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**ORIGINAL RESEARCH ARTICLE**

# Assessment of Heavy Metal and Fecal Contamination in Domestic Well Water in Gumel Metropolis, Nigeria: Public Health Implications

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## ABSTRACT

Access to safe drinking water remains a critical public health challenge in many semi-arid regions of Nigeria. This study evaluated the bacteriological, physicochemical, and heavy metal quality of well water in Gumel Metropolis, Jigawa State, to assess its safety and potential health risks. Twenty-four well water samples were collected from four villages (Garin Gambo, Zuge, Maikarya, and Mele) over three months and analyzed using standard methods. The results revealed significant contamination. Physicochemical analysis showed that pH and temperature were within World Health Organisation (WHO) limits, but conductivity (up to 1332.67 µS/cm) and turbidity (up to 11.87 NTU) exceeded WHO guidelines, indicating ionic and sedimentary pollution. Bacteriologically, all samples were contaminated with total coliforms, with Most Probable Number (MPN) values reaching 723.33 MPN/100mL. Biochemical characterization confirmed the presence of pathogenic *Escherichia coli* and *Klebsiella pneumoniae*, indicating faecal pollution and a high risk of waterborne disease. Heavy metal analysis revealed alarming concentrations of Cadmium (0.28–0.53 mg/L), Lead (up to 0.04 mg/L), and Chromium (up to 0.33 mg/L), exceeding WHO standards by factors of 93–176, 4, and 6.6, respectively. The computed Heavy Metal Pollution Index (HPI) was critically high, ranging from 623 to 1156, far surpassing the critical threshold of 100. Statistical analysis using ANOVA showed no significant spatial variation ($p > 0.05$) for most parameters, indicating widespread pollution, whereas Pearson's correlation showed a significant negative relationship between zinc and MPN ($r = -0.727$, $p < 0.05$). The study concludes that well water in Gumel Metropolis is severely contaminated with heavy metals and pathogenic bacteria, posing serious health risks.

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Heavy metal contamination, Fecal contamination, Groundwater quality, Drinking water safety



## INTRODUCTION

A vital resource and an essential component of the environment, water can be found in rivers, lakes, glaciers, rain, groundwater, and other forms. In addition to the need for drinking water, it is vital to a variety of economic sectors, including forestry, agriculture, fisheries, hydropower, animal husbandry, and other creative endeavours (Yerima *et al.,* 2022). The author goes on to say that urbanization, industrialization, and population growth are contributing to a shortage of drinkable water. Physical, chemical, and biological factors can be used to evaluate the quality of any given water. If their values exceed the threshold set by standard-setting organizations, they pose a threat to human fitness (Frantisek, 2020).

The quality of drinking water is a strong environmental factor of health (Koizumi *et al.,* 2023). Since 80% of infections in underdeveloped nations are caused by a lack of access to high-quality water, water is essential to life and a major predictor of health (Cheesbrough, 2006). For more than 150 years, managing the quality of drinking water has been a fundamental component of primary prevention, and it remains the cornerstone for the prevention and management of water-borne illnesses. One significant way that bacteria that interact with the human body are disseminated is through drinking water. Infectious diseases such as salmonellosis, cholera, diarrhoea, typhoid, shigellosis, and a host of other bacterial infections, as well as fungal, viral, and parasitic infections, are spread by contaminated water (Naik *et al.,* 2022).

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Because it directly affects people's health, it is now essential to evaluate the microbiological purity of water. The early formulation of water quality standards and monitoring techniques was prompted by the realization of the link between pollution and the need to safeguard human health, recreation, and fisheries output (Anyanwu and Okoli, 2022). One significant way that bacteria that interact with the human body are disseminated is through drinking water (Liken and Borman, 2021). Because it directly affects people's health, it is now essential to evaluate the microbiological purity of water. The early formulation of water quality standards and monitoring techniques was prompted by the realization of the link between pollution and the need to safeguard human health, recreation, and fisheries output (Yerima *et al.,* 2022). To be considered potable, water must meet specific physical, chemical, and microbiological requirements intended to ensure it is safe to drink (Tahir *et al.,* 2019).

In Nigeria, groundwater from wells is a primary source of drinking water for many rural and semi-urban communities. However, this resource is increasingly threatened by anthropogenic activities. In addition to problems with water availability, the majority of surface and groundwater are now classified as polluted due to ongoing releases of pollutants and sewage into accessible water (Singh *et al.,* 2020; Yerima *et al.,* 2022). Regrettably, safe, pure, and clean water can only be found in nature for a short time before being quickly contaminated by environmental factors prevalent and facilitated by human activity (El Boujnouni *et al.,* 2022). In Jigawa State, studies have assessed water quality in areas like Dutse and Gwaram (Abubakar *et al.,* 2020; Anteyi *et al.,* 2018), revealing issues with physicochemical and bacteriological parameters. However, there remains a notable gap in comprehensive, integrated studies that concurrently evaluate physicochemical, heavy metal, and bacteriological quality of well water in Gumel Metropolis. This area, characterized by its semi-arid climate, agricultural activities, and dense settlements, is vulnerable to contamination from geological leaching, agricultural runoff (including fertilizers and pesticides), and inadequate sanitation systems. An integrated assessment is crucial for understanding the synergistic public health risks and identifying primary contamination sources.

## MATERIALS AND METHOD

### Study Area

This study was conducted in Gumel, Jigawa State. Gumel is located in Jigawa State, and its geographical coordinates are latitude 12 ° 37' 25.19" N and longitude 9 ° 23' 13.79" E.

### Sample Collection

Water samples (well water) were collected from selected villages in Gumel (Garin Gambo, Maikarya, Zuge, and Mele), as shown in Figure 1.

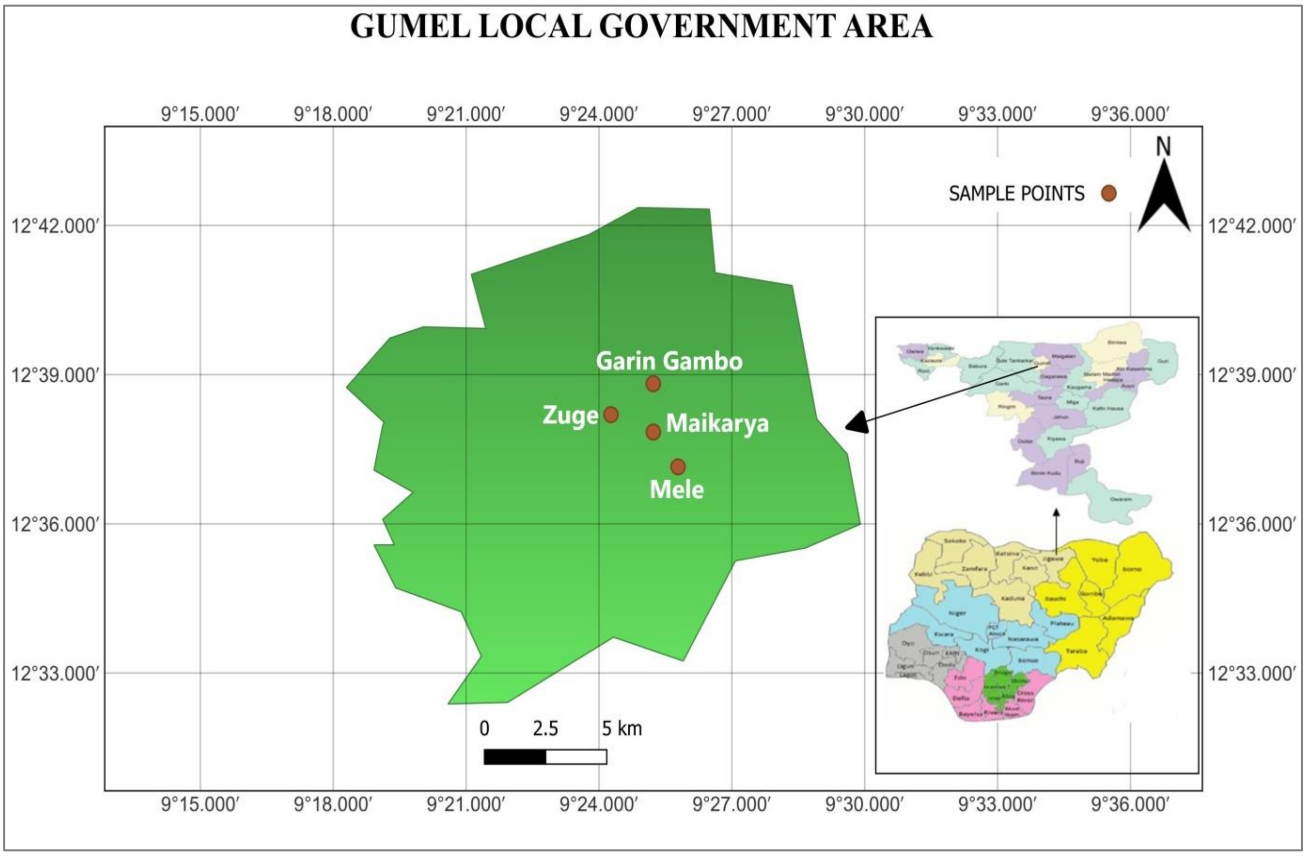


**Figure 1: Map of Gumel local government area showing sampling sites**

Two samples were collected from each village once every month, as mentioned above. Within a period of three (3) months, two (2) samples were collected from each village. The samples were aseptically collected in clean sterile one (1) liter plastic containers, rinsed with de-ionized water and subsequently with the well water before it was finally collected using stratified sampling techniques and stored in a freezer to keep them in prime condition prior to analysis as described in (Abirami *et al.,* 2023). To avoid air entrapment, the water was gathered, filled to the brim, quickly sealed, and delivered in a Cool Box container at 4ºC to the Federal University Dutse Microbiology Laboratory (Abubakar *et al.,* 2023).

**Physicochemical Analysis**

The characteristics of the water saof the water samples were examined using accepted techniques. According to Shigut *et al.* (2019), a glass thermometer filled with mercury was used to measure temperature. The thermometer was immersed in each sample for 2o 2 minutes, and the reading was recorded once the mercury column stabilized. In accordance with the method by Yerima *et al.* (2022), the pH of the water samples was measured electromagnetically using a multi-parameter data recorder equipped with a pH probe. The electrode of a digital pH meter (model pHS-25) was submerged in the samples for one to two minutes until the reading stabilized on the screen; this procedure was carried out three times to ensure accuracy (Arlyapov *et al.,* 2020). A digital conductivity meter with a measurement range of 0–1999 µS and 0–19.99 mS was used to detect electrical conductivity. After the electrode was steady, readings were obtained from the samples. To reduce electromagnetic interference, plastic beakers were utilized (Järup, 2020). The samples were incubated in BOD bottles at 20°C for 5 days, in accordance with the standard procedure described by Naik et al. (2022), to measure biological oxygen demand (BOD). The difference between the initial and final dissolved oxygen (DO) levels was used to compute BOD. About 200 mL of each sample was filtered using a vacuum filtration apparatus with a glass fibre disk and membrane filter to determine Total Dissolved Solids (TDS). Following that, 100 millilitres of each filtrate were placed in evaporating dishes that had been previously weighed and heated to 55ºC for 1 hour. The dishes were cooled in desiccators and weighed again. Prior to final weighing, samples were dried at 180°C to a consistent weight (Haruna *et al.,* 2024). The following formula was used to determine the TDS:

$$\text{TDS (mg/L)} = \frac{(A - B) \times 1000}{\text{Volume of sample}} \quad \text{(Equation 1)}$$

where *A* is the combined weight of the dish and dried residue, and *B* is the weight of the empty dish

Total hardness was measured by titrating 50 mL of each sample with EDTA after adding 2 mL of buffer solution and Eriochrome Black T, which provided a pink tint that turned blue at the endpoint. The volume of EDTA used was multiplied by a factor of 44.892 to represent hardness in mg/L (Järup, 2020). A 25 cm-diameter Secchi disc was used to evaluate turbidity according to the method outlined by Wu *et al.* (2021). The average of these depths was used to calculate the turbidity value. The disc was lowered into the water until it vanished, then raised until it reappeared. Finally, a HANNA multi-parameter spectrophotometer (HI83200) was used to measure the phosphate and nitrate concentrations. According to Ignatav *et al.* (2023) guidelines, phosphate was measured using the SulfaVer technique 8051, whereas nitrate was quantified using the cadmium reduction method 8036, in which nitrate was reduced to nitrite by Cadmium.

**Determination of Heavy Metals**

A standard digestion procedure was used to break down organic matter and release bound metals into solution in order to analyze heavy metals in water samples. Each 50 mL water sample was treated with concentrated nitric acid ($HNO_3$) and heated in a fume hood on a sand bath. Additional $HNO_3$ was added intermittently until the volume was reduced to about 20 mL. Perchloric acid ($HClO_4$) was then added, and the mixture was reheated until a clear solution indicated complete digestion. The digested samples were then cooled, diluted with deionized water, filtered, and made up to 100 mL in volumetric flasks. For maximum efficiency, the acid digestion ratio of $HNO_3$ to $HClO_4$ was kept at 5:1 (Garba *et al.,* 2018). As contamination controls, blanks prepared with only reagents and under identical conditions were used. With the use of inductively coupled plasma mass spectrometry (ICP-MS), the amounts of heavy metals were ascertained. Calibration standards were prepared by diluting standard stock solutions (1000 mg/L) of Zn, Pb, Co, Mn, Cd, As, Fe, and Cr. The amounts of the target metals were measured by analyzing digested samples after the ICP-MS apparatus was appropriately calibrated (Järup, 2020).

**Most Probable Number (MPN) Determination**

The Most Probable Number (MPN) approach was used to determine the total coliforms in water samples subjected to bacteriological examination, as outlined in the American Public Health Association (APHA, 2017) and World Health Organisation (WHO, 2022) guidelines. Three consecutive processes were included in the MPN technique: presumptive testing, confirmed testing, and finished testing. To ensure the accuracy of the results, water samples were aseptically collected from multiple wells into sterile containers, transported on ice, and processed within 6 hours of collection (Ganesh *et al.,* 2018; Niu *et al.,* 2022). Three different volumes (10 mL, 1 mL, and 0.1 mL) of each sample were added to MacConkey broth using Durham tubes for the presumptive test. The tubes were then incubated at 35–37°C for 24–48 hours; the presence of gas formation and yellow coloration suggested the possibility of coliform (Sadighara *et al.,* 2023; Adeleye *et al.,* 2021). For the verification test, Brilliant Green Lactose Bile (BGLB) broth was inoculated with positive tubes, and the presence of coliforms was confirmed by gas production and turbidity during incubation. After a loopful of culture from verified tubes was spread onto Eosin Methylene Blue (EMB) agar and allowed to incubate, the presence of *Escherichia coli* was confirmed by the formation of metallic green sheen colonies (Mahler *et al.,* 2019). Then, using conventional MPN tables to estimate coliform counts per 100 mL of sample, MPN values were computed from the combination of positive tubes across the dilutions (Cheesbrough, 2006).

### Isolation, Characterization, and Biochemical Tests

For bacterial isolation, water samples were serially diluted and plated using the pour plate method with nutrient agar. After incubation at 37°C for 24 hours, distinct colonies were sub-cultured to obtain pure isolates. These isolates were characterized by Gram staining and a series of biochemical tests including catalase, Triple Sugar Iron (TSI), indole, methyl red, Voges-Proskauer, citrate, and urease, following standard microbiological procedures (Cheesbrough, 2006).

### Statistical Analysis

All analyses were performed in triplicate, and the results are expressed as mean ± standard deviation (SD). Data were analyzed using IBM SPSS Statistics for Windows, Version 25.0. Both descriptive and inferential statistics were used to interpret the results.

## RESULT

### Physicochemical Characteristics of Selected Well Water

The physicochemical results for the well water samples from Gumel Metropolis are summarized in Table 1. The pH values across all samples (n=3) ranged from 7.13 ± 1.02 to 7.85 ± 0.26, falling within the WHO permissible range (6.5–8.5). Water temperature ranged from 27.7 ± 1.21 °C to 29.3 ± 0.15 °C. Conductivity values showed considerable variation, with the highest mean value recorded in Garin Gambo sample A (G/SA: 1332.67 ± 260.04 µS/cm) and the lowest in Maikarya sample B (MK/SB: 677.67 ± 662.34 µS/cm). The WHO guideline for conductivity is 750 µS/cm. Biochemical Oxygen Demand (BOD) levels ranged from 1.92 ± 0.29 mg/L to 2.60 ± 0.33 mg/L. Turbidity was highest in Zuge sample A (Z/SA: 11.87 ± 4.21 NTU) and lowest in Garin Gambo sample B (G/SB: 2.74 ± 2.63 NTU). Nitrate concentrations varied from 1.69 ± 1.69 mg/L to 4.90 ± 2.26 mg/L, while phosphate levels ranged from 2.44 ± 1.81 mg/L to 3.38 ± 0.75 mg/L. Total hardness ranged from 93.19 ± 13.66 mg/L to 113.53 ± 9.57 mg/L. The concentrations of heavy metals in the well water samples are presented in Table 2. Cadmium (Cd) was detected in all samples, with mean concentrations ranging from 0.28 ± 0.05 mg/L to 0.53 ± 0.13 mg/L, substantially higher than the WHO limit of 0.003 mg/L. Iron (Fe) levels exceeded the WHO limit (0.3 mg/L) in several samples, with a maximum of 0.43 ± 0.06 mg/L in G/SA. Arsenic (As) was detected at or near the WHO limit (0.01 mg/L) in all samples. Lead (Pb) was detected in concentrations up to 0.04 ± 0.02 mg/L, exceeding the WHO limit of 0.01 mg/L. Chromium (Cr) levels reached a maximum of 0.33 ± 0.03 mg/L in Z/SB, exceeding the WHO limit of 0.05 mg/L. Manganese (Mn) and Zinc (Zn) concentrations were within WHO permissible limits, while Cobalt (Co) was detected at low levels.

**Table 1: Physicochemical Characterization of Selected Well Water (mean ± SD, n=3)**

| Sample Code | pH | Temp (℃) | BOD (mg/L) | Conductivity (µS/cm) | TDS (mg/L) | Total Hardness (mg/L) | Turbidity (NTU) | Nitrate (mg/L) | Phosphate (mg/L) |
|---|---|---|---|---|---|---|---|---|---|
| G/SA | 7.67 ± 0.28 | 27.7 ± 1.21 | 2.15 ± 0.46 | 1332.67 ± 260.04 | 8.34 ± 1.46 | 113.53 ± 9.57 | 9.06 ± 1.89 | 3.78 ± 1.46 | 2.99 ± 0.19 |
| G/SB | 7.13 ± 1.02 | 28.8 ± 0.70 | 2.14 ± 0.18 | 951.67 ± 495.32 | 9.55 ± 0.64 | 107.49 ± 5.50 | 2.74 ± 2.63 | 3.72 ± 3.72 | 3.38 ± 0.75 |
| Z/SA | 7.52 ± 0.03 | 28.1 ± 0.52 | 2.36 ± 0.45 | 817.00 ± 483.16 | 9.03 ± 2.02 | 96.45 ± 12.22 | 11.84 ± 4.21 | 3.32 ± 2.81 | 2.44 ± 1.81 |
| Z/SB | 7.52 ± 0.50 | 28.5 ± 0.30 | 2.15 ± 0.47 | 993.33 ± 683.15 | 7.95 ± 2.09 | 96.93 ± 7.76 | 8.78 ± 2.49 | 3.94 ± 1.58 | 3.12 ± 0.13 |
| MK/SA | 7.68 ± 0.28 | 28.9 ± 0.72 | 1.92 ± 0.29 | 1070.67 ± 538.33 | 8.55 ± 5.20 | 93.19 ± 13.66 | 10.54 ± 2.97 | 4.09 ± 1.16 | 3.09 ± 0.27 |
| MK/SB | 7.85 ± 0.26 | 29.0 ± 0.46 | 2.50 ± 0.55 | 677.67 ± 662.34 | 5.84 ± 3.82 | 101.67 ± 16.23 | 3.63 ± 2.75 | 4.09 ± 1.47 | 2.88 ± 0.47 |
| M/SA | 7.17 ± 0.58 | 28.6 ± 1.01 | 2.24 ± 0.65 | 1231.00 ± 136.01 | 10.36 ± 1.09 | 113.05 ± 7.96 | 9.15 ± 1.86 | 2.44 ± 1.69 | 2.46 ± 2.04 |
| M/SB | 7.69 ± 0.27 | 29.3 ± 0.15 | 2.60 ± 0.33 | 1133.33 ± 391.60 | 8.13 ± 0.17 | 106.55 ± 8.15 | 8.59 ± 0.95 | 4.90 ± 2.26 | 3.16 ± 0.86 |

**Keys**: Temp-Temperature, BOD-Biological Oxygen Demand, TSD-Total Dissolve Solid, TH=Total Hardness, Tur=Turbidity, Ntr=Nitrate, Phos=Phosphate, G/SA-Garin gambo sample 1, G/SB-Garin gambo sample B, Z/SA-Zuge sample A, Z/SB-Zuge sample B, MK/SA-Maikarya sample A, MK/SB-Maikarya sample B, M/SA-Mele sample A and M/SB-Mele sample.

**Table 2: Heavy Metal Characterization of Selected Well Water Sample**

| Sample Code | Cd (mg/L) | Fe (mg/L) | As (mg/L) | Pb (mg/L) | Mn (mg/L) | Cr (mg/L) | Zn (mg/L) | Co (mg/L) |
|---|---|---|---|---|---|---|---|---|
| **M/SA** | 0.38 ± 0.08 | 0.41 ± 0.08 | 0.01 ± 0.01 | 0.02 ± 0.01 | 0.14 ± 0.10 | 0.10 ± 0.02 | 0.18 ± 0.13 | 0.02 ± 0.02 |
| **M/SB** | 0.28 ± 0.05 | 0.33 ± 0.04 | 0.01 ± 0.01 | 0.02 ± 0.01 | 0.09 ± 0.03 | 0.23 ± 0.05 | 0.25 ± 0.09 | 0.01 ± 0.02 |
| **MK/SA** | 0.45 ± 0.05 | 0.32 ± 0.02 | 0.01 ± 0.01 | 0.02 ± 0.01 | 0.18 ± 0.15 | 0.06 ± 0.04 | 0.31 ± 0.10 | 0.02 ± 0.01 |
| **MK/SB** | 0.41 ± 0.04 | 0.40 ± 0.03 | 0.01 ± 0.01 | 0.04 ± 0.02 | 0.011 ± 0.17 | 0.24 ± 0.21 | 0.40 ± 0.03 | 0.02 ± 0.01 |
| **Z/SA** | 0.50 ± 0.15 | 0.37 ± 0.02 | 0.02 ± 0.00 | 0.03 ± 0.01 | 0.15 ± 0.14 | 0.22 ± 0.21 | 0.27 ± 0.13 | 0.01 ± 0.01 |
| **Z/SB** | 0.50 ± 0.07 | 0.42 ± 0.03 | 0.01 ± 0.01 | 0.02 ± 0.01 | 0.39 ± 0.06 | 0.33 ± 0.03 | 0.27 ± 0.06 | 0.03 ± 0.02 |
| **G/SA** | 0.53 ± 0.13 | 0.43 ± 0.06 | 0.01 ± 0.01 | 0.03 ± 0.01 | 0.32 ± 0.10 | 0.23 ± 0.13 | 0.38 ± 0.05 | 0.02 ± 0.01 |
| **G/SB** | 0.41 ± 0.12 | 0.37 ± 0.05 | 0.01 ± 0.01 | 0.02 ± 0.02 | 0.22 ± 0.10 | 0.22 ± 0.09 | 0.37 ± 0.12 | 0.02 ± 0.01 |
| **WHO Limit** | **0.003** | **0.3** | **0.01** | **0.01** | **0.4** | **0.05** | **3** | **0.05** |

**Keys:** *WHO recommended limits for drinking water (WHO, 2022), **guideline values by WHO (WHO, 2022), ***WHO has not set any guidelines (WHO, 2022). Cd-Cadmium, Fe-Iron, As-Arsenic, Zn-Zinc-Zinc, Co-Cobalt, Pb-Lead, Mn-Manganese, Cr-Chromium, G/SA-Garin gambo sample A, G/SB-Garin gambo sample B, Z/SA-Zuge sample A, Z/SB-Zuge sample B, MK/SA-Maikarya sample A, MK/SB-Maikarya sample B, M/SA-Mele sample A and M/SB-Mele sample

**Variation in physicochemical parameters across sampling locations**

Table 3 presents the results of a one-way Analysis of Variance (ANOVA) conducted to determine whether there were statistically significant differences in physicochemical and heavy metal parameters across different sampling locations. The table lists the calculated F-value and corresponding p-value for each parameter, with statistical significance defined at $p < 0.05$. The analysis revealed that for the majority of the parameters tested, including pH, temperature, BOD, conductivity, TDS, turbidity, nitrate, phosphate, and most heavy metals (Cd, Fe, As, Pb, Mn, Cr, Co), no significant differences were found among the locations ($p > 0.05$). However, two parameters showed notable variation. Total Hardness approached the threshold for significance ($F = 6.08$, $p = 0.05$), while Zinc (Zn) demonstrated a statistically significant variation across the sampling locations ($F = 6.80$, $p = 0.04$). The microbial population (MPN) did not show significant spatial variation ($F = 2.46$, $p = 0.20$).

**Correlation matrix between physicochemical and microbial variables**

Table 4 presents the Pearson correlation coefficient (r) between MPN and 17 measured physicochemical parameters across the water samples. The correlations are sorted by strength (highest r first), and significance levels are indicated as $p < 0.05$ (*), $p < 0.01$ (**), or not significant (ns). Among the measured parameters, only zinc (Zn) showed statistically significant correlation with MPN. All other parameters were not significantly correlated with MPN in this dataset.

**Heavy Metal Pollution Index (HPI)**

Table 5 summarizes the results of the Heavy Metal Pollution Index (HPI) assessment for the collected well water samples. The HPI scores for all sampled locations exceeded the critical pollution threshold of 100, ranging from 623 to 1156. Consequently, all well water samples were classified as being of "Critical" pollution level. The analysis identified the main heavy metals contributing to this severe pollution. Cadmium (Cd) was the primary contaminant across all sampling sites, with observed concentrations exceeding permissible limits by factors ranging from 93 to 176 times. Other significant contributors included Chromium (Cr), Lead (Pb), and in some instances, Iron (Fe) and Arsenic (As), all of which were found at levels above their respective safety standards in multiple samples.

**Identification of Bacterial Isolates**

The colonial, microscopic, and biochemical characteristics of the bacterial isolates are summarized in Table 6. Two primary pathogens were identified: Isolate 1 was confirmed as *Escherichia coli*, exhibiting a green metallic sheen on EMB agar, a negative Gram reaction (rod-shaped), and positive results for indole and TSI tests.

Isolate 2 was identified as *Klebsiella pneumoniae*, characterized by pink mucoid colonies on EMB agar, a negative Gram reaction (rod-shaped), and positive results for citrate, urease, and catalase tests.

**Table 3: ANOVA Results Showing Variation across Sampling Locations**

| Parameters | F-value | P-value | Significance (P < 0.05) |
|---|---|---|---|
| pH | 0.74 | 0.58 | No |
| Temperature | 1.30 | 0.38 | No |
| BOD | 0.24 | 0.89 | No |
| Conductivity | 0.24 | 0.89 | No |
| TDS | 0.87 | 0.52 | No |
| Total Hardness | 6.08 | 0.05 | No |
| Turbidity | 0.62 | 0.63 | No |
| Nitrate | 0.10 | 0.95 | No |
| Phosphate | 0.48 | 0.71 | No |
| Cd | 3.37 | 0.13 | No |
| Fe | 0.31 | 0.81 | No |
| As | 1 | 0.47 | No |
| Pb | 0.44 | 0.73 | No |
| Mn | 1.47 | 0.34 | No |
| Cr | 0.86 | 0.53 | No |
| Zn | 6.80 | 0.04 | Yes |
| Co | 0.2 | 0.89 | No |
| MPN | 2.46 | 0.20 | No |

**Table 4: Summary of significant correlations between selected physicochemical parameters and microbial population (MPN)**

| Parameters | Correlation coefficient (r) with MPN | Significance |
|---|---|---|
| Zn | -0.727 | * |
| BOD | -0.695 | NS |
| Co | -.0.653 | NS |
| Conductivity | 0.551 | NS |
| As | 0.482 | NS |
| Phosphate | 0.475 | NS |
| Cd | -0.389 | NS |
| Mn | -0.386 | NS |
| Cr | -0.246 | NS |
| TDS | 0.249 | NS |
| Total Hardness | 0.232 | NS |
| Temperature | 0.287 | NS |
| Pb | 0.133 | NS |
| Fe | 0.081 | NS |
| Nitrate | 0.081 | NS |
| pH | 0.071 | NS |
| Turbidity | 0.028 | NS |

Significance levels; p < 0.05 = *, p < 0.01 = **, NS = Not significance

**Table 5: Heavy Metal Pollution Index (HPI) Assessment of well water samples**

| Sample Code | HPI Score | Pollution level | Main Contributing Metals |
|---|---|---|---|
| G/SA | 1128 | Critical | Cd (176×), Cr (4.6×), Fe (1.4×) |
| G/SB | 832 | Critical | Cd (137×), Cr (4.4×) |
| Z/SA | 1020 | Critical | Cd (167×), Cr (4.4×), As (2.0×) |
| Z/SB | 1156 | Critical | Cd (167×), Cr (6.6×), Mn (0.98×) |
| MK/SA | 927 | Critical | Cd (150×), Pb (2.0×) |
| MK/SB | 898 | Critical | Cd (137×), Cr (4.8×), Pb (4.0×) |
| M/SA | 760 | Critical | Cd (127×), Fe (1.4×) |
| M/SB | 623 | Critical | Cd (93×), Pb (4.6×) |

**Table 6: Colonial, Microscopic and Biochemical Characterization of the Isolates**

| Isolate ID | Colonial Appearance | G.R | Shape | Ind | TSI | Cit | Ur | Cat | Identification |
|---|---|---|---|---|---|---|---|---|---|
| **Isolate 1** | Green metallic sheen | − | Rod | + | + | − | − | + | *Escherichia coli* |
| **Isolate 2** | Pink | − | Rod | − | + | + | + | + | *Klebsiella pneumoniae* |

**Keys: G.R = Gram Reaction, TSI = Triple Sugar Ion Test, Ind = Indole, Cit = Citrate, Ur = Urease- = Negative and + = Positive.**

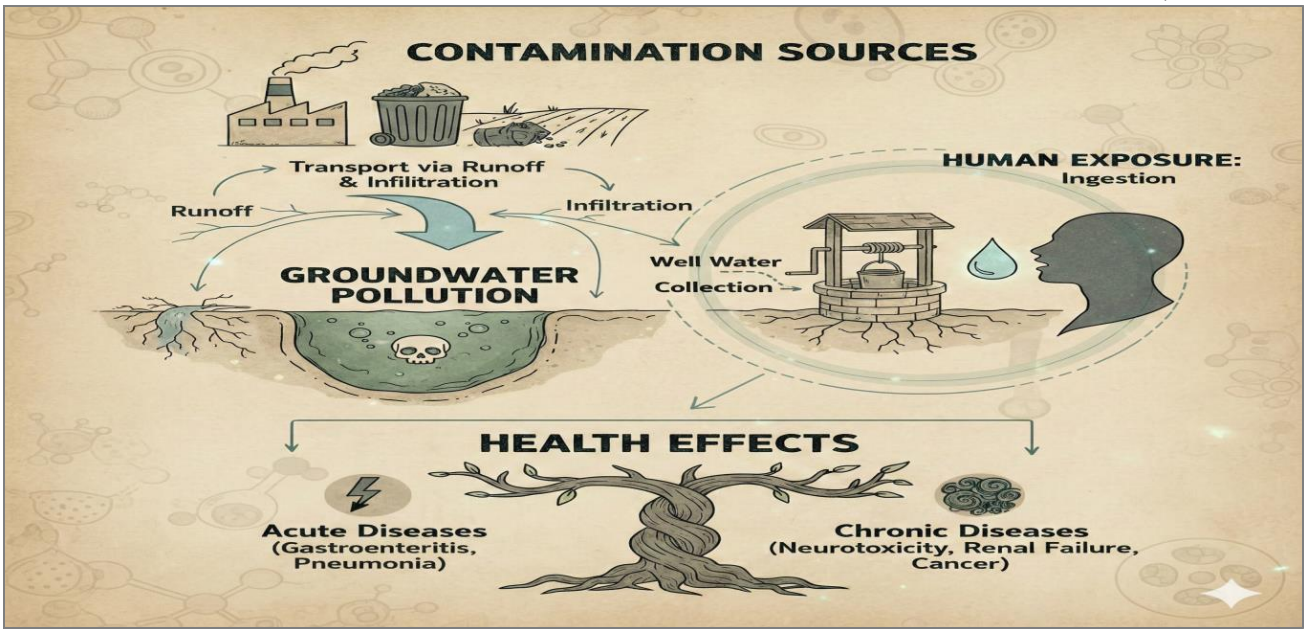


**Figure 2: Conceptual model linking contamination sources to human health risks**

## DISCUSSION

The assessment of the groundwater quality in Gumel metropolis reveals critical contamination levels that could pose significant public health risks. Figure 2 demonstrates the conceptual overview of the contamination pathways and health risks identified in this study. The integration of physicochemical, heavy metal, and bacteriological analyses, supplemented by statistical analyses, offers a multifaceted understanding of pollution sources and their implications. The physicochemical parameters of the well water samples indicate that the system is under anthropogenic stress. While pH (7.13–7.85) and temperature (27.7–29.3°C) fell within the WHO (2011) permissible range of 6.5–8.5 and ambient conditions, respectively, other parameters showed concerning trends. The elevated conductivity in samples such as G/SA (1332.67 µS/cm) and M/SA (1231.00 µS/cm), which exceed the WHO guideline of 750 µS/cm, indicates significant ionic pollution. This is likely due to the dissolution of geological minerals and leaching from agricultural fertilizers and sewage in the semi-arid environment (Verla *et al.,* 2020; Tahir *et al.,* 2019). The low, highly variable conductivity in MK/SB (677.67 ± 662.34 µS/cm) suggests inconsistent water quality, possibly due to fluctuating surface water infiltration. The ANOVA results (Table 3) further illuminate this, showing no statistically significant spatial variation ($p > 0.05$) for most physicochemical parameters, including conductivity, pH, and nitrate. This indicates that contamination is a widespread, regional issue rather than being confined to isolated hotspots, a finding consistent with studies across Northern Nigeria that report similar pervasive groundwater quality challenges (Anteyi *et al.,* 2018; Yerima *et al.,* 2022). Turbidity levels, particularly in Z/SA (11.87 NTU), exceed the WHO (2022) and SON (2007) standard of 5 NTU, suggesting inadequate wellhead protection and susceptibility to surface runoff containing eroded sediments (Mahler *et al.,* 2019). Although nitrate (1.69–4.90 mg/L) and phosphate (2.44–3.38 mg/L) concentrations were below the WHO limits of 50 mg/L and 5 mg/L, respectively, their presence is a clear indicator of incipient contamination from agricultural and domestic waste. The concentrations are comparable to those reported by Garba *et al.* (2018) in Dutse, underscoring a common threat from non-point source pollution in Jigawa State.

The heavy metal profile presents the most alarming evidence of pollution. The computed Heavy Metal Pollution Index (HPI) for all samples was high, ranging from 623 to 1156 (Table 5), far exceeding the critical threshold of 100. This uniformly classifies the well water as "critically polluted" and unfit for human consumption without treatment. Cadmium (Cd) was the predominant contaminant, with concentrations (0.28–0.53 mg/L) exceeding the WHO (2022) and SON (2007) limit of 0.003 mg/L by factors of 93-176. Such extreme levels, also observed near mining areas in Northern Nigeria, are linked to renal dysfunction and bone demineralization (Badamasi *et al.,* 2021; WHO, 2022). Chromium (Cr) levels, notably in Z/SB (0.33 mg/L), were 6.6 times the permissible limit (0.05 mg/L), posing carcinogenic risks (Sall *et al.,* 2020). Lead (Pb) and Iron (Fe) were also detected at levels exceeding guidelines in several samples, associated with neurodevelopmental toxicity in children and hepatic damage, respectively (Ajibo *et al.,* 2023; Sadighara *et al.,* 2023). The ANOVA results (Table 3) confirmed that Zinc (Zn) was the only heavy metal with statistically significant spatial variation ($F=6.80$, $p=0.04$), which may reflect localized pollution sources, such as galvanized pipe corrosion or agricultural activities. The pervasive, non-significant variation of other deadly metals like Cd and Cr underscores a widespread geogenic and/or diffuse anthropogenic source, such as the use of phosphate fertilizers and improper electronic waste disposal, which has been documented in other parts of Jigawa State (Bwire *et al.,* 2020; Ahmed *et al.,* 2023). The bacteriological quality of the well water is a direct threat to public health. The Most Probable Number (MPN) values, reaching up to 723.33 MPN/100mL in G/SA, drastically exceed the WHO and SON standard of 0 MPN/100mL for drinking water. This indicates severe and recent fecal contamination from sources such as pit latrines, septic tanks, and livestock areas, a common finding in Nigerian communities with inadequate sanitation (Lawan *et al.,* 2020; Adeleye *et al.,* 2021). The isolation and biochemical confirmation of *Escherichia coli* and *Klebsiella pneumoniae* confirm the presence of high-risk pathogens capable of causing diarrheal diseases, pneumonia, and urinary tract infections (Muhtar *et al.,* 2022; Saima *et al.,* 2023). The prevalence of *K. pneumoniae* is particularly concerning due to its known antibiotic resistance, potentially compromising treatment options and transforming water sources into reservoirs for drug-resistant infections.

The Pearson correlation analysis (Table 4) provided a crucial insight: a significant negative correlation was found between Zinc (Zn) and MPN ($r = -0.727$, $p < 0.05$). This inverse relationship is intriguing and warrants further investigation; it may suggest a suppressive effect of certain metal ions on microbial survival or, more likely, reflect complex, independent contamination pathways. The lack of significant correlation between MPN and nutrients such as nitrate and phosphate, as observed in other studies (Velusamy et al., 2022; Adesakin et al., 2020), suggests that bacteriological contamination in Gumel is driven more by direct faecal ingress than by nutrient loading from agricultural runoff.

## CONCLUSION

The groundwater resources of Gumel Metropolis are critically compromised. The integration of HPI, ANOVA, and correlation analyses has quantitatively demonstrated severe heavy metal pollution of geogenic and anthropogenic origin, widespread physicochemical indicators of environmental stress, and acute bacteriological contamination due to inadequate sanitation. This study's findings align with, but also critically extend, previous regional research by quantifying extreme HPI levels and identifying specific statistical relationships among parameters. The implications for public health are severe, necessitating immediate and multi-level interventions. At the policy level, these findings should inform the Jigawa State government's implementation of the National Water Quality Policy and provide a baseline for tracking progress towards SDG 6. At the community level, urgent actions are required, including source protection, public health campaigns, point-of-use treatment, and long-term solutions. Without such interventions, the population of Gumel remains at high risk of waterborne diseases and chronic heavy metal poisoning, perpetuating a cycle of poverty and ill health.

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