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Research Article

Assessing Groundwater Quality in Islamabad: A Microbiological and Physicochemical Analysis in Compliance with WHO Standards for Potable Water

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Abstract: The study was conducted in Islamabad, Pakistan, aimed to evaluate the microbiological and physicochemical quality of potable water from various sites. Sampling was conducted in spring 2023 across 20 sites in Islamabad, selection was based on population density and proximity to potential contamination sources (urban runoff, agriculture. Microbiological parameters (total coliforms, fecal coliforms, and *E. coli* using the Most Probable Number (MPN) method and physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, hardness, chloride, and nitrate were measured using standard procedures. The findings highlighted significant disparities in *E. coli* contamination across different sites, with the highest count at Site H (21.8) and the absence of *E. coli* at multiple sites (A, E, G, K, and N), indicating a need for site-specific microbial monitoring. Physicochemical analysis revealed variability in water quality, with pH levels ranging from slightly acidic to slightly alkaline. Notably, turbidity levels were highest at Sites D1 measuring a 93.5 Nephelometric Turbidity Unit (NTU), while Site F exhibited the highest EC (4020 µS) and TDS (3015 mg/L). High EC, turbidity and TDS at these specific sites were attributed to geological mineral dissolution, agricultural runoff, and inadequate sewage management. Site H recorded the highest nitrate concentration at 20 mg/L, suggesting contamination from agricultural runoffs or sewage. The study underscores the importance of continuous monitoring and tailored interventions to ensure safe drinking water standards across different locations and mitigate public health risks associated with contaminated groundwater.

Keywords: Groundwater, WHO Standards, Water Quality Monitoring, Coliforms, Physicochemical Parameters, Microbiological Contamination.

1. INTRODUCTION

Water is a fundamental element for all forms of life, serving as an essential component for maintaining human health and well-being globally. Clean drinking water is a basic necessity, utilized for drinking, cooking, personal hygiene, and various domestic activities. Additionally, water plays a crucial role in transportation, hydroelectric power generation, and various industrial and commercial applications. Despite its importance, freshwater, the source of potable water, is a limited resource. Surface freshwater sources (including rivers, lakes, dams, wells, springs, and rain) provide a limited supply of potable water, with only 3% of the world's water being freshwater and an even smaller fraction

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(0.01%) being suitable for human consumption [1]. On earth the amount of water is now the same as billion years ago, only 2.8% is available as fresh water of which about 20% constitutes groundwater. It is principal freshwater supply which reaches people water demand generally acts for expends demand [2].

Contaminated water poses a significant global health threat. Water pollution causes many diseases like diarrhea, gastroenteritis (infectious diarrhea), stomach cramps and aches and degradation of immune function are included which caused by water pollution [3]. World Health Organization (WHO) evaluated 10% of the global population lacks access to resources for improving drinking water quality [4]. This problem is exacerbated by the increasing contamination of water resources worldwide with microorganisms and chemicals in the 21st century [5]. Each year, 4 billion cases of diarrhea are reported in the world because of the consumption of contaminated water. In Pakistan, rapid population growth and urbanization have further compromised water quality. Several studies across Pakistan including Lahore, Karachi, and Rawalpindi have documented microbial contamination, elevated nitrate levels, and physicochemical imbalances in both surface and groundwater resources [6-8]. Specifically in Islamabad, studies by Haq *et al.* [9] and Shinwari *et al*. [10] reported spatial disparities in groundwater quality, with certain sectors exhibiting fecal coliforms and turbidity beyond WHO guidelines.

Potable water, free from pathogens and harmful chemical substances, is crucial for public health. Various physicochemical parameters, such as microbial contamination, pH, TDS, EC, dissolved oxygen (DO), hardness, and temperature, are used to assess drinking water quality. Physicochemical and microbiological assessments are essential for effective water resource management [11]. Generally, the perception is that if the concentration of any given contaminant is below the standard limit defined according to WHO guidelines, the water is safe but if it is above this limit it is unsafe [12].

Recent studies highlight the alarming escalation of global water pollution, with comprehensive data from 2022 revealing critical regional disparities that demand immediate attention. China leads as the most polluted country globally, accounting for 30% of global pollution, followed by the US at 15%, India at 7%, and Russia at 5%, upsetting water pollution statistics [13]. While 44% of all wastewaters on earth returns to the environment untreated, meaning human waste, household sewage, and toxic medical waste are released directly into ecosystems. A groundbreaking 2024 analysis of 625 studies from 63 countries demonstrated that global urbanization profoundly degraded water quality worldwide, making it the leading landscape change responsible for water-quality deterioration over the past two decades [14]. Furthermore, nitrogen pollution from agriculture and human waste, along with plastics, threatens clean water supplies in many watersheds worldwide, potentially contributing to public health declines. Pollution poses big risks to global clean water supplies, emphasizing the urgent need for comprehensive international water management strategies [15].

Given the critical importance of water quality for public health and well-being, this study aims to assess the quality of potable water consumed in different sectors of Islamabad. This research brings novelty by providing the first comprehensive spatial assessment of groundwater quality across diverse urban and peri-urban areas of Islamabad, establishing baseline data for future monitoring programs. The significance of this study lies in its ability to provide localized insights into drinking water safety, thereby informing both regulatory actions and targeted public health interventions. Specifically, the study aimed to assess the compliance of groundwater quality with established WHO standards, to identify geographic areas exhibiting elevated risks of contamination, and to recommend appropriate remedial measures tailored to the site-specific findings.

2. MATERIALS AND METHODS

2.1. Materials

All chemicals used in the study were of analytical grade with ≥ 99% purity. Sterilized 250 mL borosilicate glass vials (Duran®, Germany) and 1.5 L HDPE plastic containers (Nalgene®, Thermo Fisher Scientific, USA) were used for sample collection. Sterile distilled water was prepared using the Milli-Q® purification system (Millipore®, USA). The pH of water samples was measured using a HI-8424 portable pH meter (Hanna Instruments®, USA), while EC was recorded using a Model 152 Conductivity Meter (Fisher Scientific®, USA). Turbidity measurements were performed using a DRT-15CE Digital Turbidity Meter (HF Scientific®, USA), calibrated with standard NTU solutions. MacConkey Agar (CM0007, Oxoid®, UK), Peptone Water (Merck®, Germany), and Kovacs' Indole Reagent (Fisher Scientific®, USA) were utilized. Diamond Green Bile Broth (2%) was sourced from Merck®, Germany. Nitrate concentration was determined using the LaMotte® Nitrate Test Kit (Model 3354-01, LaMotte Company®, Maryland, USA) and chloride concentration using the LaMotte® Chloride Test Kit (Model 4503-DR-01, LaMotte Company®, USA). Hardness testing was performed using Reagents 5 and 7 from the LaMotte® Hardness Test Kit.

2.2. Sampling Sites

Sites were designated alphabetically (A–T) and strategically distributed across diverse geographical zones of Islamabad. Samples were collected directly from unfiltered groundwater sources (boreholes/hand pumps) used for drinking. Each site was comprised of five sub-sites, labelled with corresponding alphabetical and numerical identifiers (e.g., A1–A5), resulting in the collection of approximately 100 water samples.

A stratified random sampling design was employed to systematically capture the spatial variability in groundwater quality across twenty different zones of Islamabad to represent a wide range of hydrogeological diversity and contamination risks (sewage infiltration, agricultural runoff) in the region. To ensure statistical significance and minimise local variability, it was decided to collect five samples from each site, giving 100 samples. These sites, identified by abbreviations, are listed as follows: E-7 (A1-A5), F-4 (B1-B5), F-6 (C1-C5), F-7 (D1-D5), F-8 (E1-E5), F-10 (F1-F5), F-11 (G1-G5), G-3 (H1-H5), G-6 (I1-I5), G-7 (J1-J5), G-8 (K1-K5), G-9 (L1-L5), G-10 (M1-M5), G-11 (N1-N5), I-8 (O1-O5), I-9 (P1-P5), I-10 (Q1-Q5), Khanna Pul (R1-R5), Chakshahzad (S1-S5), Bhara kahu (T1-T5) as shown in Figure 1.

This methodological approach ensured comprehensive and detailed coverage of all critical hydrological characteristics of the study area, resulting in highly representative data, eliminating the possibility of systematic errors and providing a sound basis for subsequent integrated analysis.

2.3. Sampling and Preparation for Analysis

Sampling was conducted according to established international standards (ISO 5667-3:2018) for preparing and transporting aqueous samples [16]. It was essential to prevent contamination and secure the samples before delivery to the laboratory. All water samples in this study were collected directly from unfiltered groundwater sources, including boreholes and hand pumps, which are used as primary drinking water sources

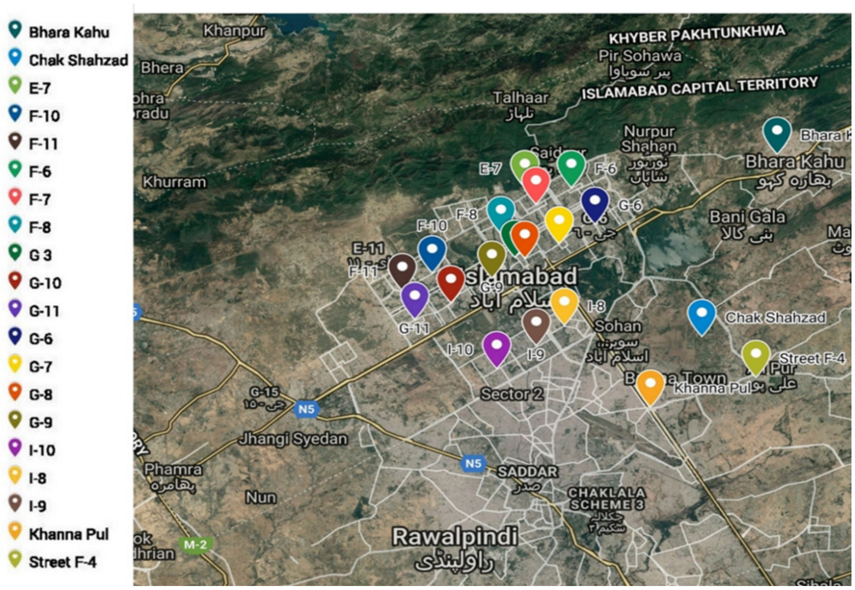

Fig. 1. Various locations of Islamabad selected for testing water quality (source: Google Maps).

by the local residents at all 20 sites. Each sample was collected into sterilised 250 mL borosilicate glass vials, pre-treated and rinsed according to the ISO 19458:2006 protocol [17]. The vials ensured minimal reaction between the walls of the container and the water contained in it as these all vials were composed of high-quality borosilicate glass (Duran®, Germany), known for its chemical inertness and minimal reactivity with aqueous solutions. To analyse physicochemical parameters, an additional 1.5 litres of water was collected in plastic containers, also pretreated with 10% nitric acid and rinsed three times with deionised water to exclude contamination. Sterile distilled water was used as a control. All glassware and instruments were sterilised in an autoclave at 121 °C for 15 minutes prior to field use. Pre-sterilisation was confirmed with autoclave tape indicator.

2.4. Microbiological Analysis

MPN methodology was used for microbiological analysis of water, providing sensitive and reliable detection of coliform bacteria, including fecal coliforms and *E. coli* [18]. MacConkey medium isolates and cultivates coliforms while inhibiting Gram-positive microorganisms. Peptone water is used for the indole test to identify *E. coli*, and Kovacs' indole reagent visualizes indole to confirm the presence of *E. coli*. For MPN estimation, water samples were inoculated into tubes with double concentrations of MacConkey medium and incubated at 35-37 °C for 24 hours. Tubes showing no gas were further incubated to reduce false negatives. Positive samples were then transferred to Diamond Green Bile Broth and incubated at 44 ± 0.5 °C. *E. coli* presence was confirmed by the indole test using Kovacs' reagent, which indicates indole with a red color.

2.5. Physico-Chemical Analysis

Physico-chemical analyses of water samples were carried out using high-precision instrumentation to assess key water quality parameters [19]. EC was measured using a conductivity meter, which had a detection limit of 1 μS/cm, calibrated with standard solutions of 1413 μS/cm and 12.88 mS/cm. Turbidity was measured using a digital turbidity meter, calibrated using standards of 0, 10, 100, and 1000 NTU, and possessing a detection limit of 0.01 NTU. EC was the basis for calculating TDS, calculated by multiplying conductivity readings (in microsiemens, μS or millisiemens, mS) by a factor of 0.75 to obtain accurate dissolved salt concentrations.

The pH was measured using a pH meter, it had a detection limit of 0.01 pH units, and was calibrated using buffer solutions at pH 4.01, 7.01, and 10.01. The presence of sediments was assessed visually, where the water sample was classified as containing sediments ('Present') or not containing sediments ('Absent'). A visual methodology was also used to comprehensively assess the appearance and colour of the water, where the sample was classified as transparent, turbid, reddish, brown turbid or white turbid to provide a comprehensive characterisation of its visual and physicochemical properties.

2.5.1. Hardness as $CaCO_3$

The water hardness of the tested sample was evaluated using the EDTA Titrimetric method for increased precision [20]. The titrimetric method for hardness had a minimum detectable concentration of 0.29 gpg as $CaCO_3$. For this analysis, 12.9 mL of the water sample was taken, and five drops of Hardness Reagent 5 (containing sodium sulfide, sodium hydroxide, and sodium borate) were added. After that, the indicator tablet was added, causing the solution to turn purple. Using the hardness reagent 7 containing EDTA and magnesium chloride the sample was stirred until light blue color without titanium appeared. The hardness was noted in mg/L as $CaCO_3$.

2.5.2. Nitrate-NO_3

Nitrate was determined by LaMotte method which is a nitrate test kit [21]. For chemical analysis, nitrate and chloride detection limits were derived from the LaMotte test kit documentation: 0.1 mg/L for nitrate. From the sample a volume of 2.5 mL of water was taken and mixed with 5 mL of a mixed acid reagent which contains acetic acid, copper sulfate, ammonium chloride, sodium chloride, citric acid and sodium phosphate. Nitrate reducing powder was then added to the solution and after shaking, visually the solution was tested against a color standard using a Nitrate – N comparator. Nitrate content is expressed in ppm, this way aiming to give the level of nitrate in the freshwater.

2.5.3. Chloride

The LaMotte automatic burette chloride test kit was also employed for the determination of chloride levels [22]. According to the test Kit manual, the detection limit for chloride analysis was established at 0.5 mg/L. A 50 mL water sample was taken in an Erlenmeyer flask, and chloride reagents were added dropwise. If no red color appeared instantly in the solution, then sodium hydroxide was added in drops till a red color developed. Thereafter, the treatment with hydrogen peroxide and sulfuric acid was performed, after which the solution was titrated with silver nitrate until the color changed from yellow to orange, brown. When using the formula, ppm chloride = 0.1 x (burette reading-0.2); the estimation of chloride concentration was performed by subtracting the mL on the burette from the value obtained by placing the internal standards in the whole sample drawn out.

3. RESULTS

The study aimed to evaluate the bore water's quality by examining various crucial characteristics, including appearance, pH, EC, TDS, chloride, hardness, nitrate, turbidity, total coliforms, fecal coliforms, and *E. coli* count. As shown in Figure 2, all of the samples collected from site P and R were found to be clear in appearance. Visual analysis of water from site A, B, C, E, F, G, I, J, K, L, M, Q, and S were determined to be clear, with the exception of one sub-site which exhibited turbidity. Among the samples collected from site H, N, O, and T, two of the sub-sites were found to be turbid, while the other three were clear. Out of the samples collected from site D, three sub-sites exhibited higher levels of turbidity, while the rest of the samples had a clear look. These findings indicate that the majority of water samples from all sites were visually clear, varying levels of turbidity were observed at a minority of locations, most notably at sites D, H, N, O, and T.

Sterile distilled water was processed alongside all experimental samples demonstrated no contamination, thereby confirming assay specificity. Among the tested chemical parameters, the pH values at different locations varied from mildly acidic to mildly alkaline. The majority of sites maintained a pH level that fell within the permitted range for drinking water, which is typically between 6.5 and 8.5 (Table 1), indicating that most locations falling within the acceptable drinking water standards of 6.5-8.5 pH units.

The turbidity levels differed greatly among the sites, with some locations having clear water and others displaying considerable turbidity. Site A, specifically sub-site D1, had the highest turbidity with a measurement of 93.5 NTU, indicating a significant presence of suspended particles. Additional noteworthy high turbidity measurements are seen at sub-sites H4 (42.5 NTU), G5 (23.8 NTU), and N4 (58.8 NTU) (Table 1). These findings indicate that the water quality is not uniform across the area and that specific locations are significantly impacted by pollution or environmental disturbances.

The EC values, which represent the overall number of ions in the water, varied significantly from 265 µS to 4020 µS. Locations with the highest EC values, such as Site F (reaching up to 4020

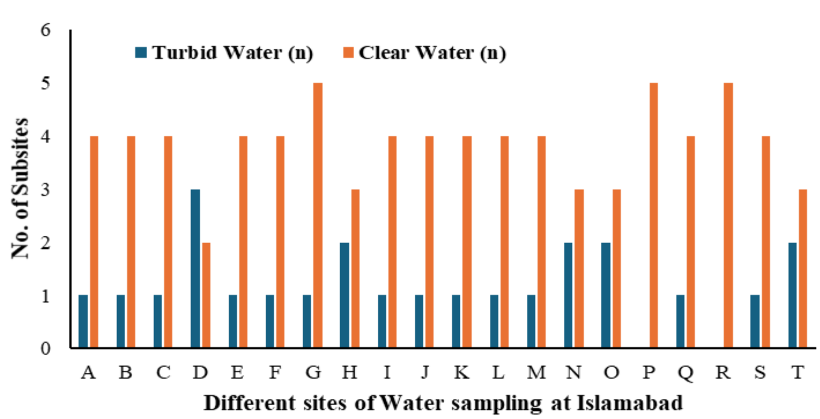

Fig. 2. Findings of physical appearance of water at various sub-sites of water sampling.

µS), indicate a notable concentration of dissolved salts, potentially resulting from the dissolution of minerals or human activities. In contrast, locations such as Site I, which have lower EC values (265 to 695 µS) (Table 1), indicate lesser ionic content and potential dilution effects.

The TDS levels varied between 198 mg/L to 3015 mg/L at the different sites. Elevated TDS levels observed at Site F (reaching a maximum of 3015 mg/L) and Site D (reaching a maximum of 1402 mg/L) indicate substantial mineral content, which may be attributable to either the geological characteristics of the area or potential pollution sources. The lower TDS values seen at sites such as Site I (from 198 to 524 mg/L) indicate the presence of relatively purer water (Table 1).

The nitrate levels observed at most sites were predominantly low, with a range of values between 0.25 mg/L and 20 mg/L. Site H shows the highest nitrate concentration at 20 mg/L, indicating the presence of agricultural runoff or sewage contamination. The nitrate levels observed at sites, including Site Q, generally remained low, with values from 0.25 to 1 mg/L (Table 1).

Table 1. Findings of physicochemical investigation of water samples and their compliance with WHO standards.

Parameter	Observed Range	Mean value	Standard Deviation	Key Findings	WHO Standards	Compliance Status
pH	6.5 – 8.0	7.0	± 0.4	- Majority within WHO range (6.5–8.5). - Highest at Site D (7.4–8.0). - Lowest at Site B (6.5–7.5).	6.5 – 8.5	Compliant (All sites)
Turbidity (NTU)	0 – 93.5	12	± 9.2	- Exceeded at sub-sites D1 (93.5), H4 (42.5), G5 (23.8), N4 (58.8). - Most sub-sites <5.	< 5	Non-compliant (exceeded at D1, H4, G5, N4)
EC (µS/cm)	265 – 4020	312	± 80	- Highest at Site F (4020 µS/cm). - Lowest at Site I (265–695 µS/cm). - Indicates high mineralization.	< 400	Non-compliant (exceeded at Sites F, D, etc.)
TDS (mg/L)	198 – 3015	223	± 69	- Highest at Site F (3015 mg/L). - Lowest at Site I (198–524 mg/L). - Exceeds WHO limit at Sites F, D.	< 1000	Non-compliant (exceeded at Sites F, D)
Nitrate (NO_3, mg/L)	0.25 – 20	08	± 4	- Highest at Site H (20 mg/L). - Lower values at Sites Q (0.25–1 mg/L).	< 10	Non-compliant (exceeded at Site H)
Hardness (gpg)	10.5 to > 10.5	10	± 2	- Water at Sites B5, J, and K was classified as very hard, with hardness levels >10.5 gpg. Site I exhibited both hard and very hard water, with values ranging from 10.5 gpg to >10.5 gpg.	< 1	Non-compliant (exceeded at Sites B, J, K, I)
Chloride (mg/L)	9.8 – 39.4	10.1	± 3	- Highest at Site F (39.4 mg/L). - Lowest at Site S (9.8 mg/L).	< 250	Compliant (All sites)

Investigation of water hardness revealed that the water in the study area was very hard in most cases. Water samples from Sites B5, J, and K consistently exhibited very hard characteristics, exceeding 10.5 gpg. Similarly, water at Site I ranged from 10.5 gpg to values exceeding 10.5 gpg, classifying it as hard to very hard.

The examination of chloride concentrations in the water samples unveiled significant variations among the locations. At site F, the chloride level reached a maximum of 39.4 mg/L. In contrast, site S had the lowest chloride content, measuring 9.8 mg/L. The results demonstrate the variation in chloride concentration among different places, (Table 1). The microbiological analysis of groundwater quality in the study area unveiled alarming levels of contamination, raising serious concerns about public health and water safety. Total Coliforms were detected in every sampling site, with concentrations ranging from 8.4 to a staggering 36.8 CFU/100 mL (Table 2). The highest counts were found at Sites H (36.8 CFU/100 mL), B (32.2 CFU/100 mL), and Q (32.6 CFU/100 mL), indicating significant pollution. In contrast, the lowest levels were recorded at Sites O (8.4 CFU/100 mL), N (11 CFU/100 mL), and K (11.8 CFU/100 mL). These findings indicate that all groundwater sources in the study area are microbiologically contaminated with Total Coliforms, exceeding WHO safety standards and posing a significant threat to public health.

When it comes to Fecal Coliforms, the situation is equally concerning. These bacteria, which indicate fecal contamination, ranged from 0.4 to 25.6 CFU/100 mL. The highest levels were again at Sites H (25.6 CFU/100 mL) and B (22 CFU/100 mL), while Sites E (0.9 CFU/100 mL), I (2.6 CFU/100 mL), and N (0.4 CFU/100 mL) showed relatively lower counts. However, only Sites E, I, and N managed to comply with the WHO standard of 0 CFU/100 mL, underscoring a critical need for improved sanitation measures (Table 2). These findings indicate widespread fecal contamination across most sites, with only a few meetings the WHO standard, highlighting an urgent need for improved sanitation and water treatment measures.

The presence of *E. coli* further compounds the issue, with concentrations ranging from 0 to 21.8 CFU/100 mL, peaking at Site H (21.8 CFU/100 mL) (Table 2). While some sites like A, E, G, K, and N showed no detectable *E. coli*, others such as B, C, D, and F did not fare as well, contributing to a non-compliance status against the WHO standard (Table 2). These findings indicate that *E. coli* contamination is present in several groundwater sources, with some sites exceeding safe limits, further emphasizing the health risks and the need for urgent water quality interventions.

4. DISCUSSION

The comprehensive evaluation of groundwater quality in Islamabad reveals significant spatial heterogeneity in both physicochemical and microbiological parameters, with important implications for public health and water management.

Table 2. Microbiological contamination levels in groundwater and their compliance with WHO standards.

Parameter	Observed Range (CFU/100 mL)	Key Findings	WHO Standards	Compliance Status
Total Coliforms	8.4 - 36.8	- Highest at Sites B (32.2), H (36.8), Q (32.6). - Lowest at Sites K (11.8), N (11), O (8.4).	0 CFU/100 mL	Non-compliant (presence detected at all sites)
Fecal Coliforms	0.4 - 25.6	- Highest at Sites B (22), H (25.6). - Lowest at Sites E (0.9), I (2.6), N (0.4).	0 CFU/100 mL	Non-compliant (presence detected at all sites except E, I, N)
E. coli	0 - 21.8	- Highest at Site H (21.8 CFU/100 mL). - Absent at Sites A, E, G, K, N.	0 CFU/100 mL	Non-compliant (detected at Sites B, C, D, F, H, etc.)

The pH values recorded across all sampling sites (6.5-8.0) remained within the WHO acceptable range of 6.5-8.5 for drinking water, indicating generally satisfactory acidic-alkaline balance. This finding aligns with previous groundwater quality assessments conducted in similar hydrogeological settings. Khan *et al.* [23] reported comparable pH ranges (6.4-8.2) in their comprehensive study of groundwater quality in South Asian aquifers, suggesting that the natural buffering capacity of the aquifer system maintains pH stability. The slight variations observed between sites (highest at Site D: 7.4-8.0; lowest at Site B: 6.5-7.5) likely reflect localized differences in rock-water interactions and mineral dissolution processes, consistent with findings reported by Ghani *et al.* [24] in the study of groundwater geochemistry.

The turbidity measurements revealed significant spatial heterogeneity, with values ranging from 0 to 93.5 NTU. Four sub-sites (D1, H4, G5, N4) exceeded the WHO guideline of < 5 NTU, with sub-site D1 showing critically high turbidity (93.5 NTU). These elevated turbidity levels indicate substantial suspended particulate matter, potentially originating from surface infiltration, aquifer disturbance, or inadequate wellhead protection. Similar findings were reported by Khatri and Tyagi [25] in their assessment of groundwater quality in agricultural regions, where turbidity spikes were attributed to poor well construction and surface contamination. The high turbidity at specific locations suggests localized contamination sources that require immediate remedial attention.

The EC values exhibited extreme variation (265-4020 µS/cm), with Site F showing exceptionally high mineralization (4020 µS/cm). This substantial range indicates significant hydrogeochemical diversity across the study area. The strong positive correlation between EC and TDS ($R^2 > 0.95$) confirms the reliability of conductivity as a proxy for dissolved salt content, consistent with established hydrogeochemical principles [26]. The elevated EC and TDS values at Sites F and D (TDS: 3015 mg/L and 1402 mg/L, respectively) exceed WHO guidelines (< 1000 mg/L), indicating potential salinization processes. Such high mineralization patterns have been documented in similar hydrogeological settings by Mohit and Suprita [26], who attributed elevated TDS to prolonged water-rock interactions and anthropogenic contamination.

Nitrate levels varied considerably (0.25-20 mg/L), with Site H exhibiting concentrations (20 mg/L) that exceed WHO standards (< 10 mg/L). Elevated nitrate concentrations in groundwater are typically indicative of agricultural runoff, sewage infiltration, or septic system leakage. The spatial distribution of nitrate contamination, with highest levels at Site H and lowest at Site Q (0.25-1 mg/L), suggests point-source contamination rather than diffuse pollution. This pattern is consistent with findings reported by Yulian *et al.* [27] in their study of groundwater contamination in rural areas, where localized nitrate hotspots were linked to intensive agricultural practices and inadequate waste management.

Study on water hardness demonstrated that water hardness is a significant concern across the study area, with most sites falling into the very hard category. The consistently high hardness levels at Sites B5, J, and K point to persistent exposure to elevated concentrations of calcium and magnesium ions. Site I, showing a range from hard to very hard, further supports this trend. The widespread distribution of such hardness levels suggests underlying geological formations rich in mineral deposits or prolonged interaction with mineral-laden groundwater. This finding is consistent with studies by Wen *et al.* [28], who reported similar hardness patterns in carbonate aquifer systems.

Chloride concentrations remained well within WHO guidelines (<250 mg/L), ranging from 9.8 to 39.4 mg/L. The relatively low chloride levels across all sites suggest minimal influence from marine intrusion or industrial contamination, which is consistent with the inland location of the study area. Similar chloride patterns have been reported by Panjwani *et al.* [29] in their assessment of groundwater quality in crystalline aquifers.

The universal presence of total coliforms across all sampling sites (8.4-36.8 CFU/100 mL) represents a critical public health concern, as WHO standards mandate zero coliform presence in drinking water. The highest contamination levels at Sites H (36.8 CFU/100 mL), B (32.2 CFU/100 mL), and Q (32.6 CFU/100 mL) indicate severe bacterial pollution. These findings are consistent with previous studies in similar settings, where

Traoré *et al.* [30] reported widespread coliform contamination in groundwater sources from developing regions, attributing the contamination to inadequate sanitation infrastructure and poor wellhead protection.

The detection of fecal coliforms (0.4-25.6 CFU/100 mL) and *E. coli* (0-21.8 CFU/100 mL) across multiple sites indicates direct fecal contamination, posing serious health risks. The co-occurrence of high levels at Sites H and B suggests common contamination sources, potentially linked to sewage infiltration or animal waste runoff. Only three sites (E, I, and N) showed compliance with WHO standards for fecal coliforms, while several sites remained *E. coli*-free. The presence of these indicators strongly suggests inadequate source protection and contamination pathways from surface activities, consistent with findings reported by Bekoe *et al.* [31] in studies of groundwater vulnerability in populated areas.

The comprehensive analysis reveals a complex groundwater quality scenario characterized by significant spatial heterogeneity in both physicochemical and microbiological parameters. The simultaneous occurrence of elevated TDS, hardness, and microbial contamination at certain sites suggests multiple contamination sources and inadequate source protection measures. This multi-parameter contamination pattern has been documented in similar hydrogeological settings by Zehra *et al.* [32], who emphasized the need for integrated water quality management approaches.

The microbiological contamination presents the most immediate health threat, as consumption of bacteria-contaminated water can lead to waterborne diseases including gastroenteritis, typhoid, and cholera [33]. The physicochemical non-compliance, particularly elevated TDS and hardness, poses long-term health risks and aesthetic concerns that may affect water acceptability and consumption patterns.

In addition to WHO guidelines, Pakistan's National Drinking Water Quality Standards (NDWQS) were also considered for a more regionally contextualized evaluation. The NDWQS, formulated by the Pakistan Council of Research in Water Resources (PCRWR), prescribe permissible limits for various water quality parameters including pH (6.5-8.5), turbidity (< 5 NTU), EC (< 1,500 µS/cm), TDS (< 1,000 mg/L), nitrate (< 10 mg/L as NO_3^-), hardness (< 500 mg/L as $CaCO_3$), and chloride (< 250 mg/L). When the observed data were cross compared with both WHO and NDWQS guidelines, the compliance status remained largely consistent, except for EC, where the NDWQS upper limit is slightly higher than WHO's reference for potable water quality [34].

Based on these findings, immediate implementation of water treatment systems, improved source protection measures, and regular monitoring protocols are essential. The spatial variability in contamination patterns suggests that site-specific treatment approaches may be more effective than uniform interventions, consistent with recommendations by Bekoe *et al.* [31] for groundwater quality management in heterogeneous aquifer systems.

This study's scope was limited to a subset of key water quality indicators, including pH, turbidity, EC, TDS, nitrate, hardness, and chloride, rather than the full range recommended by standards. These parameters were chosen for their public health relevance and the feasibility of their measurement with available resources. Consequently, contaminants like heavy metals and pesticides were excluded from the analysis. The primary reason for this exclusion was the lack of access to advanced analytical equipment. Despite these constraints, the selected indicators provide a reliable assessment of groundwater suitability for consumption in the area. Future research should aim to incorporate a more comprehensive set of parameters for a complete risk assessment.

4. CONCLUSIONS

This study aimed to assess the physicochemical and microbiological quality of groundwater used for drinking purposes across various sectors of Islamabad, comparing findings against WHO standards. The assessment of groundwater quality revealed variability in water quality. The pH and chloride levels were in limits across most sites. However, various physicochemical parameters like EC, turbidity, TDS, nitrate, hardness, and chloride, frequently exceeded the permissible WHO limits in specific locations (e.g., Sites D1, H4, G5, N4 for turbidity; Sites F, D for EC/TDS; Site H for nitrate;

Sites B5, J, K for hardness), suggesting issues related to mineralization, potential pollution from agricultural or urban runoff, and geological factors. Microbiological analysis revealed widespread contamination, with total coliforms, fecal coliforms, and E. coli. Total Coliforms were present in all tested samples, indicating a universal failure to meet the WHO standard of zero coliforms per 100 mL. Furthermore, the frequent detection of Fecal Coliforms and *E. coli* (particularly high at sites like H and B) points towards significant fecal contamination in many areas. The presence of these pathogens poses significant health risks, emphasizing the need for immediate remedial actions. Overall, the groundwater quality in many parts of Islamabad is compromised and often unsuitable for direct consumption without treatment, based on WHO standards. To address Islamabad's groundwater contamination, immediate actions should include installing filtration systems (e.g., RO) in high-turbidity areas and nitrate removal units in agricultural zones, along with repairing sewage infrastructure near highly contaminated sites.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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