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ORIGINAL RESEARCH ARTICLE

# Assessment of groundwater quality for drinking purposes near the industrial area of Bharatpur, Chitwan, Nepal: Physicochemical, microbiological, and statistical approaches

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**Abstract:** Groundwater quality in rapidly urbanizing Bharatpur areas with unregulated industries remains a critical, understudied challenge. This study addresses this knowledge gap by comprehensively assessing the physicochemical and microbiological contamination of drinking water near the Bharatpur industrial area, Nepal, using a statistical approach. Twelve physicochemical and microbiological parameters were analyzed based on the Nepal Drinking Water Quality Standard (NDWQS) and the World Health Organization (WHO) guidelines. Statistical methods (correlation and regression) and an index-based assessment (water quality index [WQI]) were used to interpret contamination patterns. The results showed that the mean values of pH, conductivity, total dissolved solids, hardness, alkalinity, and $Cl^-$ were within the WHO/NDWQS guidelines. However, $NO_3^-$, $PO_4^{3-}$ (4.3–9.8 mg/L), $NH_3$ (7–19.5 mg/L), free Carbon dioxide ($CO_2$), and *Escherichia coli* (0–9 colony-forming unit/100 mL) exceeded the limits, indicating industrial and fecal contamination. The WQI values ranged from 560 to 663, indicating that all groundwater samples were unsuitable for drinking without treatment. Statistical analysis revealed strong positive correlations among key parameters. Conductivity was strongly associated with total dissolved solid, hardness, alkalinity, $CO_2$, $NH_3$, $Cl^-$, $PO_4^{3-}$, and *E. coli*. Hardness, alkalinity, and $CO_2$ showed near-perfect intercorrelations, while additional strong associations were observed between $Cl^-$ and *E. coli*, $PO_4^{3-}$ and $NO_3^-$, and pH and $NO_3^-$. Further validation was performed using regression analysis with a first-degree linear equation. The findings indicate that groundwater near Bharatpur's industrial zone is critically contaminated, necessitating the urgent need for policy interventions, such as wastewater treatment to safeguard public health.

**Keywords:** Groundwater quality parameters; Statistical analysis; Correlation coefficient; Regression coefficient; Water quality index; Drinking water contamination; Industrial area

## 1. Introduction

Water is a fundamental component of life, playing a crucial role in the daily functioning of living organisms and influencing climatic conditions and land formation. Groundwater, which resides beneath the Earth's surface, represents the most abundant source of usable freshwater, constituting approximately 99% of the total volume. In comparison, surface water in lakes, rivers, and wetlands accounts for 0.87%, while atmospheric moisture constitutes 0.16%.[1,2] Around one-third of the world's population depends on groundwater for drinking.[3] This resource is especially essential in dry and semi-arid areas, where surface water and rainfall are limited.[4] Maintaining a safe and sustainable groundwater supply is a key to long-term national progress. Clean water is essential for the survival of living organisms and the proper functioning of communities, ecosystems, and economies.[5] Therefore, it is imperative to regularly assess the quality of untreated groundwater to minimize health risks before consumption.[6] Nevertheless, groundwater quality is increasingly threatened by urbanization, agricultural practices, industrial activities, and climate change. Water contamination primarily results from increased waste discharge associated with population growth and various human activities, raising significant concerns about maintaining a safe water supply.[7,8] Heavy chemical contaminants frequently enter groundwater due to untreated industrial and agricultural discharges in urban areas.[9] The presence of chemical impurities in groundwater can have detrimental impacts on public health.[10] Contamination may occur not only at the source but also through the formation of chemical by-products during groundwater movement.[11] Consequently, water must meet specific physical, chemical, and microbiological standards to be considered potable and safe for consumption.[12]

Contaminants, such as toxic metals, hydrocarbons, trace organic compounds, pesticides, microplastics, and nanoparticles pose significant threats to human health, ecosystems, and sustainable development.[13,14] Many of these groundwater pollutants originate from naturally occurring mineral deposits dissolved in the Earth's crust.[15,16] Groundwater contamination occurs when harmful substances are introduced into the subsurface due to human activities. These contaminants are often colorless and odorless, making their detection and their impacts on human health both challenging and chronic.[17] Remediation of contaminated groundwater is complex and costly due to its subsurface location and long residence times.[18-20] Even after contamination sources are removed, natural purification of groundwater can take hundreds of years.[21] Contaminants are typically categorized into chemical, biological, and radioactive types.[22] Toxic metals and metalloids present significant health risks to both humans and the environment. High levels of these substances can lead to severe poisoning, although some are essential as trace micronutrients.[23] For example, exposure to hexavalent chromium is linked to a higher risk of cancer.[24] Arsenic is classified as a human carcinogen by both the United States Environmental Protection Agency and the International Agency for Research on Cancer.[25,26] Over 200 organic contaminants, many of which are carcinogenic, have been detected in groundwater, and this number continues to rise.[27,28] These organic substances, derived from carbohydrates, proteins, fats, and oils, may degrade slowly or not at all, posing a persistent threat to groundwater quality.[29,30]

Contaminated groundwater can adversely impact human health, environmental quality, and socioeconomic development. Excessive levels of fluoride ($F^-$), chloride ($Cl^-$), nitrate ($NO_3^-$), metals, and organic pollutants are associated with significant health risks.[31] Infants are particularly vulnerable to these contaminants.[15,18,31] In addition, the use of untreated groundwater containing heavy metals and persistent contaminants for irrigation can lead to the accumulation of toxic elements in crops, posing risks to consumers.[32-35] Groundwater contamination also negatively affects soil and forest quality, with high groundwater salinity contributing to soil salinization in arid agricultural regions.[36] Furthermore, contamination-induced water shortages may exacerbate conflicts over water resources and hinder socioeconomic development.[37]

Groundwater quality research worldwide encounters considerable challenges due to the large number of water quality parameters, limited data availability, and the complex nature of groundwater systems. Çiner *et al*.[38] explored the carcinogenic risks associated with arsenic exposure in South-Central Turkey, where levels frequently exceeded guideline limits. Their study utilized multivariate statistical analysis to identify trace elements, revealing that geogenic processes played a substantial role in contamination. Yadav *et al*.[39] assessed groundwater quality in relation to arsenic in the Nawalparasi district, Nepal, using multivariate statistical techniques. The study found that nickel (Ni), cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As) levels exceeded the World Health Organization (WHO) permissible limits for drinking water, with arsenic concentrations ranging from 60 to 31,000 μg/L during the pre-monsoon and monsoon periods, respectively. Variations in water quality were primarily associated with water-rock interactions, mineralization, and anthropogenic inputs. Industrial activities and municipal waste have been identified as significant sources of groundwater contamination. Raja *et al*.[40] investigated the impact of industrial activities and municipal dumpsites on metal contamination in Virudhunagar, India. This research is crucial for developing strategies to mitigate industrial impacts on groundwater. In Uttar Pradesh, India, Tiwari and Singh[41] conducted a hydrogeochemical investigation, revealing that groundwater was alkaline and exceeded desirable limits for $NO_3^-$, $F^-$, total dissolved solids (TDS), and total hardness (TH). This underscores the importance of considering multiple water quality parameters in assessments. Ali *et al*.[42] assessed groundwater quality in the Achnera block, Agra district, India, using the water quality index (WQI) and principal component analysis (PCA). Analysis of 50 groundwater samples revealed that the water was alkaline, with WQI values ranging from 105 to 185, indicating that most samples were unsuitable for drinking. PCA identified pH, sodium ions, calcium ions ($Ca^{2+}$), bicarbonate ions ($HCO_3^-$), and $F^-$ as key factors related to geogenic $F^-$ contamination. Thus, treatment is necessary to render the water potable. Similarly, Mahato *et al.*[43] investigated aquifer contaminants and groundwater quality, observing that all parameters under analysis fell within the WHO's permissible limits for drinking water, except for pH, iron, ammonia ($NH_3$), and turbidity. $F^-$ and manganese concentrations did not meet the Nepal Drinking Water Quality Standards (NDWQSs).[44]

In the Terai region of Nepal, extensive exploitation of aquifers through tube wells supplies water to approximately 90% of the population. Fractured basement aquifers are predominantly replenished by monsoon precipitation.[45] Over 98% of groundwater withdrawals connected to rivers flowing across the Siwalik Hills are found to be enriched with arsenic,[46,47] potentially due to baseflow contributions. Globally, aquifers face increasing pollution threats from industrial and urban activities. Thus, extensive studies on groundwater quality are necessary to inform practical measures for protecting groundwater resources.[1] Unregulated and mismanaged groundwater exploitation has led to significant health impacts, with an estimated 25,000 deaths occurring daily due to water contamination. Moreover, one-third of urban dwellers in developing nations do not have access to clean drinking water.[48] Addressing these issues through targeted research and periodic water quality parameters is essential for regulating hydrochemical processes and safeguarding groundwater quality.

The groundwater quality in the industrial area of Bharatpur, Chitwan district, is potentially affected by anthropogenic activities, such as industrial discharge, agricultural runoff, and improper waste disposal. Contaminants, such as $NO_3^-$, heavy metals, and pathogens, may pose health risks to the population. This study introduces a novel assessment of groundwater quality near the industrial area, which has not been previously explored, highlighting a significant research gap in this context. By focusing on the specific impacts of industrial activities on groundwater, this research uncovers critical contamination issues that have not been extensively documented in this region to date. A systematic assessment of groundwater quality is essential to ensure safe drinking water and to inform policy decisions. Despite the heavy reliance on groundwater in Chitwan, comprehensive data on its physicochemical characteristics and quality remain limited. Existing studies of nearby areas, such as Kathmandu and Lalitpur,[49-51] are often localized or focus on specific contaminants, leaving a gap in understanding the overall groundwater quality and its spatial and temporal variations. Therefore, the novelty of this work lies in it being the first detailed analysis of groundwater quality in the Bharatpur industrial zone, where no prior studies have systematically examined contamination risks. Moreover, the integration of statistical analyses (correlation and regression) to identify pollution sources and interrelationships between parameters has not previously been applied in this region. The findings provide critical baseline data for local authorities to enforce industrial waste management regulations.

This study aims to evaluate the groundwater quality near the industrial area of Bharatpur, Chitwan, Nepal, a region facing unregulated industrial discharges, to assess its suitability for drinking and to identify contamination sources by applying statistical tools, such as correlation, regression, and the WQI to interpret contamination patterns. It also aims to determine whether the groundwater parameters comply with the WHO[48] and NDWQS[44] standards. The investigation of increased pollutants, such as $NH_3$, phosphate ($PO_4^{3-}$), and *Escherichia coli* represents a pioneering approach to evaluating the extent and sources of groundwater contamination due to industrial processes. The implications of these findings are substantial for both national prosperity and public health. These techniques help identify the major factors affecting groundwater quality and potential contamination sources. The findings will assist policymakers, environmental agencies, industrial stakeholders, and local authorities in addressing water quality concerns and implementing necessary interventions to protect public health, safeguard groundwater resources, ensure public health, and support sustainable industrial development.

## 2. Materials and methods

### 2.1. Study area

The area under investigation (Figure 1) is located in Bharatpur Metropolitan City, Wards No. 8 and 9, Chitwan, Nepal. Bharatpur Metropolitan City spans an area of 433 $km^2$ within the Terai region and is situated at an elevation of 208 m above sea level. The city lies along the banks of the Narayani River. It is the third most populous city in Nepal and the second largest metropolitan area by land area. The city comprises 29 wards and functions as the commercial and service hub of the district, offering significant facilities for higher education, healthcare, and transportation.

Groundwater samples for this investigation were collected from the Gondrang area of Bharatpur, Wards 8 and 9. This area lies to the south of the East–West Highway, near the Bandevi Barandabhar forest corridor, and is part of the semi-urban region of Bharatpur.

### 2.2. Site selection

The study area was selected based on its proximity to industrial facilities and human settlements, focusing on a 4-km stretch encompassing both densely populated areas with significant anthropogenic activities and relatively less populated zones. Sewage discharge from factory drainage sites is shown in Figure 2. Groundwater samples were collected in the 1st week of February 2024. Physicochemical parameters were analyzed at the Saptagandaki Multiple Campus (SMC) laboratory, Tribhuvan University, Nepal, and microbiological parameters were tested at the Water Quality Testing Laboratory of Bharatpur Metropolitan City.

Sampling was conducted at three distinct locations (Table 1), chosen based on their association with industrial activities and identified using a portable Global Positioning System. The selected sites were: Iron factory (IF; Site 1), Royal Paint factory (RPF; Site 2), and Coca-Cola factory (CF; Site 3). Each site was divided into four sampling zones—East, West, North, and South—relative to the industrial facilities. Samples were labeled as follows: Site 1 – Samples A, B, C, and D; Site 2 – Samples E, F, G, and H; and Site 3 – Samples I, J, K, and L.

### 2.3. Sampling and analytical methods

*2.3.1. Sample collection*

Assessing water quality involves a range of complex processes, making it challenging to design a standardized procedure that meets specific evaluation objectives.[52] For this investigation, groundwater samples were collected from handpumps located near three industrial facilities. A total of 12 samples were randomly obtained from residential households situated within 50 m of the industries.


**Figure 1. Satellite image of the study area (Google Earth)**

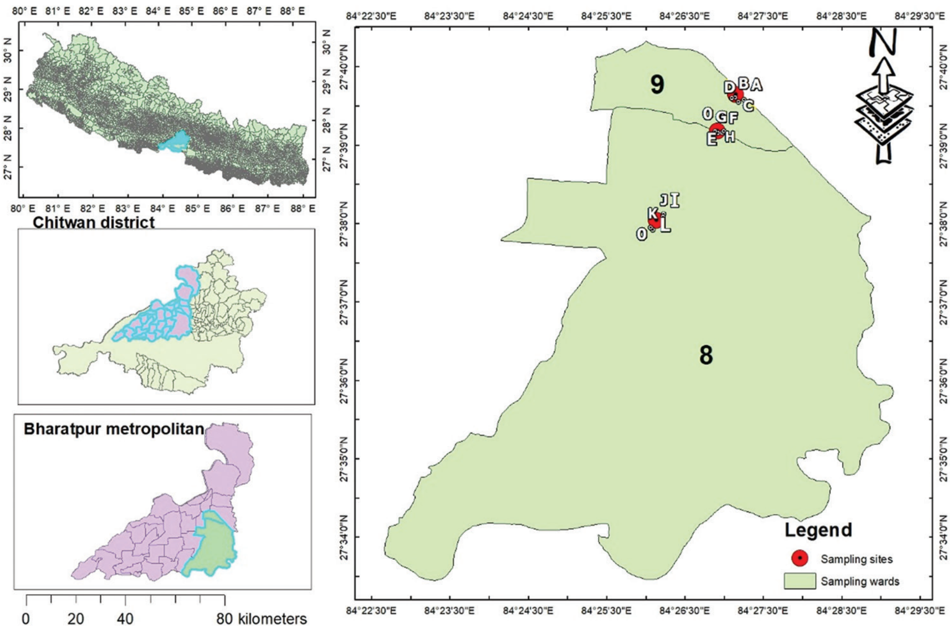


**Figure 2. Sewage outflow from the factories (drainage sites)**

**Table 1. Global Positioning System locations of sampling points and site descriptions**

| Sites | Latitude | Longitude | Elevation (m) | Site description | Population pressure | Human influence |
|---|---|---|---|---|---|---|
| Iron factory | 27°37’55.7” | 084°26’05.6” | 182 | Near buffer zone | Less populated | Minimal human activities |
| Royal Paint factory | 27°39’09.7” | 084°26’55.5” | 121 | Near buffer zone | Moderately populated | Limited human activities |
| Coca-Cola factory | 27°39’36.9” | 084°27’08.9” | 196 | North of East–West Highway | Densely populated | High human activities |

The water samples were collected in February 2024, before the onset of the monsoon season. On-site measurements included temperature, pH, dissolved oxygen, conductivity, and other basic parameters. Samples for additional analyses were collected in clean, sterile plastic bottles, transferred, and stored under refrigeration. Before collection, bottles were first rinsed with distilled water. Groundwater was then collected directly into these bottles from the sampling sites. The bottles were properly labeled and sealed with both inner and outer cover caps to prevent contamination and air ingress. The samples were subsequently transported to the SMC laboratory and stored in a refrigerator until analysis was carried out using standardized procedures and calibrated instruments. To preserve the samples for chemical analysis, they were stored at 4°C in pre-cleaned plastic bottles with nitric acid (pH <2) to prevent metal adsorption, following American Public Health Association (APHA) guidelines. Microbial analysis was conducted within 24 h, and chemical parameters were analyzed within 7 days. Instruments, such as pH meters and spectrophotometers were calibrated daily. In addition, 10% of the samples were tested in duplicates to ensure precision, maintaining a relative standard deviation of <5%. Rigorous quality assurance/quality control measures were implemented throughout the study. The collection, preservation, and analysis of groundwater samples followed the standard procedures established by the APHA.[7,53-56]

The selection of parameters was based on their relative importance in evaluating groundwater pollution potential.[43] The following criteria guided the selection of groundwater quality parameters:

*2.3.1.1. The WzHO/NDWQS regulatory criteria, along with health relevance*

As the study focuses on the drinking water quality, parameters were selected based on their direct or indirect impact on human health. These were guided by the WHO[57] and NDWQS.[44]

*2.3.1.2. Previous publications*

Selection was also informed by previous studies carried out in similar regions of Nepal and neighboring areas,[17,43,49-51,58-63] which identified key indicators influencing groundwater quality in rural areas and peri-urban settings.

*2.3.1.3. Prevalence and local context*

Parameters were chosen based on the geographical and anthropogenic context of Bharatpur and surrounding regions, including Terai and Kathmandu.[39,50,51,61,64,65] For instance, hardness is common in groundwater across the Terai, so it was included. Parameters, such as $NO_3^-$ and sulfate, were added due to potential agricultural contamination (from livestock and fertilizers). Microbiological indicators, such as *E. coli* were considered due to poor sanitation and wastewater management in rural areas.[43]

*2.3.1.4. Analytical feasibility*

Parameters were selected based on the availability of reliable testing techniques and tools, ensuring precise and reproducible outcomes.

By using this systematic approach, the parameters chosen for this study enable a comprehensive assessment of groundwater quality, considering both environmental and public health concerns specific to the industrial region of Bharatpur, Chitwan.

Table 2 presents the specifics of the chosen parameters used for the assessment of groundwater quality, along with their corresponding WHO guideline range.

*2.3.2. Analysis of physicochemical parameters*

The physicochemical properties of groundwater provide critical information about its quality, suitability for drinking, and potential sources of contamination. The following parameters were analyzed using standard methods:

*2.3.2.1. Temperature*

Groundwater temperature is a critical parameter that influences various physical, chemical, and biological processes.[73] It was measured using a mercury thermometer, which was immersed in a beaker containing the water sample. The readings were recorded in a field notebook. To ensure measurement accuracy, the thermometer was calibrated against a standard thermometer of known precision.

*2.3.2.2. pH*

The pH of the water was determined using a digital pH meter. Before use, the meter was calibrated with standard buffer solutions at pH 4 and pH 7. The glass electrode was thoroughly rinsed with distilled water before and after each measurement, and the pH readings were recorded accordingly.

*2.3.2.3. Electrical conductivity*

Electrical conductivity was measured using a conductivity meter calibrated with a 0.01N potassium

**Table 2. Details of selected parameters for groundwater quality analysis with the WHO guideline ranges**

| No. | Parameters | Unit | WHO guideline range | References |
|---|---|---|---|---|
| 1. | Conductivity | µS/cm | 1,000 | 59,60 |
| 2. | Turbidity | NTU | 5 | 54,68 |
| 3. | pH | - | 6.5–8.5 | 66,67 |
| 4. | Nitrate ($NO_3^-$) | mg/L | 50 | 60,69 |
| 5. | Total hardness ($CaCO_3$) | mg/L | 500 | 66 |
| 6. | Phosphate ($PO_4^{3-}$) | mg/L | 0.1–1.0 | 64 |
| 7. | Free $CO_2$ | mg/L | No prescribed limits | 64,71 |
| 8. | *Escherichia coli* | CFU/100 | 0 | 49,66 |
| 9. | Chloride ($Cl_-$) | mg/L | 250 | 69 |
| 10. | Total alkalinity ($CaCO_3$) | mg/L | 500 | 70 |
| 11. | Ammonia | mg/L | 1.5 | 49,64 |
| 12. | Total dissolved solids | mg/L | 1,000 | 54,72 |

Abbreviations: $CaCO_3$: Calcium carbonate; CFU: Colony-forming unit; $CO_2$: Carbon dioxide; NTU: Nephelometric turbidity unit; WHO: World Health Organization.

chloride standard solution. The electrode was cleaned and rinsed with distilled water before and after immersion in the sample. Conductivity readings were taken once the values stabilized.

*2.3.2.4. Total alkalinity*

Total alkalinity, indicative of the presence of salts from strong bases and weak acids, was determined through titration. A 100 mL water sample was placed in a conical flask, and two drops of phenolphthalein indicator were added. If a pink color appeared, it indicated the presence of carbonates, which were titrated with 0.02 N sulfuric acid ($H_2SO_4$) until the color disappeared. Then, two drops of methyl orange indicator were added, and titration continued until the color changed from yellow to red, indicating the presence of $HCO_3^-$. Alkalinity was calculated using the following formulas from Trivedi and Goel.[52,64,71]

$$PAasCaCO_3\left(mg/L\right)=\frac{A\times Normality\ of\ H_2SO_4\times 1000\times 50}{Volume\ of\ sample} \quad \text{(I)}$$

$$TAasCaCO_3\left(mg/L\right)=\frac{B\times Normality\ of\ H_2SO_4\times 1000\times 50}{Volume\ of\ sample} \quad \text{(II)}$$

where $A$ = volume of $H_2SO_4$ used with phenolphthalein only;

$B$ = total volume of $H_2SO_4$ used with phenolphthalein and methyl orange;

$PA$ = phenolphthalein alkalinity; and

$TA$ = total alkalinity.

*2.3.2.5. TH*

TH was measured using direct complexation titration with ethylene diamine tetraacetic acid (EDTA), which has a high affinity for $Ca^{2+}$ and magnesium ($Mg^{2+}$) ions. The endpoint of the titration was marked by a color change from wine red to blue using Eriochrome Black T indicator, indicating that all $Ca^{2+}$ and $Mg^{2+}$ had reacted with EDTA.[64,71]

$$Total\ hardness\ as\ CaCO_3\left(mg/\mathrm{L}\right)=\frac{Volume\ of\ EDT\ Aused}{Volume\ of\ sample}\times 1000 \quad \text{(III)}$$

*2.3.2.6. Total dissolved solids*

Total dissolved solids were quantified gravimetrically by evaporating a known volume of the water sample and weighing the remaining solid residue. The weight of the empty basin ($W_1$) and the final weight after evaporation ($W_2$) were used to calculate the TDS concentration:[64,71]

$$Amount\ of\ dissolved\ solids\ \left(ppm\right)=\frac{(\mathrm{W}_2-\mathrm{W}_1)}{100}\times 10^6 \quad \text{(IV)}$$

*2.3.2.7. Free carbon dioxide*

Free carbon dioxide ($CO_2$) was estimated by adding 5–10 drops of phenolphthalein to a 100 mL water sample. If the solution did not turn pink, indicating the presence of free $CO_2$, the sample was titrated with 0.05N sodium hydroxide (NaOH) until a persistent pink color was achieved. The concentration of free $CO_2$ was calculated using the following formula:[64,71]

$$Free\ CO\ \left(mg\quad L\right)\quad \frac{Volume\ of\ NaOH\ used\times Normality\ of\ \mathrm{NaOH}\times 44\times 1000}{Volume\ of\ sample} \quad \text{(V)}$$

*2.3.2.8. Chloride*

Chloride concentration was assessed using the argentometric method. A 50 mL sample was mixed with 3–4 drops of potassium chromate indicator and titrated with a standard silver nitrate solution until the yellow color changed to red, indicating the formation of silver chromate. The same procedure was followed for a blank sample using distilled water.[64,71]

*2.3.2.9. Nitrate*

Nitrate concentration was measured using a colorimetric method. A 10 mL water sample was mixed with 2 mL NaOH, followed by the addition of 10 mL $H_2SO_4$ and 0.5 mL brucine solution. The mixture was heated in a water bath for 20 min, and then cooled. Absorbance was measured at 410 nm using a spectrophotometer (Spectronic 21; Milton Roy, USA. A standard calibration curve was prepared to quantify $NO_3^-$ concentration.[74]

*2.3.2.10. Phosphate*

Phosphate concentration was determined using the ammonium molybdate–stannous chloride method. A 50 mL water sample was mixed with 2 mL of ammonium molybdate and five drops of stannous chloride. After 10–15 min, the resulting blue color was measured at 690 nm using a spectrophotometer (Spectronic 21; Milton Roy Company, USA). Distilled water with the same reagents was used as a blank.[52]

*2.3.2.11. Ammonia*

Ammonia concentration was determined using a colorimetric method. A 20 mL sample was mixed with 2 mL phenol-nitroprusside solution and 2 mL reagent B, and then diluted to 25 mL with distilled water. The mixture was kept in a dark place at 25°C for 1 h before measuring absorbance at 635 nm using a spectrophotometer. A calibration curve was used to determine the $NH_3$ concentration.

*2.3.2.12. E. coli*

*E. coli* was detected using the membrane filtration method. A 100 mL water sample was filtered through Whatman filter paper using a suction pump. The filter paper was then placed in a sterilized petri dish containing M-lauryl sulfate broth to promote bacterial growth. The dish was incubated at 44°C for 24 h, and colonies were enumerated through direct visualization using standardized identification techniques.[64,71]

*2.3.3. WQI*

The WQI was calculated based on drinking water quality standards using the weighted arithmetic method refined by Brown *et al*.[74] and Shrestha *et al*. and Tirkey *et al*.[49,75] The weighted arithmetic WQI is expressed as:

$$\mathrm{WQI} = \sum_{i=1}^{n} W_i Q_i \Big/ \sum_{i=1}^{n} W_i \quad \text{(VI)}$$

where $n$ = number of variables or parameters,
$W_i$ = unit weight for the i-th parameter,
$Q_i$ = quality rating (sub-index) of the i-th water quality parameter.

The unit weight (Wi) for each water quality parameter is inversely proportional to its recommended standard value.

$$W_i = K/S_n \quad \text{(VII)}$$

where, $W_i$ = unit weight for the i-th parameter,
$S_n$ = standard permissible value for the i-th parameter,
$K$ = proportional constant.

The value of K is taken as "1" here and calculated using the following equation:[49,75]

$$K = 1/\sum(1/S_n) \quad \text{(VIII)}$$

The quality rating or sub-index (Qi) is determined by Shrestha *et al*., Brown *et al*. and Tirkey *et al.*:[49,74,75]

$$Q_i = 100\,[(V_0 - V_i)/(S_n - V_i)] \quad \text{(IX)}$$

where $V_o$ = observed value of the i-th parameter at a given sampling site,
$V_i$ = ideal value of the i-th parameter in pure water,
$S_n$ = standard permissible value of the i-th parameter.

For drinking water, the ideal values (Vi) are considered zero for all parameters except pH and dissolved oxygen.[56] The ideal pH value is 7.0 (for pure water), with a permissible upper limit of 8.5 (for polluted water). For dissolved oxygen, the ideal value is 14.6 mg/L, and the permissible minimum is 5 mg/L. Therefore, the quality rating for pH is calculated as:[49,74-76]

$$Q_{pH} = 100[(V_{pH} - 7.0)/(8.5 - 7.0)] \quad \text{(X)}$$

where, $V_{pH}$ = observed pH value.

If $Q_i = 0$, it indicates the complete absence of contaminants. A value of $0 < Q_i < 100$ suggests that contaminants are within acceptable limits, while $Q_i > 100$ indicates that contaminants exceed the standard thresholds.

*2.3.4. Data analysis*

The collected data were analyzed using MS Excel 2010. Statistical analysis included the calculation of mean, median, and standard deviation. The concentrations of the measured parameters were expressed in mg/L, equivalent to ppm.

## 3. Results and discussion

### 3.1. Result of physicochemical parameters

The detailed results of the physicochemical and biological parameters, along with their variations across different sampling sites, are presented in this section.

*3.1.1. Temperature*

The analysis revealed that groundwater temperatures across the sampled sites ranged from 21°C to 23°C, with an average temperature of 22.0°C. Figure 3 illustrates the temperature variations across the study sites. The highest average temperature was observed near the IF at 22.3°C, while the lowest was recorded near the CF at 21.8°C.

Although not specifically regulated by the WHO or NDWQS, temperature affects various water quality parameters, including gas solubility and biological activity. Groundwater tends to be more thermally stable compared to surface water due to insulation by surrounding soil and rock layers. Temperature variations in groundwater are typically minimal but can influence chemical reactions and microbial processes.[77,78] For instance, higher temperatures may accelerate chemical reactions and microbial growth, potentially increasing levels of contaminants.[79] In this context, the observed temperature range appears stable and is unlikely to significantly affect water quality.

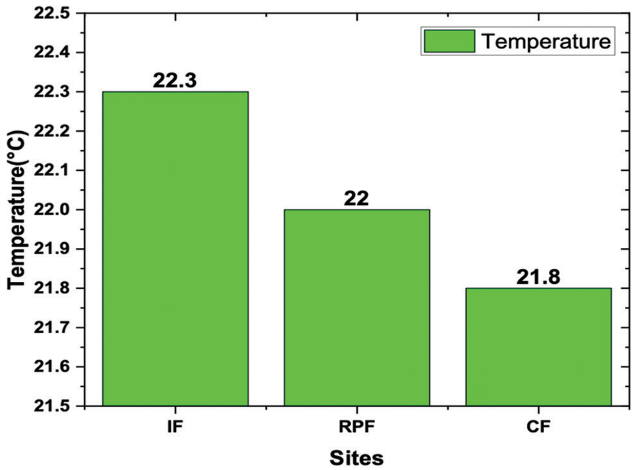


**Figure 3. Variation of water temperature in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

*3.1.2. pH*

The pH, which reflects hydrogen ion concentration, indicates the acidity or alkalinity of water. Pure water has a neutral pH, serving as a baseline for pH measurements. In this study, average pH values were 7.5 near the IF, 7.2 near the RPF, and 7.3 near the CF. Figure 4 shows that pH was slightly higher around the IF and lower near the RPF. Overall, pH ranged from 7.0 (Sample G) to 7.9 (Sample B), indicating mildly basic conditions.

These values fall within the WHO and NDWQS recommended range of 6.5–8.5. A near-neutral pH is generally optimal for drinking water as it reduces corrosion and scaling in plumbing, ensures chemical stability,[57,80] and minimizes the solubility of toxic metals.[78] pH is influenced by the equilibrium among $CO_2$, $HCO_3^-$, and carbonate ions ($CO_3^{2-}$) and may be altered by industrial effluents, domestic sewage discharge, and atmospheric deposition of acidic compounds.

The observed values suggest that the groundwater is chemically balanced and suitable for consumption. pH is a critical parameter in assessing water quality, as it affects the solubility and toxicity of contaminants.[57] Recent research highlights that maintaining pH within the recommended range is essential for ensuring safe water. For instance, Prest *et al*.[77] emphasize how pH variations can impact the effectiveness of water treatment processes and the stability of disinfectants.

*3.1.3. Electrical conductivity*

Electrical conductivity refers to the ability of an aqueous solution to conduct electricity[81-84] and is influenced by the concentration, mobility, and valence of dissolved ions, as well as temperature. Electrolytes dissociate into positive and negative ions in solution, contributing to conductivity.

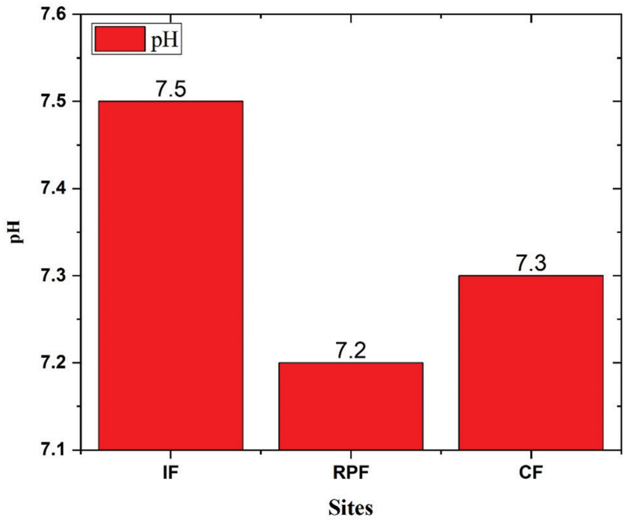


**Figure 4. Variation of pH in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

The study found average electrical conductivity values of 280 µS/cm at the IF, 490 µS/cm at the RPF, and 601 µS/cm at the CF (Figure 5). Electrical conductivity ranged from a minimum of 203 µS/cm (Sample B) to a maximum of 994 µS/cm (Sample K) at the IF and CF, respectively. The overall mean EC for all sites was 456.5 µS/cm, with a median of 420 µS/cm —well below the WHO and NDWQS limit of 1500 µS/cm. Conductivity is a key indicator of the ionic content in water, reflecting concentrations of dissolved salts and minerals, which can affect taste and treatment efficiency.[83,84] The observed electrical conductivity levels are acceptable and indicate that the groundwater is not excessively mineralized.

Although high conductivity can suggest increased salinity or pollution, the measured values fall within typical groundwater ranges. Recent studies[5,54,80,85] have confirmed that groundwater with moderate conductivity is generally safe for consumption, though higher values may influence taste and require treatment.

*3.1.4. Total alkalinity*

The analysis of water samples revealed that the average alkalinity values were 62 mg/L at the IF, 104 mg/L at the RPF, and 137 mg/L at the CF, as illustrated in Figure 6.

The alkalinity across the groundwater samples ranged from a maximum of 215 mg/L (Sample K at CF)

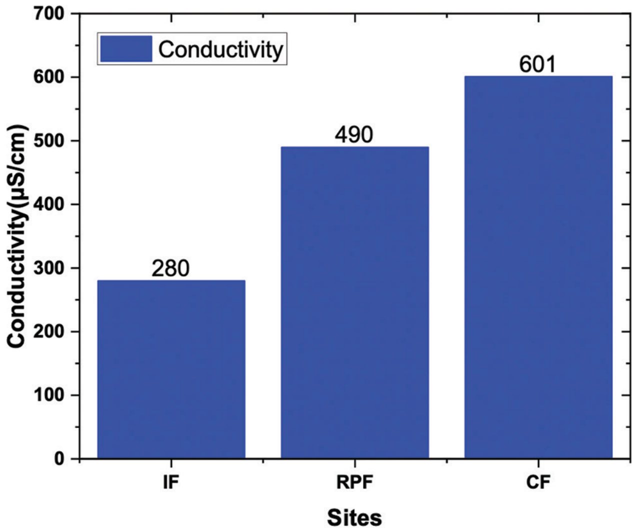


**Figure 5. Variation of electrical conductivity in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

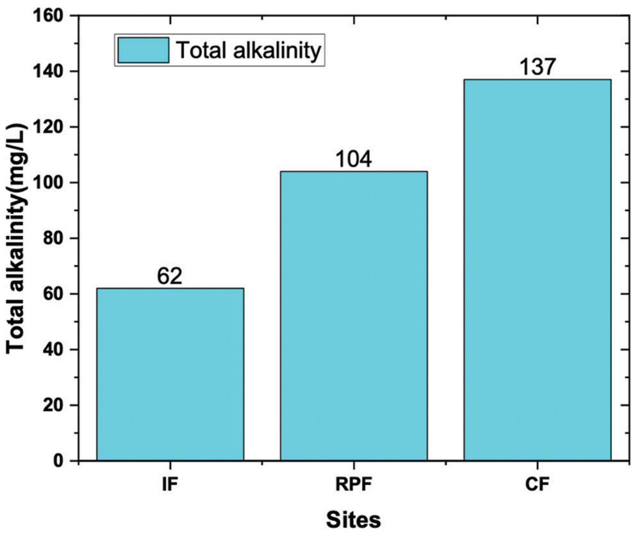


**Figure 6. Variation of total alkalinity in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

to a minimum of 53 mg/L (Sample Cat IF). Naturally, less polluted water tends to be more alkaline than acidic. Alkalinity is a reliable indicator of the presence of dissolved inorganic carbon, such as $HCO_3^-$ and $CO_3^{2-}$. Although not specifically regulated by the WHO or NDWQS, alkalinity is important for buffering capacity and pH stability. Higher alkalinity levels help maintain a stable pH and mitigate acidification.[80,86] Previous investigations[11,87-89] have shown that adequate alkalinity prevents corrosive water conditions and supports the effectiveness of water treatment processes.[90] The observed values indicate a sufficient buffering capacity in the groundwater, supporting its stability and suitability for drinking.

*3.1.5. TH*

The average TH measured at the IF, RPF, and CF was 137 mg/L, 221 mg/L, and 276 mg/L, respectively, as shown in Figure 7. The TH ranged between 99 mg/L and 405 mg/L, with the highest value recorded at 405 mg/L in Sample K near the CF and the lowest hardness at 99 mg/L in Sample C near the IF.

Water hardness traditionally refers to how well water reacts with soap, with hard water requiring a large amount of soap to form a lather. Hardness is primarily caused by divalent cations, including $Ca^{2+}$, $Mg^{2+}$, and other alkaline earth metals, such as iron, manganese, and strontium. These values are below the WHO and NDWQS guideline of <500 mg/L. TH, mainly due to $Ca^{2+}$ and $Mg^{2+}$ ions, can affect water's suitability for various uses.[50,60,90,91] Recent research highlights that while hard water generally does not pose a health risk, it can impact household appliances and plumbing. Previous studies[66,69,92,93] found that water hardness above 300 mg/L can lead to scaling in boilers, making it unsuitable for industrial usage and reducing efficiency in water heaters and other appliances. The observed hardness levels indicate moderate hardness, which is typical for many groundwater sources.

*3.1.6. Total dissolved solids*

The average TDS in groundwater samples collected from the IF, RPF, and CF were 225 mg/L, 125 mg/L, and 175 mg/L, respectively, as depicted in Figure 8. Samples from the IF exhibited the highest average TDS levels. Overall, TDS values ranged from 0 to 400 mg/L across all samples.

Substances that pass through filter paper but remain as residue when water evaporates include dissolved minerals and salts, as well as organic compounds, such as humic substances and tannins. All measured TDS values are within the WHO and NDWQS limit of <1000 mg/L. TDS is a measure of all dissolved substances in water and affects both water quality and taste.[57,66,80] The observed levels are acceptable for drinking water and suggest that the groundwater is relatively low in dissolved solids, which is desirable for maintaining water quality and taste.

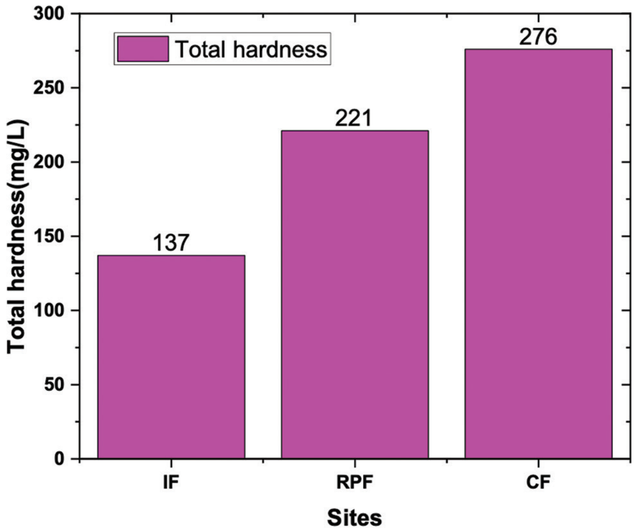


**Figure 7. Variation of total hardness in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

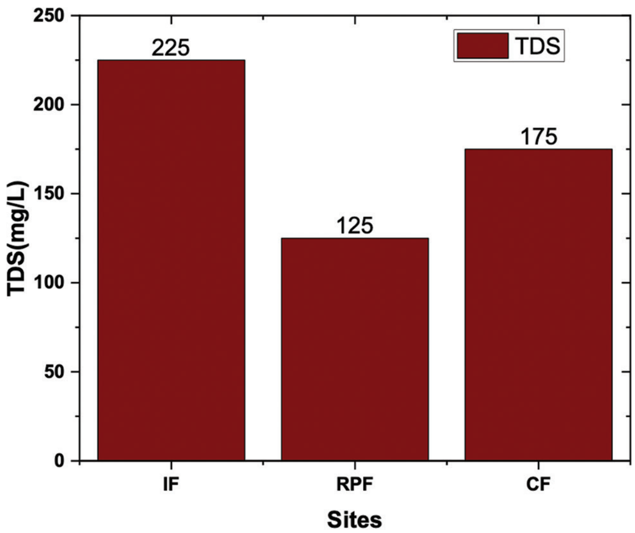


**Figure 8. Variation of TDS in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory; TDS: Total dissolved solids.

According to recent research, lower TDS levels generally correlate with better water quality and palatability. Previous studies[43,94,95] found that water with TDS levels below 500 mg/L is typically considered acceptable for drinking and irrigation purposes. The observed TDS levels suggest that the groundwater is low in dissolved solids and should be suitable for drinking.

*3.1.7. Free carbon dioxide*

The average concentrations of free $CO_2$ in groundwater samples were 36 mg/L at IF, 49 mg/L at RPF, and 63 mg/L at CF, as illustrated in Figure 9. CF showed the highest average free $CO_2$ levels, followed by RPF, while IF had the lowest. The concentration of free $CO_2$ ranged from a minimum of 28.6 mg/L at IF to a maximum of 89.1 mg/L at CF, with Sample B from IF having the highest concentration and Sample K from CF the lowest.

The primary sources of free $CO_2$ in water bodies are respiration and decomposition by aquatic organisms. $CO_2$ reacts with water to partially form calcium bicarbonate; in the absence of $HCO_3^-$, it can convert into $CO_3^{2-}$, releasing additional $CO_2$. High levels of free $CO_2$ can contribute to the formation of carbonic acid, affecting the pH and corrosiveness of water. Although the WHO and NDWQS do not specify limits for $CO_2$, its concentration is crucial for understanding water chemistry. Regular monitoring is essential to assess its impact on water chemistry and infrastructure. Recent studies by Khadka and Khanal[71] and Budhathoki[64] highlight that elevated free $CO_2$ levels can indicate high natural acidity or anthropogenic influences, such as contamination from organic waste. The observed $CO_2$ levels suggest a moderate presence, which is not likely to cause immediate concern but warrants ongoing monitoring.[64,71]

*3.1.8. Chloride*

Chloride concentrations were highest around CF at 68 mg/L, lowest around IF at 50 mg/L, and moderate around RPF at 61 mg/L, as shown in Figure 10. $Cl^-$ levels ranged from a minimum of 22.7 mg/L in Sample B to a maximum of 142.2 mg/L in Sample K. The WHO and NDWQS guideline for $Cl^-$ in drinking water is <250 mg/L, indicating that the observed levels are well within safe limits.

Elevated $Cl^-$ levels can render water unpleasant and unsuitable for drinking or watering livestock. $Cl^-$, a common anion in wastewater, serves as a useful indicator of pollution sources. High $Cl^-$ concentrations can also damage metal pipes and structures and adversely affect agricultural plants. High $Cl^-$ levels can affect taste and contribute to corrosion.[57] They may also indicate pollution sources, such as road salts or industrial discharges. The observed levels are acceptable for drinking water and do not suggest significant contamination.

Previous studies[61,67,96,97] show that while $Cl^-$ is not typically harmful at these concentrations, elevated

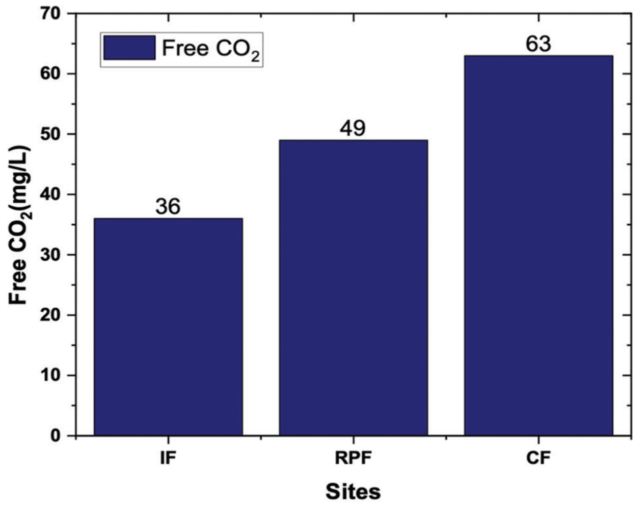


**Figure 9. Variation of free $CO_2$ in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory; $CO_2$: Carbon dioxide.

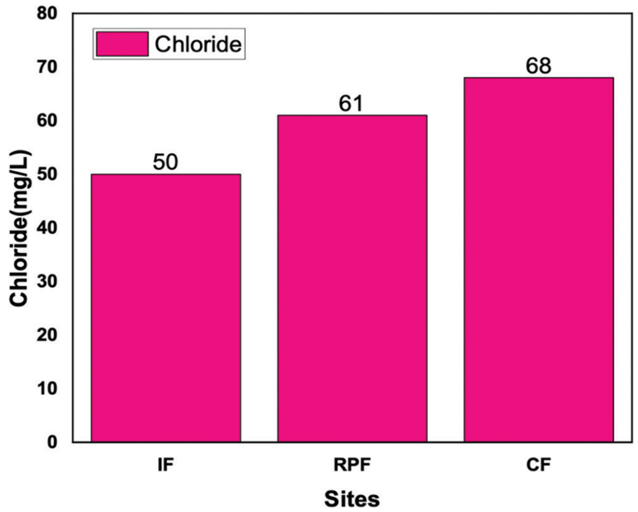


**Figure 10. Variation of chloride in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

levels could indicate pollution or saltwater intrusion, especially in coastal areas. The observed $Cl^-$ levels are typical for many groundwater sources and suggest no significant immediate concerns.[6,42,98]

*3.1.9. Nitrate*

The average $NO_3^-$ concentrations in groundwater samples collected from IF, RPF, and CF were 32 mg/L, 39 mg/L, and 42 mg/L, respectively, as illustrated in Figure 11. CF exhibited the highest average

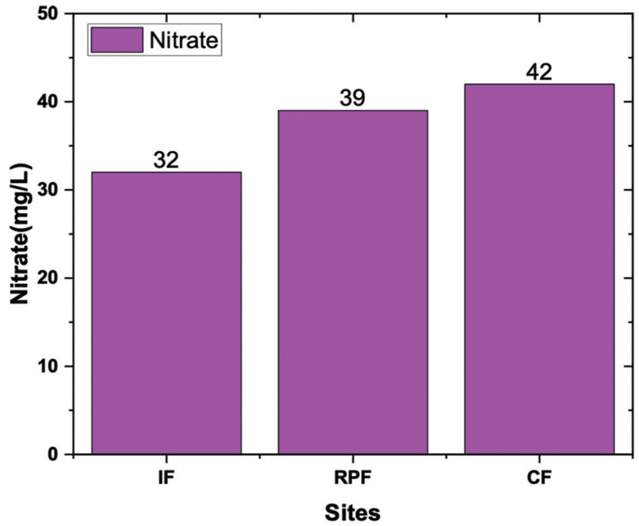


**Figure 11. Variation of nitrate in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

$NO_3^-$ concentration. The $NO_3^-$ levels ranged from a minimum of 23.3 mg/L in Sample A to a maximum of 45.8 mg/L in Sample K. These $NO_3^-$ levels are below the WHO and NDWQS guideline of 50 mg/L, indicating that $NO_3^-$ concentrations are generally within safe limits for drinking water. However, the levels are relatively high compared to those in other groundwater sources, which can be a concern as they may contribute to eutrophication and impact water quality. The variability suggests the influence of agricultural runoff or other $NO_3^-$ sources.

Nitrate contamination in groundwater is often linked to agricultural activities, particularly the use of synthetic fertilizers and manure.[64,71,99] Natural sources of $NO_3^-$ include igneous rocks, domestic sewage, land drainage, and the growth and decay of plants. The typical natural concentration of $NO_3^-$ is 0.1 ppm, but this level can increase due to sewage, industrial effluents, and $NO_3^-$ fertilizers. High $NO_3^-$ levels can lead to conditions, such as methemoglobinemia (blue baby syndrome) in infants, where the ability of blood to carry oxygen is reduced.[1,60,96,99,100]

Previous studies[54,89,93,96,99,101,102] have shown that elevated $NO_3^-$ levels are prevalent in areas with intensive agriculture and can pose long-term risks to water quality and human health. The $NO_3^-$ levels observed in this study suggest that while they are within the recommended limits, ongoing monitoring and management practices are crucial to prevent potential increases in contamination.

*3.1.10. Phosphate*

The average $PO_4^{3-}$ concentration was highest around RPF, at 7.8 mg/L, and lowest around CF at 6.2 mg/L. The concentration of $PO_4^{3-}$ at IF was found to be 6.4 mg/L, as shown in Figure 12. Overall, $PO_4^{3-}$ concentrations varied between 4.3 mg/L (minimum) in Sample E and 9.8 mg/L (maximum) in Samples F and K.

Although there are no specific WHO or NDWQS guidelines for $PO_4^{3-}$, these levels are generally acceptable for groundwater. High $PO_4^{3-}$ concentrations can contribute to the eutrophication of water bodies and promote algal blooms if the water is used in surface water bodies or for irrigation. The observed levels are within a typical range and do not pose immediate health risks.[2,60,93]

Recent research[2,69,87,103,104] highlights that while moderate levels of $PO_4^{3-}$ are generally not a health risk, high concentrations can lead to environmental concerns and impact water quality. In natural water and wastewater, phosphorus is present as orthophosphates, polyphosphates, and organically bound $PO_4^{3-}$. Orthophosphates, often used as fertilizers on agricultural land, can enter water bodies through runoff and percolation. The $PO_4^{3-}$ levels observed in this study are within a typical range for groundwater, but should be monitored to prevent potential environmental impacts.[2,60,93]

*3.1.11. Ammonia*

The $NH_3$ concentrations in groundwater samples were highest around the CF at 11.7 mg/L, moderate around IF at 8.1 mg/L, and lowest around RPF at 8.0 mg/L, as depicted in Figure 13. The $NH_3$ concentrations ranged from a minimum of 7.0 mg/L in Sample I to a maximum of 19.5 mg/L in Sample L, both from the same site. The average $NH_3$ concentration was 9.3 mg/L, with a median value of 8.1 mg/L. Both WHO and NDWQS recommend a maximum of 1.5 mg/L for $NH_3$, indicating that the observed levels are significantly higher. Elevated $NH_3$ levels can be indicative of pollution from agricultural runoff or wastewater discharge and pose health risks, including toxicity to aquatic life and potential impacts on water taste and odor. Immediate remediation and monitoring are recommended to address potential sources of contamination.[49,105]

Recent studies[49,43,64,103,105] confirm that high $NH_3$ concentrations are often linked to agricultural and industrial sources, highlighting the need for targeted pollution control measures. The high levels observed in this study suggest that immediate action may be needed to address potential contamination sources and ensure water safety. One possible reason for the higher $NH_3$ concentrations may be the presence of industries and agricultural areas.

*3.1.12. Microbiological parameter*

The enumeration of *E. coli* colonies in the water samples, determined using the membrane filtration method and direct visualization, ranged from 0 to 9 colonies/100 mL sample. The average colony count was 4.3 per sample at the CF, 2.5 per sample at the IF, and 1.4 per sample at the RPF, as illustrated in Figure 14. The overall mean colony count across all samples was 2.8.

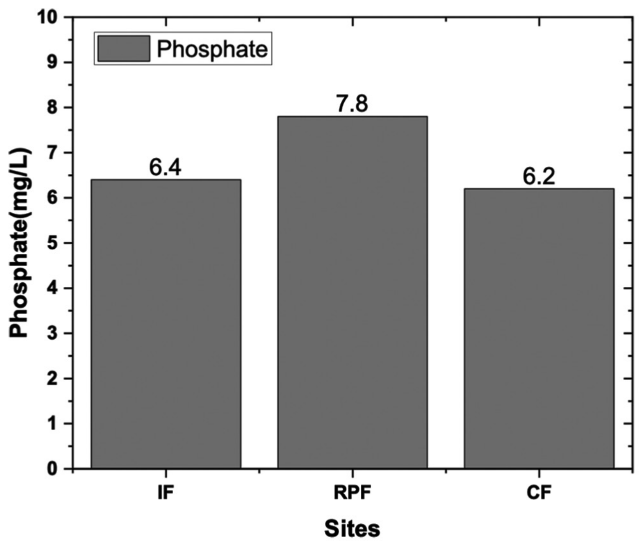


**Figure 12. Variation of phosphate in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory.

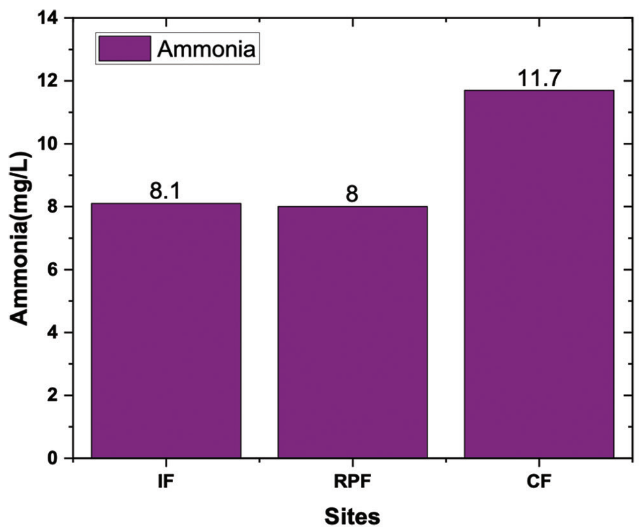


**Figure 13. Variation of ammonia in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal paint factory.

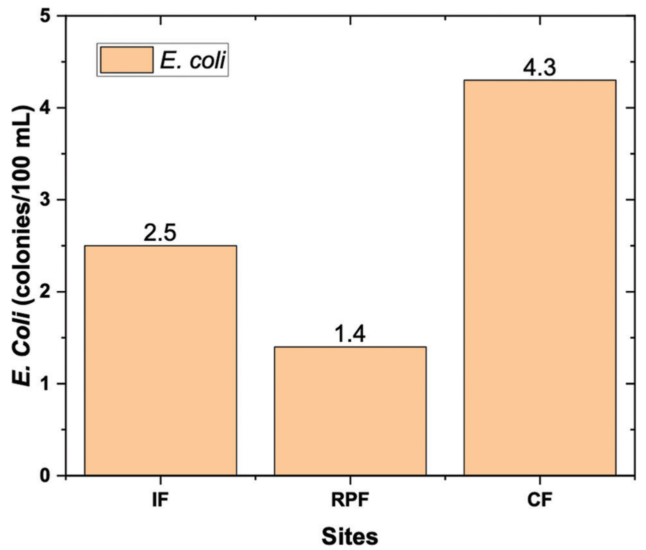


**Figure 14. Variation of *Escherichia coli* in the groundwater of Bharatpur**

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal paint factory.

Out of 12 samples, one-third—that is, Samples A, C, E, and G—from sites IF and RPF contained zero colonies per 100 mL of sample water. However, all other samples—B, D, F, H, I, J, K, and L—contained 1, 9, 1, 6, 3, 7, 2, and 5 colonies per 100 mL of water, respectively. All four samples from site CF exceeded the permissible limit of drinking water quality (Figure 15).

*E. coli* is a key indicator of fecal contamination and the presence of pathogenic microorganisms in water. Both WHO[48] and NDWQS[44] set a standard of 0 colonies/100 mL for drinking water, indicating that the presence of *E. coli* at any detectable level is a concern.

The presence of *E. coli* in groundwater suggests potential contamination from animal waste, inadequate sewage treatment, or other sources of fecal pollution.[106] Even low levels of *E. coli* indicate a risk of exposure to harmful pathogens, which can cause gastrointestinal illnesses and other health problems. Recent studies[49,89,106,107] emphasize the importance of maintaining zero *E. coli* levels in drinking water to ensure safety. They also highlight that even low levels of *E. coli* can pose health risks, particularly in areas with poor sanitation infrastructure. From this study, the presence of *E. coli* might be due to animal waste, leakage from septic tanks, or improper sewage treatment from industrial areas.[106] Therefore, despite the relatively low mean concentration observed, it is crucial to address the sources of contamination and implement effective water treatment and sanitation practices.

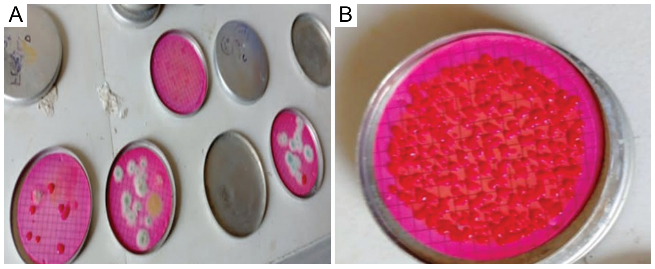


**Figure 15. Result of microbiological analysis for samples from the Coca-Cola factory. (A) *E. Coli.* colony formation in agar (B) Total Coliform in sample water.**

### 3.2. WQI

The results of the WQI, as referenced in the literature,[60,74,108,109] are presented in Table 3.

The calculated WQI values ranged from 560 to 663. Analysis of these WQI values indicates that none of the sampling sites fall into the categories of excellent, good, poor, or even very poor quality. Instead, all samples from the sites were classified as 100% unsuitable for drinking. This finding suggests that the groundwater in the Gondrang area, located near industrial activities in Chitwan, Nepal, does not meet the WHO standards for potable water.

The WQI values[110-112] calculated in this study range from 560 to 663 (Tables S1, S2, and S3), indicating that all samples from the selected sites are deemed unsuitable for drinking. Detailed physicochemical and microbiological parameters of water samples from different sites are given in Table S4. This finding contrasts with the results reported by Ram *et al.*,[76] who observed WQI values between 4.75 and 115.93. Their study suggested that groundwater in their area was generally safe for consumption, except for a few sites in the Charkhari and Jaitpur blocks. Das *et al.* and Das and Choudhary[59,60] reported WQI values ranging from 84.54 to 403.14, noting that elevated WQI values were attributed to higher levels of turbidity, free $CO_2$, and arsenic. That study emphasized the need for groundwater treatment and protection against contamination.

Comparatively, the WQI values obtained in this study are substantially higher than those reported by both Ram *et al.*[76] and Das *et al.* and Das and Choudhary.[59,60] The WQI values from Das *et al.* are closer to our obtained values, whereas those reported by Ram *et al.* are much lower. The elevated WQI values observed in the present study are primarily due to higher concentrations of $NH_3$, $PO_4^{3-}$, and free $CO_2$.

### 3.3. Statistical analysis

All 12 samples from three sites, values were analyzed using descriptive statistics. Maximum, minimum, mean, median, standard deviation, and range were calculated from the observed values. The standard deviation indicates the spread of values from the mean, while the median represents the middle value. The calculated standard deviation and range are presented in Table 4.

#### *3.3.1. Comparison of parameters with water quality standards*

The observed values of all parameters were compared with NDWQS, WHO, and Irrigation Water Quality Standards. From this comparison (Table 5), the average pH, conductivity, TDS, TH, total alkalinity, and $Cl^-$ concentrations were found below the specified limits of both NDWQS and WHO. The concentration of $NO_3^-$ was found below the NDWQS value but above the recommended standard of the WHO. Parameters, such as free $CO_2$, $NH_3$, and $PO_4^{3-}$ exceeded the standard value of the WHO guidelines.

#### *3.3.2. Discussion of physicochemical parameters*

Water is a vital resource for all living organisms, and its management influences environmental, economic, and social aspects. This study examined the physical, chemical, and microbiological characteristics of groundwater to assess its quality. The results (Tables S1-S4) highlight differences in groundwater quality at three distinct sites within the study area based on the evaluated physicochemical parameters.

#### *3.3.3. Statistical analysis of water quality parameters*

Using Statistical Package for the Social Sciences (SPSS) software, the correlation coefficient values (*r*) were determined for each set of water quality measurements. The following formula was used to calculate the correlation coefficient (*r*) between two variables, X and Y:[66]

$$r = \frac{\sum XY - \frac{\sum X \sum Y}{n}}{\sqrt{[\sum X^2 - \frac{(\sum X^2)}{n}][\sum Y^2 - \frac{(\sum Y^2}{n}]}} \quad \text{(XI)}$$

**Table 3. Comparison of WQI standard values with observed values[60,74,108,109]**

| Category of water | WQI range | Percentage of samples | Sample sites | Class |
|---|---|---|---|---|
| Very good water | 0–25 | 0 | - | A |
| Good water | 26–50 | 0 | - | B |
| Poor water | 51–75 | 0 | - | C |
| Very poor water | 76–100 | 0 | - | D |
| Unsuitable for drinking | >100 | 100 | IF, RPF, CF | E |

Abbreviations: CF: Coca-Cola factory; IF: Iron factory; RPF: Royal Paint factory; WQI: Water quality index.

**Table 4. Maximum, minimum, mean, median, standard deviation, and range of measured parameters**

| Parameters | Minimum | Maximum | Mean | Median | SD | Range |
|---|---|---|---|---|---|---|
| Temperature (°C) | 21 | 23 | 22.0 | 22 | 0.7 | 21–23 |
| pH | 7.0 | 7.9 | 7.3 | 7.3 | 0.3 | 7.0–7.9 |
| Conductivity (µs/cm) | 203 | 994 | 456.5 | 420 | 222 | 203–994 |
| TDS (mg/L) | 0 | 400 | 175 | 200 | 154.5 | 0–400 |
| Total hardness (mg/L) | 99 | 405 | 211.2 | 208 | 82.3 | 99–405 |
| Total alkalinity (mg/L) | 53 | 215 | 101.2 | 98 | 44.7 | 53–215 |
| Free $CO_2$ (mg/L) | 28.6 | 89.1 | 49.5 | 45.1 | 17.3 | 28.6–89.1 |
| Chloride (mg/L) | 22.7 | 142.2 | 60 | 48.4 | 38.1 | 22.7–142.2 |
| Phosphate (mg/L) | 4.25 | 9.8 | 6.8 | 6.8 | 1.8 | 4.3–9.8 |
| Ammonia (mg/L) | 7.0 | 19.5 | 9.3 | 8.1 | 3.4 | 7.0–19.5 |
| Nitrate (mg/L) | 23.3 | 45.8 | 37.8 | 40 | 7.8 | 23.3–45.8 |
| *Escherichia coli* (colonies/100 mL) | 0 | 9 | 2.8 | 1.5 | 3.2 | 0–9 |

Abbreviations: $CO_2$: Carbon dioxide; TDS: Total dissolved solids.

 doi: 10.36922/AJWEP025120083

**Table 5. Comparison of observed parameters with water quality standards**

| Parameters | IF | RPF | CF | NDWQS | WHO |
|---|---|---|---|---|---|
| Temperature (°C) | 22.3 | 22.0 | 21.8 | - | - |
| pH | 7.5 | 7.2 | 7.3 | 6.5–8.5 | 6.5–8.5 |
| Conductivity (μs/cm) | 280 | 490 | 601 | 1500 | 1500 |
| TDS (mg/L) | 225 | 125 | 175 | 1000 | 1000 |
| Total hardness (mg/L) | 137 | 221 | 276 | 500 | 300 |
| Total alkalinity (mg/L) | 62 | 104 | 137 | - | - |
| Free $CO_2$ (mg/L) | 36 | 49 | 63 | - | - |
| Chloride (mg/L) | 50 | 61 | 68 | 250 | 250 |
| Phosphate (mg/L) | 6.4 | 7.8 | 6.2 | - | - |
| Ammonia (mg/L) | 8.1 | 8.0 | 11.7 | 1.5 | 1.5 |
| Nitrate (mg/L) | 32 | 39 | 42 | 50 | 10 |
| *Escherichia coli* (colonies/100 mL) | 2.5 | 1.4 | 4.3 | 0 | 0 |

Abbreviations: CF: Coca-cola factory; $CO_2$: Carbon dioxide; IF: Iron factory; NDWQS: Nepal Drinking Water Quality Standard; RPF: Royal Paint Factory; TDS: Total dissolved solids; WHO: World Health Organization.

A strong association between two variables, *X* and *Y*, is indicated if their correlation coefficient (*r*) is relatively large. The linear equation of the form y = Ax + B becomes valid under such conditions.[66]

Traditional graphs used to display groundwater quality data may not adequately illustrate the true relationships between variables, especially when multiple parameters are involved. Given that each parameter falls into a distinct quality class, analyzing them individually becomes complex when additional parameters are introduced into the evaluation. This makes interpreting the results challenging. Accurately analyzing the type and extent of water pollution thus becomes difficult and complicated.[113] Correlation analysis is a widely used and effective statistical method for studying water quality, as it reveals which properties influence water chemistry. It demonstrates the relationships between the variables. Two variables are said to be positively correlated if an increase in one causes an increase in the other, and negatively correlated if an increase in one results in a decrease in the other. The correlation coefficient (*r*) ranges from +1 to −1.[92] According to Das *et al*. and Das and Das,[92,114] correlation is considered weak if its magnitude lies in the range 0.0 ± 0.5, moderate if it lies between ±0.5 and ±0.8, and very strong if it lies between ±0.8 and ±1.0.[66,114] Equation XI was used to calculate the correlation coefficient. The interaction mode of the parameters was further examined using regression analysis. Linear regression can be applied to determine the relationships between parameters.[92]

To identify the most significant groundwater quality parameters and their relationships with other relevant factors, a correlation matrix analysis was conducted. To describe the type and strength of relationships among highly correlated characteristics, the concentrations of dependent parameters were plotted against independent variables. SPSS was used to perform regression analysis between parameters with strong correlations (Figures 16 and S1-S10). Table 6 presents the Pearson correlation (P. correlation) coefficient values for 12 parameters.

### 3.3.4. Correlation results

The groundwater datasets are complex and contain various variables. This complexity highlights the importance of developing sustainable water management plans and solutions. Correlation and regression analyses simplify these datasets by emphasizing the most important factors, making the data more accessible to scientists, decision-makers, and the general public.[96] As such, regression and correlation are essential methods for analyzing groundwater quality, helping to identify patterns, predict trends, and demonstrate relationships among various WQIs. Another advantage of correlation analysis is that it measures the strength and direction of the linear relationship between two parameters. For instance, if conductivity and $NO_3^-$ levels are positively correlated, this could indicate that $NO_3^-$ contamination is associated with higher salinity. Regression analysis builds upon correlation by also offering a predictive equation. This allows for the simulation of how

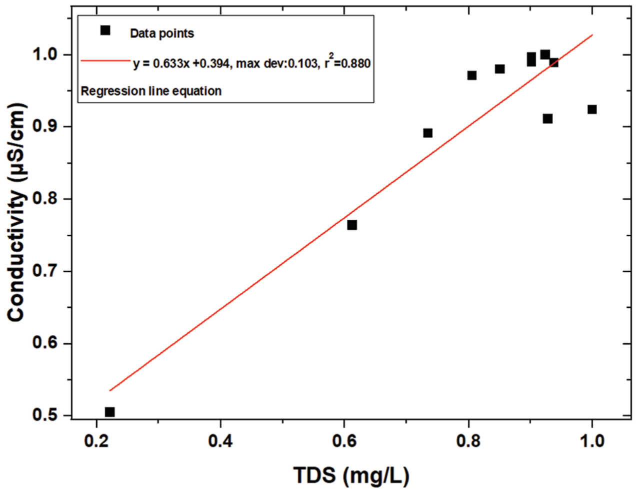


**Figure 16. Regression plot of conductivity versus TDS**
Abbreviation: Max dev: Maximum deviation; TDS: Total dissolved solids.

one water quality variable (e.g., TDS) responds to changes in another (e.g., $Cl^-$ concentration).[43,54,85,115-121] Perfect positive and negative linear relationships are indicated by correlation coefficient values close to +1 and −1, respectively, while a value of 0 denotes no linear relationship. Strong correlations are typically represented by *P. correlation* values near +1 or −1, as shown in Table 6. The statistical significance of a correlation is determined by its significance (Sig. [2-tailed]) value—a value <0.05 indicates significance at the 5% level, while a value <0.01 denotes significance at the 1% level. Asterisks indicate statistically significant correlations (*at the 0.05 level; **at the 0.01 level).

Regression and correlation analysis not only allow the interpretation of groundwater quality data but also help relate observed patterns to hydrogeological processes. These methods are valuable for describing the groundwater system and providing insights into its behavior. The simple correlation coefficient ($r$) quantifies the degree of linearity between any two water quality measures.[54,85,115-120] Table 6 presents the significance levels (2-tailed) and correlation matrix for several key water quality parameters.

The following important findings are derived from the statistical analysis (Table 6). Conductivity was strongly positively correlated with TDS ($r$ = 0.924, $p$=0.025), significant at the 0.05 level. This high correlation is expected, as TDS comprises charged ions that contribute to electrical conductivity. In addition, conductivity was significantly positively correlated at the 0.01 level with TH ($r$ = 0.990, $p$=0.001), indicating that increased dissolved minerals (ions) contribute to both parameters. The correlation between conductivity and total alkalinity was also strong ($r$ = 0.997, $p$=0.000), likely due to the presence of $CO_3^{2-}$ and $HCO_3^-$, which contribute to both alkalinity and conductivity. A strong positive correlation was observed between conductivity and free $CO_2$ ($r$ = 0.980, $p$=0.003), signifying that $CO_2$ dissolution increases ion concentration, thus enhancing conductivity through the formation of carbonic acid or $HCO_3^-$. Moreover, $Cl^-$ showed a strong positive correlation with conductivity ($r$ = 0.989, $p$=0.001), consistent with the fact that $Cl^-$ is highly conductive in water. Similarly, a significant correlation existed between conductivity and $NH_3$ ($r$ = 0.971, $p$=0.006), showing that $NH_3$ increases conductivity by forming ammonium ions ($NH_4^+$) in water. A positive correlation between conductivity and $PO_4^{3-}$ ($r$ = 0.891, $p$=0.042) indicates that $PO_4^{3-}$ also contributes to conductivity. In addition, conductivity was positively correlated with *E. coli* ($r$ = 0.911, $p$=0.032), implying that *E. coli* presence may be associated with increased organic and inorganic dissolved substances, thus influencing conductivity.

TH showed an almost perfect positive correlation, significant at the 0.01 level, with alkalinity ($r$ = 0.995, $p$=0.000), indicating that both parameters are influenced by dissolved minerals, such as calcium, magnesium, and carbonates, which explains their strong relationship. Furthermore, a very strong positive correlation was observed between TH and free $CO_2$, significant at the 0.01 level ($r$ = 0.994, $p$=0.001), suggesting that $CO_2$ dissolution in water affects hardness, possibly through precipitation or dissolution of carbonate compounds. In addition, TH showed a strong correlation with $NH_3$ ($r$ = 0.969, $p$=0.007). The presence of $NH_3$ correlates with hardness, likely due to $NH_3$ forming complex compounds with dissolved minerals. In addition, total alkalinity showed a very strong positive correlation, significant at the 0.01 level, with free $CO_2$ ($r$ = 0.990, $p$=0.001), indicating that alkalinity and free $CO_2$ are chemically linked through the carbonate buffer system. Total alkalinity also showed a strong correlation with $NH_3$ ($r$ = 0.981, $p$=0.003), suggesting a possible interaction between $NH_3$ and alkalinity parameters, likely due to $NH_3$'s effect on pH and carbonate equilibrium. Moreover, $Cl^-$ and *E. coli* demonstrated a strong positive correlation, significant at the 0.01 level ($r$ = 0.961, $p$=0.009), indicating a potentially concerning relationship. High $Cl^-$ levels may signal contamination sources (e.g., sewage or industrial waste) that also contribute to *E. Coli* presence. *E. coli* is a fecal

**Table 6. Statistical table of correlations between various water quality parameters**

| Parameters | pH | Conductivity | TDS | Total hardness | Total alkalinity | Free $CO_2$ | $Cl^-$ | $PO_4^{3-}$ | $NH_3$ | $NO_3^-$ | *Escherichia coli* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | | | | | | | | | | | |
| P. correlation | 1.00 | - | - | - | - | - | - | - | - | - | - |
| Sig. (2-tailed) | - | - | - | - | - | - | - | - | - | - | - |
| Conductivity (µS/cm) | | | | | | | | | | | |
| P. correlation | 0.505 | 1.00 | - | - | - | - | - | - | - | - | - |
| Sig. (2-tailed) | 0.385 | - | - | - | - | - | - | - | - | - | - |
| TDS (mg/L) | | | | | | | | | | | |
| P. correlation | 0.222 | 0.924* | 1.00 | - | - | - | - | - | - | - | - |
| Sig. (2-tailed) | 0.719 | 0.025 | - | - | - | - | - | - | - | - | - |
| Total hardness (mg/L) | | | | | | | | | | | |
| P. correlation | 0.601 | 0.990** | 0.902* | 1.00 | - | - | - | - | - | - | - |
| Sig. (2-tailed) | 0.284 | 0.001 | 0.036 | - | - | - | - | - | - | - | - |
| Total alkalinity (mg/L) | | | | | | | | | | | |
| P. correlation | 0.562 | 0.997** | 0.902* | 0.995** | 1.00 | - | - | - | - | - | - |
| Sig. (2-tailed) | 0.324 | 0.000 | 0.036 | 0.000 | - | - | - | - | - | - | - |
| Free $CO_2$ (mg/L) | | | | | | | | | | | |
| P. correlation | 0.665 | 0.980** | 0.851 | 0.994** | 0.990** | 1.00 | - | - | - | - | - |
| Sig. (2-tailed) | 0.221 | 0.003 | 0.068 | 0.001 | 0.001 | - | - | - | - | - | - |
| Cl− (mg/L) | | | | | | | | | | | |
| P. correlation | 0.385 | 0.989** | 0.938* | 0.960** | 0.977** | 0.944* | 1.00 | - | - | - | - |
| Sig. (2-tailed) | 0.522 | 0.001 | 0.018 | 0.010 | 0.004 | 0.016 | - | - | - | - | - |
| $PO_4^{3-}$ (mg/L) | | | | | | | | | | | |
| P. correlation | 0.823 | 0.891* | 0.735 | 0.943* | 0.917* | 0.959** | 0.817 | 1.00 | - | - | - |
| Sig. (2-tailed) | 0.087 | 0.042 | 0.157 | 0.016 | 0.028 | 0.010 | 0.091 | - | - | - | - |
| $NH_3$ (mg/L) | | | | | | | | | | | |
| P. correlation | 0.641 | 0.971** | 0.806 | 0.969** | 0.981** | 0.985** | 0.945* | 0.917* | 1.00 | - | - |
| Sig. (2-tailed) | 0.244 | 0.006 | 0.099 | 0.007 | 0.003 | 0.002 | 0.015 | 0.028 | - | - | - |
| $NO_3^-$ (mg/L) | | | | | | | | | | | |
| P. correlation | 0.886* | 0.764 | 0.613 | 0.846 | 0.799 | 0.864 | 0.665 | 0.970** | 0.796 | 1.00 | - |
| Sig. (2-tailed) | 0.045 | 0.133 | 0.272 | 0.071 | 0.105 | 0.059 | 0.221 | 0.006 | 0.107 | - | - |
| *Escherichia coli* (colonies/100 mL) | | | | | | | | | | | |
| P. correlation | 0.117 | 0.911* | 0.928* | 0.847 | 0.880* | 0.816 | 0.961** | 0.627 | 0.829 | 0.440 | 1.00 |
| Sig. (2-tailed) | 0.851 | 0.032 | 0.023 | 0.070 | 0.049 | 0.092 | 0.009 | 0.257 | 0.082 | 0.459 | - |

Notes: *Significant correlation at the 0.05 level (2-tailed). **Significant correlation at the 0.01 level (2-tailed). High values (>0.5) are indicated in bold.

Abbreviations: $Cl^-$: Chloride; $CO_2$: Carbon dioxide; $NH_3$: Ammonia; $NO_3^-$: Nitrate; $PO_4^{3-}$: Phosphate; P. correlation: Pearson correlation; Sig.: Significance; TDS: Total dissolved solids.

indicator, and its correlation with $Cl^-$ suggests sewage leakage or wastewater infiltration into groundwater.[87,89] Therefore, while $Cl^-$ is not a direct contaminant, its association with *E. coli* implies co-contamination from organic waste. $PO_4^{3-}$ and $NO_3^-$ showed a very strong positive correlation, significant at the 0.01 level ($r$ = 0.970), indicating that both nutrients often originate from similar sources (e.g., agricultural runoff or wastewater). Furthermore, pH and $NO_3^-$ displayed a moderate positive correlation, significant at the 0.05 level ($r$ = 0.886, $p$=0.045), implying that higher $NO_3^-$ levels may be associated with higher pH, possibly due to the presence of alkaline substances or their effect on the buffering capacity of water. Free $CO_2$ demonstrated a strong correlation with $NH_3$ ($r$ = 0.985, $p$=0.002), suggesting that $NH_3$ levels may be influenced by $CO_2$ levels, likely through pH shifts affecting the $NH_4^+/NH_3$ equilibrium. Free $CO_2$ also showed a strong positive correlation with $Cl^-$ ($r$ = 0.944, $p$=0.016), possibly indicating a shared source, such as industrial pollution or waste discharge. A strong correlation was also found between $Cl^-$ and $NH_3$ (r = 0.945, $p$=0.015), suggesting a link between $Cl^-$ and $NH_3$ levels, potentially from human or animal waste or fertilizer application. Similarly, TDS and *E. Coli* showed a strong positive correlation ($r$ = 0.928, $p$=0.023), indicating that high levels of dissolved solids are associated with microbial contamination, likely due to the presence of organic matter. Meanwhile, TH and E. *coli* demonstrated a moderate correlation ($r$ = 0.847, $p$=0.070), suggesting a potential link between water hardness and bacterial presence. Some parameters exhibited low correlation ($r$ < 0.5), indicating minimal or no relationship—for example, pH and E. *coli* ($r$ = 0.117, $p$=0.851), suggesting no direct link between pH and microbial contamination. Similarly, pH and $PO_4^{3-}$ ($r$ = 0.823, $p$=0.087) demonstrated a moderate but not statistically significant correlation. Similarly, $NO_3^-$ and *E. Coli* showed a weak correlation ($r$ = 0.440, $p$=0.459), suggesting that $NO_3^-$ levels alone do not significantly influence the presence of *E. coli*.

Conductivity was highly correlated with nearly all other parameters, especially TH, total alkalinity, free $CO_2$, and $Cl^-$, indicating that dissolved minerals significantly influence water chemistry. This suggests that conductivity is a good indicator of overall water quality, as it reflects the concentration of dissolved ions. TH and total alkalinity are almost perfectly correlated, reinforcing the idea that they are influenced by similar factors (e.g., dissolved $CO_3^{2-}$ and $HCO_3^-$). *E. coli* showed strong positive correlations with $Cl^-$ and conductivity, indicating contamination likely linked to human, animal, or industrial waste, as both are associated with sewage inputs. Importantly, no strongly negative correlations were observed in the dataset. The findings align with previously reported statistical evaluations of groundwater quality in the literature.[2,54,66,85,88,89,96,115,117-119,121,122]

There was a strong and favorable correlation between $F^-$ and sulfate, as reported by Dobaradaran *et al.*[123] However, a negative correlation between $NO_3^-$ and pH and sulfate was observed. Memon *et al*.[66] also computed correlation coefficients among various parameters, showing less significant correlations between them. A linear regression equation was developed to predict the concentration of elements influencing water quality. There was a very strong positive correlation, ranging between 1% and 5%, across many parameters. The results for sulfate (0.994), $Cl^-$ (0.988), and TH (0.969) were deemed significant using the conventional significance criterion (0.05). However, there were no appreciable changes in overall water quality.[66] Mumtaz *et al.*[54] collected groundwater samples to determine the WQI and measured the levels of water quality parameters that exceeded standard limits. As these districts do not meet APHA standards, they are considered unfit for human consumption according to the WQI scale. However, neither arsenic nor total suspended solids were detected in any of the samples.[54] To assess the present state of groundwater quality, Ashfaq and Ahmad[70] also evaluated groundwater characteristics in Agra city, including pH, $Cl^-$, turbidity, TDS, TH, and alkalinity. As a result, the correlation and regression analyses by identifying the most influential variables and measuring the strength and direction of their linear relationships helped simplify and better interpret the complexity of groundwater quality variations. The statistical study revealed a substantial positive association between conductivity and TDS, alkalinity, hardness, free $CO_2$, $NH_3$, and $PO_4^{3-}$. There was a modest correlation between TH and $PO_4^{3-}$, and a strong positive correlation between TH and total alkalinity, $CO_2$, and $NH_3$. Regression analysis using a first-degree linear equation further validated the correlations among the aforementioned water quality metrics.

In 2024, Das *et al.*[113] carried out more sophisticated research by examining and monitoring groundwater pollution in coastal areas using state-of-the-art technologies, including PCA and factor analysis (FA), multiple linear regression (MLR), and the ground-WQI (GWQI). By using these advanced methods over conventional approaches, complicated analytical tasks were further simplified.[113] Eight groundwater quality parameters were evaluated in this study. PCA/FA identified three principal components that explained nearly 81% of the total variation. Based on GWQI results, approximately 13% of the samples were categorized as "awful" to "extremely poor," while 87% were classified as "good." A model incorporating turbidity, iron, electrical conductivity, manganese, TH, and $Cl^-$ as independent variables was proposed as a more realistic predictor of GWQI, based on the MLR analysis. Furthermore, our MLR model demonstrated that turbidity, with the highest beta coefficient (0.820), was the most substantial contributor to groundwater quality in the affected area.

*3.3.5. Regression analysis*

A simple linear regression analysis was conducted using SPSS software, with temperature as the dependent variable and the other components as independent variables. Among all the parameters considered, the effects of total alkalinity, conductivity, TDS, $PO_4^{3-}$, and TH were found to be significant at the standard significance level (0.05). However, these parameters failed to sufficiently explain fluctuations in the dependent variable, as evidenced by the adjusted $r^2$ values, which were observed to be moderate to very low in many cases. The correlations between these parameter pairs are graphically displayed in the regression charts below (Figure 16). The $r^2$ value provides information on the goodness of fit, with values closer to 1 denoting a better fit, while the slope indicates the direction and strength of the relationship.

*3.3.5.1. Conductivity versus total dissolved solids*

The regression line equation: y = 0.633x + 0.394 (maximum deviation = 0.103, $r^2$ = 0.880) was obtained by plotting conductivity against TDS, as shown in Figure 16. The regression analysis revealed a strong, statistically significant, positive linear relationship, as indicated by the high $r^2$ value (0.880). This equation suggests that for every unit increase in TDS, conductivity increases by 0.633 units. This relationship is consistent with the expected behavior, as TDS represents the total concentration of dissolved ions in water, and conductivity measures the water's ability to conduct electricity,[82-85] which is directly influenced by the presence of those ions. The small maximum deviation (0.103) further confirms the robustness of the regression model in predicting conductivity based on TDS.

*3.3.5.2. Conductivity versus TH*

The regression line equation for the conductivity versus TH regression plot in Figure S1 is y = 0.762x + 0.226 (maximum deviation = 0.107, $r^2$ = 0.925). This high $r^2$ value indicates an extremely strong positive linear association. Thus, it can be concluded that there is a strong correlation between conductivity and TH. The equation suggests that for every unit increase in TH, conductivity increases by 0.762 units. This relationship is consistent with the expected behavior, as higher TH, typically due to dissolved ions, such as $Ca^{2+}$ and $Mg^{2+}$, leads to increased conductivity. The small maximum deviation (0.107) further confirms the robustness of the regression model in predicting conductivity based on TH.

*3.3.5.3. TH versus total dissolved solids*

The regression line equation for the TH versus TDS plot in Figure S2 is y = 0.447x + 0.555 (maximum deviation = 0.320, $r^2$ = 0.700). This value indicates a strong and statistically significant positive linear relationship. The equation implies that for every unit increase in TH, TDS increases by 0.447 units. This relationship is expected, as TH, primarily caused by dissolved $Ca^{2+}$ and $Mg^{2+}$, contributes to the overall TDS in water. The maximum deviation of 0.320 indicates that while the regression model provides a reasonable fit to the data, other factors may also influence TDS.

*3.3.5.4. TH versus free carbon dioxide*

The regression line equation y = 1.09x − 0.0849 (maximum deviation = 0.0931, $r^2$ = 0.942) was obtained by plotting TH against free $CO_2$, as shown in Figure S3. The regression analysis revealed a strong positive linear relationship, as indicated by the high coefficient of determination ($r^2$ = 0.942). This equation suggests that for every unit increase in free $CO_2$, TH increases by 1.09 units. This relationship is consistent with the expected behavior, as free $CO_2$ in water can react with carbonate minerals (e.g., calcium carbonate) to form $HCO_3^-$, which contributes to TH. The small maximum deviation (0.0931) further confirms the robustness of the regression model in predicting TH based on free $CO_2$.

*3.3.5.5. TH versus ammonia*

The regression line equation y = 0.995x + 0.0231 (maximum deviation = 0.115, $r^2$ = 0.905) was obtained by plotting TH against $NH_3$, as depicted in Figure S4. The regression analysis revealed a strong positive linear relationship, indicated by the high $r^2$ value (0.905). This equation suggests that for every unit increase in $NH_3$, TH increases by 0.995 units. This relationship may be attributed to the interaction of $NH_3$ with minerals in the water (such as calcium and magnesium) or its influence on the solubility of carbonate minerals, which contribute to TH. The small maximum deviation (0.115) further confirms the robustness of the regression model.

*3.3.5.6. TH versus total alkalinity*

The regression line equation y = 1.10x − 0.0963 (maximum deviation = 0.0440, $r^2$ = 0.974) was obtained by plotting TH against total alkalinity, as shown in Figure S5. The high $r^2$ value (0.974) indicates a very strong positive relationship. Moreover, this $r^2$ value is higher than for TH versus $NH_3$ (0.905), free $CO_2$ (0.942), conductivity (0.925), and TDS (0.700), suggesting that total alkalinity is the strongest predictor of TH among the variables analyzed. This difference may be due to the direct relationship between total alkalinity and the carbonate minerals that contribute to TH.

*3.3.5.7. Total alkalinity versus chloride*

The regression line equation y = 0.664x + 0.331 (maximum deviation = 0.196, $r^2$ = 0.902) was obtained by plotting total alkalinity against $Cl^-$, as shown in Figure S6. The $r^2$ value of 0.902 indicates a strong positive linear relationship. This equation implies that for every unit increase in $Cl^-$ concentration, total alkalinity increases by 0.664 units. This relationship may be attributed to the coexistence of $Cl^-$ ions with other ions (such as sodium, $Ca^{2+}$, or $Mg^{2+}$) that contribute to alkalinity, or it may reflect indirect geochemical processes linking $Cl^-$ and alkalinity. The relatively small maximum deviation (0.196) further supports the reliability of the regression model in predicting total alkalinity based on $Cl^-$ concentration.

*3.3.5.8. Total alkalinity versus ammonia*

The regression line equation y = 1.11x − 0.0804 (maximum deviation = 0.0909, $r^2$ = 0.899) was obtained by plotting total alkalinity against $NH_3$, as shown in Figure S7. The regression analysis revealed a strong positive linear relationship, as indicated by the high coefficient of determination ($r^2$ = 0.899). This equation suggests that for every unit increase in $NH_3$ concentration, total alkalinity increases by 1.11 units. This relationship may be attributed to the reaction of $NH_3$ with water to form $NH_4^+$, which can influence the buffering capacity of water and contribute to alkalinity. In addition, $NH_3$ may coexist with other ions (such as $CO_3^{2-}$ or $HCO_3^-$) that directly contribute to alkalinity. The small maximum deviation (0.0909) further confirms the robustness of the regression model in predicting total alkalinity based on $NH_3$ concentration.

*3.3.5.9. Conductivity versus total alkalinity*

The regression line equation y = 0.876x + 0.119 (maximum deviation = 0.0370, $r^2$ = 0.983) was obtained by plotting conductivity against total alkalinity, as depicted in Figure S8. The regression analysis revealed a very strong positive linear relationship, as indicated by the high coefficient of determination ($r^2$ = 0.983). This equation suggests that for every unit increase in total alkalinity, conductivity increases by 0.876 units. This relationship is consistent with the expected behavior, as total alkalinity is primarily influenced by $CO_3^{2-}$ and $HCO_3^-$, which are conductive and contribute to the overall ion concentration in water. The very small maximum deviation (0.0370) further confirms the robustness of the regression model.

The $r^2$ value for total alkalinity versus conductivity (0.983) is higher than those for total alkalinity versus $Cl^-$ (0.902), $NH_3$ (0.899), and TH (0.974). This suggests that total alkalinity is the strongest predictor of conductivity among the variables analyzed.

*3.3.5.10. Free carbon dioxide versus ammonia*

The regression line equation y = 0.906x + 0.103 (maximum deviation = 0.0898, $r^2$ = 0.951) was obtained by plotting free $CO_2$ against $NH_3$, as depicted in Figure S9. The regression analysis revealed a very strong positive linear relationship, as indicated by the high value of $r^2$ (0.951). This equation suggests that for every unit increase in $NH_3$ concentration, free $CO_2$ increases by 0.906 units. This relationship may be attributed to the reaction of $NH_3$ with water to form $NH_4^+$ and hydroxide ions, which can influence the equilibrium of $CO_2$ in water and shift it toward the formation of more free $CO_2$. The small maximum deviation (0.0898) further supports the robustness of the regression model.

*3.3.5.11. Escherichia coli versus total dissolved solids*

The regression line equation y = 1.18xm − 0.187 (maximum deviation = 0.280, $r^2$ = 0.953) was obtained by plotting *E. coli* against TDS, as shown in Figure S10. The regression analysis revealed a very strong positive linear relationship, indicated by the high $r^2$ value. This equation suggests that for every unit increase in TDS, *E. coli* concentration increases by 1.18 units. This relationship may be attributed to the fact that higher TDS levels often indicate the presence of organic matter, nutrients, or other dissolved substances that support the growth and survival of *E. coli* and other bacteria. The relatively small maximum deviation (0.280) further confirms the robustness of the regression model in predicting *E. coli* concentration based on TDS.

## 4. Limitations

Groundwater samples for this investigation were collected only from the Gondrang area of Bharatpur Metropolitan City, specifically Wards no. 8 and 9 of Chitwan. Only a limited number of parameters were analyzed, namely, pH, temperature, electrical conductivity, free chlorine, alkalinity, hardness, $PO_4^{3-}$, $NO_3^-$, $Cl^-$ ions, TDS, and $NH_3$. In addition, the study was confined to the pre-monsoon season.

## 5. Recommendations

Based on the findings of this study, the following recommendations are proposed to improve groundwater quality and mitigate associated health risks:

(i) To address groundwater quality issues near industrial areas, it is crucial to implement strict regulations on industrial discharges and to establish routine groundwater monitoring and assessment programs.

(ii) To ensure that water quality remains within safe limits, regular monitoring of residential areas adjacent to industrial sites should be implemented, focusing on parameters, such as TDS, hardness, $NO_3^-$, and *E. coli*.

(iii) To ensure safe drinking water quality for local communities, it is essential to promote groundwater treatment methods, such as activated carbon filtration, membrane-based techniques, such as reverse osmosis for removing particulate matter and contaminants, and disinfection techniques, such as chlorination, ultraviolet treatment, or ozonation. Additional methods, including coagulation-flocculation or chemical precipitation, should also be considered where appropriate.

(iv) To identify potential sources of contamination and their impacts on human health and the environment, detailed investigations (including multi-seasonal data) should be conducted. These investigations can involve comprehensive assessments of additional water quality parameters, particularly heavy metals (e.g., Pb, Cd, As), and larger sample sizes. Such studies will support the development of more precise and targeted water management strategies.

## 6. Conclusion

Findings from the present investigation revealed that all tested parameters, except $NO_3^-$, $PO_4^{3-}$, $NH_3$, free $CO_2$, and *E. coli*, complied with NDWQS and WHO standards. The WQI values ranged from 560 to 663, indicating that the groundwater is unsuitable for drinking purposes. This poor rating is primarily attributed to elevated concentrations of $NH_3$, free $CO_2$, and $PO_4^{3-}$, suggesting significant groundwater contamination. Elevated levels of TDS and hardness reflect substantial mineral content, likely resulting from nearby industrial activities, such as iron processing. Increased $Cl^-$ and $PO_4^{3-}$ levels further suggest contributions from industrial processes and discharges, which may have harmful effects on human health. The presence of *E. coli* in the samples indicates microbial contamination, potentially arising from inadequate waste disposal or sanitation practices associated with industrial activities in the studied area, contributing to various waterborne diseases. Elevated concentrations of pollutants were detected, including $NH_3$ (7–19.5 mg/L), $PO_4^{3-}$ (4.3–9.8 mg/L), and free $CO_2$. In addition, increased $NO_3^-$ levels and the presence of *E. coli* (0–9 colony-forming unit/100 mL) indicated potential health risks.

Descriptive statistics, such as mean, standard deviation, and minimum and maximum values were calculated. In addition, correlation and regression simplified the complexities of variance by highlighting the most significant variables, making data interpretation easier, and quantifying the degree and direction of linear relationships between variables. The statistical analysis indicates the following key findings: Conductivity is strongly positively correlated with TDS ($r$ = 0.924, $p$=0.025), TH ($r$ = 0.990, $p$=0.001), total alkalinity ($r$ = 0.997, $p$=0.000), free $CO_2$ ($r$ = 0.980, $p$=0.003), $NH_3$ ($r$ = 0.971, $p$=0.006), $Cl^-$ ($r$ = 0.989, $p$=0.001), $PO_4^{3-}$ ($r$ = 0.891, $p$=0.042), and *E. coli* ($r$ = 0.911, $p$=0.032), signifying that higher conductivity is associated with higher values of these parameters. TH showed an almost perfect positive correlation with total alkalinity ($r$ = 0.995, $p$=0.000), free $CO_2$ ($r$ = 0.994, $p$=0.001), and $NH_3$ ($r$ = 0.969, $p$=0.007). Total alkalinity also demonstrated a very strong positive correlation with free $CO_2$ ($r$ = 0.990, $p$=0.001) and $NH_3$ ($r$ = 0.981, $p$=0.003). Moreover, $Cl^-$ and *E. coli* ($r$ = 0.961, $p$=0.009) were strongly positively correlated. pH and $NO_3^-$ exhibit a moderate positive correlation ($r$ = 0.886, $p$=0.045). Free $CO_2$ was strongly correlated with $NH_3$ ($r$ = 0.985, $p$=0.002), suggesting that $NH_3$ is influenced by $CO_2$ levels, likely through pH shifts affecting $NH_4^+/NH_3$

equilibrium. Free $CO_2$ also showed a strong positive correlation with $Cl^-$ ($r$ = 0.944, $p$=0.016), which may indicate a common source, such as industrial pollution or waste discharge. A strong correlation between $Cl^-$ and $NH_3$ ($r$ = 0.945, $p$=0.015) suggests a shared source, potentially from human/animal waste or fertilizers. Similarly, the strong positive correlation between $PO_4^{3-}$ and $NO_3^-$ ($r$ = 0.970, $p$=0.006) suggests a common origin, such as agricultural runoff or wastewater contamination. Regression analysis using a first-degree linear equation further supported the correlations between many of the aforementioned water quality metrics. These findings provide useful insights for decision-makers in developing mitigation plans to monitor water quality in the studied areas and reduce the health risks associated with contaminated groundwater.

Overall, the findings highlight an urgent need for improved water treatment, continuous monitoring, and stringent pollution control measures to address the adverse effects of industrial activities on groundwater quality and public health.

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## Conflict of interest

The authors declare that they have no competing interests.

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## Availability of data

Data are available from the corresponding author upon reasonable request.

## References

1. Oluseyi T, Olayinka K, Adeleke I. Assessment of ground water pollution in the residential areas of Ewekoro and Shagamu due to cement production. *Afr J Environ Sci Technol.* 2011;5:786-794.
2. Boateng TK, Opoku F, Acquaah SO, Akoto O. Groundwater quality assessment using statistical approach and water quality index in Ejisu-Juaben municipality, Ghana. *Environ Earth Sci.* 2016;75:489. doi: 10.1007/s12665-015-5105-0
3. Milanović P, Stevanović Z. Fifty years of history of the karst commission of the international association of hydrogeologists. *Hydrogeol J.* 2021;29:7-19. doi: 10.1007/s10040-020-02261-4
4. Li P, Tian R, Xue C, Wu J. Progress, opportunities, and key fields for groundwater quality research under the impacts of human activities in China with a special focus on Western China. *Environ Sci Pollut Res.* 2017;24:13224-13234. doi: 10.1007/s11356-017-8753-7
5. Kassegne AB, Leta S. Assessment of physicochemical and bacteriological water quality of drinking water in Ankober District, Amhara Region, Ethiopia. *Cogent Environ Sci.* 2020;6:1791461. doi: 10.1080/23311843.2020.1791461
6. Sitaram DU. Study of the physio-chemical parameters for testing water: A review. *World J Adv Res Rev.* 2022;14:570-575. doi: 10.30574/wjarr.2022.14.3.0600
7. Reza R, Singh G. Physico-chemical analysis of ground water in Angul-Talcher region of Orissa, India. *J Am Sci*. 2009;5:53-58.
8. Harter T. *Groundwater Quality and Groundwater Pollution*. California: University of California, Agriculture and Natural Resources; 2003. doi: 10.3733/ucanr.8084
9. Qureshi SS, Channa A, Memon SA, *et al*. Assessment of physicochemical characteristics in groundwater quality parameters. *Environ Technol Innov.* 2021;24:101877. doi: 10.1016/j.eti.2021.101877

10. Daud MK, Nafees M, Ali S, *et al*. Drinking water quality status and contamination in Pakistan. *Biomed Res Int.* 2017;2017:7908183. doi: 10.1155/2017/7908183
11. Haile Reda A. Physico-chemical analysis of drinking water quality of Arbaminch Town. *J Environ Anal Toxicol.* 2016;6:2. doi: 10.4172/2161-0525.1000356
12. Ottong DJ, Ekanem JO. Physicochemical and heavy metals analysis of Udo Awankwo River in Ikot Ekpene, South-South, Nigeria. *World J Adv Res Rev.* 2021;10:392-398. doi: 10.30574/wjarr.2021.10.3.0282
13. Li P. To make the water safer. *Expo Health*. 2020;12:337-342. doi: 10.1007/s12403-020-00370-9
14. Li P, Wu J. Sustainable living with risks: Meeting the challenges. *Hum Ecol Risk Assess.* 2019;25:1-10. doi: 10.1080/10807039.2019.1584030
15. Subba Rao N, Ravindra B, Wu J. Geochemical and health risk evaluation of fluoride rich groundwater in Sattenapalle Region, Guntur District, Andhra Pradesh, India. *Hum Ecol Risk Assess.* 2020;26:2316-2348. doi: 10.1080/10807039.2020.1741338
16. He X, Li P, Wu J, Wei M, Ren X, Wang D. Poor groundwater quality and high potential health risks in the Datong Basin, Northern China: Research from Published Data. *Environ Geochem Health*. 2021;43:791-812. doi: 10.1007/s10653-020-00520-7
17. Chakraborti D, Rahman MM, Mukherjee A, *et al*. Groundwater arsenic contamination in Bangladesh-21 years of research. *J Trace Elem Med Biol*. 2015;31:237-248. doi: 10.1016/j.jtemb.2015.01.003
18. He X, Li P, Ji Y, Wang Y, Su Z, Elumalai V. Groundwater arsenic and fluoride and associated arsenicosis and fluorosis in China: Occurrence, distribution and management. *Expo Health.* 2020;12:355-368. doi: 10.1007/s12403-020-00347-8
19. Wang D, Wu J, Wang Y, Ji Y. Finding high-quality groundwater resources to reduce the hydatidosis incidence in the Shiqu County of Sichuan Province, China: Analysis, assessment, and management. *Expo Health*. 2020;12:307-322. doi: 10.1007/s12403-019-00314-y
20. Su Z, Wu J, He X, Elumalai V. Temporal changes of groundwater quality within the groundwater depression cone and prediction of confined groundwater salinity using grey Markov model in Yinchuan Area of Northwest China. *Expo Health*. 2020;12:447-468. doi: 10.1007/s12403-020-00355-8
21. Tatti F, Petrangeli Papini M, Torretta V, Mancini G, Boni MR, Viotti P. Experimental and numerical evaluation of groundwater circulation wells as a remediation technology for persistent, low permeability contaminant source zones. *J Contam Hydrol.* 2019;222:89-100. doi: 10.1016/j.jconhyd.2019.03.001
22. Elumalai V, Nethononda VG, Manivannan V, Rajmohan N, Li P, Elango L. Groundwater quality assessment and application of multivariate statistical analysis in Luvuvhu Catchment, Limpopo, South Africa. *J Afr Earth Sci*. 2020;171:103967. doi: 10.1016/j.jafrearsci.2020.103967
23. Hashim MA, Mukhopadhyay S, Sahu JN, Sengupta B. Remediation technologies for heavy metal contaminated groundwater. *J Environ Manage.* 2011;92:2355-2388. doi: 10.1016/j.jenvman.2011.06.009
24. He X, Li P. Surface water pollution in the middle Chinese loess plateau with special focus on hexavalent chromium (Cr6+): Occurrence, sources and health risks. *Expo Health.* 2020;12:385-401. doi: 10.1007/s12403-020-00344-x
25. Abbas G, Murtaza B, Bibi I, *et al.* Arsenic uptake, toxicity, detoxification, and speciation in plants: Physiological, biochemical, and molecular aspects. *Int J Environ Res Public Health*. 2018;15:29. doi: 10.3390/ijerph15010059
26. Rebelo FM, Caldas ED. Arsenic, lead, mercury and cadmium: Toxicity, levels in breast milk and the risks for breastfed infants. *Environ Res.* 2016;151:671-688. doi: 10.1016/j.envres.2016.08.027
27. Lesser LE, Mora A, Moreau C, *et al*. Survey of 218 organic contaminants in groundwater derived from the world's largest untreated wastewater irrigation system: Mezquital valley, Mexico. *Chemosphere*. 2018;198:510-521. doi: 10.1016/j.chemosphere.2018.01.154
28. Sorensen JPR, Lapworth DJ, Nkhuwa DCW, *et al*. Emerging contaminants in urban groundwater sources in Africa. *Water Res*. 2015;72:51-63. doi: 10.1016/j.watres.2014.08.002
29. Lapworth DJ, Baran N, Stuart ME, Manamsa K, Talbot J. Persistent and emerging micro-organic contaminants in chalk groundwater of England and France. *Environ Pollut.* 2015;203:214-225. doi: 10.1016/j.envpol.2015.02.030
30. Schulze S, Zahn D, Montes R, *et al*. Occurrence of emerging persistent and mobile organic contaminants in European water samples. *Water Res.* 2019;153:80-90. doi: 10.1016/j.watres.2019.01.008
31. Wu J, Zhang Y, Zhou H. Groundwater chemistry and groundwater quality index incorporating health risk weighting in Dingbian County, Ordos Basin of Northwest China. *Chem Erde*. 2020;80:125607. doi: 10.1016/j.chemer.2020.125607
32. Jenifer MA, Jha MK. Comprehensive risk assessment of groundwater contamination in a weathered hard-rock aquifer system of India. *J Clean Prod*. 2018;201:853-868. doi: 10.1016/j.jclepro.2018.08.005

33. Jha MK, Shekhar A, Jenifer MA. Assessing groundwater quality for drinking water supply using hybrid fuzzy-GIS-based water quality index. *Water Res.* 2020;179:115867. doi: 10.1016/j.watres.2020.115867
34. Yuan Y, Xiang M, Liu C, Theng BKG. Chronic impact of an accidental wastewater spill from a smelter, China: A study of health risk of heavy metal (Loid)s via vegetable intake. *Ecotoxicol Environ Saf.* 2019;182:109401. doi: 10.1016/j.ecoenv.2019.109401
35. Njuguna SM, Makokha VA, Yan X, Gituru RW, Wang Q, Wang J. Health risk assessment by consumption of vegetables irrigated with reclaimed waste water: A case study in Thika (Kenya). *J Environ Manage*. 2019;231:576-581. doi: 10.1016/j.jenvman.2018.10.088
36. Wu J, Li P, Qian H, Fang Y. Assessment of soil salinization based on a low-cost method and its influencing factors in a semi-arid agricultural area, Northwest China. *Environ Earth Sci*. 2014;71:3465-3475. doi: 10.1007/s12665-013-2736-x
37. Schillinger J, Özerol G, Güven-Griemert Ş, Heldeweg M. Water in war: Understanding the impacts of armed conflict on water resources and their management. *Wiley Interdiscipl Rev Water* 2020;7:e1480. doi: 10.1002/wat2.1480
38. Çiner F, Sunkari ED, Şenbaş BA. Geochemical and multivariate statistical evaluation of trace elements in groundwater of Niğde Municipality, South-Central Turkey: Implications for arsenic contamination and human health risks assessment. *Arch Environ Contam Toxicol*. 2021;80:164-182. doi: 10.1007/s00244-020-00759-2
39. Yadav IC, Devi NL, Mohan D, Shihua Q, Singh S. Assessment of groundwater quality with special reference to arsenic in Nawalparasi District, Nepal using multivariate statistical techniques. *Environ Earth Sci.* 2014;72:259-273. doi: 10.1007/s12665-013-2952-4
40. Raja V, Lakshmi RV, Sekar CP, Chidambaram S, Neelakantan MA. Health risk assessment of heavy metals in groundwater of industrial Township Virudhunagar, Tamil Nadu, India. *Arch Environ Contam Toxicol*. 2021;80:144-163. doi: 10.1007/s00244-020-00795-y
41. Tiwari AK, Singh AK. Hydrogeochemical investigation and groundwater quality assessment of Pratapgarh District, Uttar Pradesh. *J Geol Soc India*. 2014;83:329-343. doi: 10.1007/s12594-014-0045-y
42. Ali S, Verma S, Agarwal MB, *et al*. Groundwater quality assessment using water quality index and principal component analysis in the Achnera Block, Agra District, Uttar Pradesh, Northern India. *Sci Rep.* 2024;14:5381. doi: 10.1038/s41598-024-56056-8
43. Mahato S, Mahato A, Karna PK, Balmiki N. Investigating aquifer contamination and groundwater quality in Eastern Terai Region of Nepal. *BMC Res Notes*. 2018;11:321. doi: 10.1186/s13104-018-3445-z
44. National Drinking Quality Standards and Directives (NDWQS). Implementation directives for national drinking water quality standards. Government of Nepal, Ministry of Physical Planning and Works, Kathmandu. *Tribhuvan Univ J Microbiol.* 2023;5: 83-88.
45. Andermann C, Longuevergne L, Bonnet S, Crave A, Davy P, Gloaguen R. Impact of transient groundwater storage on the discharge of Himalayan rivers. *Nat Geosci*. 2012;5:127-132. doi: 10.1038/ngeo1356
46. Mukherjee A, Fryar AE, Shea BMO. Major Occurrences of Elevated Arsenic. Vol. 6. United States: John Wiley & Sons, Ltd. Inc.; 2008. p. 1-47. doi: 10.1002/9780470741122.ch6
47. Diwakar J, Johnston SG, Burton ED, Shrestha S. Das arsenic mobilization in an alluvial aquifer of the Terai Region, Nepal. *J Hydrol Reg Stud*. 2015;4:59-79. doi: 10.1016/j.ejrh.2014.10.001
48. WHO. *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda.* Geneva: World Health Organization; 2022.
49. Shrestha S, Bista S, Byanjankar N, Shrestha S, Joshi DR, Prasai Joshi T. Groundwater quality evaluation for drinking purpose using water quality index in Kathmandu Valley, Nepal. *Water Sci*. 2023;37:239-250. doi: 10.1080/23570008.2023.2237278
50. Ghimire M, Regmi T, Kayastha SP, Bhuiyan C. Groundwater quality and community health risk in Lalitpur Metropolitan City, Nepal-a geospatial analysis. *Geocarto Int.* 2023;38:2168069. doi: 10.1080/10106049.2023.2168069
51. Sarkar B, Mitchell E, Frisbie S, Grigg L, Adhikari S, Maskey Byanju R. Drinking water quality and public health in the Kathmandu Valley, Nepal: Coliform bacteria, chemical contaminants, and health status of consumers. *J Environ Public Health*. 2022;2022:3895859. doi: 10.1155/2022/3895859
52. Trivedy RK, Goel PK. Chemical and biological methods for water pollution studies, Karad (India): Environmental publications. *J Raman Spectrosc*. 1986;6:10. doi: 10.1128/jcm.34.12.2914-2920.1996
53. Wagner B. Resolution submitted to APHA protecting children from overexposure to lead in candy and protecting children by lowering the blood lead "level of concern" standard. *J Nevada*. 2005;1:8-13.
54. Mumtaz M, Jahanzaib SH, Khan S, Ismail S, Hussain W, Khan FA. Implementation of water quality index for measuring groundwater quality. *Migr Lett.* 2024;21:273-287. doi: 10.59670/ml.v21is11.10691
55. Hasan AA, Al-Obaidi I, Abed ZM. Using lime to remove chromium from tannery factory industrial wastewater in

Baghdad. *J Eng Sustain Dev.* 2025;29:120-126. doi: 10.31272/jeasd.1220
56. Xu Z. *Dissolved Oxygen Dynamics and Modeling - a Case Study in a Subtropical Shallow Lake*. Vol. 22. Netherlands: Elsevier Sci. Ltd.; 2014. p. 114.
57. Sayato Y. WHO guidelines for drinking-water quality. *Eisei Kagaku*. 2022;35:307-312. doi: 10.1248/jhs1956.35.307
58. Khatri N, Tyagi S, Rawtani D, Tharmavaram M, Kamboj RD. Analysis and assessment of ground water quality in Satlasana Taluka, Mehsana District, Gujarat, India through Application of Water Quality Indices. *Groundw Sustain Dev.* 2020;10:100321. doi: 10.1016/j.gsd.2019.100321
59. Das BD, Mishra RK, Choudhary SK. Groundwater quality in Biratnagr of Morang District, Nepal. *Int J Res GRANTHAALAYAH*. 2021;9:368-377. doi: 10.29121/granthaalayah.v9.i5.2021.3961
60. Das BD, Choudhary SK. Application of water quality index (WQI) for groundwater quality assessment of Biratnagar, Nepal. *Our Nat.* 2021;19:54-61. doi: 10.3126/on.v19i1.41260
61. Pant BR. Ground water quality in the Kathmandu valley of Nepal. *Environ Monit Assess.* 2011;178:477-485. doi: 10.1007/s10661-010-1706-y
62. Oinam JD, Ramanathan AL, Singh G. Geochemical and statistical evaluation of groundwater in Imphal and Thoubal District of Manipur, India. *J Asian Earth Sci.* 2012;48:136-149. doi: 10.1016/j.jseaes.2011.11.017
63. Verma A, Pandey G. Study of some physico-chemical parameters of groundwater in Gorakhpur District. *Int J Eng Res Technol*. 2013;2:2967-2973.
64. Budhathoki R. *Analysis of the Physico-Chemical and Bacteriological Parameters of Bottled Water Available in Kathmandu Valley a Case Study on the Partial Fulfillment of the Requirements for M. Sc., First Year, Environment Science, T. U.; M.Sc. Thesis, Central Department of Microbiology*, TU; 2010. p. 1-36.
65. Paudyal R, Kang S, Sharma CM, Tripathee L, Sillanpaä M. Variations of the physicochemical parameters and metal levels and their risk assessment in urbanized Bagmati River, Kathmandu, Nepal. *J Chem*. 2016;2016:6025905. doi: 10.1155/2016/6025905
66. Memon YI, Qureshi SS, Kandhar IA, *et al*. Statistical analysis and physicochemical characteristics of groundwater quality parameters: A case study. *Int J Environ Anal Chem.* 2023;103:2270-2291. doi: 10.1080/03067319.2021.1890064
67. Laghari AN, Siyal ZA, Bangwar DK, Soomro MA, Walasai G, Shaikh FA. Groundwater quality analysis for human consumption. *Technol Appl Sci Res.* 2018;8:2616-2620.
68. Walter N. A review of the principles of turbidity measurement. *Prog Phys Geography Br J Haematol*. 2009;8:2616-2622. doi: 10.1177/0309133317726540
69. García-Ávila F, Zhindón-Arévalo C, Valdiviezo-Gonzales L, Cadme-Galabay M, Gutiérrez-Ortega H, del Pino LF. A comparative study of water quality using two quality indices and a risk index in a drinking water distribution network. *Environ Technol Rev.* 2022;11:49-61. doi: 10.1080/21622515.2021.2013955
70. Ashfaq A, Ahmad F. Study on assessment of underground water quality. *Int J Curr Microbiol Appl Sci*. 2014;3:612-616.
71. Khadka D, Khanal G. Assessment of physicochemical parameters of drinking water in the schools of Bagnashkali, Palpa, Nepal. *Tribhuvan J.* 2023;2:1-10. doi: 10.3126/tribj.v2i1.60215
72. Wang BB. Research on drinking water purification technologies for household use by reducing total dissolved solids (TDS). *PLoS One*. 2021;16:e0257865. doi: 10.1371/journal.pone.0257865
73. Wood WW. *Guidelines for Collection and Field Analysis of Groundwater Samples for Selected Unstable Constituents. Techniques of Water-resources Investigations of the United States Geological Survey*. Vol. 1. Reston, VA: U.S. Geological Survey; 1981. p. D2-11.
74. Brown RM, McClelland NI, Deininger RA, O'Connor MF. A water quality index - crashing the psychological barrier. *Indic Environ Qual.* 1972;6:173-182. doi: 10.1007/978-1-4684-2856-8_15
75. Tirkey P, Bhattacharya T, Chakraborty S. Water quality indices- important tools for water quality assessment. *Int J Adv Chem*. 2013;1:15-28.
76. Ram A, Tiwari SK, Pandey HK, Chaurasia AK, Singh S, Singh YV. Groundwater quality assessment using water quality index (WQI) under GIS framework. *Appl Water Sci.* 2021;11:46. doi: 10.1007/s13201-021-01376-7
77. Prest EI, Hammes F, van Loosdrecht MCM, Vrouwenvelder JS. Biological stability of drinking water: Controlling factors, methods, and challenges. *Front Microbiol.* 2016;7:1-24. doi: 10.3389/fmicb.2016.00045
78. Riffat R, Husnain T. *Fundamentals of Wastewater Treatment and Engineering*. 2nd ed. London: Taylor & Francis; 2022.
79. Li P, Karunanidhi D, Subramani T, Srinivasamoorthy K. Sources and consequences of groundwater contamination. *Arch Environ Contam Toxicol.* 2021;80:1-10. doi: 10.1007/s00244-020-00805-z
80. Mohammadi AA, Morovati M, Najafi Saleh H, *et al*. Groundwater quality evaluation for drinking and industrial purposes. A case study in Northeastern Iran. *Int J Environ Anal Chem.* 2022;102:6094-6104. doi: 10.1080/03067319.2020.1807533

81. Narayan S, Rai S, Behera M, Ranjan A. Dynamic assembly and stabilization of surfactant-dye-polyelectrolyte complexes: An overview. *J Mol Liq*. 2025;421:126897. doi: 10.1016/j.molliq.2025.126897
82. Yadav SN, Rai S, Sinha B, Bhattarai A. Influence of polyelectrolyte (NaCMC) on surfactant (DTAB) in the absence and presence of methyl orange dye in ethanol - water mixed solvent at three different temperatures. *ChemistrySelect*. 2024;9:202404772. doi: 10.1002/slct.202404772
83. Narayan S, Rai S, Bhattarai A, Sinha B. Impact of sodium polystyrene sulfonate on micellization behaviour of Cetyltrimethylammonium bromide in the presence of methyl red in ethanol - water mixture: A conductometric investigation. *J Mol Liq.* 2024;399:124387. doi: 10.1016/j.molliq.2024.124387
84. Narayan S, Rai S, Shah P, Roy N, Bhattarai A. Spectrophotometric and conductometric studies on the interaction of surfactant with polyelectrolyte in the presence of dye in aqueous medium spectrophotometric and conductometric studies on the interaction of surfactant with polyelectrolyte in the presence. *J Mol Liq*. 2022;355:118949. doi: 10.1016/j.molliq.2022.118949
85. Dohare D, Deshpande S, Kotiya A. Analysis of ground water quality parameters: A review. *Res J Eng Sci*. 2014;3:2278-9472.
86. Devi S, Premkumar R. Physicochemical analysis of groundwater samples near industrial Area, Cuddalore District, Tamil Nadu, India. *Int J ChemTech Res.* 2012;4:29-34.
87. Mengstie YA, Desta WM, Alemayehu E. Assessment of drinking water quality in urban water supply systems: The case of Hawassa City, Ethiopia. *Int J Anal Chem.* 2023;2023:8880601. doi: 10.1155/2023/8880601
88. Susaiappan S, Somanathan A, Sulthan MT, Masilamani IP. Groundwater quality variation and regression analysis a case study around municipal dumpsite in India. *Rev Chim.* 2021;72:133-145. doi: 10.37358/rc.21.1.8410
89. Kothari V, Vij S, Sharma SK, Gupta N. Correlation of various water quality parameters and water quality index of districts of Uttarakhand. *Environ Sustain Indic.* 2021;9:100093. doi: 10.1016/j.indic.2020.100093
90. Porsan ZP, Zarei A, Alimohammadi M. Evaluation of corrosion and scaling potential of drinking groundwater in Gonbad-e Kavus. *Desalin Water Treat.* 2020;195:19-25. doi: 10.5004/dwt.2020.25895
91. Al-Khashman OA, Jaradat AQ. Assessment of groundwater quality and its suitability for drinking and agricultural uses in arid environment. *Stoch Environ Res Risk Assess.* 2014;28:743-753. doi: 10.1007/s00477-013-0787-x
92. Das CR, Das S, Panda S. Groundwater quality monitoring by correlation, regression and hierarchical clustering analyses using WQI and PAST tools. *Groundw Sustain Dev.* 2022;16:100708. doi: 10.1016/j.gsd.2021.100708
93. Alemu CM, Aycheh YF, Angualie GS, Engidayehu SS. Modeling on comprehensive evaluation of groundwater quality status using geographic information system (GIS) and water quality index (WQI): A case study of Bahir Dar City, Amhara, Ethiopia. *Water Pract Technol.* 2024;19:1084-1098. doi: 10.2166/wpt.2024.076
94. Abolli S, Nasab MA, Yaghmaeian K, Alimohammadi M. Determination the effects of physico-chemical parameters on groundwater status by water quality index (WQI). *Desalin Water Treat.* 2022;269:84-92. doi: 10.5004/dwt.2022.28755
95. Ji Y, Wu J, Wang Y, Elumalai V, Subramani T. Seasonal variation of drinking water quality and human health risk assessment in Hancheng City of Guanzhong Plain, China. *Expo Health.* 2020;12:469-485. doi: 10.1007/s12403-020-00357-6
96. Khan MK, Ayoub W, Saied S, *et al*. Statistical and geospatial assessment of groundwater quality in the megacity of Karachi. *J Water Resour Prot.* 2019;11:311-332. doi: 10.4236/jwarp.2019.113018
97. Abbasnejad B, Abbasnejad A, Derakhshani R. Groundwater evaluation of Northern Jazmourian (South Iran) for drinking, agriculture, and associated health risks of nitrate and fluoride contamination. *Hum Ecol Risk Assess.* 2023;29:36-57. doi: 10.1080/10807039.2022.2140028
98. Mohan U, Singh R. Water quality assessment and physicochemical parameters of groundwater in District Hapur, Uttar Pradesh, India. *Environ Conserv J.* 2013;14:143-149.
99. Picetti R, Deeney M, Pastorino S, *et al*. Nitrate and nitrite contamination in drinking water and cancer risk: A systematic review with meta-analysis. *Environ Res.* 2022;210:112988. doi: 10.1016/j.envres.2022.112988
100. Dahiya S, Singh B, Gaur S, Garg VK, Kushwaha HS. Analysis of groundwater quality using fuzzy synthetic evaluation. *J Hazard Mater.* 2007;147:938-946. doi: 10.1016/j.jhazmat.2007.01.119
101. Ding F, Chen L, Sun C, Zhang W, Yue H, Na S. An upgraded groundwater quality evaluation based on hasse diagram technique & game theory. *Ecol Indic.* 2022;140:109024. doi: 10.1016/j.ecolind.2022.109024
102. Subba Rao N. Groundwater quality from a part of Prakasam District, Andhra Pradesh, India. *Appl Water Sci.* 2018;8:1-18. doi: 10.1007/s13201-018-0665-2

103. Thakur JK, Diwakar J, Singh SK. Hydrogeochemical evaluation of groundwater of Bhaktapur Municipality, Nepal. *Environ Earth Sci.* 2015;74:4973-4988. doi: 10.1007/s12665-015-4514-4
104. Hanipha M, Hussain Z. Study of groundwater quality at Dindigul Town, Tamilnadu, India. *Int Res J Environ Sci.* 2019;2:68-73.
105. Pei-Yue L, Hui Q, Jian-Hua W. Groundwater quality assessment based on improved water quality index in Pengyang County, Ningxia, Northwest China. *E-J Chem.* 2010;7:209-216. doi: 10.1155/2010/451304
106. Olaolu TD. Pollution indicators and pathogenic microorganisms in wastewater treatment: Implication on receiving water bodies. *Int J Environ Prot Policy*. 2014;2:205. doi: 10.11648/j.ijepp.20140206.12
107. Yu F, Okamto S, Nakasone K, *et al*. Molecular cloning and functional characterization of α-humulene synthase, a possible key enzyme of Zerumbone biosynthesis in shampoo ginger (Zingiber Zerumbet Smith). *Planta*. 2008;227:1291-1299. doi: 10.1007/s00425-008-0700-x
108. Kar S. Determination of water quality index (WQI) during mass bathing in different Ghats of river ganga in Howrah and North 24 Parganas District, West Bengal, India. *Int J Res Appl Sci Eng Technol.* 2017;887:1097-1104. doi: 10.22214/ijraset.2017.9159
109. Das Kangabam R, Bhoominathan SD, Kanagaraj S, Govindaraju M. Development of a water quality index (WQI) for the Loktak Lake in India. *Appl Water Sci.* 2017;7:2907-2918. doi: 10.1007/s13201-017-0579-4
110. Lumb A, Sharma TC, Bibeault JF. A review of genesis and evolution of water quality index (WQI) and some future directions. *Water Qual Expo Health*. 2011;3:11-24. doi: 10.1007/s12403-011-0040-0
111. Şener Ş, Şener E, Davraz A. Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey). *Sci Total Environ*. 2017;584-585:131-144. doi: 10.1016/j.scitotenv.2017.01.102
112. Bora M, Goswami DC. Water quality assessment in terms of water quality index (WQI): Case study of the Kolong River, Assam, India. *Appl Water Sci.* 2017;7:3125-3135. doi: 10.1007/s13201-016-0451-y
113. Das CR, Das S, Panda S. MLR index-based principal component analysis to investigate and monitor probable sources of groundwater pollution and quality in coastal areas: A case study in East India. *Environ Monit Assess.* 2023;195:1158. doi: 10.1007/s10661-023-11804-7
114. Das CR, Das S. Assessment of surface water quality for drinking by combining three water quality indices with their usefulness: Case of Damodar River in India. *Water Air Soil Pollut.* 2023;234:327. doi: 10.1007/s11270-023-06342-4
115. Olasehinde P, Amadi A, Dan-Hassan M, Jimoh M. Statistical assessment of groundwater quality in Ogbomosho, Southwest Nigeria. *Am J Min Metall.* 2015;3:21-28. doi: 10.12691/ajmm-3-1-4
116. Jena V, Sinha D. Physicochemical analysis of ground water of selected areas of Raipur City. *Indian J Sci Res*. 2017;13:61-65.
117. Gulgundi MS, Shetty A. Groundwater quality assessment of Urban Bengaluru using multivariate statistical techniques. *Appl Water Sci.* 2018;8:43. doi: 10.1007/s13201-018-0684-z
118. Singh EJK, Gupta A, Singh NR. Groundwater quality in Imphal West District, Manipur, India, with multivariate statistical analysis of data. *Environ Sci Pollut Res.* 2013;20:2421-2434. doi: 10.1007/s11356-012-1127-2
119. Trabelsi R, Zouari K. Coupled geochemical modeling and multivariate statistical analysis approach for the assessment of groundwater quality in irrigated areas: A study from North Eastern of Tunisia. *Groundw Sustain Dev.* 2019;8:413-427. doi: 10.1016/j.gsd.2019.01.006
120. Singh CK, Shashtri S, Mukherjee S. Integrating multivariate statistical analysis with GIS for geochemical assessment of groundwater quality in Shiwaliks of Punjab, India. *Environ Earth Sci*. 2011;62:1387-1405. doi: 10.1007/s12665-010-0625-0
121. Kim JH, Kim RH, Lee J, Cheong TJ, Yum BW, Chang HW. Multivariate statistical analysis to identify the major factors governing groundwater quality in the coastal area of Kimje, South Korea. *Hydrol Process*. 2005;19:1261-1276. doi: 10.1002/hyp.5565
122. Molekoa MD, Avtar R, Kumar P, Minh HVT, Kurniawan TA. Hydrogeochemical assessment of groundwater quality of Mokopane Area, Limpopo, South Africa using statistical approach. *Water (Switzerland)*. 2019;11:1891. doi: 10.3390/w11091891
123. Dobaradaran S, Mahvi AH, Dehdashti S, Dobaradaran S, Shoara R. Correlation of fluoride with some inorganic constituents in groundwater of Dashtestan, Iran. *Fluoride*. 2009;42:50-53.