Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Physicochemical and Microbiological Quality of Household Borehole Water in Garoua Cameroon

Narcisse Dobe[1,2]

dobe.narcisse@yahoo.fr

University of Maroua

Marc Anselme Kamga[3,4]

University of Maroua

Emmanuel Bourbanne Wakou

Université de Garoua

Jean Paul Nongni Tejeogue[2]

University of Maroua

Casimir Hamman Ngayam[2]

University of Maroua

Mariam Nanyanzi[7]

Kampala University

Janvier Kanna Domra

University of Maroua

Moussa Djaouda

Université de Garoua

Research Article

Keywords: Groundwater quality, Borehole water, Cameroon, Microbiological contamination

Posted Date: November 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11175346/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Physicochemical and Microbiological Quality of Household Borehole Water in Garoua Cameroon

Narcisse Dobe[1,2]*, Marc Anselme Kamga[3,4], Emmanuel Bourbanne Wakou [5], Jean Paul Nongni Tejeogue[2], Casimir Hamman Ngayam[2], Mariam Nanyanzi[7], Janvier Kanna Domra[8], Moussa Djaouda[6].

[1]*Department of Fundamental Science, National Advanced School of Mines and Petroleum Industries, University of Maroua, Cameroon*

[2]*Department of Chemistry, Faculty of Science, University of Maroua, Cameroon*

[3]*Department of Industrial Security, Quality and Environment, National Advanced School of Mines and Petroleum Industries, University of Maroua, Maroua, Cameroon*

[4]*Department of Environmental Management, Pan African University Life and Earth Sciences Institute (PAULESI), University of Ibadan, Ibadan, Nigeria*

[5]*Department of Biomedical Sciences, Higher Institute of Science, Health Technician and Management of Garoua, University of Garoua, Cameroon*

[6]*Department of Biology, Faculty of Science, University of Garoua, Cameroon*

[7]*Department of Environmental Management, Natural Sciences and Agriculture, Kampala University, Kampala, Uganda*

[8]Department of Mining, Petroleum, Gas and Water Resources Exploration, *National Advanced School of Mines and Petroleum Industries, University of Maroua, Cameroon*

***Corresponding author:**

Narcisse Dobe; Postal address: P.O. Box 08, Kaele, Cameroon; Email: dobe.narcisse@yahoo.fr; ORCID: 0000-0003-1975-5078

Abstract

Access to safe drinking water remains a major public-health challenge in developing countries, where the consumption of poor-quality water contributes to the prevalence of waterborne diseases. This study assesses the physicochemical and bacteriological quality of borehole water in the city of Garoua (northern Cameroon) and examines user perceptions and practices. The methodology combined a cross-sectional survey of 340 households with laboratory analyses of 34 boreholes. The results reveal a marked reliance on groundwater, with 32.36% of households relying exclusively on boreholes. In physicochemical terms, the water is generally acidic (mean pH of 5.67), with electrical conductivity peaking at 2120 µS/cm, reflecting heterogeneous mineralization. Alarming nitrite concentrations (up to 410 mg/L) were detected, far exceeding

drinking-water standards. Microbiologically, although contamination was sporadic, the presence of Escherichia coli at certain water points (F19 and F29) and of fecal streptococci (up to 10 CFU/100 mL) confirms fecal pollution of anthropogenic origin. The study highlights an apparent association between educational attainment and awareness of health risks. However, despite a high level of awareness (91.43%), the vulnerability of boreholes to surface infiltration (from latrines and inadequate waste management) remains a concern. These findings underscore the urgent need for regular water-quality monitoring and improved sanitation infrastructure to protect the health of Garoua's population.

Keywords: Groundwater quality, Borehole water, Cameroon, Microbiological contamination

1 Introduction

Water is essential to all forms of life on Earth. It is a vital resource whose quality is critical to human health [1]. Despite the vast volume of water available on the planet, only about 2.5% of the Earth's total water is suitable for domestic, industrial, and agricultural use, posing a major challenge in meeting humanity's water needs. Surface waters, such as lakes and rivers, supply only a small proportion of drinking water, whereas groundwater meets approximately 45% of global water demand, with figures exceeding 75% in Africa [2].

Indeed, this proportion can reach up to 100% in some regions of the world, and it exceeds 75% in Africa [3], [4]. Water quality has a direct impact on health: according to the World Health Organization (WHO), approximately 80% of diseases are attributable to water quality, affecting more than 1.1 billion people without access to adequate drinking water and 2.4 billion without appropriate sanitation [5], [6], [7].

More than 2 million people, mostly children under five in developing countries, die every year from diarrheal diseases. Nearly 90% of these diseases are attributable to poor drinking-water quality and inadequate sanitation [8]. According to international guidelines, safe drinking water should pose no appreciable health risk. Socio-demographic factors such as age, sex, and educational attainment influence water-consumption practices and the perception of health risks. Several studies have shown that households with higher levels of education tend to adopt better water-storage and treatment practices [9].

In physicochemical terms, parameters such as pH, conductivity, salinity, total dissolved solids, and the concentration of major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, NO_2^-, HCO_3^-), among others, are essential for evaluating water potability and compliance with national and international standards [10].

In parallel, microbiological surveillance, including mesophilic aerobic bacterial flora, total and fecal coliforms, *E. coli*, fecal streptococci, and staphylococci, constitutes a critical indicator of fecal and anthropogenic contamination and serves as a reference for public health [11].

This work presents an integrated study combining household surveys with physicochemical and microbiological analyses of borehole water, aimed at assessing water quality and public awareness of the health risks associated with its consumption. The results are intended to inform local water-resource management strategies and to propose preventive measures adapted to local communities.

2 Materials and Methods

2.1 Study area and sampling

This study was conducted in Garoua, the capital of Cameroon's North Region, within the Garoua 1, 2, and 3 municipal subdivisions (*arrondissements*). It followed a descriptive, cross-sectional, and analytical design, using a questionnaire to collect data from borehole-water users together with water samples for laboratory analysis. For physicochemical analyses, water

samples were collected in clean, sterile containers. Samples intended for bacteriological analysis were collected under strict aseptic conditions to prevent contamination. Sampling was carried out by geographic cluster, grouping households by neighborhood, which facilitated random selection and ensured the representativeness of the results. Sample size was determined using the Schwartz formula, with a precision level of 5%. In total, 340 households and 34 boreholes were included in the study.

2.2 Data-analysis software

All data collected through the household surveys and water analyses were processed using Microsoft Excel (2019) and Origin 8.1. These software packages, used for descriptive and inferential statistical analysis, enabled the calculation of frequencies, proportions, means, and standard deviations, as well as correlation tests and group comparisons according to socio-demographic variables [12]. The physicochemical and microbiological results of the sample analyses were processed in accordance with the standardized protocols described in the Materials and Methods section, ensuring the reproducibility and reliability of the measurements. This approach allowed for the coherent integration of data from the different stages of the study, supporting a comprehensive analysis of water quality and its associated factors.

2.3 Analytical procedures

2.3.1 Household survey methods

To obtain household-level information, a cross-sectional survey was conducted on a representative sample of households in the study area. Sample size was determined using the Kish (1965) formula for population surveys, accounting for the estimated prevalence of water use and a 5% margin of error [13]. Respondents were selected through stratified random sampling by neighborhood. Data were collected using standardized, pretested questionnaires administered by trained enumerators and recorded on digital tablets via KoboToolbox to ensure the reliability and traceability of the information [14].

The age and sex of respondents were recorded directly from household members during the survey. Age was recorded in completed years and grouped into classes for analysis (15–20, 20–25, 25–30, 30–35, 35–40, 40–45, 45–50, 50–55, 55–60 years). Sex was recorded as male or female. These socio-demographic variables were used in descriptive analyses to assess differences in water consumption and knowledge according to age and sex [14].

Educational attainment was recorded for each respondent according to the national classification: none, primary, secondary, and higher education. This information was obtained by self-report during the interview. The data were analyzed to establish correlations between educational attainment and the perception of water quality, knowledge of waterborne diseases, and consumption practices [15], [16].

Water consumption was documented according to source: public water-supply networks, traditional wells, boreholes, and surface-water sources. Respondents were asked about the frequency of use of each water type (daily, weekly, or occasional). Enumerators also verified on-site the presence and condition of water points to supplement the self-reported data. This approach made it possible to relate water consumption to its source and to assess potential contamination risks [17], [18].

Knowledge of waterborne diseases (cholera, diarrhea, typhoid) was assessed using a standardized questionnaire including multiple-choice questions on transmission routes, symptoms, and preventive measures [18]. Scores were assigned to each respondent and

correlated with educational attainment to determine the effect of education on awareness of waterborne diseases. Scores were assigned to each respondent and compared across educational-attainment categories to explore differences in awareness of waterborne diseases.

2.3.2 Physical analyses

Measurement of borehole water temperature

Water temperature was measured directly in the field using a calibrated digital thermometer with a precision of ±0.1 °C. Measurements were taken by immersing the thermometer probe in the borehole water for 2 minutes to allow the reading to stabilize. Temperature is used to assess the physical condition of the water and to interpret the solubility of dissolved gases and minerals [19], [20].

Measurement of water pH

pH was determined using a portable pH meter (Hanna HI98128), calibrated before each series of measurements with buffer solutions at pH 4, 7, and 9. The electrode was immersed in the sample for 1 to 2 minutes until the reading stabilized. pH is used to assess the acidity or alkalinity of water and its potential corrosivity [21], [22].

Measurement of total dissolved solids (TDS)

Total dissolved solids (TDS) were determined by filtering samples through a 0.45 µm membrane, followed by evaporation at 105 °C in an oven until a constant weight was reached. The residue mass was expressed in mg/L. This method estimates the overall concentration of dissolved minerals and the potability of the water [23].

Measurement of borehole water electrical conductivity (σ)

Electrical conductivity was measured with a portable conductivity meter (HACH HQ440), previously calibrated with a standard solution of 1413 µS/cm. The electrode was immersed in the sample for 1 minute. Conductivity reflects the total concentration of dissolved ions and is directly correlated with salinity and TDS [24].

Measurement of borehole water salinity (S)

Salinity was calculated from electrical conductivity using Equation 1.

$S\ (g/L) = 0.64 \times \sigma\ (mS/cm)$ …… *(Equation 1)*

Measurements were supplemented by argentometric titration in selected samples for validation purposes. This analysis provides the dissolved-salt content, which is essential for evaluating the water's suitability for domestic and agricultural use [24], [25].

2.3.3 Chemical characterization of borehole water

The major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, NO_3^{-}, **NO_2^{-}**, HCO_3^{-}) were analyzed using standard titration and spectrophotometric methods. Samples were filtered (0.45 µm) and stored at 4 °C prior to analysis. Major-ion concentrations were measured to assess overall chemical composition and hydrochemical classification of the waters.

Measurement of nitrite (NO_2^{-})

Nitrite was determined using the sulfanilamide and N-(1-naphthyl)ethylenediamine dihydrochloride colorimetric method (Griess reaction). Absorbance was measured at 540 nm

using UV-Visible spectrophotometry. This method is sensitive to low concentrations and is used to assess microbiological pollution and organic contamination [26].

Measurement of potassium content (T(K))

Potassium concentration was measured by flame photometry in accordance with APHA (2017) standards. Samples were filtered and, where necessary, diluted to obtain a suitable measurement range. Potassium is an important major ion for assessing the mineral quality of water [27].

Measurement of sodium content (Na^+)

Sodium was analyzed by flame photometry with calibration against standard references. Filtered samples were diluted beforehand to fit the instrument's linear range. Sodium content is an indicator of salinity and of suitability for human consumption [28], [29].

Measurement of total hardness

Total hardness was determined by complexometric titration with 0.01 M EDTA in the presence of Eriochrome Black T as indicator. Hardness is expressed in mg/L $CaCO_3$ and reflects the combined dissolved calcium and magnesium concentration [30], [31].

Measurement of calcium hardness (TC)

Calcium hardness was assessed by EDTA titration following precipitation of magnesium with ammonium oxalate. Results are expressed in mg/L $CaCO_3$ and allow the calcium contribution to total hardness to be distinguished [32].

Measurement of magnesium hardness (TM)

Magnesium hardness was obtained as the difference between total hardness and calcium hardness. This indirect approach is standard practice for the physicochemical analysis of freshwater [32].

Method for measuring water alkalinity (TA)

Alkalinity was determined by acid titration (0.02 M HCl) to the endpoint indicated by methyl red and phenolphthalein. It is expressed in mg/L $CaCO_3$ and reflects the water's buffering capacity against acids [33].

2.3.4 Bacteriological analysis methods

Measurement of mesophilic aerobic bacterial flora

Mesophilic aerobic bacterial flora was assessed by the plate-count method on Plate Count Agar (PCA) in accordance with ISO 6222:1999. Water samples were collected in sterile bottles, transported to the laboratory at 4 °C, serially diluted, and incubated at 30 °C for 48 h. Colony-forming units (CFU) were counted and expressed as CFU/mL. This method assesses the overall microbial load of the water and its general hygienic condition [34].

Measurement of total coliforms

Total coliforms were determined using the multiple-tube method or membrane filtration in accordance with ISO 9308-1:2014. Samples were filtered through a 0.45 µm membrane and incubated on MacConkey or TTC agar to detect lactose-fermenting colonies at 37 °C for 24 h. Results were expressed as CFU/100 mL. This is a standard method for assessing overall bacterial contamination [35].

Measurement of fecal coliforms

Fecal coliforms were measured using the multiple-tube (Most Probable Number, MPN) technique or membrane filtration with incubation at 44 °C on mFC agar. Blue-green colonies were counted after 24 h and results expressed as CFU/100 mL. This method identifies fecal contamination and the associated health risks [35], [36].

Measurement of Escherichia coli

Detection of E. coli was performed by membrane filtration in accordance with ISO 9308-1:2014, followed by incubation on Chromocult agar. Characteristic red or dark-blue colonies were counted after incubation at 44 °C for 24 h and expressed as CFU/100 mL. This measurement is essential for assessing the sanitary quality of drinking water [37], [38].

Measurement of fecal streptococci

Fecal streptococci were enumerated by membrane filtration on KF (Kanamycin-Furfural) agar or Slanetz-Bartley agar, incubated at 37 °C for 48 h. Red colonies were counted and expressed as CFU/100 mL. This parameter complements coliform counts in identifying fecal contamination and assessing health risks [39], [40].

Measurement of staphylococci

Staphylococci were detected on Baird-Parker agar supplemented with tellurite, incubated at 37 °C for 24-48 h. Shiny black colonies surrounded by a zone of opalescence were counted and expressed as CFU/100 mL. This analysis detects the presence of pathogenic staphylococci capable of causing infection and indicates anthropogenic contamination [41], [42].

3 Results and Discussion

3.1 Household survey results

The survey results were analyzed according to age group, sex, educational attainment, water source, borehole-water consumption, and knowledge of waterborne-disease transmission in relation to educational attainment.

3.1.1 Results by age and sex

Figure 1 presents the mean, frequency, and standard deviation for the surveyed population. The overall mean age was 32.19 years, with a standard deviation of 13.58 years across both sexes. The frequency distribution by age class (%) was as follows: Class 1: 12.94%, Class 2: 32.65%, Class 3: 13.53%, Class 4: 9.12%, Class 5: 4.71%, Class 6: 4.71%; Class 7: 6.18%, Class 8: 7.06%, Class 9: 5.29%, Class 10: 2.65%, Class 11: 1.18%. The distribution of participants by age group and sex reveals a heterogeneous demographic structure, characterized by a strong representation of young adults and notable differences between men and women [43], [44].

The results show a strong concentration of respondents in the [20–25] and [25–30] age brackets, with a particularly marked peak among women in the [20–25] bracket (66 female participants versus 45 male participants). This predominance of young adults suggests that this age group constitutes the main population engaged in water quality surveys [45], [46].

This finding is consistent with work in participatory environmental science, which shows that certain age groups, particularly young adults and middle aged individuals, are often the most engaged in environmental data-collection activities [47], [48]. Moreover, several studies indicate that engagement with environmental issues is often linked to factors such as educational attainment and awareness, which tend to be higher in these age groups [49].

Comparative analysis reveals significant variation by sex. Women predominate in certain younger age brackets ([15–20], [20–25], [35–40], [45–50]), while men are more strongly represented in certain older brackets ([50–55], [55–60]). These results reflect differentiated participation by gender, which depends on the social and environmental context of the study area [50], [51]. Some studies report greater male involvement in meetings or activities related to water management, whereas others show stronger female involvement, reflecting women's central role in domestic water management and their direct exposure to water-quality issues [52].

Furthermore, research conducted in West Africa indicates that women often display greater environmental sensitivity, particularly with respect to water quality and health risks [53], [54]. This may explain their strong representation in certain active age groups within our sample.

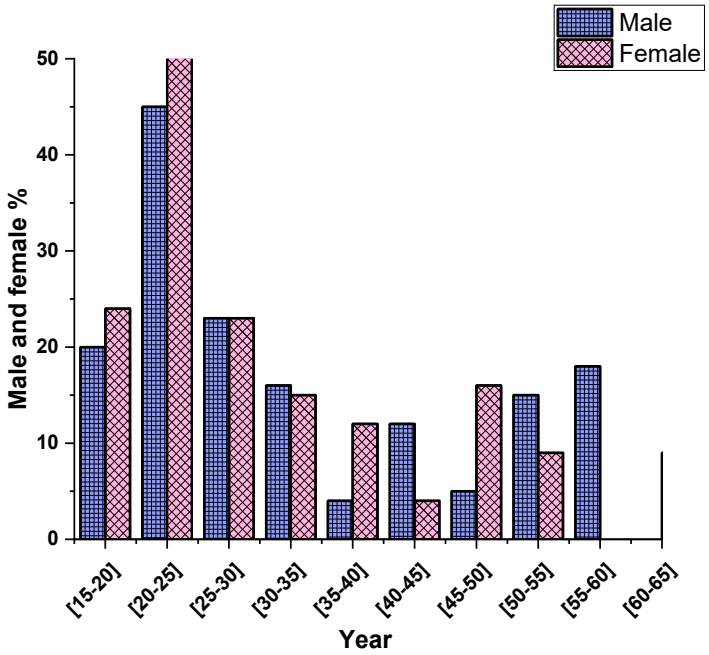


Fig. 1 Frequency distribution of surveyed age groups and sex

3.1.2 Results by educational attainment

Table I presents the distribution of the surveyed population according to educational attainment. This distribution reveals a strong predominance of educated individuals, with higher education being the most common level (45%, n = 153) [55], [56], followed by secondary education (36.47%, n = 124). By contrast, respondents with only primary education (13.82%, n = 47) and those with no formal schooling (4.71%, n = 16) were poorly represented [57]. This finding shows an over-representation of educated individuals within the sample studied. This pattern suggests that participation in the water-quality survey was strongly influenced, on the one hand, by respondents' educational capital, and, on the other, that it reflects greater environmental awareness among educated individuals—an effect likely reinforced by the fact that the sampling site is located in an urban area [59]. This high level of educational attainment also suggests a greater capacity to engage with survey instruments, particularly technical or semi-structured questionnaires [60], [61]. Educated individuals often demonstrate a better ability to interpret questions, provide coherent responses [62], [63], and appreciate the scientific relevance of the study.

Table 1 Distribution of respondents according to educational attainment

	Percentage (%)	**Count**
No formal schooling	4.71	16
Primary	13.82	47
Secondary	36.47	124
Higher	45.00	153
Overall total	**100.00**	**340**

3.1.3 Results on water consumption by source

Figure 2 presents the results on drinking-water sources used in the study area. The analysis reveals a diversity of water-supply sources, dominated by boreholes (32.36%) as the primary source, followed by tap water (29.71%), combined borehole-and-tap use (19.41%), a combination of Borehole–Well and Borehole–Well–Tap sources in smaller proportions, and finally wells alone (≈2.65%), with other marginal sources such as marigot (seasonal-pool) water (<2%) used only very rarely [60], [64]. This distribution shows that more than 80% of households rely on either boreholes, tap water, or a combination of the two, reflecting a dependence on so-called "improved" sources typical of urban settlements [65]. The predominance of boreholes suggests a strong reliance on groundwater, which is typical of areas where piped drinking-water networks are insufficient or unreliable [66]. Several studies in sub-Saharan Africa show that boreholes constitute the main source of drinking water in urban and peri-urban settings owing to their accessibility, relative protection from direct contamination, and independence from public infrastructure [67], [68].

The substantial share of combined uses (particularly borehole + tap) highlights an adaptive strategy adopted by households in response to supply constraints [69], [70]. This behavior is widely documented in the literature as a form of water-access security, health-risk management, and economic optimization. The low proportion of well use suggests either a decline in well-water quality or a progressive shift away from wells in favor of boreholes, which are perceived as safer.

Hydrological studies show that traditional wells are more vulnerable to physicochemical and microbiological contamination, particularly in densely populated areas [71], [72]. These findings are consistent with several studies showing that populations in developing countries often rely on a combination of water sources rather than a single source; that boreholes predominate in areas with limited public-network coverage; that the level of water-service provision directly influences supply behavior; and that access to an improved source does not always guarantee the sanitary quality of the water consumed. Moreover, the World Health Organization (WHO) and UNICEF, through the Joint Monitoring Programme (JMP), emphasize that the use of so-called "improved" sources (boreholes, taps) must be accompanied by quality monitoring (analysis and/or treatment) to ensure that the water is genuinely potable.

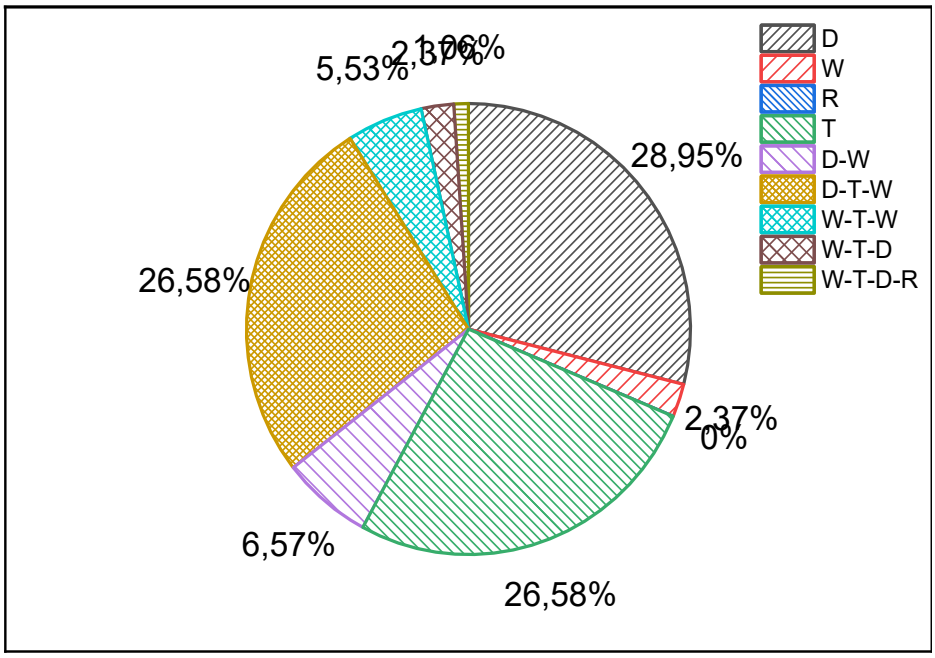


Fig. 2 Household water sources

3.1.4 Results on borehole-water consumption

Analysis of Figure 3 shows a strong predominance of positive responses regarding borehole-water consumption (78.24% “Yes” versus 21.76% “No”). This distribution reflects a majority acceptance among participants of the practice in question, likely related to perceptions of water quality, patterns of use, or an associated practice [73], [74]. The high proportion of “Yes” responses indicates a dominant trend within the study population, suggesting a positive perception, a widely adopted practice, or broad awareness of the phenomenon under study. In water-quality studies, this type of result is often associated with relative confidence in the water source used, or with the widespread adoption of certain practices (treatment, use, storage, etc.).

The non-negligible proportion of negative responses (21.76%) nevertheless reveals heterogeneity in perceptions or behaviors [75], [76]. This minority may be explained by differences in access to resources, socio-economic variation, or individual experiences related to water quality.

In the literature, it is frequently observed that even when a majority adopts a given practice, a substantial fraction of the population remains outside that trend, often for structural or cultural reasons [77], [78].

These results are consistent with several studies in environmental health showing that populations can display majority adherence to certain water-related practices, particularly when these are perceived as beneficial; however, a non-negligible fraction (20–30%) adopts different behaviors, reflecting inequalities in access or perception, since the perception of water quality is often subjective and influenced by personal experience, educational attainment, and the social environment [79].

Work by the WHO and UNICEF (JMP) also emphasizes that user perception does not always reflect the actual quality of the water, which can lead to risky behavior despite apparent confidence [80].

This distribution suggests an overall favorable trend regarding the phenomenon studied, but also points to a need for targeted intervention for the minority population, as well as the need to verify the consistency between perception and reality through physicochemical and microbiological analyses.

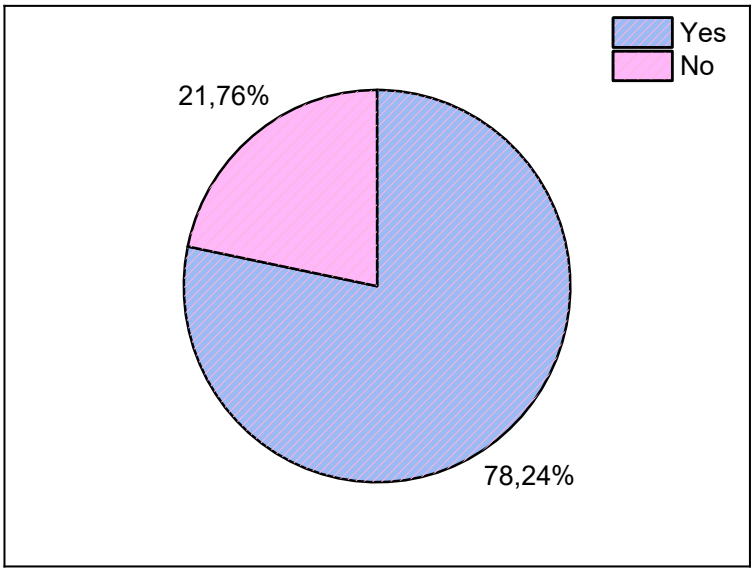


Fig. 3 Borehole-water consumption

3.1.5 Results on knowledge of waterborne-disease transmission according to educational attainment

Table 2 presents the population's level of knowledge regarding the transmission of waterborne diseases. Among the 340 households surveyed, the analysis reveals a significant relationship between educational attainment and the adoption of behaviors favorable to water-quality management. The high proportion of positive responses among individuals with secondary or higher education corroborates findings in the literature, according to which education improves the perception of health risks, access to information, and the adoption of water-treatment practices [81], [82]. In contrast, the variability observed among respondents with no formal schooling highlights their vulnerability and the need to strengthen tailored awareness-raising strategies [83]. These results confirm that educational attainment is a key lever in policies for sustainable water management and the prevention of waterborne diseases.

Table 2 Knowledge of waterborne diseases according to educational attainment

	No	Yes	Total
No formal schooling	8	8	16
Primary	8	39	47
Secondary	8	116	124
Higher	5	148	153
Overall total	**29**	**311**	**340**

3.2 Physical characterization of borehole water

3.2.1 Temperature results

Figure 4 presents the temperature values recorded for the 34 boreholes included in the study. The results show values ranging from 24.0 °C to 27.3 °C, with a relatively narrow thermal range (≈3.3 °C). This homogeneity reflects the thermal stability characteristic of aquifers in a tropical setting, where groundwater tends to reflect the mean annual air temperature. These observations are consistent with the findings of Freeze and Cherry (1979), who showed that groundwater temperature generally remains stable except where hydrogeological or anthropogenic disturbances occur. Similarly, Appelo and Postma (2005) note that temperature variations observed in aquifers are often related to depth, recharge dynamics, and the geological nature of the medium.

Moreover, the slight fluctuations observed between boreholes (with lower values around 24–24.5 °C and higher values above 26.5 °C) may be attributed to local differences in hydrogeological conditions. Lower temperatures could reflect zones of recent recharge, where the infiltration of cooler meteoric water influences the thermal regime, whereas higher temperatures could be associated with deeper boreholes or zones of low water circulation that favor gradual warming.

These results are also consistent with the observations of the World Health Organization (2017), which indicate that in tropical regions groundwater temperature generally ranges between 25 and 30 °C, with no direct impact on potability but with important implications for the water's physicochemical and microbiological properties. These findings align with the work of Bain et al. (2014), who showed that in developing countries, elevated groundwater temperatures can promote microbial proliferation, particularly where hygiene conditions and borehole protection are inadequate.

Thus, although temperature is not a limiting parameter with respect to potability standards, it acts as an indirect factor in water-quality degradation by influencing physicochemical and biological equilibria. The relative homogeneity observed in this study suggests an overall stable aquifer system, although local variations highlight the importance of considering the environmental and structural factors specific to each borehole.

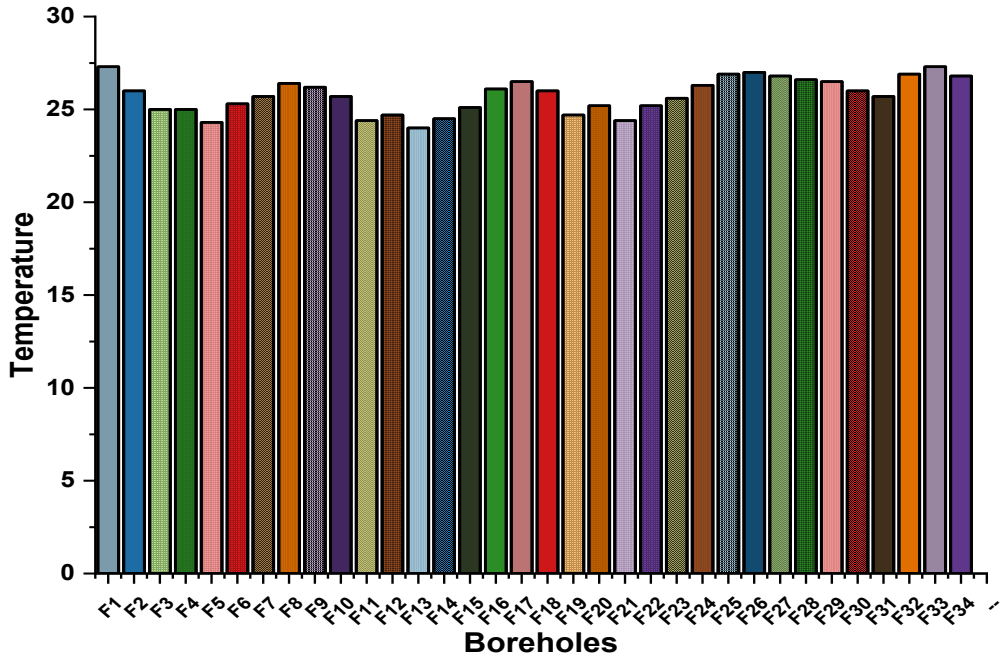


Fig. 4 Temperature variation across boreholes

3.2.2 pH results

Analysis of the pH values measured in borehole water (Figure 5) reveals a range from 4.64 to 6.87, indicating overall acidic to slightly acidic conditions. The majority of samples show values below 6.5, the recommended threshold for drinking water, reflecting a predominance of acidic conditions within the aquifer [84]. This acidity is typical of groundwater in humid tropical environments, where intense soil-leaching processes lead to depletion of basic cations (Ca^{2+}, Mg^{2+}, K^{+}) and a relative accumulation of acidifying elements [85]. These observations are consistent with the work of Appelo and Postma (2005), who demonstrated that aquifers developed in silicate rocks frequently produce acidic waters owing to their low buffering capacity. The observed acidity may also be attributed to dissolved carbon dioxide (CO_2) originating from microbial respiration and the decomposition of organic matter in the soil. This process promotes the formation of carbonic acid, thereby lowering pH [86]. This interpretation is consistent with the conclusions of Freeze and Cherry (1979), who emphasize the determining role of water–soil–atmosphere interactions in regulating groundwater pH [87].

The lowest pH values (≈4.6–5.0) could reflect zones of active recharge, where infiltration of CO_2-enriched meteoric water intensifies acidity, whereas values closer to neutral could indicate prolonged water–rock interaction allowing partial neutralization [88].

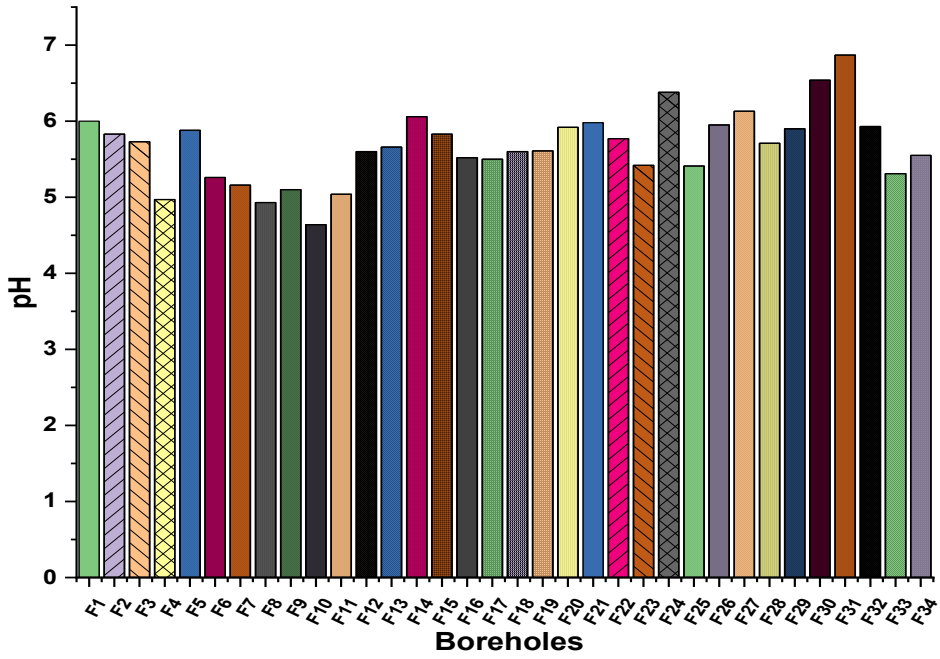


Fig. 5 pH variation in borehole water

3.2.3 Total dissolved solids (TDS) results

Analysis of total dissolved solids (TDS) in borehole water (Figure 6) reveals notable spatial variability, reflecting differences in the degree of mineralization among the aquifers studied. The observed concentrations suggest an overall predominance of weakly to moderately mineralized water, although some points show higher values indicating a stronger influence of mineral-dissolution processes. This heterogeneity can be attributed to several hydrogeochemical factors, including the lithological nature of the geological formations crossed and the residence time of water within the aquifer during water–rock interactions. According to the models described by Appelo and Postma, an increase in total dissolved solids is generally associated with enhanced mineral dissolution, particularly in aquifers rich in silicates or carbonates [89]. Furthermore, recent studies conducted between 2025 and 2026 on tropical groundwater confirmed that variations in TDS are strongly correlated with recharge dynamics and anthropogenic activities particularly agriculture and urbanization which promote the input of dissolved ions (nitrates, sulfates, chlorides) [90]. This work, including recent World Health Organization updates on drinking-water quality, emphasizes that high TDS concentrations can alter the organoleptic properties of water (taste, turbidity) and limit its acceptability, although they do not always constitute a direct health risk [91]. In addition, recent research has shown that water with elevated TDS levels can promote infrastructure corrosion and alter the bioavailability of certain trace elements [92]. The results obtained are therefore consistent with recent observations, confirming that TDS is a key indicator of overall groundwater quality, reflecting both natural processes and anthropogenic influences affecting the aquifers [93].

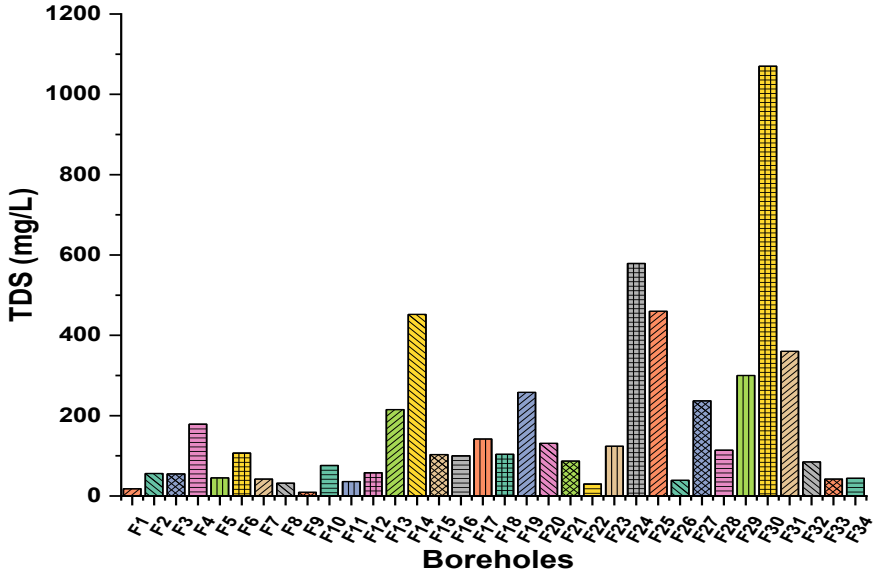


Fig. 6 TDS variation in borehole water

3.2.4 Electrical conductivity of borehole water (σ)

The results presented in Figure 7 show the electrical conductivity (σ) of borehole water (F1 to F34), expressed in $\mu S \cdot cm^{-1}$. Most boreholes show low-to-moderate values, ranging from 19 to 431 $\mu S \cdot cm^{-1}$, whereas some boreholes, F14 (905 $\mu S \cdot cm^{-1}$), F24 (1158 $\mu S \cdot cm^{-1}$), F25 (930 $\mu S \cdot cm^{-1}$), and especially F30 (2120 $\mu S \cdot cm^{-1}$), show markedly elevated conductivity, indicating an increased concentration of dissolved ions. This variability suggests marked heterogeneity in the mineralization of borehole water, likely related to local geological composition, the influence of infiltration from ion-rich shallow water tables, or localized anthropogenic inputs such as leaching from agricultural soils [94] (Adekunle et al., 2020; Mbithi et al., 2019). The elevated values detected are consistent with conductivity studies conducted in similar boreholes in tropical settings, where local variations can exceed 1000 $\mu S \cdot cm^{-1}$ (WHO, 2017; Kaseva et al., 2001). These observations confirm that, although most boreholes yield water with conductivity compatible with potability standards, some boreholes show elevated ionic levels that could affect quality [95].

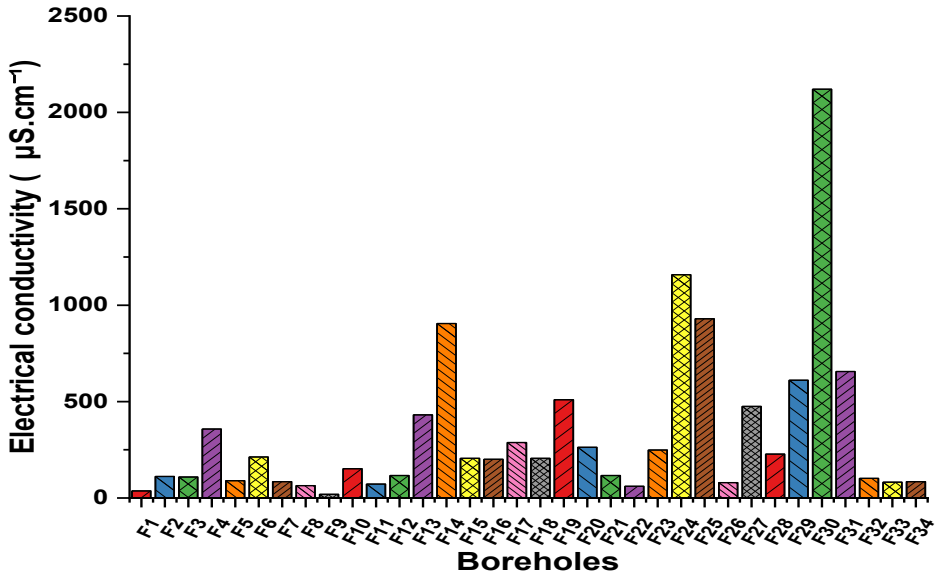


Fig. 7 Electrical conductivity variation in borehole water

3.2.5 Salinity of borehole water (S)

The results presented in Figure 8 reflect the salinity of borehole water (F1 to F34), expressed via electrical conductivity in µS·cm⁻¹, which serves as a direct indicator of the total concentration of dissolved ions. Most boreholes (F1–F12, F15–F19, F21, F22, F27, F32–F34) show low-to-moderate values (9–215 µS·cm⁻¹), indicating weakly mineralized water generally compliant with potability standards, consistent with the observations of Kaseva et al. (2001) and Mbithi et al. (2019) on the natural variability of groundwater in tropical zones. However, some boreholes show elevated salinity, such as F14 (452 µS·cm⁻¹), F24 (572 µS·cm⁻¹), F25 (460 µS·cm⁻¹), and F30 (1070 µS·cm⁻¹), indicating a high concentration of dissolved ions, which may result from local geological influences, intrusion of brackish water, or leaching from salt-rich soils, in line with the work of Adekunle et al. (2020) and WHO (2017). These results corroborate the earlier conductivity analyses and suggest that areas with elevated salinity are also more likely to be affected by anthropogenic impacts or localized contamination, as observed for the microbiological indicators (fecal streptococci and staphylococci) [96].

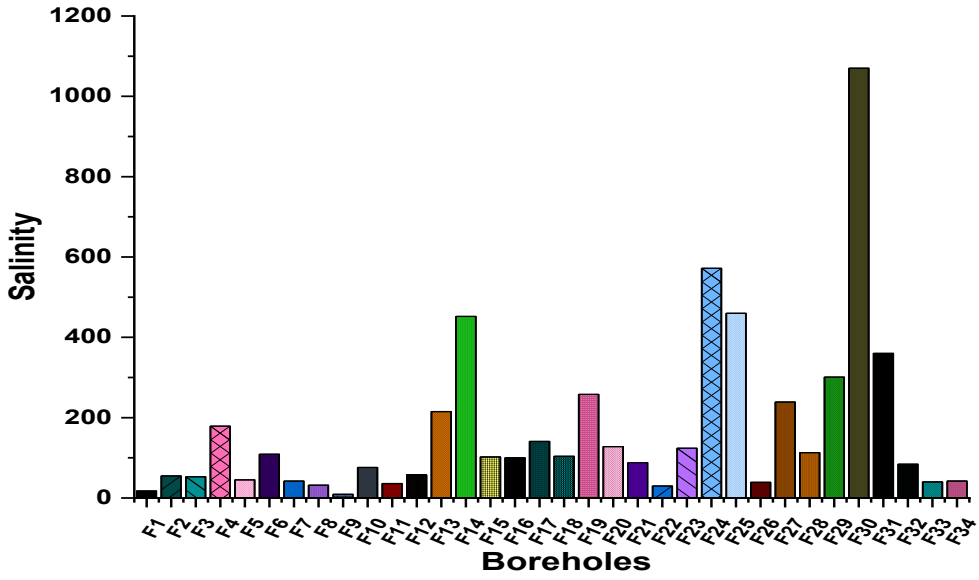


Fig. 8 Salinity variation across boreholes

3.3 Chemical characterization of borehole water

3.3.1 Nitrite results

The results presented in Figure 9 show nitrite (NO_2^-, mg/L) concentrations in borehole water (F1 to F34), revealing a heterogeneous distribution. Three main points emerge. First, most boreholes show low-to-moderate concentrations (10–100 mg/L), suggesting either minimal contamination or natural nitrite accumulation in groundwater, consistent with the observations of Kaseva et al. (2001) and Mbithi et al. (2019). Second, some boreholes show markedly elevated concentrations, notably F14 (340 mg/L), F24 (330 mg/L), F25 (160 mg/L), and F30 (410 mg/L), indicating substantial localized nitrite inputs, likely related to the infiltration of domestic or agricultural effluents, or to intense nitrification in the surrounding soils, as corroborated by Adekunle et al. (2020). Third, these elevated concentrations far exceed the recommended thresholds for drinking water (WHO, 2017), highlighting a potential risk to human health, including gastrointestinal disorders and effects associated with the formation of nitroso compounds. The correlation with the previous salinity and conductivity results, which show that the most highly mineralized boreholes (F14, F24, F30) also display the highest nitrite concentrations, together with the similarity to the microbiological results (fecal streptococci and staphylococci), confirms that these boreholes are exposed to combined chemical and microbiological contamination. These observations highlight the need for integrated monitoring and targeted water-treatment measures to ensure sanitary safety, particularly for boreholes with elevated nitrite concentrations.

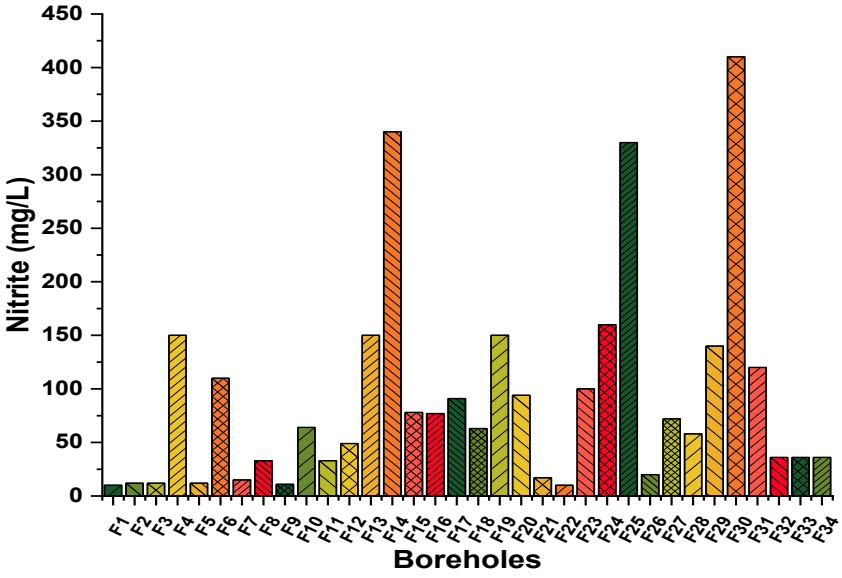


Fig. 9 Nitrite content of borehole water

3.3.2 Potassium content results (T(K))

Analysis of the distribution of potassium in the 34 boreholes (Figure 10) reveals marked spatial variability, with concentrations ranging from approximately 4 to 86 mg/L. Most points, however, fall within a natural geochemical background range of 5 to 20 mg/L, consistent with the natural weathering of potassium-bearing silicate minerals such as potassium feldspars and micas, a process widely documented in basement aquifers in tropical settings [97], [98]. In contrast, the markedly higher values observed at certain boreholes (approximately 30 to 86 mg/L) deviate significantly from this natural background and are consistent with anthropogenic enrichment, particularly the infiltration of residues from potassium fertilizers (KCl) applied in agriculture a mechanism whose importance in the salinization and potassium enrichment of aquifers has been clearly demonstrated by Buvaneshwari et al. (2020) [99] in a semi-arid agricultural context, and corroborated by Griffioen (2001), who showed, using the potassium adsorption ratio, that groundwater beneath agricultural infiltration zones displays significantly higher values than that beneath forested or undisturbed land. These anthropogenic inputs, combined with the relatively high solubility and mobility of potassium compared with other major cations during the weathering of crystalline rocks, suggest that the boreholes with the highest concentrations constitute “hot spots” warranting priority monitoring and further hydrogeochemical characterization to confirm the agricultural or domestic origin of this contamination and to guide sustainable resource-management measures [100].

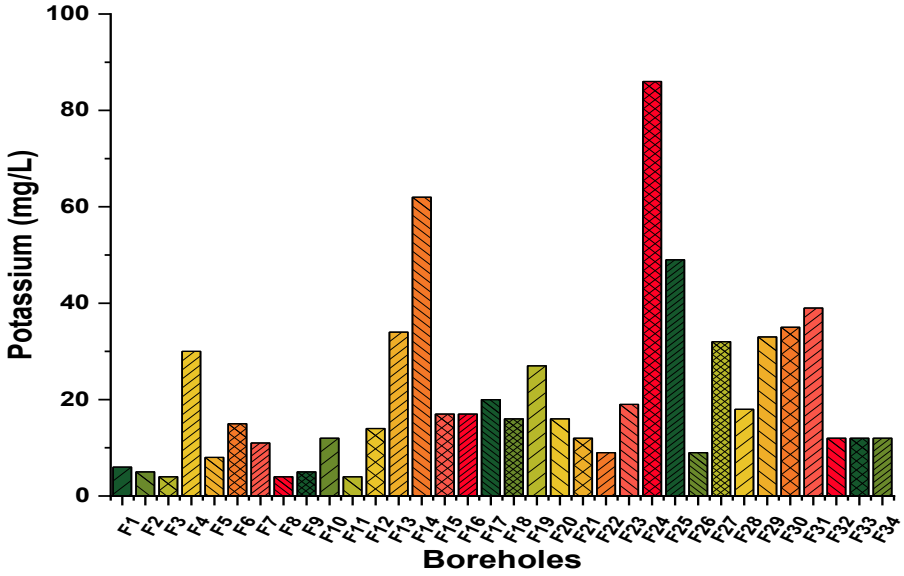


Fig. 10 Potassium content variation in borehole water

3.3.3 Sodium content results

The distribution of sodium concentrations across the 34 boreholes studied (Figure 11) reveals spatial heterogeneity even more pronounced than that observed for potassium, with values ranging from less than 10 mg/L to nearly 750 mg/L (F29), a ratio exceeding 100 between extremes. Most boreholes (approximately 75%), however, show concentrations below 50 mg/L, consistent with a natural geochemical background attributable to the weathering of sodium plagioclase in the surrounding gneissic or granitic rocks a process frequently reported as the main source of sodium in basement aquifers in tropical zones. In contrast, a subset of boreholes stands out with markedly higher concentrations: F13 (~240 mg/L), F17 (~140 mg/L), F23 (~365 mg/L), F26 (~250 mg/L), F27 (~130 mg/L), F29 (~750 mg/L), and F31 (~170 mg/L), several of which exceed the WHO guideline value of 200 mg/L set for the organoleptic acceptability of drinking water. These anomalies may be explained by several non-exclusive mechanisms: first, saline intrusion or upwelling of more mineralized water; second, an anthropogenic input such as domestic wastewater; and third, reverse cation exchange within the aquifer's clay matrix, releasing adsorbed sodium in exchange for calcium or magnesium, or a prolonged water residence time favoring more extensive weathering of sodium silicate minerals. The partial coincidence of sodium and potassium peaks (notably at boreholes F13, F23, F26, and F29) reinforces the hypothesis of a common origin, likely related to diffuse pollution of agricultural or domestic origin superimposed on the natural geological background, and justifies further hydrogeochemical characterization—including hydrochemical facies analysis and mineral saturation indices—for these points before the water is used for consumption.

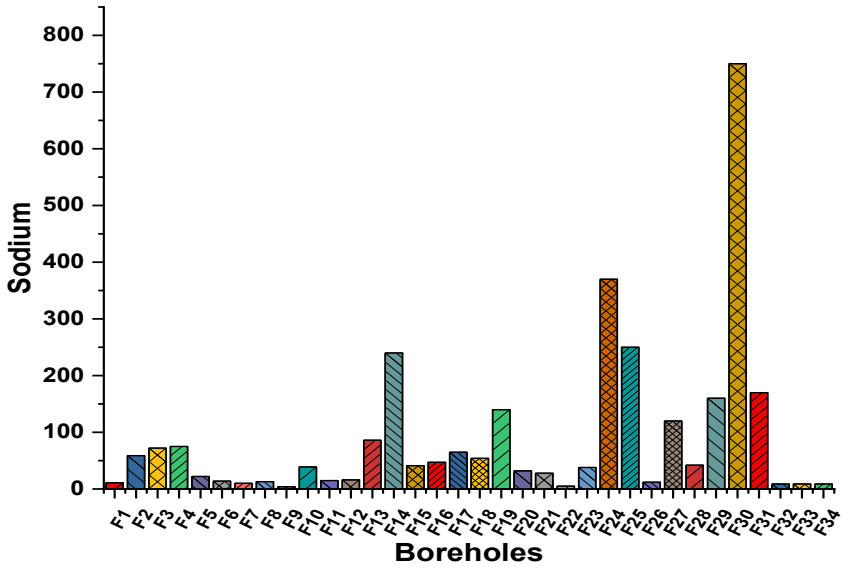


Fig. 11 Sodium variation across samples

3.3.4 Total hardness results

Examination of total hardness ($CaCO_3$, mg/L) usefully complements the sodium and potassium profiles discussed above. Nearly all boreholes show very low values, generally below 5 mg/L, which would classify these waters as soft to very soft, with the notable exception of borehole F29, which shows an extreme peak (~20 mg/L) coinciding precisely with the absolute maxima of sodium (~750 mg/L) and potassium observed in Figure 11. This convergence strongly suggests, for this single point, a common origin related either to mixing with more mineralized water (deep saline intrusion or local evaporite dissolution) or to localized anthropogenic contamination (concentrated domestic or agricultural effluents), rather than to a simple diffuse silicate-weathering process. Conversely, the other boreholes with high sodium but low hardness (F13, F17, F23, F26) illustrate a typical decoupling between alkalis (Na^+, K^+) and alkaline earths (Ca^{2+}, Mg^{2+}), consistent with a base-exchange mechanism within the aquifer's clay matrix, whereby adsorbed sodium is released into solution in exchange for the fixation of calcium and magnesium—a phenomenon recently identified as a major control on Na-dominant hydrochemical facies in both basement and sedimentary aquifers [101], [102]. This hypothesis is further reinforced by recent work confirming that, in crystalline settings, potassium is the parameter showing the greatest variability and the most pronounced seasonal significance, whereas total hardness remains primarily governed by background geological processes [102], and by a study conducted in the Egyptian Western Desert associating low hardness with sodium dominance linked to silicate weathering rather than carbonate dissolution [103]. Taken together, these elements point toward a coherent interpretation of the three parameters (Na, K, hardness): a natural hydrogeochemical background dominated by cation exchange and the weathering of sodium-potassium silicates, punctuated by one or more anthropogenic hot spots, foremost among them F29.

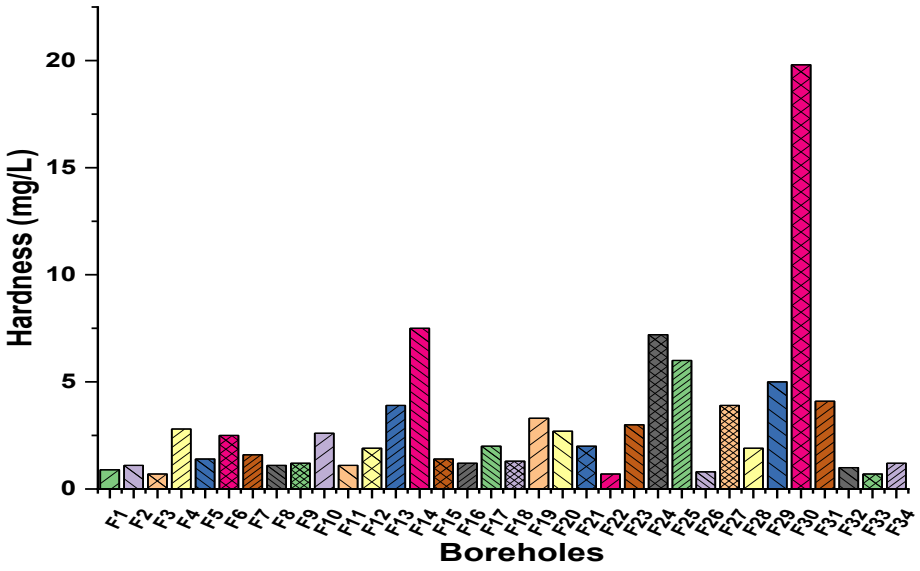


Fig. 12 Total hardness of borehole water

3.3.5 Calcium hardness (TC)

Analysis of calcium hardness, presented in Figure 13, shows that across the 34 boreholes, TC values remain predominantly below 5 mg/L, with the exception of borehole F29, which displays an extreme peak of approximately 19.5 mg/L, nearly identical to the total hardness value measured at the same point (~19.8 mg/L), indicating that the magnesium contribution there is negligible and that total hardness is almost exclusively of calcium origin. This finding, combined with the previously noted coincidence of the sodium (~750 mg/L) and potassium maxima at the same borehole, points toward a congruent dissolution process involving mixed evaporite minerals (gypsum, $CaSO_4 \cdot 2H_2O$, associated with halite, NaCl, and probably sylvite, KCl) rather than two independent mechanisms. This interpretation is directly supported by recent studies on aquifers affected by salt-bearing formations, which demonstrate that a significant proportion of samples showing a Ca–Cl facies results from the dissolution of halite deposits associated with gypsiferous formations, producing a simultaneous enrichment in calcium, sodium, and chloride [104], as well as by a study of fossil groundwater in the Egyptian Western Desert reporting a moderate-to-strong correlation between sodium and calcium attributable to the joint dissolution of calcite, gypsum, and halite within the same aquifer system [105]. Conversely, for most of the remaining boreholes where calcium hardness remains low despite sometimes notable sodium concentrations (F13, F17, F23, F26), the Ca–Na decoupling supports the previously proposed hypothesis of base exchange on clay minerals, a mechanism also identified as dominant in crystalline aquifers, where calcium remains preferentially controlled by plagioclase weathering outside any evaporitic zone [106]. Overall, the combined pattern across the four parameters (Ca, Na, K, total hardness) identifies F29 as a singular point of mixing or complex mineral contamination.

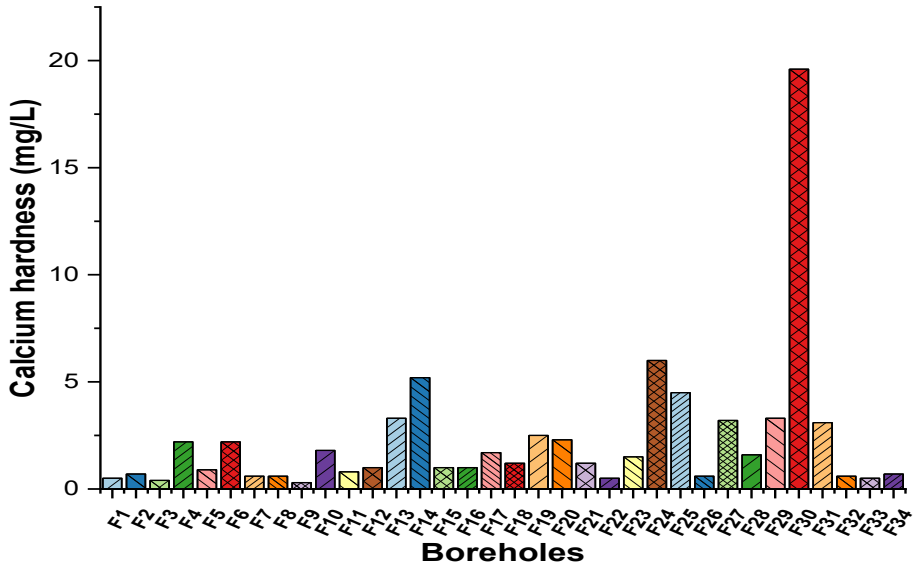


Fig. 13 Calcium hardness variation in borehole water

3.3.6 Water alkalinity (TA)

Examination of alkalinity, presented in Figure 14, decisively complements the cross-analysis of the four preceding parameters and reveals geochemically informative concordances and discrepancies. Borehole F14, already identified as a singular point of co-enrichment in potassium (~61 mg/L), sodium (~65 mg/L), total hardness (~7.5 mg/L), and calcium hardness (~5.2 mg/L), also shows the second-highest alkalinity value (~1.3 mg/L), confirming the consistency of a shared carbonate/silicate weathering process coupled with bicarbonate mineralization at this location, in line with the HCO_3–Ca·Mg facies widely reported as the dominant geochemical signature in basement aquifers under tropical conditions [106]. Conversely, borehole F29, which showed the absolute maxima in sodium (~750 mg/L), total hardness (~19.8 mg/L), and calcium hardness (~19.5 mg/L), displays here a low alkalinity value (~0.2 mg/L), producing a marked discordance between alkalinity and hardness. According to the principle that an alkalinity value far lower than total hardness indicates the existence of non-carbonate hardness associated with sulfates and/or chlorides rather than bicarbonates [107], this strongly supports the previously proposed hypothesis of an evaporitic origin (congruent dissolution of gypsum and halite/sylvite) for this point, rather than a classic carbonate origin—a hypothesis further supported by recent studies showing that joint enrichment in Ca^{2+}, Na^{+}, and Cl^{-}/SO_4^{2-} without a proportional increase in alkalinity is characteristic of Ca–Cl and Ca–Na–SO_4 facies derived from the dissolution of salt-bearing formations [104]. Finally, the isolated and maximal alkalinity peak observed at borehole F3 (~2.2 mg/L), unaccompanied by corresponding anomalies in Na, K, or hardness, suggests a localized and independent process, likely related to recharge enriched in biogenic CO_2 (a zone of high root activity or soil organic matter) or to an input of bicarbonate of agricultural origin (calcium-magnesium amendments), rather than to deep water–rock interaction. This cross-analysis illustrates the diagnostic value of the alkalinity/hardness pair in distinguishing, within a single set of boreholes, carbonate-related processes (silicate-carbonate, coherent and multi-parametric, as at F14) from non-carbonate evaporitic processes (discordant with respect to alkalinity, as at F29).

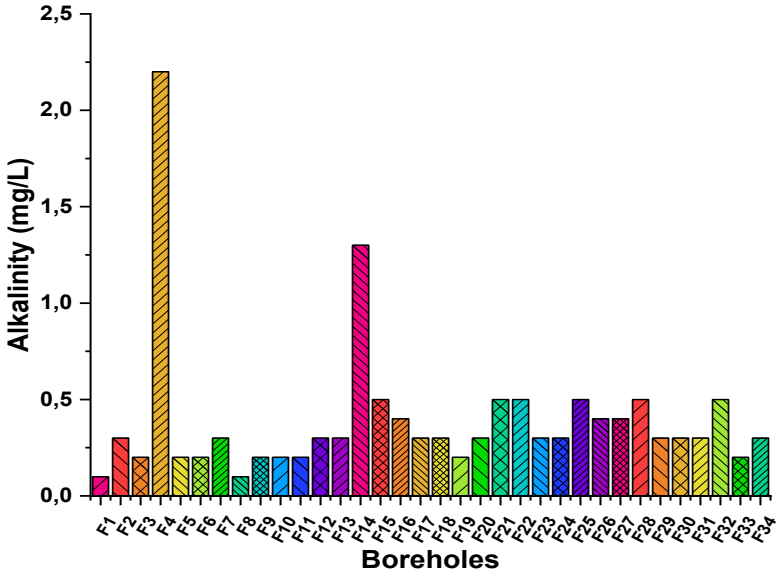


Fig. 14 Alkalinity of borehole water

3.4 Bacteriological characteristics of borehole water

3.4.1 Mesophilic aerobic bacterial flora results

The results of the bacteriological analysis of the water samples are presented in Figure 15. The distribution of total bacterial flora abundance across the boreholes reveals marked spatial heterogeneity in microbiological contamination, with loads ranging from 0 to 210 CFU/mL [108]. The highest values, observed at boreholes F23 (210 CFU/mL) and F13 and F15 (≈140 CFU/mL), reflect substantial contamination, likely related to infiltration of surface water carrying organic matter and fecal micro-organisms [109]. These results are consistent with the work of Akoachere et al. (2019) and Bonsor et al. (2018), who showed that in urban and peri-urban areas of sub-Saharan Africa, proximity to latrines, waste-disposal sites, and agricultural activities promotes the percolation of microbial contaminants into groundwater [110]. Similarly, the intermediate concentrations observed at some boreholes (F27, F31, F29) suggest moderate contamination, possibly attenuated by natural soil self-purification processes such as mechanical filtration and adsorption [111], [112], as described by Hillel (2004) and more recently confirmed by Lapworth et al. (2020).

Conversely, the low or negligible loads observed at boreholes such as F3, F17, and F21 indicate either better sanitary protection of the structures or favorable hydrogeological conditions limiting microbial survival and transport. These observations corroborate the conclusions of Howard et al. (2003) and MacDonald et al. (2021), who emphasize that borehole depth, the integrity of the well apron, and the nature of the geological substrate play a decisive role in reducing bacterial contamination [113]. In addition, the observed variability may also be influenced by seasonal and climatic factors, particularly rainfall, which increases soil leaching and facilitates the transfer of contaminants toward aquifers [114], as demonstrated by Taylor et al. (2019).

Overall, these results confirm that the microbiological quality of borehole water in the study area is strongly dependent on local environmental conditions and anthropogenic practices [115], [116]. The presence of high loads at several catchment points constitutes a non-negligible indicator of health risk for consumers [117], in line with WHO (2017) recommendations, which stipulate that water intended for human consumption should not contain indicator micro-organisms of contamination [118]. This study therefore highlights the need to implement sustainable water-resource management strategies, including the protection of catchment perimeters, improved sanitation infrastructure, and regular monitoring of groundwater microbiological quality.

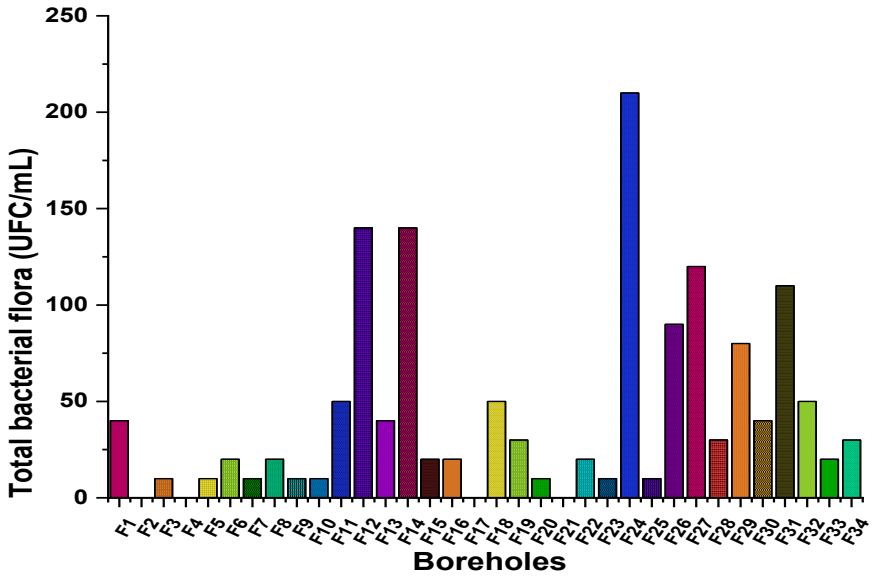


Fig. 15 Total bacterial flora abundance across boreholes

3.4.2 Total coliform results

Total coliforms have long been used as indicators of microbiological water quality because they can be indirectly associated with fecal pollution [60], [119]. Figure 16 presents the total coliform counts in the water samples analyzed. Of the 34 boreholes, 9 tested positive for total coliforms. Bacterial abundance varied considerably, with the highest count (54 CFU/100 mL) recorded at borehole F29 and the lowest (0 CFU/100 mL) at most other boreholes [120].

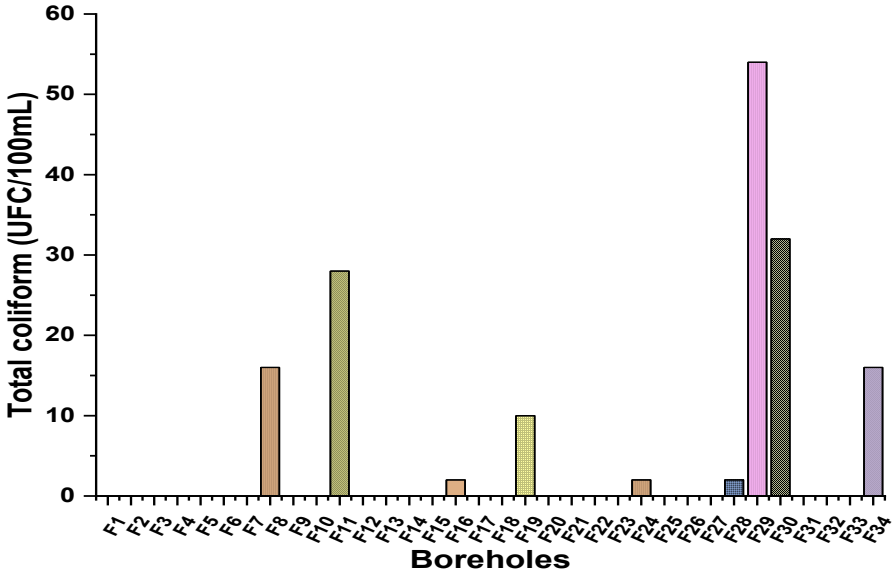


Fig. 16 Total coliform abundance in borehole water

3.4.3 Fecal coliform results

Figure 17 presents the variation in fecal coliform abundance across the boreholes analyzed. The distribution of total coliform abundance in borehole water reveals overall low but spatially heterogeneous microbiological contamination [121], with values ranging from 0 to 54 CFU/100 mL. Most boreholes (F1–F7, F9, F13–F15, F17, F21–F23, F25, F27, F31) showed no detectable contamination, reflecting either the apparent absence of recent contamination or the effectiveness of natural soil self-purification processes [122]. However, some boreholes showed non-negligible levels, notably F29 (54 CFU/100 mL), F31 (32 CFU/100 mL), F11 (28 CFU/100 mL), F9 (16 CFU/100 mL), and F33 (16 CFU/100 mL), indicating localized episodes of fecal or environmental contamination. These results suggest localized infiltration of organic matter of anthropogenic origin, possibly linked to proximity to latrines, agricultural activities, or defects in borehole protection [123].

These observations corroborate the work of Akoachere et al. (2019) and Bain et al. (2014), who showed that the presence of total coliforms in groundwater is a reliable indicator of vulnerability to fecal contamination, particularly in areas with high population density and limited sanitation coverage [110]. In addition, the peaks observed, notably at borehole F29, could be associated with hydrogeological conditions favoring rapid microbial transport, such as permeable or fissured soils, consistent with the findings of Lapworth et al. (2020) on the dynamics of microbial contaminant transfer in shallow aquifers [110].

Furthermore, the low concentrations (2 to 10 CFU/100 mL) recorded at some boreholes (F17, F19, F23, F27) may reflect diffuse contamination attenuated by natural self-purification mechanisms [124], notably filtration, microbial predation, and bacterial die-off, as described by Hillel (2004). The absence of coliforms at several boreholes may also reflect better catchment conditions, such as greater depth, sound structural sealing, or greater distance from pollution sources [125], consistent with the observations of Howard et al. (2003).

Overall, although most boreholes show acceptable microbiological quality, the presence of total coliforms at some water points constitutes a health-related warning sign [126], in accordance

with WHO (2017) recommendations, which call for the absence of these indicators in water intended for human consumption. These results highlight the need for regular monitoring of microbiological quality, as well as the implementation of borehole-protection measures and sanitation improvements to reduce contamination risks and protect public health [110].

Overall, the results of both total and fecal coliform analyses reveal heterogeneous microbiological contamination, dominated by localized anthropogenic inputs, underscoring the importance of a multi-parameter approach for a reliable assessment of groundwater quality. These observations are consistent with WHO (2017) recommendations, which emphasize the need to use specific microbiological indicators in addition to overall parameters [127]. These results therefore confirm the urgency of strengthening borehole-protection measures, including the establishment of sanitary perimeters, adequate management of potential pollution sources, and awareness-raising among local populations, in order to limit the health risks associated with consuming this water [128].



Fig. 17 Fecal coliform abundance in borehole water

3.4.4 Escherichia coli results

Figure 18 shows the presence of E. coli at two sampling points (F19 and F29). Analysis of Escherichia coli concentrations in borehole water reveals overall low but locally significant fecal contamination, with values ranging from 0 to 2 CFU/100 mL [129]. Most boreholes showed a complete absence of E. coli, reflecting satisfactory microbiological quality and the absence of recent fecal contamination at these water points. However, the detection of E. coli at certain boreholes (values of 2 CFU/100 mL) constitutes a critical indicator of recent fecal pollution, given that this bacterium is recognized as a specific and reliable bio-indicator of contamination by human or animal fecal matter [130].

These results are consistent with the work of Bain et al. (2014) and WHO (2017), who emphasize that the presence of Escherichia coli in drinking water, even at low concentrations, constitutes a health risk, as it may be associated with the presence of enteric pathogens [131]. Moreover, the localized distribution of this contamination suggests point-source infiltration of

microbial pollutants, likely favored by deficiencies in borehole protection (absence of a watertight apron, proximity to latrines) or by hydrogeological conditions facilitating rapid transfer of micro-organisms [60], as demonstrated by Lapworth et al. (2020).

The concordance between the presence of E. coli, total coliforms, and high total-flora loads at certain boreholes confirms the anthropogenic origin of the contamination and highlights the vulnerability of these water points [132]. This relationship has been widely described by Akoachere et al. (2019), who showed that the simultaneous detection of these microbiological indicators strengthens the reliability of fecal-pollution diagnosis [133]. Conversely, the absence of E. coli at several boreholes, despite the occasional presence of total flora, suggests that these points may be subject to non-fecal environmental contamination or to effective self-purification processes [134].

Overall, these results confirm heterogeneous microbiological contamination of borehole water, with localized but concerning fecal inputs. In accordance with WHO (2017) recommendations, which require the total absence of E. coli in water intended for human consumption, boreholes with positive results should be considered non-compliant and require urgent corrective measures [135]. This study therefore highlights the importance of regular microbiological monitoring, strengthened sanitary protection of boreholes, and improved sanitation practices to reduce health risks for the population [136].

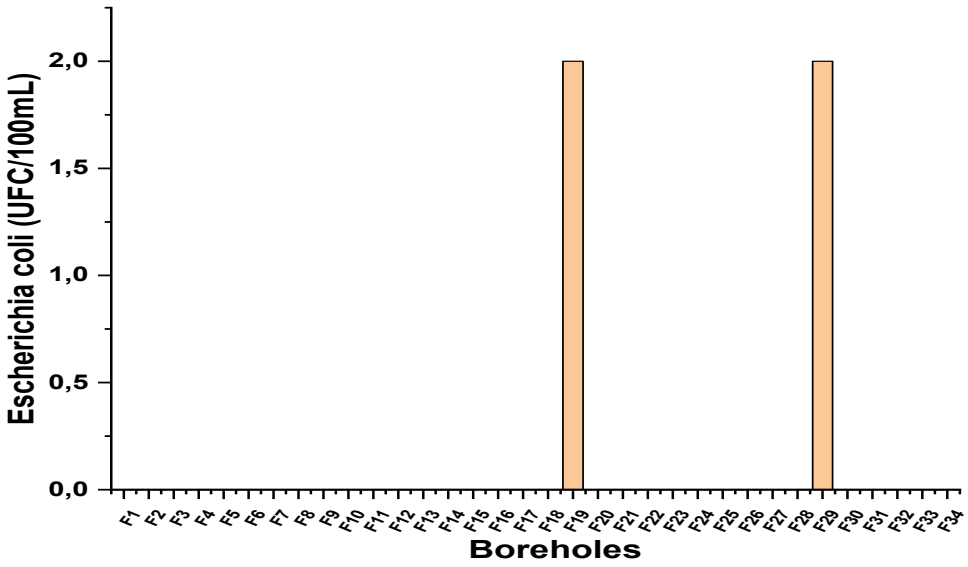


Fig. 18 Escherichia coli abundance in borehole water

3.4.5 Fecal streptococci results

Figure 19 presents the distribution of fecal streptococci concentrations (CFU/100 mL) across the boreholes (F1 to F34). The results show elevated bacterial loads of 6 CFU/100 mL each at boreholes F13 and F19. Borehole F23 showed moderate contamination of 4 CFU/100 mL. Borehole F31 showed the maximum value of 10 CFU/100 mL, while the remaining boreholes showed 0 CFU/100 mL, indicating no detectable contamination. These results indicate sporadic contamination by fecal streptococci [137]. This variability is consistent with the observations of WHO (2017) and earlier studies (Mbithi et al., 2019; Adekunle et al., 2020), which show that

groundwater contamination depends on proximity to fecal-contamination sources (latrines, animal waste) [138], as well as on borehole depth and integrity and on local hydrogeological conditions favoring infiltration [139].

Boreholes F13, F19, and F31 exceed the recommended thresholds for drinking water (0 CFU/100 mL according to the WHO), indicating an increased risk of fecal contamination. This may be related to direct infiltration or to sealing defects. The presence of fecal streptococci underscores the risk of waterborne-disease transmission [133], [140]. Contaminated boreholes require treatment measures such as chlorination, filtration, or temporary restriction of use [141].

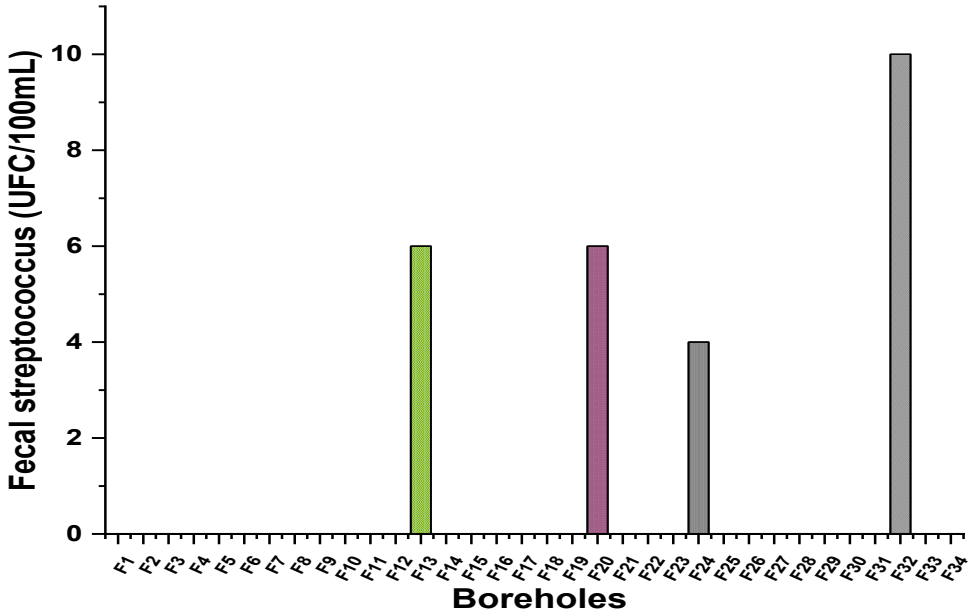


Fig. 19 Variation in fecal streptococcus abundance across boreholes

3.4.6 Staphylococci results

Figure 20 presents the enumeration of staphylococci in the boreholes. The results show the distribution of staphylococci in borehole water (F1 to F33). Most boreholes (F1–F6, F9–F14, F16, F18, F20, F22, F24, F26, F28, F30, F32–F33) showed no detection, whereas some boreholes showed moderate-to-high contamination: F7 and F17 with 2 CFU/100 mL, F21 with 4 CFU/100 mL, F23, F25, and F27 with 6 CFU/100 mL, and F29 with 4 CFU/100 mL. This heterogeneous distribution confirms that staphylococcal contamination of borehole water is localized and sporadic [142], [143], consistent with the observations of Mbithi et al. (2019) and Adekunle et al. (2020), who showed that skin- or fecal-derived micro-organisms can enter groundwater through point-source infiltration or casing defects [144], [60]. These results also corroborate earlier analyses of fecal streptococci in the same area (WHO, 2017; Kaseva et al., 2001), where contamination was likewise localized and strongly dependent on environmental and hydrogeological conditions [145]. The presence of staphylococci at certain boreholes thus underscores the importance of regular monitoring and targeted treatment measures, such as chlorination or filtration, to ensure the sanitary safety of water intended for consumption [146], [147].

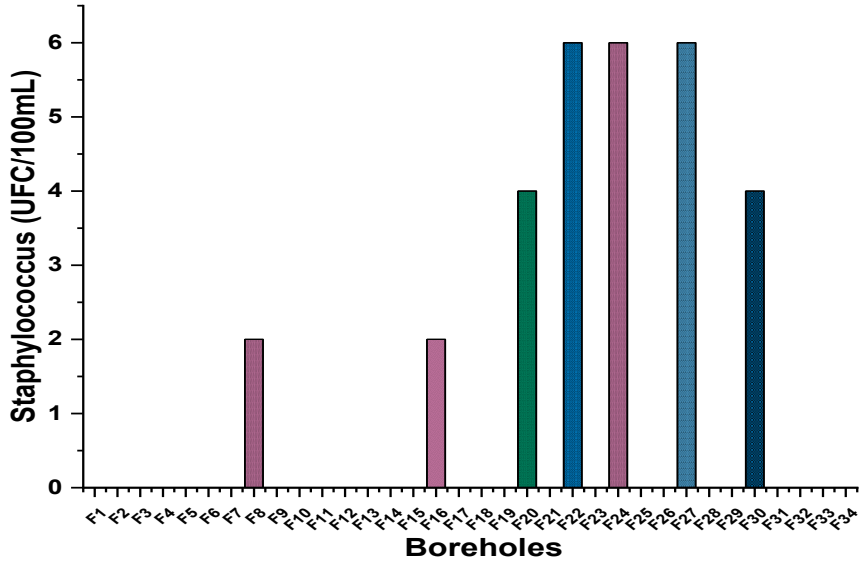


Fig. 20 Staphylococcus abundance in borehole water

4 Conclusion

This study shows that borehole water in Garoua does not uniformly meet drinking-water quality expectations, despite boreholes being the main alternative to an inadequate public distribution network. Physicochemically, the water is generally acidic (mean pH 5.67) and, at several boreholes, carries nitrite concentrations well above WHO guidance (up to 410 mg/L), indicating localized chemical vulnerability likely linked to soil-leaching processes and anthropogenic inputs. Microbiologically, although contamination was sporadic, the detection of Escherichia coli and fecal streptococci at specific boreholes is consistent with localized fecal contamination pathways, rendering the affected water points unsuitable for direct consumption under WHO guidelines. Notably, high overall awareness of waterborne-disease risk (over 90% of respondents) did not consistently translate into protective household practices, revealing a gap between knowledge and behavior that awareness campaigns alone are unlikely to close. Addressing this will require a combined approach: routine borehole-water-quality monitoring, physical protection of vulnerable boreholes, improved sanitation infrastructure, and household-level support for water treatment. These findings illustrate the broader challenge of managing groundwater safety in rapidly urbanizing, sanitation-constrained settings, and support the case for integrated, locally targeted groundwater-management strategies in Garoua and comparable urban centers.

Statements and Declarations

Funding

This research received no specific funding from any public, commercial, or not-for-profit funding agency.

Competing interests

The authors declare no competing interests.

Ethical Approval and accordance

The study protocol was reviewed and approved by the Regional Ethics Committee for Human Health Research of the North Region of Cameroon (approval No. 00102/CERSH/NO/2024, dated 12 November 2024) before fieldwork began in the Garoua subdivisions. All procedures involving human participants were performed in accordance with the guidelines of this committee, the Cameroonian national regulations on research involving human participants, and the ethical principles of the Declaration of Helsinki of the World Medical Association. Participation was voluntary, all participants gave informed consent before data collection, and no names or other personal identifiers were recorded.

Consent to participate

Informed consent was obtained from all individual participants before the interview. Enumerators explained the aim of the study, the type of questions, the voluntary nature of participation and the right to stop the interview at any time, in French or Fulfulde according to the respondent's preference. For respondents aged 15 to 20 years, informed consent was first obtained from a parent or legal guardian present in the household, and the young respondent's own agreement was then requested; no child under 15 years was interviewed. Because some respondents or guardians could not read or write, consent was given orally before the first question. This oral consent procedure was approved by the Regional Ethics Committee for Human Health Research of the North Region of Cameroon (approval No. 00102/CERSH/NO/2024), and consent was obtained in accordance with the guidelines of that committee and with the Declaration of Helsinki.

Consent for publication

Not applicable; no identifiable individual data or images are reported.

Data availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

All authors contributed to the study conception and design, data collection and/or analysis, interpretation of results, and drafting or critical revision of the manuscript. All authors read and approved the final manuscript.

Clinical trial number: not applicable.

References

[1] S. Sanogo, “Profil de la qualité des eaux analysées au Laboratoire National de la Santé de Bamako-Mali de 2012 à 2020”, PhD thesis, USTTB, 2021.

[2] F. F. Befolo Abina, “BILAN DE LA CONSOMMATION D’EAU DU CAMPUS ARLON ET RECHERCHE DE SOLUTIONS”, 2022.

[3] K. Danert, D. Adekile, M. Malik, L. Museteka, and D. Abuuru, “Réalisations et enseignements tirés de la mise en œuvre de la réglementation des eaux souterraines en Zambie”.

[4] F. Zidouni, “Contribution à l’évaluation de la qualité des eaux souterraines de la région sud-est de la wilaya d’Oum El Bouaghi (Algérie)”, 2021.

[5] A. B. Bakatubala and A. N. Lusamba, “Analyse microbiologique de l’eau de boisson de différentes sources consommées par la population de la Province du Kasaï Central: Cas de la Zone de Santé Rurale de Mutoto”, 2021.

[6] O. mondiale de la Santé, “Situation de dans le monde l’assainissement: un appel pressant à améliorer l’assainissement au profit de la santé, de l’environnement, de l’économie et de la société”, 2021.

[7] Y. F. Kouame, A. B. B. Kedi, S. S. Kouassi, E. S. Assohoun, O. B. Yapo, and T. Gnagne, “Caractéristiques physico-chimiques des eaux de forages à usage domestique dans la ville de Daloa (centre-ouest de la Côte d’Ivoire)”, Int. J. Biol. Chem. Sci., vol. 15, no. 2, p. 835-845, 2021.

[8] C. Diop et al., “Approvisionnement en eau dans la commune des Parcelles Assainies de Dakar (Sénégal): perception de la qualité et pratiques des populations”, 2021.

[9] L. Fewtrell, R. B. Kaufmann, D. Kay, W. Enanoria, L. Haller, and J. M. Colford, “Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis”, Lancet Infect. Dis., vol. 5, no. 1, p. 42-52, Jan. 2005, https://doi.org/10.1016/S1473-3099(04)01253-8.

[10] J. K. Summers, Water Quality: Science, Assessments and Policy. BoD – Books on Demand, 2020.

[11] X. Wen et al., “Microbial Indicators and Their Use for Monitoring Drinking Water Quality—A Review”, Sustainability, vol. 12, no. 6, p. 2249, Jan. 2020, https://doi.org/10.3390/su12062249.

[12] K. Black, Business Statistics: For Contemporary Decision Making. John Wiley & Sons, 2019.

[13] G. Kalton and S. Heeringa, Leslie Kish: Selected Papers. John Wiley & Sons, 2003.

[14] Nations Unies, Guide pratique pour la conception d’enquêtes sur les ménages. in Etudes méthodologiques (Ser. F). UN, 2010. https://doi.org/10.18356/4d6e0831-fr.

[15] S. A. Inah, J. E. Egbung, P. A. Kanu, B. E. Esu, C. P. Ugbor, and N. C. Osuchukwu, “Knowledge, Perceptions and Preventive Practices Against Waterborne Diseases among Residents of Obubra Local Government Area, Cross River State, Nigeria”, 4 May 2026, Research Square. https://doi.org/10.21203/rs.3.rs-9415696/v1.

[16] C. D. Toderescu et al., “Hydration Knowledge, Water Consumption, and Attitudes Toward Drinking Water Quality Among Adults in Romania: A Cross-Sectional Study”, Nutrients, vol. 18, no. 3, p. 419, Jan. 2026, https://doi.org/10.3390/nu18030419.

[17] A. Santos, “DEVELOPMENT OF STEWARDSHIP AND DRINKING WATER QUALITY INDICATORS TOWARDS PRIVATE WELL WATER SAFETY IN SASKATCHEWAN”, 2026, Accessed: 11 July 2026. [Online]. Available at: https://hdl.handle.net/10388/18091

[18] E. E. Bonham, T. Xu, K. A. Hamilton, and R. L. Muenich, “Water quality signatures for prioritizing abandoned mine land ground-truthing in the Southwestern United States”, Environ. Res., vol. 300, p. 124380, Jun. 2026, https://doi.org/10.1016/j.envres.2026.124380.

[19] T. Joseph, “Water temperature as a groundwater tracer in fractured rock”.

[20] N. Aranzabal, J. Martos, H. Steger, P. Blum, and J. Soret, “Temperature measurements along a vertical borehole heat exchanger: A method comparison”, Renew. Energy, vol. 143, p. 1247-1258, Dec. 2019, https://doi.org/10.1016/j.renene.2019.05.092.

[21] P. Phansi, K. Inthichit, M. Trongdee, N. Kaewkong, and D. Nacapricha, “A Single Microfluidic Paper-Based Analytical Device for the Determination of Ammonia and pH Using Mulberry Fruit Extract as a Natural Indicator”, J. Anal. Chem., vol. 80, no. 8, p. 1411-1421, Aug. 2025, https://doi.org/10.1134/S1061934825600854.

[22] K. C. Aluwong, M. H. B. Mohd Hashim, and S. Ishmail, “Design of wireless-based Based Sensor for real-time monitoring pH and TDS in Surface and Groundwater using IoT”, J. Min. Environ., vol. 15, no. 4, p. 1309-1320, Oct. 2024, https://doi.org/10.22044/jme.2024.14388.2693.

[23] Š. Zezulka, B. Maršálek, E. Maršálková, K. Odehnalová, M. Pavlíková, and A. Lamaczová, “Suspended Particles in Water and Energetically Sustainable Solutions of Their Removal—A Review”, Processes, vol. 12, no. 12, p. 2627, Dec. 2024, https://doi.org/10.3390/pr12122627.

[24] R. Benjankar, R. Kafle, S. Satyal, and N. Adhikari, “Analyses of Spatial and Temporal Variations of Salt Concentration in Waterbodies Based on High Resolution Measurements Using Sensors”, Hydrology, vol. 8, no. 2, p. 64, Jun. 2021, https://doi.org/10.3390/hydrology8020064.

[25] J. D. Rhoades, N. A. Manteghi, P. J. Shouse, and W. J. Alves, “Soil Electrical Conductivity and Soil Salinity: New Formulations and Calibrations”, Soil Sci. Soc. Am. J., vol. 53, no. 2, p. 433-439, 1989, https://doi.org/10.2136/sssaj1989.03615995005300020020x.

[26] M. F. Filgueiras, P. C. de Jesus, and E. M. Borges, “Quantification of Nitrite in Food and Water Samples Using the Griess Assay and Digital Images Acquired Using a Desktop Scanner”, J. Chem. Educ., vol. 98, no. 10, p. 3303-3311, Oct. 2021, https://doi.org/10.1021/acs.jchemed.0c01392.

[27] S. O. Sey, “Assessment of surface water quality and potential health effects on its users. A case of Awusavu reservoir.”, Oct. 2024, Accessed: 11 July 2026. [Online]. Available at: http://41.74.91.244:8080/handle/123456789/4912

[28] D. C. Patra, R. R. Suresh, C. Hazra, R. Dastidar, P. Sengupta, and G. Dutta, “Point-of-care sodium ion detection using membrane-free MnO2 nanoparticle modified LIG electrodes in human saliva”, Biosens. Bioelectron. X, vol. 30, p. 100791, Aug. 2026, https://doi.org/10.1016/j.biosx.2026.100791.

[29] C. Crowley, G. Duffy, and J. P. Kerry, “Measurement of Sodium Chloride (NaCl) Content in Dry-Fermented Sausages: Mohr Titration vs Instrumental Determination via Dicromat-II”, Food Anal. Methods, vol. 19, no. 3, p. 125, Feb. 2026, https://doi.org/10.1007/s12161-026-03003-0.

[30] N. W. Futasa, A. A. Ante, and D. B. Adugna, “Groundwater hardness characterization and selection of softening technology for development of a centralized treatment plant: A case study in Haramaya University, Ethiopia”, PLOS Water, vol. 5, no. 6, p. e0000454, Jun. 2026, https://doi.org/10.1371/journal.pwat.0000454.

[31] N. Aslanova, “Application OF Titrimetric Analysis Methods in Evaluating the Chemical Purity OF Water Samples”, Sci. Collect. “InterConf”, no. 269, p. 279-283, 2025.

[32] C. E. Boyd, “Total Hardness”, in Water Quality: An Introduction, C. E. Boyd, Éd., Cham: Springer International Publishing, 2020, p. 205-214. https://doi.org/10.1007/978-3-030-23335-8_10.

[33] L. M. L. Nollet and L. S. P. D. Gelder, Handbook of Water Analysis. CRC Press, 2000.

[34] Á. Francés et al., “Characterization of microbial diversity, chemical hazards and antimicrobial resistant bacteria in wash water from a fresh-cut vegetable processing plant”, Int. J. Food Microbiol., vol. 452, p. 111667, May 2026, https://doi.org/10.1016/j.ijfoodmicro.2026.111667.

[35] P. Vergine, C. Salerno, E. Barca, G. Berardi, and A. Pollice, “Identification of the faecal indicator Escherichia coli in wastewater through the β-D-glucuronidase activity: comparison between two enumeration methods, membrane filtration with TBX agar, and Colilert®-18”, J. Water Health, vol. 15, no. 2, p. 209-217, Dec. 2016, https://doi.org/10.2166/wh.2016.119.

[36] A. Dabrowska et al., “Expanding access to water quality monitoring with the open-source WaterScope testing platform”, Npj Clean Water, vol. 7, no. 1, p. 68, Jul. 2024, https://doi.org/10.1038/s41545-024-00357-y.

[37] S. E. Sellami, A. Taleb, M. Elhachoumi, and B. Elfathi, “Bacteriological analysis of Oued Oum Er-Rbia water: Evolution and impact on quality and osmosis membrane”, BIO Web Conf., vol. 211, p. 01026, 2026, https://doi.org/10.1051/bioconf/202621101026.

[38] H. Raqraq et al., “Impact of natural lagooning wastewater treatment on antibiotic-resistant bacteria in Morocco”, PLOS Water, vol. 5, no. 3, p. e0000464, Mar. 2026, https://doi.org/10.1371/journal.pwat.0000464.

[39] L. Volterra, L. Bonadonna, and F. A. Aulicino, “Fecal streptococci recoveries in different marine areas”, Water. Air. Soil Pollut., vol. 29, no. 4, p. 403-413, Aug. 1986, https://doi.org/10.1007/BF00283446.

[40] T. H. Ericksen and A. P. Dufour, “Methods to Identify Waterborne Pathogens and Indicator Organisms”, in Waterborne Diseases in the US, CRC Press, 1986.

[41] L. A. DEVRIESE, “Baird-Parker Medium Supplemented with Acriflavine, Polymyxins and Sulphonamide for the Selective Isolation of Staphylococcus aureus from Heavily Contaminated Materials”, J. Appl. Bacteriol., vol. 50, no. 2, p. 351-357, Apr. 1981, https://doi.org/10.1111/j.1365-2672.1981.tb00899.x.

[42] N. Gundogan, O. Ataol, and F. O. Torlak, “Determination of Some Virulence Factors in Staphylococcus aureus, Enterococcus faecalis and Enterococcus faecium Isolated from Meat and Milk Products”, J. Food Saf., vol. 33, no. 4, p. 387-393, 2013, https://doi.org/10.1111/jfs.12062.

[43] M. T. Lahrech et al., “Overcoming Barriers to Youth Economic Inclusion in Rural Morocco: A Case Study of Daït Aoua”, Societies, vol. 15, no. 1, p. 4, Jan. 2025, https://doi.org/10.3390/soc15010004.

[44] S. L. Young, H. J. Bethancourt, Z. R. Ritter, and E. A. Frongillo, “Estimating national, demographic, and socioeconomic disparities in water insecurity experiences in low-income and middle-income countries in 2020–21: a cross-sectional, observational study using nationally representative survey data”, Lancet Planet. Health, vol. 6, no. 11, p. e880-e891, Nov. 2022, https://doi.org/10.1016/S2542-5196(22)00241-8.

[45] S. L. Musy, J. M. Thornton, T. Ferre, A. Sills, D. Hunkeler, and P. Brunner, “Community views on hydrogeology education: A global perspective from 2024”, Hydrogeol. J., Jun. 2026, https://doi.org/10.1007/s10040-026-03089-0.

[46] M. Smol, P. Marcinek, and K. Ramm, “Understanding Stakeholders Opinions and Behaviours as a Way to Shape Circular Economy Policies in the Water and Wastewater Sector”, Bus. Strategy Environ., vol. 35, no. 1, p. 1272-1287, 2026, https://doi.org/10.1002/bse.70235.

[47] R. Mascia, A. Smith, M. Crockatt, and Y. Malhi, “Community (citizen) science for assessing nature’s benefits: A systematic review and survey”, People Nat., vol. 8, no. 1, p. 165-180, 2026, https://doi.org/10.1002/pan3.70209.

[48] İ. Atay Kaya and E. N. Güngör, “Contextual influences on park design: participatory insights from diverse age groups”, CoDesign, vol. 0, no. 0, p. 1-22, Jun. 2026, https://doi.org/10.1080/15710882.2026.2685028.

[49] P. Chen, X. Yang, F. Hao, and R. Tao, “Decoding electric vehicle adoption using XGBoost and SHAP analysis”, Travel Behav. Soc., vol. 42, p. 101125, Jan. 2026, https://doi.org/10.1016/j.tbs.2025.101125.

[50] S. Duric et al., “Athletes’ origin trends in participation and performance of master runners in the New York City marathon (1999–2024): a sex- and age-group analysis”, Sci. Rep., vol. 16, no. 1, p. 5136, Jan. 2026, https://doi.org/10.1038/s41598-026-36101-4.

[51] R. Leiva-Granados et al., “Sex differences in social connectedness, health, and quality of life: evidence from a cross-sectional survey in urban Accra, Ghana”, BMC Public Health, vol. 26, no. 1, p. 45, Nov. 2025, https://doi.org/10.1186/s12889-025-25322-3.

[52] K. L. Larson and D. Lach, “Participants and non-participants of place-based groups: An assessment of attitudes and implications for public participation in water resource management”, J. Environ. Manage., vol. 88, no. 4, p. 817-830, Sep. 2008, https://doi.org/10.1016/j.jenvman.2007.04.008.

[53] D. K. Joseph, D. Dwomoh, J. M. K. Aheto, and J. N. Fobil, “Impact of household air pollution on under 5 mortalities and ARI in sub saharan africa: evidence from demographic and health survey 2010–2020”, Sci. Rep., vol. 16, no. 1, p. 9020, Feb. 2026, https://doi.org/10.1038/s41598-026-38186-3.

[54] C. K. John and J. H. Pu, “Climate-Driven Water Scarcity and Its Public Health Implications: A Multi-Regional Assessment Across Vulnerable Socio-Ecological Systems”, Water, vol. 18, no. 6, p. 699, Jan. 2026, https://doi.org/10.3390/w18060699.

[55] S. C. C. Izah, “Patterns of Suya (roasted beef) consumption, awareness of trace metal contamination, and food safety practices among residents of Yenagoa Metropolis, Nigeria”, Front. Public Health, vol. 14, Mar. 2026, https://doi.org/10.3389/fpubh.2026.1779695.

[56] W. Jiang, Y. Li, Y. Li, Q. Guo, and D. Liu, “Factors associated with willingness to receive an adult tetanus booster in China: A cross-sectional study incorporating behavioral factor analysis”, Hum. Vaccines Immunother., vol. 22, no. 1, p. 2683761, Jul. 2026, https://doi.org/10.1080/21645515.2026.2683761.

[57] H. Tolonen, A. Dobson, S. Kulathinal, and for the WHO MONICA Project, “Effect on Trend Estimates of the Difference between Survey Respondents and Non-respondents: Results from 27 Populations in the WHO MONICA Project”, Eur. J. Epidemiol., vol. 20, no. 11, p. 887-898, Nov. 2005, https://doi.org/10.1007/s10654-005-2672-5.

[58] P. Devi and F. K. SuDan, “EXPLORING DETERMINANTS OF ACCESS TO HIGHER EDUCATION: A STUDY OF GRADUATE STUDENTS IN JAMMU DISTRICT"”.

[59] Q. Mayne and Y. Peters, “Where you sit is where you stand: education-based descriptive representation and perceptions of democratic quality”, West Eur. Polit., vol. 46, no. 3, p. 526-549, Apr. 2023, https://doi.org/10.1080/01402382.2022.2071044.

[60] J. Vazzaz, F. Matcham, M. Economides, H. Bolton, and K. Cavanagh, “USleep: efficacy of app-based audio interventions to improve sleep disturbance in working adults, a multi-arm randomized controlled trial”, Sleep, p. zsag154, Jun. 2026, https://doi.org/10.1093/sleep/zsag154.

[61] D. K. Bird, “The use of questionnaires for acquiring information on public perception of natural hazards and risk mitigation – a review of current knowledge and practice”, Nat. Hazards Earth Syst. Sci., vol. 9, no. 4, p. 1307-1325, Jul. 2009, https://doi.org/10.5194/nhess-9-1307-2009.

[62] R. W. Paul, “Critical thinking in North America: A new theory of knowledge, learning, and literacy”, Argumentation, vol. 3, no. 2, p. 197-235, May 1989, https://doi.org/10.1007/BF00128149.

[63] R. Nadeau and R. G. Niemi, “Educated Guesses: The Process of Answering Factual Knowledge Questions in Surveys”, Public Opin. Q., vol. 59, no. 3, p. 323-346, 1995.

[64] V. O. Agyemang, “Groundwater resources development for a sustainable water supply in developing countries: A case study of Ghana”, Clean. Water, vol. 4, p. 100104, Dec. 2025, https://doi.org/10.1016/j.clwat.2025.100104.

[65] Z. Deng, “Understanding urban water utility performance, water network topology and geographic water access: case studies in Sub-Sahara Africa”, PhD thesis, University of Southampton, 2025. Accessed: 21 July 2026. [Online]. Available at: https://eprints.soton.ac.uk/505908/

[66] Q. Shoukat, H. Ajab, A. Yaqub, B. S. Zeb, A. Baig, and R. Naseem, “Prevalence of Waterborne Diseases in Different Union Councils of Abbottabad District”, World, vol. 6, no. 2, p. 45, Jun. 2025, https://doi.org/10.3390/world6020045.

[67] A. A. Akongonguba, J. Miyalu, and A. Tshefu, “Factors affecting the non-durability of water boreholes in the Bolobo Health Zone, Democratic Republic of the Congo”, J. Glob. Health Econ. Policy, vol. 6, Mar. 2026, https://doi.org/10.7189/001c.159343.

[68] S. A. Islam, A. Ambelu, Z. Seidu, R. D. Cronk, J. K. Bartram, and M. B. Fisher, “Sanitary inspection characteristics, precipitation, and microbial water quality - A three-country study of rural boreholes in Sub-Saharan Africa”, PLOS Water, vol. 4, no. 5, p. e0000281, May 2025, https://doi.org/10.1371/journal.pwat.0000281.

[69] G. Bennett, M. M. Tembo, M. Mboje, S. Lupyana, L. T. Kaaya, and S. Twisa, “Household water scarcity coping strategies and challenges hindering sustainable water management in the Bahi Swamp Sub-Basin, Tanzania”, J. Water Sanit. Hyg. Dev., p. washdev2026308, Jun. 2026, https://doi.org/10.2166/washdev.2026.308.

[70] O. W. Iyoha, A. J. Omotoso, B. E. Usiobaifo, M. O. Raimi, and T. N. Ofor, “Beyond the Tap: Water Insecurity, Environmental Contamination, and Health Inequities in Uselu, Benin City (Preprint)”, 1 novembre 2025, JMIR Preprints. https://doi.org/10.2196/preprints.86938.

[71] J. O. Alao et al., “Sources of Groundwater Contamination: Current Trends, Socio-Economic, and Public Health Implications, and Future Directions—Case Study, Nigeria”, in A Global Perspective on Contaminants in Groundwater: Assessment and Vulnerability, S. Ali and A. Negm, Éd., Cham: Springer Nature Switzerland, 2026, p. 189-229. https://doi.org/10.1007/978-3-032-18014-8_8.

[72] K. M. Al-Kindi and G. S. S. AAl-Thani, “The potential of spatial machine learning to detect and map Escherichia coli and coliform bacteria concentrations in groundwater”, Appl. Water Sci., vol. 16, no. 6, p. 189, Jun. 2026, https://doi.org/10.1007/s13201-026-02870-6.

[73] S. C. Weller, “Cultural Consensus Theory: Applications and Frequently Asked Questions”, Field Methods, vol. 19, no. 4, p. 339-368, Nov. 2007, https://doi.org/10.1177/1525822X07303502.

[74] E. Tvinnereim and K. Fløttum, “Explaining topic prevalence in answers to open-ended survey questions about climate change”, Nat. Clim. Change, vol. 5, no. 8, p. 744-747, Aug. 2015, https://doi.org/10.1038/nclimate2663.

[75] M. K. Lee, “Understanding perception of algorithmic decisions: Fairness, trust, and emotion in response to algorithmic management”, Big Data Soc., vol. 5, no. 1, p. 2053951718756684, Jan. 2018, https://doi.org/10.1177/2053951718756684.

[76] S. Schubert, U. Kluge, U. Hess, and T. Ringeisen, “A latent profile analysis of Germans’ threat perceptions, intergroup emotions and attitudes toward refugees”, BMC Psychol., vol. 14, no. 1, p. 780, May 2026, https://doi.org/10.1186/s40359-026-04554-x.

[77] S. Sultana, S. I. Ahmed, and J. M. Rzeszotarski, “Seeing in Context: Traditional Visual Communication Practices in Rural Bangladesh”, Proc. ACM Hum.-Comput. Interact., vol. 4, no. CSCW3, p. 214:1-214:31, Jan. 2021, https://doi.org/10.1145/3432913.

[78] D. Young, K. Block, and L. Gibbs, “Social Capital Development via Sport for Migrant Women and Girls: Understanding”the Intersectional Stuff That Comes With Being a Woman From a Particular Cultural Background”“, J. Sport Soc. Issues, p. 01937235261462494, Jun. 2026, https://doi.org/10.1177/01937235261462494.

[79] A. K. Lenka and R. Chanchal, “Water, Sanitation, and Hygiene Practices Among Slums Population in Bhubaneswar City, Odisha”, in Paradigm Shifts in Population and Health in India: A Multidimensional Approach to SDGs, S. S. Acharya, S. Kundu, and S. Singh, Éd., Singapore: Springer Nature, 2025, p. 147-160. https://doi.org/10.1007/978-981-95-1719-0_11.

[80] S. Berry, “The Alignment Risks of AI Overconfidence about Consciousness”, J. Appl. Philos., vol. 43, no. 3, p. 733-753, 2026, https://doi.org/10.1002/japp.70087.

[81] A. A. Tetteh and E. Tettey, “Water Pollution and Public Health”, in The Palgrave Handbook of Ecosystems and Wellbeing, Palgrave Macmillan, Cham, 2025, p. 1-25. https://doi.org/10.1007/978-3-031-24952-5_21-1.

[82] R. F. da Silva, F. L. S. Pereira, A. J. M. N. Valdes, and M. N. M. Dimande, “AWARENESS THROUGH ENVIRONMENTAL EDUCATION ON THE POTABLE WATER SITUATION IN MOZAMBIQUE”, INTED2024 Proc., p. 7790-7794, 2024, https://doi.org/10.21125/inted.2024.2082.

[83] E. O. McGee, “Threatened and Placed at Risk: High Achieving African American Males in Urban High Schools”, Urban Rev., vol. 45, no. 4, p. 448-471, Nov. 2013, https://doi.org/10.1007/s11256-013-0265-2.

[84] M. Yasin, T. Ketema, and K. Bacha, “Physico-chemical and bacteriological quality of drinking water of different sources, Jimma zone, Southwest Ethiopia”, BMC Res. Notes, vol. 8, no. 1, p. 541, Oct. 2015, https://doi.org/10.1186/s13104-015-1376-5.

[85] U. C. Sharma, M. Datta, and V. Sharma, “Chemistry, Microbiology, and Behaviour of Acid Soils”, in Soil Acidity: Management Options for Higher Crop Productivity, U. C. Sharma, M. Datta, and V. Sharma, Éd., Cham: Springer Nature Switzerland, 2025, p. 121-322. https://doi.org/10.1007/978-3-031-76357-1_3.

[86] C. Wang and Y. Kuzyakov, “Soil organic matter priming: The pH effects”, Glob. Change Biol., vol. 30, no. 6, p. e17349, 2024, https://doi.org/10.1111/gcb.17349.

[87] X. Zhang et al., “Nitrogen optimization management for green transition of crop and livestock systems in river basins: a systematic review”, Circ. Agric. Syst., vol. 5, no. 1, Nov. 2025, https://doi.org/10.48130/cas-0025-0015.

[88] B. Yo, J. Yaméogo, and P. I. Yanogo, “Assessment of the physical and chemical quality of groundwater in developed rural areas: health and environmental issues in the municipality of Koudougou, Burkina Faso”, World News Nat. Sci., vol. 64, p. 205-221, 2026.

[89] H. Guo, Z. Gao, and S. Xing, “Water–Rock Interactions”, in Medical Geology, John Wiley & Sons, Ltd, 2023, p. 111-127. https://doi.org/10.1002/9781119867371.ch7.

[90] H. H. Khan, A. Khan, S. Ahmed, and J. Perrin, “GIS-based impact assessment of land-use changes on groundwater quality: study from a rapidly urbanizing region of South India”, Environ. Earth Sci., vol. 63, no. 6, p. 1289-1302, Jul. 2011, https://doi.org/10.1007/s12665-010-0801-2.

[91] S. Biswas, A. Chattopadhyay, and S. Chatterjee, “Perceived versus measured drinking water quality in rural West Bengal, India: a comparative cross-sectional mixed-method case study”, Sci. Rep., vol. 16, no. 1, p. 20854, May 2026, https://doi.org/10.1038/s41598-026-50626-8.

[92] S. S. Kaushal et al., “Freshwater salinization syndrome: from emerging global problem to managing risks”, Biogeochemistry, vol. 154, no. 2, p. 255-292, Jun. 2021, https://doi.org/10.1007/s10533-021-00784-w.

[93] X. Gu et al., “Natural and anthropogenic factors affecting the shallow groundwater quality in a typical irrigation area with reclaimed water, North China Plain”, Environ. Monit. Assess., vol. 189, no. 10, p. 514, Sep. 2017, https://doi.org/10.1007/s10661-017-6229-3.

[94] J. Baka, S. L. Brantley, T. Wen, L. Xue, S. Shaheen, and O. Harrington, “Using Geoscientific Analysis and Community Engagement to Analyze Exposures to Potential Groundwater Contamination Related to Hydrocarbon Extraction in Southwestern Pennsylvania”, Res. Rep. Health Eff. Inst., no. 233, p. 1-50, Dec. 2025.

[95] A. A. Christine, J. K. Kibet, A. K. Kiprop, and M. L. Were, “The assessment of bore-hole water quality of Kakamega County, Kenya”, Appl. Water Sci., vol. 8, no. 1, p. 47, Mar. 2018, https://doi.org/10.1007/s13201-018-0688-8.

[96] S. Tagar et al., “Surface Water Analysis for Physical Parameters, Fecal Indicator Bacteria, and Identification of the Origin of Contamination”, Water. Air. Soil Pollut., vol. 236, no. 2, p. 118, Jan. 2025, https://doi.org/10.1007/s11270-024-07712-2.

[97] B. A. Karimi, B. A. Sulaiman, A. B. Ahmadullah, and A. S. Irshad, “Integrated hydrogeochemical assessment and groundwater quality mapping for irrigation suitability and health risk in Kandahar City, Afghanistan”, Sci. Rep., May 2026, https://doi.org/10.1038/s41598-026-55421-z.

[98] M. Ximenes, J. A. M. S. Pratas, J. M. M. De Azevedo, Fernando. P. O. O. Figueiredo, and M. Currell, “Identification of hydrochemical processes and assessment of groundwater quality: a case study of the intergranular aquifer in Dili City, Timor-Leste”, Geol. Ecol. Landsc., vol. 10, no. 1, p. 238-260, Jan. 2026, https://doi.org/10.1080/24749508.2025.2449622.

[99] S. Buvaneshwari et al., “Potash fertilizer promotes incipient salinization in groundwater irrigated semi-arid agriculture”, Sci. Rep., vol. 10, no. 1, p. 3691, Feb. 2020, https://doi.org/10.1038/s41598-020-60365-z.

[100] L. Schwendimann et al., “Agricultural groundwater with high nitrates and dissolved salts given to pregnant mice alters brain development in the offspring”, Ecotoxicol. Environ. Saf., vol. 224, p. 112635, Nov. 2021, https://doi.org/10.1016/j.ecoenv.2021.112635.

[101] A. M. Auwal et al., “Integrated hydrogeochemical and multivariate statistical assessment of groundwater in Gashua, northeastern Nigeria: implications for arid zone aquifer

management", Model. Earth Syst. Environ., vol. 12, no. 2, p. 95, Feb. 2026, https://doi.org/10.1007/s40808-026-02727-6.

[102] S. Subudhi et al., "Prediction of groundwater quality assessment by integrating boosted learning with DE optimizer", Sci. Rep., vol. 16, no. 1, p. 618, Dec. 2025, https://doi.org/10.1038/s41598-025-30122-1.

[103] S. A. Mohallel, "Study of the hydrogeochemical processes and its impact on the quality of groundwater in the area between Abu Simbil and Tushka, Western Desert, Egypt", Sci. Rep., vol. 15, no. 1, p. 8400, Mar. 2025, https://doi.org/10.1038/s41598-025-90669-x.

[104] B. Hamma et al., "Hydrogeochemical assessment of groundwater for agricultural suitability in the Ksour Mountains, Algeria", Sci. Rep., vol. 15, no. 1, p. 36441, Oct. 2025, https://doi.org/10.1038/s41598-025-20352-8.

[105] A.-H. El-Aassar, K. Hagagg, R. Hussien, H. Oraby, and H. Shawky, "Deciphering geochemical indicators controlling the fossil groundwater quality in some localities, western desert, Egypt", Appl. Water Sci., vol. 16, no. 6, p. 190, Jun. 2026, https://doi.org/10.1007/s13201-026-02844-8.

[106] A. A. A. Promilton, A. A. Ravindran, V. S. Pitchaimani, J. V. Kingston, and S. Karuppannan, "Comprehensive hydrogeochemical characterization and seasonal water quality index analysis for sustainable groundwater management in Valliyur region, Southern Tamil Nadu, India", Sci. Rep., vol. 15, no. 1, p. 33251, Sep. 2025, https://doi.org/10.1038/s41598-025-18285-3.

[107] M. Schürch, "Détermination des paramètres hydrauliques et hydrochimiques d'un aquifère alluvial dans une vallée alpine (Valais, Suisse)", 2000, https://doi.org/10.35662/unine-thesis-1502.

[108] E. Ndoma, K. Kelly, and A. Hussaini, "GROUNDWATER SUITABILITY ASSESSMENT IN RELATION TO LEACHATE CONTAMINATION FROM DUMPSITES IN CALABAR MUNICIPALITY, CROSS RIVER STATE, NIGERIA.", J. Enviromental Sci. Built Environental Res., vol. 1, no. 2, p. 180-195, Jul. 2026, https://doi.org/10.83374/jesber.vol1no2.46.

[109] P. Ghosh, M. Aghababaei, J. Adhikari, A. Basu, S. Majumder, and D. Chatterjee, "Hydrogeochemical and microbial risk assessment of arsenic-contaminated groundwater in Chakdah block, Nadia District, India", Discov. Water, vol. 6, no. 1, p. 18, Jan. 2026, https://doi.org/10.1007/s43832-025-00334-7.

[110] E. Akabutu and S. T. Odonkor, "Groundwater Contamination and Public Health Risks in Eastern Ghana: Evidence for Strengthening Water Safety in Sub-Saharan Africa", J. Environ. Clim. Ecol., vol. 3, no. 1, p. 36-45, Mar. 2026, https://doi.org/10.69739/jece.v3i1.1561.

[111] B. Dave et al., "Enhancing Microbial Biodegradation of PPCPs in Wastewater via Natural Self-Purification in a Novel Constructed Wetland System", Sustainability, vol. 18, no. 1, p. 548, Jan. 2026, https://doi.org/10.3390/su18010548.

[112] M. S. Kalmakhanova, Y. K. Reimbayev, Z. E. Karimbayeva, A. P. Ferreira, and H. T. Gomes, "Permeable Reactive Barriers in Groundwater Remediation: A Review of Efficiency

in Removing Pharmaceuticals and Heavy Metals", Sustainability, vol. 18, no. 9, p. 4508, Jan. 2026, https://doi.org/10.3390/su18094508.

[113] C. A. Rolland, "Leveraging microbial processes to mitigate hydrogen pressure buildup in radioactive waste repositories", EPFL, 2026. https://doi.org/10.5075/epfl-thesis-11563.

[114] Y. Li et al., "Enzyme-Induced Carbonate Precipitation (EICP) for Soil Stabilization: A Review of Mechanisms, Applications, and Future Challenges", Geotechnics, vol. 6, no. 2, p. 53, Jun. 2026, https://doi.org/10.3390/geotechnics6020053.

[115] A. M. Taiwo et al., "Groundwater quality and microbial contamination of hand-dug wells near market waste-collection bins in Abeokuta, Nigeria", Discov. Environ., vol. 4, no. 1, p. 82, Feb. 2026, https://doi.org/10.1007/s44274-026-00561-2.

[116] Y. A. Youssef et al., "Hydrochemical and GIS-based evaluation of groundwater suitability for irrigation using IWQI in the desert hinterland of western Nile Delta Egypt", Sci. Rep., vol. 16, no. 1, p. 8724, Mar. 2026, https://doi.org/10.1038/s41598-026-39089-z.

[117] F. G. Gebeyehu et al., "Fecal contamination of drinking water from source to point of use and associated factors among households in Debre-Tabor town, Northwest Ethiopia", Trop. Dis. Travel Med. Vaccines, vol. 12, no. 1, p. 1, Jan. 2026, https://doi.org/10.1186/s40794-025-00285-w.

[118] A. U. Usman and T. Agbabiaka, "BACTERIOLOGICAL ANALYSIS OF TREATED AND IT'S RAW WATER SOURCE IN AGBA-DAM, ILORIN AN INNOVATIVE APPROAVE FOR ADVANCING EDUCATION", CUSTECH Int. J. Educ., vol. 4, no. 1, p. 327-336, Nov. 2025.

[119] S. A. Aram, B. M. Saalidong, and P. O. Lartey, "Comparative assessment of the relationship between coliform bacteria and water geochemistry in surface and ground water systems", PLOS ONE, vol. 16, no. 9, p. e0257715, Sep. 2021, https://doi.org/10.1371/journal.pone.0257715.

[120] G. Mai Ndardaiwa, J. S. Eheth, D. Dawaï, B. B. Koubala, S. Liang, and M. Djaouda, "Impact of anthropogenic activities and rock nature on the suitability of groundwater for domestic and irrigation uses in the Far North Region of Cameroon", Discov. Water, vol. 5, no. 1, p. 61, Jul. 2025, https://doi.org/10.1007/s43832-025-00265-3.

[121] U. D. Archibong and J. U. Don, "Assessment of Physicochemical Quality and Microbial Contamination in Borehole Water from Benin City, Nigeria", Int. J. Renew. Energy Environ., vol. 4, no. 2, p. 399-411, Jul. 2026, https://doi.org/10.5281/zenodo.21224318.

[122] E. Kichana, S. A. Minyila, B. Apambire, C. Gbeti, A. Wumbei, and F. Alhassan, "Drinking Water Quality and Health Risk Assessment in Rural Ghana: Evidence from North-East and North Gonja Districts in the Savannah Region", Int. J. Environ. Res. Public. Health, vol. 23, no. 6, p. 821, Jun. 2026, https://doi.org/10.3390/ijerph23060821.

[123] R. K. Tamrakar, S. Butoliya, and K. Upadhyay, "Chapter 2 - Water pollution: sources, causes, and effects", in Current Advancements in Nanomaterials for Wastewater Remediation, I. Krupa, D. Ponnamma, and S. Bhagyaraj, Éd., in Micro and Nano Technologies. , Elsevier, 2026, p. 31-50. https://doi.org/10.1016/B978-0-443-16112-4.00009-8.

[124] Y. Gao et al., “Overcoming bacterial fouling: Self-cleaning CNTs-PEI/Cu-ZnIn2S4 membranes for sustained water disinfection”, Chem. Eng. J., vol. 545, p. 179374, Oct. 2026, https://doi.org/10.1016/j.cej.2026.179374.

[125] E. M. Pică and T. Rusu, “PhD Student: PhD Supervisor: Eng. Nicolae – Leontin PETRUȚA Prof. Dr. Eng. Tiberiu RUSU”.

[126] H. Shrestha, J. Maharjan, S. K. Shah, and A. Bhattarai, “ASSESSMENT OF DRINKING WATER QUALITY IN GOVERNMENT SCHOOLS OF RAMDHUNI MUNICIPALITY, NEPAL”, J. Inst. Sci. Technol., vol. 31, no. 1, p. 277-290, Jul. 2026, https://doi.org/10.3126/jist.v31i1.78211.

[127] A. Freddi et al., “Fecal microbial pollution in river and coastal environments: Influence of weather conditions”, Mar. Pollut. Bull., vol. 224, p. 119156, Mar. 2026, https://doi.org/10.1016/j.marpolbul.2025.119156.

[128] R. A. Kristanti and T. Hadibarata, “Radiological contaminant in drinking water: Contamination, treatment, and policy perspectives–A review”, Curr. Opin. Environ. Sci. Health, vol. 50, p. 100709, Apr. 2026, https://doi.org/10.1016/j.coesh.2026.100709.

[129] S. O. Umide, M. A. Shuaibu, S. Musa, A.-T. Usman, O. A. Usman, and Y. Barik, “Assessment of Water Quality of River and Borehole Sources in Igbedor Community, Anambra West LGA, Nigeria: Public Health Implications”.

[130] M. Yadav, A. R. Patel, S. N. Dev, N. Patel, and R. Jadeja, “Chapter 5 - Microbes as biological indicators for assessment of environmental pollution”, in Role of Microbes in Ecosystem Processes and Environmental Management, R. Mishra, D. Mishra, S. Madhav, and R. S. Sharma, Éd., in Developments in Applied Microbiology and Biotechnology. , Academic Press, 2026, p. 77-89. https://doi.org/10.1016/B978-0-443-34272-1.00018-5.

[131] S. O. Julius et al., “Antibiotic Resistance Patterns of Escherichia coli Isolated from Drinking Water Sources: Implications for Public Health and Surveillance Strategies”, 2026.

[132] D. F. Kassa et al., “Bacteriological quality, antimicrobial resistance profile of Escherichia coli, and associated risk factors in tap water, Addis Ababa, Ethiopia”, Sci. Rep., vol. 16, no. 1, p. 9793, Feb. 2026, https://doi.org/10.1038/s41598-026-40058-9.

[133] N. Gaur, S. Shankar, R. Chaudhary, N. Akhtar, and A. Vyas, “Fecal Contamination in Drinking Water: A review of detection techniques, pathogen dynamics, and sustainable remediation approaches”, Environ. Monit. Assess., vol. 198, no. 4, p. 296, Mar. 2026, https://doi.org/10.1007/s10661-026-15135-1.

[134] I. Endacott, “Ungulate community ecology and gastrointestinal parasite diversity at the livestock-wildlife interface in Botswana”, PhD thesis, University of Liverpool, University of Liverpool, 2026. https://doi.org/10.17638/03198215.

[135] R. C. Rioba, “Identification and Characterization of Bacterial Resistome from Potable Water and Ice Pops in Juja, Kenya”, Thesis, COPAS- JKUAT, 2026. Accessed: 24 July 2026. [Online]. Available at: http://localhost/xmlui/handle/123456789/6932

[136] T. Nhabe and N. J. Malebo, “Assessing food safety and hygiene practices in old age homes in Mangaung and Lejweleputswa regions, free state”, Front. Food Sci. Technol., vol. 5, Feb. 2025, https://doi.org/10.3389/frfst.2025.1541499.

[137] A. M.-P. Kammegne et al., “Comparative Assessment of Faecal Bacterial Contamination of Vegetables from the Central and Fresh Food Markets in Foumbot, West-Cameroon”, J. Glob. Ecol. Environ., vol. 21, no. 2, p. 153-163, Apr. 2025, https://doi.org/10.56557/jogee/2025/v21i29269.

[138] O. Mupepi, T. Kundishora, and R. Mavugara, “Groundwater contamination and public health burden in an emerging urban settlement: A mixed-methods assessment from Charlton Park, Gweru, Zimbabwe”, Phys. Chem. Earth Parts ABC, vol. 144, p. 104485, Oct. 2026, https://doi.org/10.1016/j.pce.2026.104485.

[139] F. F. C. L. Viana, L. B. L. da Silva, M. H. Alencar, and A. T. de Almeida, “Hazard and vulnerability analysis of NaTech disasters induced by hydrological events to support probabilistic safety assessment in natural gas pipelines”, Reliab. Eng. Syst. Saf., vol. 273, p. 112381, Sep. 2026, https://doi.org/10.1016/j.ress.2026.112381.

[140] D. Amenu, W. Gobena, and T. Tafesse, “Assessment of bacterial profile of drinking water from different sources in Nekemte and their antibiotic susceptibility pattern, Western Ethiopia”, Sci. Rep., vol. 16, no. 1, p. 18411, Apr. 2026, https://doi.org/10.1038/s41598-026-49165-z.

[141] P. Esperanço et al., “Emerging contaminants in water resources: Monitoring gaps, treatment limitations and governance challenges with insights from Portugal”, 2026, Accessed: 24 July 2026. [Online]. Available at: http://hdl.handle.net/10400.11/10941

[142] “JBJI - Gentamicin fails to eradicate Staphylococcus aureus biofilm in vitro, even in combination with rifampin”. Accessed: 24 July 2026. [Online]. Available at: https://jbji.copernicus.org/articles/11/65/2026/

[143] A. Walusansa et al., “Antimicrobial-resistance in clinically harmful bacteria contaminating household drinking water in Eastern Uganda highlights urgent need for enhanced antibiotic resistance stewardship”, Sci. Rep., vol. 16, no. 1, p. 17241, Apr. 2026, https://doi.org/10.1038/s41598-026-47699-w.

[144] O. Taofeek, “Assessment of groundwater contamination from septic tanks in low-income communities: implications for sustainable water and sanitation infrastructure”, Agric. Assoc. Text. Chem. Crit. Rev., vol. 14, no. 2, p. 60-70, Apr. 2026, https://doi.org/10.21276/AATCCReview.2026.14.02.60.

[145] L. Meng et al., “Interpretable spatiotemporal machine learning reveals hydrogeological and climatic controls on groundwater heavy metal transport in acid mine drainage”, J. Hazard. Mater., vol. 505, p. 141566, Mar. 2026, https://doi.org/10.1016/j.jhazmat.2026.141566.

[146] A. G. Rabiu et al., “A review of the role of drinking water as a potential reservoir for the spread of antibiotic-resistant bacteria in Nigeria”, Environ. Monit. Assess., vol. 198, no. 2, p. 184, Jan. 2026, https://doi.org/10.1007/s10661-026-15039-0.

[147] J. Og, N. Beb, and A. C. and I. Ca, “Assessment of the Relationship between Hygiene Practices and Water contamination levels of waters used by Restaurants and Local food vendors

in Aba, Abia State, Nigeria.", MISJ-Int. J. Med. Res. Allied Sci., vol. 4, no. 02, p. 28-36, May 2026, https://doi.org/10.5281/zenodo.20470963.