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Research Paper

"Groundwater Under Threat: A Multivariate Analysis of Physico-Chemical and Microbial Contaminants in Relation to Urbanization, Agriculture, and Industrial Effluents".

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Abstract:

Groundwater contamination has become a global environmental and public health concern due to rapid urbanization, industrial expansion, and poor waste management. This study evaluates the physico-chemical characteristics of groundwater, influenced by landfill leachate and sewage effluents. Using a lysimetric setup and seasonal field sampling (2022–2024), water samples from hand pumps, bore wells, and open wells were analyzed for pH, electrical conductivity (EC), total dissolved solids (TDS), hardness, alkalinity, major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, NO_3^-, PO_4^{3-}), and pollution indicators (BOD, COD, DO). Microbial assessment was performed using MPN and coliform analysis. Results indicated seasonal variability and anthropogenic influence, with nitrate (up to 86.9 mg/L), chloride (up to 497.6 mg/L), sulphate (up to 445.0 mg/L), and phosphate (>1.0 mg/L) exceeding WHO/BIS limits. BOD (14.69 mg/L) and COD (33.26 mg/L) values confirmed organic contamination, while microbial analysis revealed high fecal coliform counts, raising health concerns. Findings emphasize the need for integrated groundwater monitoring, stricter regulation of sewage/industrial effluents, and sustainable waste management.

Keywords: *groundwater contamination, lysimetric setup, seasonal variability, microbial pollution, urbanization*

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I. Introduction:

Over the past few decades, the world has witnessed unprecedented population growth, a trend that is particularly acute in developing nations such as India. This demographic expansion has exerted tremendous pressure on natural resources and public infrastructure, especially water supply systems, sanitation facilities, and public health frameworks. As populations surge, the demand for freshwater escalates, while improper waste management and unsustainable urban planning compromise the quality and availability of groundwater—an essential source of drinking water for billions of people worldwide. According to WHO and UNICEF, despite progress under the Millennium Development Goals (MDGs), millions of people across South-East Asia, Sub-Saharan Africa, and other low-income regions still lack access to safe drinking water and adequate sanitation. The persistence of this challenge highlights the complex nexus between human development, environmental sustainability, and public health.

Groundwater, which accounts for nearly one-third of the world's freshwater reserves, remains particularly vulnerable to contamination due to its concealed nature and limited natural purification capacity. Rapid urbanization has exacerbated this vulnerability, as poorly designed drainage systems, inadequate sewage treatment, and the unregulated disposal of solid waste introduce a wide spectrum of contaminants into the subsurface. Landfill leachate, generated by the decomposition of municipal solid waste, is a major pollutant in this regard. If not adequately managed, leachate infiltrates soils, migrates into aquifers, and severely compromises groundwater quality. Such contamination is often difficult to detect until it reaches advanced stages, by which point remediation becomes costly and technically challenging. The situation is especially pronounced in expanding metropolitan regions, such as Alexandria in Egypt or cities across South Asia, where urban sprawl outpaces the development of waste management infrastructure.

Agriculture, another dominant sector in developing economies, adds to the burden on groundwater resources. The intensive use of chemical fertilizers, pesticides, and herbicides has led to the accumulation of nitrates, phosphates, and other agrochemicals in aquifers. These pollutants not only disrupt the ecological balance of aquatic systems but also pose severe risks to human health, including methemoglobinemia ("blue baby syndrome"), cancers, and endocrine disruptions. Furthermore, the rise of large-scale irrigation has accelerated groundwater extraction, leading to declining water tables and salinity intrusion, which further degrade water quality.

Industrialization compounds these issues by introducing heavy metals, dyes, hydrocarbons, and other toxic effluents into groundwater systems. Many small- and medium-scale industries, often operating in unregulated settings, discharge untreated or partially treated wastewater into surface water bodies, which then infiltrates aquifers. The cumulative effects of urban, agricultural, and industrial activities create a complex contamination profile that is both spatially and temporally variable, demanding sophisticated analytical approaches to assess and mitigate the risks.

In addition to chemical pollutants, microbial contamination represents an equally critical concern. Approximately 1.8 billion people globally consume water contaminated with fecal matter, leading to persistent outbreaks of diarrhea, cholera, typhoid, dysentery, and other waterborne diseases. Children under the age of five are disproportionately affected, with diarrhea-related illnesses accounting for nearly 2 million deaths annually. Microbial contaminants often originate from untreated sewage, septic tank leakages, and improperly managed solid waste dumps. The infiltration of these pathogens into groundwater highlights the urgent need for integrated monitoring and management strategies.

Interestingly, while microbial activity is often viewed as a source of contamination, it also holds potential for remediation. Microbial leaching, or bioleaching, has emerged as a promising biotechnological approach to detoxify contaminated soils and waste. Certain bacteria and archaea are capable of mobilizing or immobilizing toxic metals and organic pollutants, thereby reducing their bioavailability and ecological impact. Similarly, microbial consortia play a vital role in sewage treatment, where they decompose organic matter and neutralize hazardous compounds. Harnessing these microbial processes offers opportunities for sustainable waste management, reduced environmental footprints, and improved groundwater protection.

Given the dual pressures of rising population and inadequate infrastructure, groundwater contamination from urbanization, agriculture, and industrial effluents has become a critical environmental and public health issue. Understanding the extent, sources, and interactions of contaminants requires comprehensive multivariate analyses that integrate physicochemical parameters with microbial profiles. Such an approach enables the identification of pollution patterns, risk factors, and potential pathways for intervention.

Therefore, the present study undertakes a detailed investigation into the threats facing groundwater resources, focusing on the interplay between urban expansion, agricultural intensification, and industrial discharges. By applying multivariate statistical techniques, it aims to disentangle the complex contamination dynamics and assess both physicochemical and microbial pollutants. Furthermore, the study explores the potential role of microbial leaching as a sustainable strategy for mitigating groundwater pollution. Insights from this research are expected to contribute to the development of informed policies and practices for groundwater protection, waste management, and public health improvement, particularly in regions where water scarcity and contamination converge to create acute vulnerabilities.

II. Methodology:

This study was conducted using groundwater, drainage, and landfill leachate samples collected from selected sites representing varying degrees of exposure to urbanization, agriculture, and industrial activities. A range of laboratory materials and equipment were employed to ensure accurate assessment of groundwater quality. The experimental setup included a lysimetric system designed to simulate percolation dynamics, supported by personal protective equipment for safe handling of samples, and standard laboratory glassware such as burettes, pipettes, flasks, and measuring cylinders. Digital instruments, including pH meters, conductivity meters, turbidity meters, and dissolved oxygen meters, were used for in-situ and laboratory analyses. Reagents were prepared for titrations and spectrophotometric analyses, while microbial testing was conducted using culture media procured from SRL and HiMedia. Photographic documentation was maintained throughout sampling and experimental procedures. Statistical analyses were carried out using GraphPad Prism, applying Student's t-test and one-way ANOVA for testing significance at $p \leq 0.05$. All stock solutions were prepared using double-distilled deionized water, and laboratory glassware was thoroughly rinsed with the same water before use to minimize contamination.

Groundwater samples were obtained from 16 tube wells located within 500 m to 2 km of dumping sites and agricultural or industrial zones. Sampling was conducted seasonally during March, June, September, and December from 2022 to 2024 to capture seasonal variability in groundwater characteristics. Samples were collected in sterile 100 ml polyethylene bottles, which had been pre-sterilized with ethanol and oven-dried at 40 °C. To ensure representativeness, triplicate samples were collected from each site between 08:00 and 11:00 A.M. All samples were immediately preserved at 4 °C in insulated iceboxes and transported to the laboratory, where analyses were performed within five hours to prevent significant physicochemical or microbial changes.

A controlled lysimetric setup was developed to mimic natural percolation processes and quantify pollutant infiltration. Soil used in the lysimeters was collected from the same groundwater sampling sites and characterized for texture, porosity, and hydraulic conductivity. The lysimeter columns were packed with compacted soil layers to simulate natural stratification. Environmental conditions, including temperature, light, and humidity, were controlled to reproduce field conditions. Sensors were embedded at different depths to continuously record key parameters such as pH, electrical conductivity (EC), temperature, turbidity, salinity, dissolved oxygen (DO), and total dissolved solids (TDS).

To simulate rainfall infiltration, distilled water was applied to the lysimeter surface, and leachate samples were collected at different depths and time intervals. These samples were analyzed alongside groundwater samples to evaluate the physicochemical and microbial quality of percolating water and to estimate pollutant transport dynamics.

Physicochemical analyses were conducted according to standard protocols outlined in APHA (2017) and ISI 10500:2012 guidelines. Parameters such as pH were measured using a calibrated digital pH meter, while EC and TDS were measured using conductivity and portable TDS meters, respectively. Calcium and magnesium hardness were determined using EDTA titrations with appropriate indicators, and total hardness was estimated by the Eriochrome Black-T method. Total alkalinity was assessed through acid-base titration using H_2SO_4 with phenolphthalein and methyl orange as indicators. Nitrate levels were quantified via UV-spectrophotometry at 220 nm, with calibration performed using potassium nitrate standards. Phosphate concentrations were measured using the stannous chloride colorimetric method, recording absorbance at 690 nm. Dissolved oxygen was determined using Winkler's method, while biochemical oxygen demand (BOD) was estimated by measuring DO on day 0 and after five days of incubation at 20 °C. Chemical oxygen demand (COD) was measured by the dichromate reflux method followed by titration with ferrous ammonium sulfate. All results were reported in mg/L, except EC (µS/cm) and pH (unitless).

Microbial quality of groundwater was assessed through total bacterial count, total coliforms, and fecal coliforms. Total bacterial colonies were enumerated using the pour plate technique on nutrient agar after serial dilution and incubation at 37 ± 0.5 °C for 24–48 hours. Total and fecal coliforms were quantified by the multiple-tube fermentation method using Lauryl Tryptose Broth for presumptive tests, Brilliant Green Lactose Bile Broth for confirmation, and Eosin Methylene Blue Agar for completion. Isolates were further verified by Gram staining and spore staining. The most probable number (MPN) index was calculated using the 10-tube method with 10 ml aliquots, and results were reported with 95% confidence limits. Fecal coliforms, specifically *Escherichia coli*, were further assessed using the NF T 90-433 microplate method.

Risk assessment was performed at two levels. Biological risk assessment used the Beta-Poisson model (Haas et al., 1999) to estimate infection risks from *E. coli*. Model parameters included exposure dose (d), median infective dose ($N50 = 8.60 \times 10^7$), and the probability parameter ($\alpha = 0.1778$). Results were compared with WHO thresholds, which recommend ≤1 fecal coliform per 100 ml of water. Human health risk assessment for nitrate exposure was conducted for both oral and dermal pathways. Oral exposure was quantified using the chronic daily intake (CDI) model, which incorporates nitrate concentration, ingestion rate, exposure duration, body weight, and average exposure time. Dermal exposure was assessed using the dermal absorbed dose (DAD) model, which included parameters such as the dermal adsorption coefficient, contact time, bathing frequency, skin surface area, and conversion factors. Non-carcinogenic risk was evaluated through the Hazard Quotient (HQ), where an $HQ > 1$ indicated potential risk.

All analyses were performed in triplicate, and results were expressed as mean ± standard deviation. Statistical analyses were performed using GraphPad Prism, with Student's t-test used for comparing two groups and one-way ANOVA applied to compare multiple groups. Significance was determined at $p \leq 0.05$. Multivariate analyses, including Principal Component Analysis (PCA) and Cluster Analysis (CA), were employed to identify correlations between physicochemical parameters, microbial loads, and contamination sources linked to urbanization, agriculture, and industrial effluents.

III. Results:

The study area experiences three distinct climatic seasons—summer, rainy, and winter—which directly influence groundwater characteristics. During 2023–2024, the average maximum temperature was recorded at 31.5 °C, while the minimum fell to 18.95 °C. Rainfall was concentrated between July and September, producing an average annual precipitation of 148.85 mm over 50–55 rainy days. Groundwater samples collected throughout these seasons were consistently clear and odorless, with measured temperatures ranging from 27.0–31.0 °C in the rainy season, 29.01–41.5 °C in summer, and 10.05–22.06 °C in winter. Seasonal variation strongly influenced turbidity and dissolved oxygen levels, reflecting hydrological recharge and geochemical dynamics within the aquifers.

The analysis of physicochemical parameters revealed that groundwater pH ranged from 6.1–7.4 in hand pumps, 5.9–7.0 in bore-wells, and 5.9–7.3 in wells. These values fall within the WHO and BIS permissible range of 6.5–8.5, indicating that groundwater in the study area is generally neutral to slightly alkaline. Minor seasonal shifts were observed, with slightly lower pH values during the monsoon, likely due to surface runoff and organic inputs. Turbidity also exhibited marked seasonality, with values between 2.5–3.7 NTU during the rainy season, 0.6–1.4 NTU in winter, and 2.1–2.3 NTU in summer. All samples remained within acceptable limits of ≤5 NTU, with elevated turbidity during rainfall periods reflecting higher inflows from surface sources.

Total Dissolved Solids (TDS) levels varied across groundwater sources. Hand pump samples ranged from 318.6–1710.0 mg/L, bore-wells from 205–1391 mg/L, and wells from 170–650.98 mg/L. All values were within the WHO guideline of 2000 mg/L, confirming potability. Elevated TDS concentrations in hand pumps suggest mineral dissolution from shallow aquifers and possible anthropogenic influences. Electrical Conductivity (EC) values ranged from 480–2640 µS/cm, with averages of 1152.67 µS/cm for hand pumps, 1130.33 µS/cm for bore-wells, and 1138.44 µS/cm for wells. These values closely correlated with TDS, confirming moderate mineralization of groundwater. Localized higher EC values were attributed to possible saline intrusion or agricultural inputs such as fertilizer residues.

Total Hardness (TH) ranged from 76.6–135 mg/L in hand pumps, 81–137 mg/L in bore-wells, and 71–133 mg/L in wells. All readings fell well below the permissible limit of 500 mg/L, indicating water suitability for domestic purposes without the risk of excessive scaling.

Assessment of major constituents showed that sodium concentrations ranged between 51–75 mg/L across all sources, remaining below the WHO limit of 200 mg/L. Potassium concentrations were low, ranging from 2.5–7.4 mg/L and posing no concern. Calcium concentrations varied more widely, between 26–145 mg/L, contributing to overall hardness but still within acceptable limits. Magnesium remained relatively stable at 10.4–11.5 mg/L across all samples. Chloride levels, however, varied considerably: 83.3–181.3 mg/L in bore-wells, 106–320 mg/L in hand pumps, and 152–460 mg/L in wells. Occasional elevations, particularly in well water, suggest possible sewage infiltration or agricultural leaching. Total Alkalinity (TA) was very low, ranging from 0.7–3.93 mg/L, reflecting limited buffering capacity of the groundwater.

Minor constituents and indicator parameters provided further insights into contamination sources. Nitrate concentrations were found to be 20.08–83.6 mg/L in hand pumps, 20.1–48.3 mg/L in bore-wells, and 45.6–86.9 mg/L in wells. Several well samples exceeded the WHO permissible limit of 50 mg/L, indicating anthropogenic contamination likely from fertilizer runoff and sewage seepage. Sulphate concentrations ranged from 135.5–405 mg/L in hand pumps, 263–367 mg/L in bore-wells, and 106.6–226.6 mg/L in wells. While all values remained within the WHO limit of 500 mg/L, elevated levels in bore-wells point towards possible industrial effluents or intensive agricultural activity. Phosphate concentrations were generally low, ranging from 0.08–1.15 mg/L, with the highest levels observed in bore-wells, likely linked to detergent usage and fertilizer application.

Oxygen demand indicators further reflected groundwater quality. Dissolved oxygen remained stable across sources, with values of 6.1 mg/L in hand pumps, 6.3 mg/L in bore-wells, and 6.6 mg/L in wells. These values, being above 5 mg/L, indicate good oxygenation; however, microbial activity during the rainy season may cause localized reductions. Biochemical Oxygen Demand (BOD) values ranged from 5.4–8.2 mg/L in hand pumps, 4.2–7.3 mg/L in bore-wells, and 4.9–7.3 mg/L in wells. These slightly elevated values, particularly in hand pumps, suggest localized organic contamination. Chemical Oxygen Demand (COD) ranged from 10.9–21.9 mg/L in hand pumps, 10.8–23.9 mg/L in bore-wells, and 10.5–24.0 mg/L in wells, reflecting moderate levels of organic and inorganic loads, with bore-wells showing the highest variability.

Comparative assessment with WHO and BIS standards indicated that most physicochemical parameters were within permissible limits, confirming the general potability of groundwater. However, localized exceedances were observed for nitrates, particularly in well samples, chlorides in certain wells, and sulphates in bore-wells. These results highlight the impact of anthropogenic activities, especially agricultural fertilizer use, landfill leachate infiltration, and inadequate sanitation infrastructure.

The groundwater quality in the study area is largely acceptable for drinking and domestic purposes, but seasonal fluctuations and site-specific contamination remain concerns. Nitrates and chlorides represent the most significant risks, especially in wells that are more exposed to surface contamination. Organic pollution indicators, such as BOD and COD, also suggest localized wastewater intrusion, with hand pumps and bore-wells showing elevated values. Continuous monitoring is therefore recommended, particularly in agricultural and landfill-adjacent zones, to mitigate groundwater degradation and protect public health.

Figure 1: Graph showing the A) different pH values obtained, B) Electrical conductivity, C) Total Dissolved Solid (TDS), and D) Total Hardness (TH) recorded from the different sites.

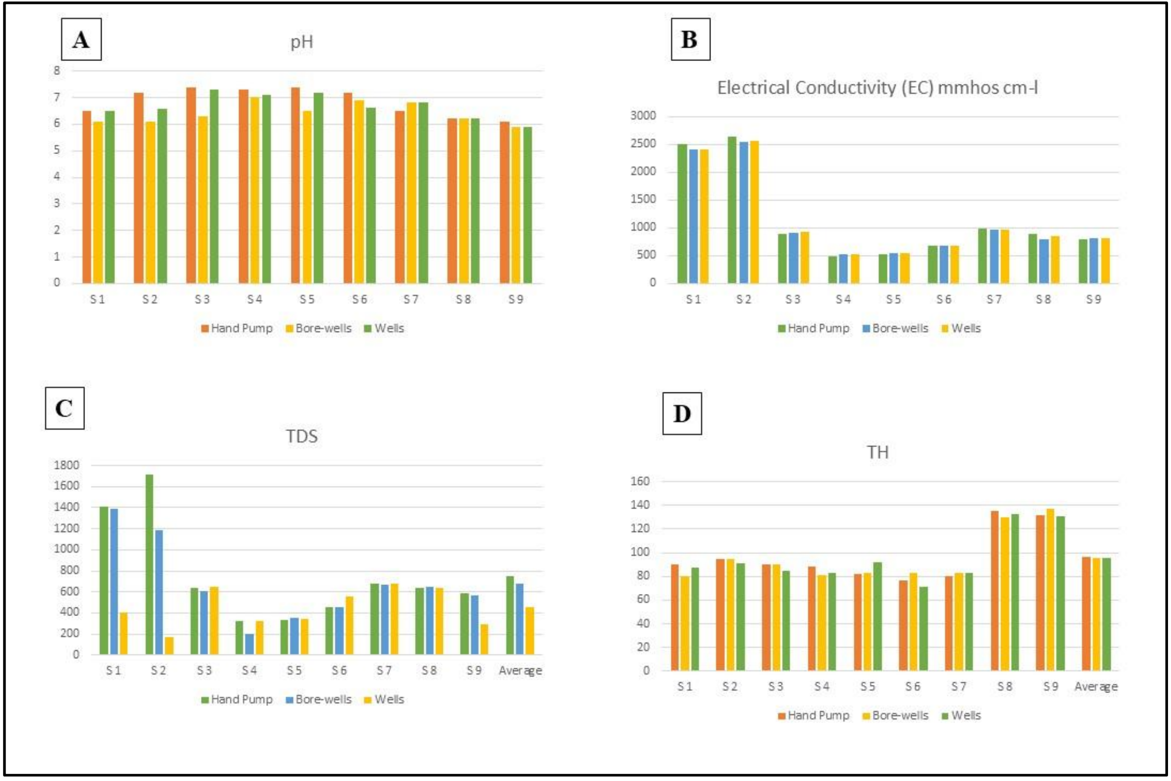


Figure 2: Graph representing the Major Constituents including A) Sodium (Na), B) Potassium (K); C) Calcium (Ca); D) Magnesium (Mg); (E) Chloride (Cl), and (F) Total Alkalinity recorded from the different sites .

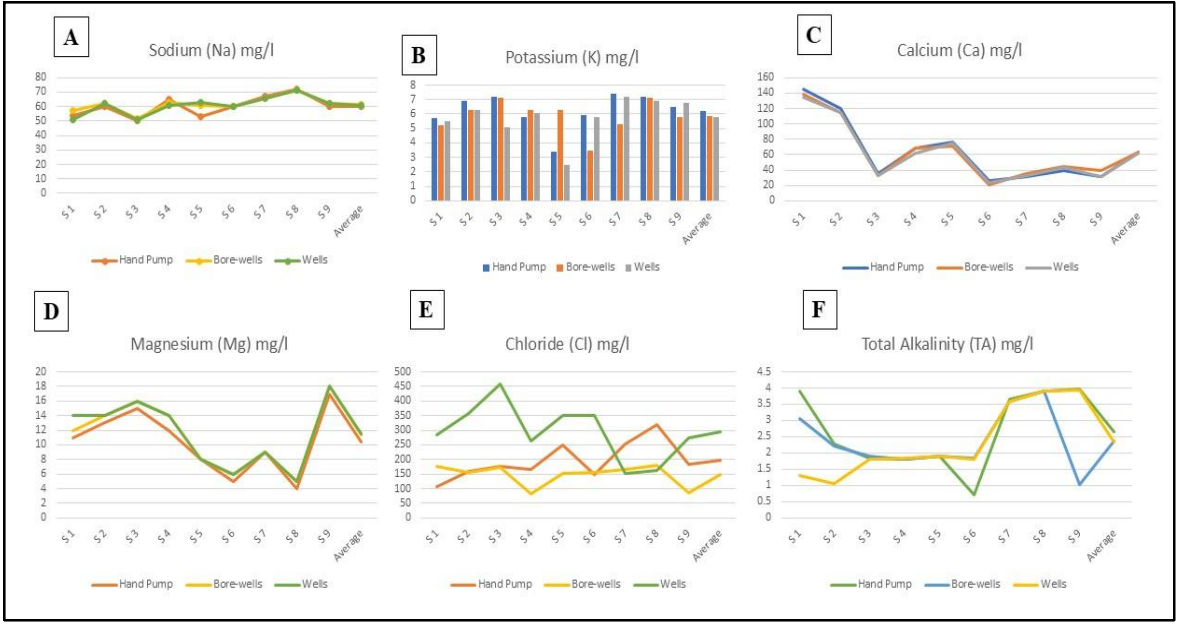
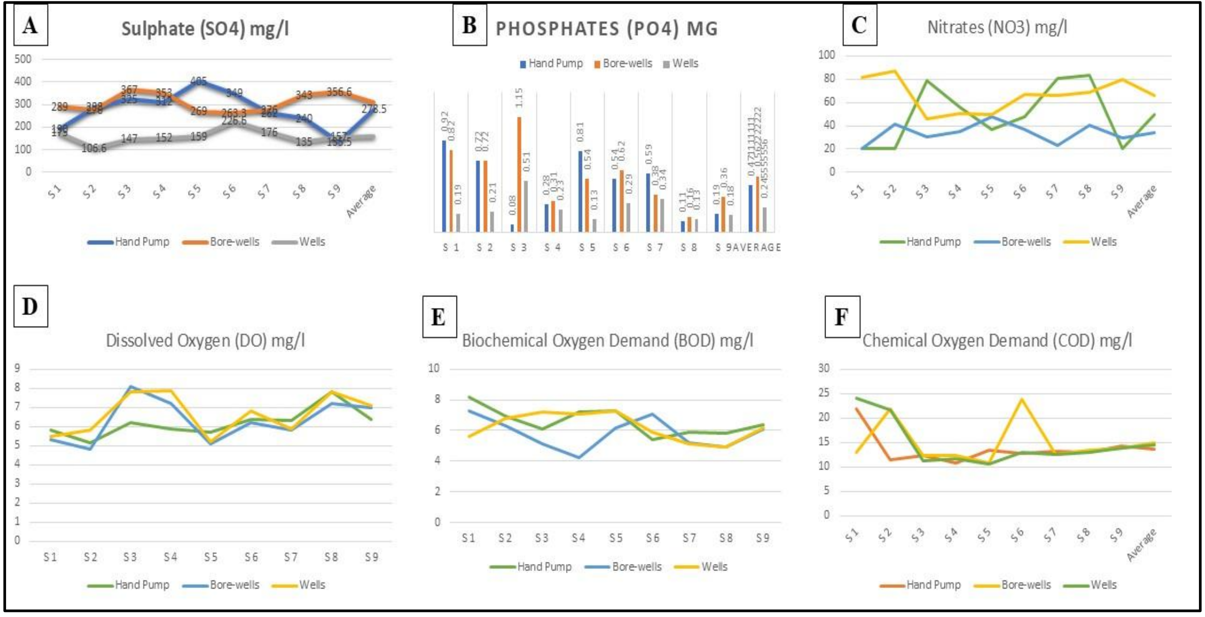


Figure 3: Figure representing the minor constituents including (A) Sulphate (SO_4) mg/l; (B) Phosphates (PO_4) mg/l; (C) Nitrates (NO_3) mg/l and Indicator Parameters including (D) Dissolved Oxygen (DO); (E) Biochemical Oxygen Demand (BOD) mg/l; (F) Chemical Oxygen Demand (COD).



IV. Discussion:

Groundwater remains one of the most dependable and cost-effective sources of potable water, playing a vital role in supporting domestic, agricultural, and industrial needs. However, the current study reveals significant deterioration in groundwater quality as a result of anthropogenic pressures such as rapid urbanization, unregulated industrialization, and the overuse of chemical fertilizers in agriculture. The findings confirm that both the physicochemical and microbial characteristics of groundwater are strongly influenced by proximity to urban centers, dumping sites, and industrial/agricultural zones.

Temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and hardness exhibited seasonal fluctuations, highlighting the dynamic nature of aquifer systems. Elevated EC and TDS values—particularly near sewage and industrial discharge sites—indicate high salinity and pollutant infiltration. Hardness levels exceeding the WHO guideline reflect increased concentrations of calcium and magnesium salts, rendering the water less suitable for domestic and industrial applications. Although not acutely toxic, such conditions can indirectly contribute to cardiovascular and renal health issues, as well as technical challenges like scaling in pipelines.

Organic contamination, measured through Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), showed alarming values well above permissible limits. BOD values ranging from 3.59 to 14.69 mg/L and COD ranging from 10.5 to 33.26 mg/L are indicative of sewage infiltration, industrial effluents, and leachate percolation from dumping sites. These high levels not only signify oxygen depletion in aquifers but also impair soil hydraulic conductivity, reducing the natural filtration capacity of soils and increasing vulnerability to further contamination.

Nutrient enrichment through elevated nitrate and phosphate levels presents another critical concern. Nitrate concentrations exceeded the WHO/BIS limit of 45 mg/L in several sites, posing risks of methemoglobinemia (blue baby syndrome) and other gastrointestinal disorders. Excessive phosphate (>1.0 mg/L in summer) encourages eutrophication, which could further degrade aquatic ecosystems linked to groundwater recharge areas. The elevated chloride and sulphate concentrations, surpassing BIS and WHO permissible thresholds in many cases, highlight the combined impacts of sewage inflows, agricultural runoff, and industrial discharges.

Microbial contamination was found to be widespread, with coliform and fecal coliform counts confirming infiltration of untreated sewage and fecal sludge into groundwater reserves. Such contamination represents a direct public health hazard, particularly in rural and peri-urban communities dependent on untreated groundwater. The findings are consistent with earlier studies reporting that microbial contamination contributes to diarrheal diseases, infant mortality, and other waterborne illnesses across developing nations.

Multivariate statistical analyses (PCA and cluster analysis) further emphasized the strong correlations between land-use patterns and contamination profiles. Industrial zones showed clustering with COD, EC, and chloride, while agricultural zones correlated with nitrate and phosphate, and urban settlements with coliform counts and BOD. This underlines the interconnected nature of anthropogenic activities and their collective impact on groundwater quality.

Overall, the study provides compelling evidence that groundwater in the study region is under severe threat from both organic and inorganic pollutants, necessitating urgent attention from policymakers, regulators, and local communities.

V. Conclusion:

The present study underscores the deteriorating state of groundwater resources in regions influenced by urbanization, agriculture, and industrial activities. Elevated levels of BOD, COD, nitrate, phosphate, chloride, sulphate, and hardness, combined with widespread microbial contamination, reveal a complex contamination profile driven by multiple anthropogenic sources. Seasonal fluctuations further exacerbate these problems, with summer months amplifying pollutant concentrations due to reduced dilution and higher infiltration rates.

The results make it clear that groundwater in the study region is increasingly unsafe for direct human consumption and faces declining suitability for agricultural and industrial use. Without intervention, the continued reliance on this compromised resource poses escalating risks to public health, ecosystem stability, and long-term water security.

To mitigate these challenges, a multipronged strategy is essential. This includes strengthening sewage and industrial effluent treatment facilities, enforcing strict regulations on pollutant discharges, adopting sustainable agricultural practices with reduced fertilizer inputs, and implementing community-driven groundwater protection measures. Regular monitoring and systematic classification of water quality through hydrochemical and microbial analyses should form the basis of long-term groundwater management strategies.

Ultimately, safeguarding groundwater requires integrated water resource management supported by strong policy frameworks, technological innovations, and active public participation. Only through such coordinated efforts can the safety, sustainability, and resilience of groundwater resources be restored for present and future generations.

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