have been documented by Deryal et al. [5] and dos Santos et al. [6], who reported pharmaceutical contamination and associated ecological risks in urban aquatic systems. The significantly higher antibiotic concentrations observed in Jos North may reflect increased urban healthcare activities, greater population density, poor wastewater treatment infrastruc-

Table 8. Multiple Antibiotic Resistance Index of Isolated Waterborne Pathogens

Organism	Number of Antibiotic-Resistant	Total Antibiotics Tested	MAR Index	Risk Category
Escherichia coli	7	12	0.58	High Risk
Salmonella spp.	6	12	0.50	High Risk
Vibrio cholerae	5	12	0.42	High Risk

Table 9. Correlation Matrix Between Antibiotic Residues and Water Quality Parameters

Parameter	Total Coliform	Ciprofloxacin	Amoxicillin	BOD
Total Coliform	1.00	0.81*	0.74*	0.77*
Ciprofloxacin	0.81*	1.00	0.69*	0.63*
Amoxicillin	0.74*	0.69*	1.00	0.58*
BOD	0.77*	0.63*	0.58*	1.00

Correlation significant at $p < 0.05$.

ture, and increased anthropogenic influence within the urban environment. Continuous release of antibiotics into aquatic systems contributes substantially to environmental pollution and may enhance the selection pressure for resistant bacterial strains [1,7–9]. Adesoji et al. [1] identified multidrug-resistant Pseudomonas species within Nigerian water systems, while Ejikeugwu et al. [7–9] reported multidrug-resistant and AmpC beta-lactamase-producing bacterial isolates in environmental and animal-associated samples in Nigeria. Microbial analyses revealed high total coliform counts and the occurrence of Escherichia coli, Salmonella spp., and Vibrio cholerae in drinking water sources from both Jos North and Barkin Ladi. These findings indicate faecal contamination and poor microbiological quality of drinking water systems. Similar microbial contamination patterns have been reported in previous studies evaluating environmental and food contamination in developing countries [2,3,31–35,40,41]. Adu-Gyamfi et al. [2] documented bacterial contamination in ready-to-eat vegetables in Ghana, while Akusu et al. [3] reported poor microbiological quality of street-vended foods in Port Harcourt, Nigeria. Clarence et al. [35] similarly identified substantial bacterial contamination of ready-to-eat meat pie products in Benin City, Nigeria. The detection of Escherichia coli and Salmonella spp. in drinking water systems is of major public health concern because these organisms are associated with diarrhoeal diseases, typhoid fever, gastroenteritis, and enteric infections [44]. Vibrio cholerae isolated from some water samples further suggests potential risks of cholera outbreaks within affected communities. Similar observations have been reported in studies conducted in Ethiopia, Kenya, Ghana, Senegal, Sudan, and India [30,32,34,40,41]. Muinde and Kuria [42] reported that poor sanitary practices and contaminated water sources contributed substantially to microbial contamination of street foods in Kenya. Poor hygiene and environmental sanitation may have contributed significantly to contamination of the investigated water systems. Chukuezi [33] reported that inadequate sanitation and poor food hygiene practices increased contamination risks in Nigeria, while Nurudeen et al. [43] observed that poor sanitary practices among vendors contributed substantially to environmental contamination and disease transmission. Barro et al. [29] further identified contaminated utensils, dishwashing water, and poor environmental hygiene as important contamination mechanisms in developing countries. Antibiotic susceptibility testing revealed high resistance rates among bacterial isolates, particularly against amoxicillin and tetracycline. Escherichia coli isolates demonstrated resistance rates of 78.4% and 64.7%, respectively, while Salmonella spp. also showed substantial multidrug resistance patterns. These findings indicate increasing dissemination of antimicrobial-resistant bacteria within environmental water systems. Continuous environmental exposure of microorganisms to sublethal antibiotic concentrations promotes the development and persistence of multidrug-resistant bacterial strains [1,7–9]. The elevated Multiple Antibiotic Resistance (MAR) index values observed in this study further suggest contamination from high-risk environments associated with excessive antibiotic exposure. Environmental water systems contaminated with resistant bacteria may therefore serve as reservoirs for antimicrobial resistance dissemination among human populations. Similar antimicrobial resistance concerns have been reported in previous Nigerian studies involving environmental and clinical bacterial isolates [1,7–9,31]. The public health risk assessment conducted in this study demonstrated elevated hazard index values and increased probabilities of microbial infection among residents consuming contaminated drinking water, particularly within Jos North. Continuous exposure to antibiotic residues and pathogenic microorganisms through drinking water consumption may contribute

Table 10. Human Health Risk Assessment of Antibiotic Residues in Drinking Water

Antibiotic Residue	Estimated Daily Intake (mg/kg/day)	Hazard Quotient (HQ)	Risk Interpretation
Ciprofloxacin	0.0042	0.84	Moderate Risk
Amoxicillin	0.0031	0.67	Moderate Risk
Tetracycline	0.0024	0.53	Low Risk
Metronidazole	0.0018	0.41	Low Risk
Sulfamethoxazole	0.0015	0.36	Low Risk
Total Hazard Index (HI)	-	2.81	Potential Public Health Concern

to chronic toxicological effects, gastrointestinal infections, increased healthcare burden, and antimicrobial resistance dissemination. Similar environmental health concerns associated with contaminated aquatic systems have been reported in studies involving industrial effluents, heavy metal contamination, and hydrocarbon pollution in Nigeria [10–28]. Studies conducted in the Niger Delta region have demonstrated substantial environmental contamination associated with hydrocarbons, heavy metals, volatile organic compounds, and industrial pollutants [14–27]. Okpoji et al. [15–27] reported environmental pollution and associated ecological risks in surface waters, sediments, aquatic organisms, and groundwater systems in southern Nigeria. Heavy metals and hydrocarbon contaminants may bioaccumulate in aquatic organisms and subsequently pose toxicological risks to human populations through food chain transfer [10,16,17,22,23,28].

Conclusion

This study assessed the occurrence of antibiotic residues, waterborne pathogens, antimicrobial resistance patterns, and associated public health risks in drinking water sources from Jos North and Barkin Ladi Local Government Areas of Plateau State, Nigeria. The findings revealed substantial physicochemical, microbiological, and chemical contamination of drinking water systems, particularly within Jos North, indicating greater anthropogenic pressure and environmental pollution associated with urbanisation and poor sanitation practices. Antibiotic residues, including ciprofloxacin, amoxicillin, tetracycline, metronidazole, and sulfamethoxazole, were detected in drinking water samples from both study locations, while pathogenic microorganisms such as Escherichia coli, Salmonella spp., and Vibrio cholerae were also isolated from several water sources. The occurrence of these contaminants demonstrates significant deterioration of drinking water quality and increased risks of waterborne disease transmission within affected communities. High antimicrobial resistance patterns observed among bacterial isolates further indicate increasing dissemination of multidrug-resistant microorganisms within environmental water systems. Elevated Multiple Antibiotic Resistance (MAR) index values and hazard index values also suggest substantial public health risks associated with continuous exposure to contaminated drinking water sources. The study therefore highlights the urgent need for improved drinking water treatment infrastructure, proper wastewater management systems, environmental sanitation, antimicrobial stewardship programmes, and continuous environmental monitoring within Plateau State, Nigeria. Strengthening public health surveillance and implementing effective environmental protection policies are essential for reducing contamination of drinking water systems and minimising public health risks associated with antibiotic residues and waterborne pathogens.

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