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Original Research

Evaluating Public Health Risks from Bottled Water Consumption in Erbil-Kurdistan: A Multivariate Assessment

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Abstract

Background and Aim Bottled water are widely consumed as a safer alternative to tap water; however, its quality may vary due to contamination with chemical pollutants and heavy metals. Ensuring compliance with World Health Organization (WHO) drinking-water standards is essential to safeguard public health in rapidly developing urban regions such as Erbil, Iraq. This study aimed to evaluate the physicochemical properties, heavy metal concentrations, and potential health risks associated with commonly available bottled water brands in Erbil.

Methods Five bottled water brands were analyzed for key physicochemical parameters (pH, electrical conductivity, total dissolved solids, turbidity, nitrate, fluoride, chloride, sulfate, and phosphate) and trace metals (lead, cadmium, arsenic, and mercury). The results were compared with WHO guideline values. Human health risks were assessed using the Hazard Quotient (HQ) and Hazard Index (HI) models for non-carcinogenic effects.

Results Most physicochemical parameters were within acceptable limits, except for nitrate (48–57 mg/L) and fluoride (1.4–1.6 mg/L), which slightly exceeded WHO recommendations in several brands. Mean concentrations of lead (9–12 µg/L), cadmium (2.8–3.2 µg/L), arsenic (9–11 µg/L), and mercury (0.9–1.3 µg/L) were detected. HQ values for lead, cadmium, and mercury were below 1, indicating minimal non-carcinogenic risk, whereas arsenic exceeded unity (HQ > 1), signifying potential health concern. The total HI ranged from 1.1 to 1.5, reflecting moderate cumulative exposure dominated by arsenic contribution.

Conclusion Although bottled water in Erbil generally meets WHO quality standards, slight exceedances of nitrate, fluoride, and arsenic were observed. The elevated arsenic-related HQ and HI values highlight the need for regular monitoring, improved quality control, and enforcement of regulatory standards to ensure safe bottled-water consumption and protect public health in the Kurdistan Region of Iraq.

Keywords Bottled water · Health Risk Assessment · Hazard Quotient · Water Quality · Carcinogens

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Introduction

In recent decades, global reliance on bottled water has grown significantly, driven by concerns over municipal water safety and limited access to reliable treatment systems (Salehi, 2022, Qader). In many regions, bottled water is perceived as a safer alternative to tap water, particularly where infrastructure is inadequate or contamination is suspected. The World Health Organization (WHO) recognizes access to safe drinking water as a fundamental human right and a cornerstone of public health (Organization, 2024). However, water quality continues to deteriorate due to anthropogenic activities such as industrial discharges, mining effluents, and accidental chemical spills (Endale et al., 2021). Many low- and middle-income countries face limitations in removing these pollutants due to outdated technologies, financial constraints, and increasing water demand (Sharma and Bhattacharya, 2017).

In addition, seasonal variation, climate change, and mining operations contribute to fluctuations in water quality (Akhtar et al., 2021, Mohammed et al., 2025). These dynamic influences highlight the need to evaluate bottled water as a potential source of chronic exposure to hazardous substances. Trace metals of concern including Pb, Cd, As, and Hg, originate from both natural and anthropogenic sources such as mineral weathering, industrial operations, municipal wastewater, agriculture, and traffic emissions (Kumar et al., 2021, Qader and Shekha, 2022, Qader and Shekha, 2023). These contaminants may also infiltrate supply systems through pipeline leaks and cross-connections (Wu et al., 2018). Studies have reported consumer preference for bottled water due to its taste and perceived safety. Consumption exceeded 200 billion liters annually by 2022 and continues to rise (Minghui and Chelliah, 2022). Despite this demand, bottled water has been reported to contain microbial and chemical contaminants, including heavy metals exceeding WHO and FDA limits (Gambino et al., 2020, Ungureanu et al., 2022).

Chronic exposure to these contaminants has been linked to serious health outcomes (Saravanan et al., 2024, Yuan et al., 2025). Health risk assessments through indices such as Estimated Daily Intake (EDI), Chronic Daily Intake (CDI), and Hazard Quotient (HQ), are critical in quantifying potential risks (Dippong et al., 2020, Endale et al., 2021, Ngubane et al., 2023). Recent studies emphasized the significance of monitoring bottled and drinking water quality to ensure compliance with international safety standards. (Karbalayi et al., 2025), highlighted the increasing detection of contaminants even in commercially bottled products, whereas Kamarehie et al. (2019) and Shams et al. (2019), discussed the analytical advancements in water quality evaluation and reporting consistency. These findings underscore the global need for improved bottled water monitoring and transparency.

This study provides the comprehensive assessment of bottled water quality in Erbil, Kurdistan Region of Iraq, uniquely combining physicochemical analysis, heavy metal evaluation, and quantitative health risk assessment to address a critical gap in regional water safety research. This study aims to (i) assess key water quality parameters and trace metal levels, (ii) estimate associated non-carcinogenic and carcinogenic risks, and (iii) compare findings against international regulatory standards to inform consumer safety and public health policies.

Materials and Methods

Sampling and physio-chemical parameters analysis

Five bottled water brands commonly available in Erbil: Safin (Brand 1), Masafi (Brand 2), Life (Brand 3), Mira (Brand 4), and Koch (Brand 5) were selected for analysis. All selected brands are locally produced within the Kurdistan Region of Iraq. Three bottles per brand were purchased randomly from retail markets. Samples were transported under controlled conditions and stored at 4 °C to prevent microbial growth and chemical alteration. All analyses were completed within 24 h of collection to ensure integrity. Physicochemical parameters measured included pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate (NO_3^-), ammonia (NH_3), phosphate (PO_4^{3-}), chloride (Cl^-), fluoride (F^-), sulfate (SO_4^{2-}), dissolved oxygen (DO), and biological oxygen demand (BOD). Methods followed the Standard Methods for the Examination of Water (Association, 2017).

Heavy metal analysis

Lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) concentrations were determined using Atomic Absorption Spectrophotometry (AAS; PerkinElmer Analyst 400, USA) following digestion with concentrated nitric acid. Pb, Cd, and As were quantified using (Association, 2017, Mielcarek et al., 2022). Quality assurance included analysis of method blanks, triplicate samples, and certified reference standards. Detection limits and recovery rates were verified to ensure data reliability and reproducibility. The limits of detection (LOD) and quantification (LOQ) for Pb, Cd, As, and Hg were 0.002–0.005 mg/L and 0.006–0.015 mg/L, respectively

Statistical analysis

Data analysis was performed with SPSS v 26.0.

Descriptive statistics were generated for all physicochemical and heavy metal parameters. Relationships between water quality variables and health risk factors were examined using Pearson correlation coefficients. To assess differences among bottled water brands, a one-way analysis of variance (ANOVA) was applied with a significance threshold of $p \leq 0.05$. Health risk estimation was carried out using regression models based on the concentrations of contaminants detected in bottled water samples Linear and multiple regression models were then used to quantify associations between physicochemical parameters and health risk indices, including Estimated Daily Intake (EDI), Chronic Daily Intake (CDI), and Hazard Quotient (HQ). Non-carcinogenic risks were evaluated using CDI and HQ, while Incremental Lifetime Cancer Risk (ILCR) was calculated to estimate carcinogenic risks. In addition, composite indices of contamination were determined for each brand, including the Contamination Potential Index (CPI), Heavy Metal Pollution Index (HPI), and Pollution Load Index (PLI), to provide an integrated measure of overall pollution levels (Pant et al., 2025, Chidiac et al., 2023, Luo et al., 2024, Gupta and Gupta, 2021).

Comprehensive Pollution Index (CPI)

The CPI provides an average pollution index based on pollutant concentrations relative to their permissible limits. This index helps in assessing overall water pollution severity (Pramanik et al., 2020, Jiang et al., 1999, Imneisi and Aydin, 2018, Singh et al., 2004). It is expressed as:

$$\textbf{CPI} = = \sum \frac{\text{Si}\, Ci}{\text{n}} \qquad (1)$$

Ci is the observed concentration of the pollutant, Si is the standard permissible limit, n is the number of pollutants considered

Pollution Load Index (PLI)

The Pollution Load Index (PLI) was calculated for each station and year to quantify the overall pollution level in the water before and after treatment. The PLI is computed by taking the geometric mean of the Contamination Factor (CF) values for each parameter (Ogbeibu et al., 2014, Tomlinson et al., 1980).

$$\textbf{PLI} = \frac{Ci}{Si} \qquad (2)$$

Ci = Concentration of metal in the contaminated environment. Si = Background concentration of the metal. A PLI value of 1 indicates baseline levels, >1 signifies pollution, and <1 indicates no pollution.

Water Quality Index (WQI)

Water quality parameters were assessed by comparing the measured values with the WHO guidelines for drinking water. These standards serve as international benchmarks to evaluate the safety and acceptability of drinking water. (Table 1) summarized the WHO acceptable ranges for key physicochemical and toxicological parameters, which were used to interpret the suitability of the water samples for human consumption. WQI values classify water conditions into five categories as shown in (Table 2) (Chidiac et al., 2023).

$$\textbf{WQI} = \frac{\sum(\text{Wi}*\text{Qi})}{\sum \text{Wi}} * 100 \quad \textbf{Qi} = \frac{Ci}{\text{Si}} * 100 \quad (3)$$

where Ci is the measured concentration of the parameter (mg/L), Si is the WHO guideline value (mg/L), Wi is the assigned weight of the parameter, and Qi is the quality rating scale. Unitless index values were obtained by normalizing concentrations to standards.

Health Risk Index (HRI): is a systematic approach used to estimate the potential impact of environmental contaminants on human health. This process involves four principal stages: (1) hazard identification, (2) dose–response assessment, (3) exposure evaluation, and (4) risk characterization, as outlined in prior studies (Rahman et al., 2018, Ma et al., 2007). Additionally, to evaluate the health implications of heavy metal exposure, several risk indices were computed.

Chronic Daily Intake (CDI)

The CDI quantifies the average daily exposure to contaminants over a specified period and is particularly used for assessing chronic non-carcinogenic and carcinogenic health risks. Two critical toxicological reference values are considered in this context: (1) Slope Factor (SF): Used to evaluate cancer risk. (2) Reference Dose (RfD): Used for assessing non-carcinogenic effects (Lim et al., 2008). The oral exposure method was considered for the estimation and the CDI of elements which calculated by using Eq. 4 (Means, 1989, Karimi et al., 2020).

$$\textbf{CDI} = \frac{\text{C}*\text{IR}*\text{EF}*\text{ED}}{\text{RBW}*\text{ATfD}} \qquad (4)$$

C = metals concentration, IR is the ingestion rate (Oguri et al., 2018). EF is the exposure frequency and ED is the exposure duration. BW is the mean body weight and AT is the mean time of life (EF x ED). RfD: reference dose of metals (Shen et al., 2019, Agency, 1986). The reference dose (RfD) and cancer slope factor (CSF) values were adopted from (Agency, 1986). Pb (RfD = 0.0035 mg/kg/day, CSF = 0.0085), Cd (RfD = 0.001, CSF = 6.3), As (RfD = 0.0003, CSF = 1.5), Hg (RfD = 0.0003, CSF = 0.0).

The Hazard Quotient (HQ)

The HQ defines the non-carcinogenic risk being calculated based on the computation of the ratio of CDI to RfD of certain elements (Means, 1989), by using the Eq. 5, used to evaluate the risk of non-carcinogenic impacts of a contaminant. HQ as well as HI are critical in the assessment of human health hazards. The Hazard Quotient is a very crucial tool to estimate the non-carcinogenic health risks by calculating related to Hazard Coefficient.

$$\mathbf{Q} = \frac{\text{CDI}}{\text{RfD}} \qquad (5)$$

where HQ = hazard quotient, CDI = chronic daily intake, and RfD = reference dose. The toxicity responses of trace metals for the RfD. An HQ value above 1 indicates a potential non-carcinogenic health concern. The Hazard Index (HI) is computed as the sum of HQs for all assessed metals and indicates the cumulative non-carcinogenic risk: HI > 1, combined exposures may pose a significant health risk. HI ≤ 1, risk is considered negligible (Dippong et al., 2020).

Carcinogenic risk assessment (ILCR)

The ILCR is expected to be the cumulative likelihood of personal cancer during a lifetime as the consequence of exposure to a potential carcinogen (Miao et al., 2017). The carcinogenic risk equations in a linear dose Eq. 6, were used for individual exposure routes (Means, 1989).

$$\mathbf{ILCR} = \text{CDI} * \text{CSF} \qquad (6)$$

Where: CDI=Chronic Daily Intake, CSF = Cancer slope factor of metals. ILCR values $<10^{-6}$ are considered negligible, 10^{-6}–10^{-4} represent acceptable or moderate risk, and $>10^{-4}$ indicate high carcinogenic risk according to (Agency, 1986).

Results

Physicochemical Parameters

The physicochemical parameters of the five bottled water brands analyzed showed significant variations (*Table 1*). The recorded pH values ranged from 6.6 ± 0.02 to 7.1 ± 0.03, with Brand 2 recorded the highest and Brands 1 and 5 the lowest values. All values remained within the WHO-recommended range (6.5–8.5). Electrical conductivity (EC) differed significantly among brands ($p = 0.045$), with Brand 4 indicated the highest value (570 ± 15 µS/cm), reflecting elevated mineral content. Total dissolved solids (TDS) exceeded WHO guidelines (≤500 mg/L) in Brands 4 (540 ± 12 mg/L) and 5 (550 ± 10 mg/L).

Table 1: WHO Acceptable Ranges for Drinking Water Parameters

Parameter	WHO Guideline Limit	Unit
pH	6.5 – 8.5	
Electrical Conductivity (EC)	< 1500	µS/cm
Total Dissolved Solids (TDS)	≤ 1000	mg/L
Turbidity	≤ 5	NTU
Nitrate (NO_3^-)	50	mg/L
Ammonia	1.5	mg/L
Chloride (Cl^-)	≤ 250	mg/L
Fluoride (F^-)	1.5	mg/L
Sulfate (SO_4^{2-})	≤ 250	mg/L
Lead (Pb)	0.01	mg/L
Cadmium (Cd)	0.003	mg/L
Arsenic (As)	0.01	mg/L
Mercury (Hg)	0.006	mg/L

Note: WHO guideline values were used as reference standards to evaluate the acceptability of physicochemical and heavy metal parameters in drinking water.

Turbidity varied significantly ($p = 0.031$), peaking in Brand 5 (5.4 ± 0.3 NTU), exceeding WHO guidelines and indicated possible particulate or organic contamination (*Figure 1*). Nitrate concentrations surpassed the WHO limit of 50 mg/L in Brands 4 (55 ± 2 mg/L) and 5 (57 ± 3 mg/L). Ammonia was elevated in the same brands (0.70 ± 0.04 mg/L). Mean phosphate concentrations exceeded the WHO permissible limit (1.0 mg/L), with Brand 4 recording the highest value (1.3 ± 0.05 mg/L, $p = 0.041$). Chloride (Cl^-) and fluoride (F^-) levels also surpassed guideline values. Fluoride exceeded the WHO limit of 1.5 mg/L in all brands, reaching 1.6 ± 0.02 mg/L in Brands 1, 4, and 5.

Heavy Metal Concentrations

Heavy metal analysis revealed widespread contamination (*Table 2*). Lead (Pb) exceeded the WHO limit of 10 µg/L in most brands, with Brand 5 showing the highest concentration (12 ± 0.3 µg/L, $p = 0.065$). Cadmium (Cd) and arsenic (As) were detected above permissible limits, with Brand 5 again demonstrated the highest levels. Mercury (Hg) concentrations were slightly elevated in some samples, notably in Brand 3 (1.31 ± 0.05 µg/L, $p = 0.051$).

Water Quality and Contamination Indices

The Water Quality Index (WQI) ranged from 167.91 to 200.15 across brands (*Table 3*). Brand 2 recorded the lowest score (167.91, Marginal), Brands 1, 3, and 4 ranged from 191.57–197.43 (Poor), and Brand 5 (200.15) fell into the Very Poor category, indicating substantially compromised quality. Elevated turbidity, TDS, nitrate, ammonia, and heavy metals were the main contributors to reduced water quality.

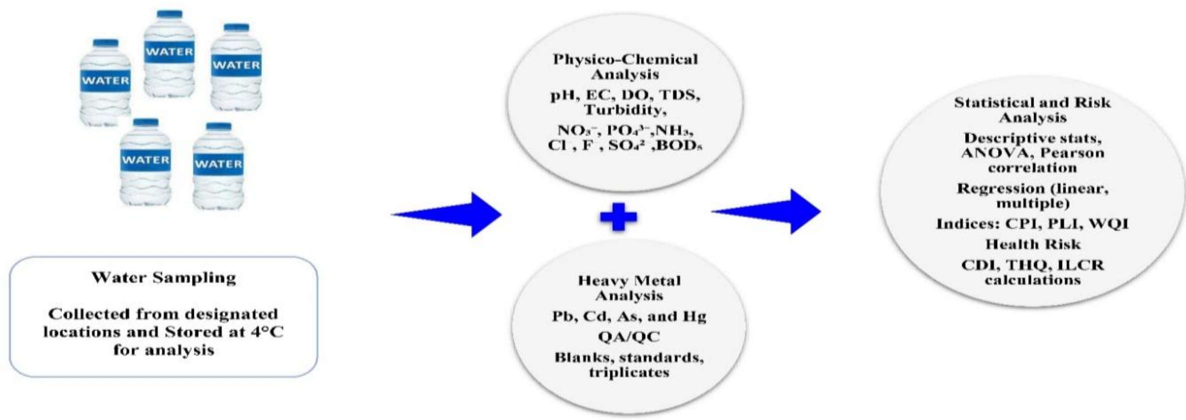

Figure 1: Flowchart of the methodological framework for water quality assessment and health risk evaluation.

Table 2: Water Quality Categories Based on Water Quality Index.

WQI Range	Category	Water Quality Status
0 – 50	Excellent	Very clean; suitable for drinking
51 – 100	Good	Slight contamination; generally acceptable
101 – 200	Poor	Moderate contamination; treatment recommended
201 – 300	Very Poor	Heavy contamination; requires advanced treatment
> 300	Unsuitable for Drinking	Severely polluted; unfit for human consumption

Note: Water quality status was classified based on Water Quality Index (WQI) ranges to determine suitability for human consumption.

Table 3: Physio-Chemical Parameters Across Different Brands (Mean±SE)

Parameter	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5	p-value
pH	6.6 ± 0.09^{d}	7.1 ± 0.09^{a}	6.9 ± 0.09^{b}	6.7 ± 0.09^{c}	6.6 ± 0.09^{d}	0.082
EC	550 ± 15.9^{c}	480 ± 15.9^{d}	550 ± 15.9^{c}	570 ± 15.9^{a}	560 ± 15.9^{b}	0.045
TDS	510 ± 10.0^{a}	490 ± 10.0^{a}	520 ± 10.0^{a}	540 ± 10.0^{b}	550 ± 10.0^{b}	0.048
Turbidity	5.1 ± 0.09^{d}	4.9 ± 0.09^{e}	5.2 ± 0.09^{c}	5.3 ± 0.09^{b}	5.4 ± 0.09^{a}	0.031
NO_3	52 ± 1.5^{c}	48 ± 1.5^{d}	55 ± 1.5^{b}	55 ± 1.5^{b}	57 ± 1.5^{a}	0.038
NH_3	0.55 ± 0.04^{c}	0.48 ± 0.04^{d}	0.60 ± 0.04^{b}	0.70 ± 0.04^{a}	0.70 ± 0.04^{a}	0.067
PO4	1.1 ± 0.07^{c}	0.9 ± 0.07^{d}	1.2 ± 0.07^{b}	1.3 ± 0.07^{a}	1.2 ± 0.07^{b}	0.041
Chloride	255 ± 4.3^{c}	240 ± 4.3^{d}	265 ± 4.3^{a}	260 ± 4.3^{b}	260 ± 4.3^{b}	0.089
Fluoride	1.6 ± 0.04^{a}	1.4 ± 0.04^{c}	1.5 ± 0.04^{b}	1.6 ± 0.04^{a}	1.6 ± 0.04^{a}	0.071
SO_4	260 ± 5.4^{b}	240 ± 5.4^{c}	270 ± 5.4^{a}	270 ± 5.4^{a}	260 ± 5.4^{b}	0.092
DO	4.9 ± 0.11^{b}	5.1 ± 0.11^{a}	4.7 ± 0.11^{c}	4.6 ± 0.11^{d}	4.5 ± 0.11^{e}	0.054
BOD_5	5.1 ± 0.11^{d}	4.8 ± 0.11^{e}	5.3 ± 0.11^{b}	5.4 ± 0.11^{a}	5.2 ± 0.11^{c}	0.038
Lead	11 ± 0.49^{b}	9 ± 0.49^{c}	11 ± 0.49^{b}	11 ± 0.49^{b}	12 ± 0.49^{a}	0.065
Cadmium	3.1 ± 0.08^{b}	2.8 ± 0.08^{c}	3.1 ± 0.08^{b}	3.1 ± 0.08^{b}	3.2 ± 0.08^{a}	0.079
Arsenic	11 ± 0.49^{a}	9 ± 0.49^{b}	11 ± 0.49^{a}	11 ± 0.49^{a}	11 ± 0.49^{a}	0.073
Mercury	1.1 ± 0.07^{b}	0.9 ± 0.07^{c}	1.3 ± 0.07^{a}	1.1 ± 0.07^{b}	1.1 ± 0.07^{b}	0.051

Note: Values are expressed as mean ± standard error, and different superscript letters within rows indicate statistically significant differences among brands ($p < 0.05$).

Composite contamination indices confirmed these findings (*Table 4; Figure 2*). The Contamination Potential Index (CPI) ranged from 1.506 (Brand 2) to 1.893 (Brand 4), while the Pollution Load Index (PLI) varied between 0.955 (Brand 2) and 1.097 (Brand 4). Similarly, the Heavy Metal Pollution Index (HPI) ranged from 90.83 (Brand 2) to 113.33 (Brand 3). Only Brand 2 (HPI = 90.83) fell below the critical threshold of 100, whereas all other brands indicated considerable heavy metal pollution.

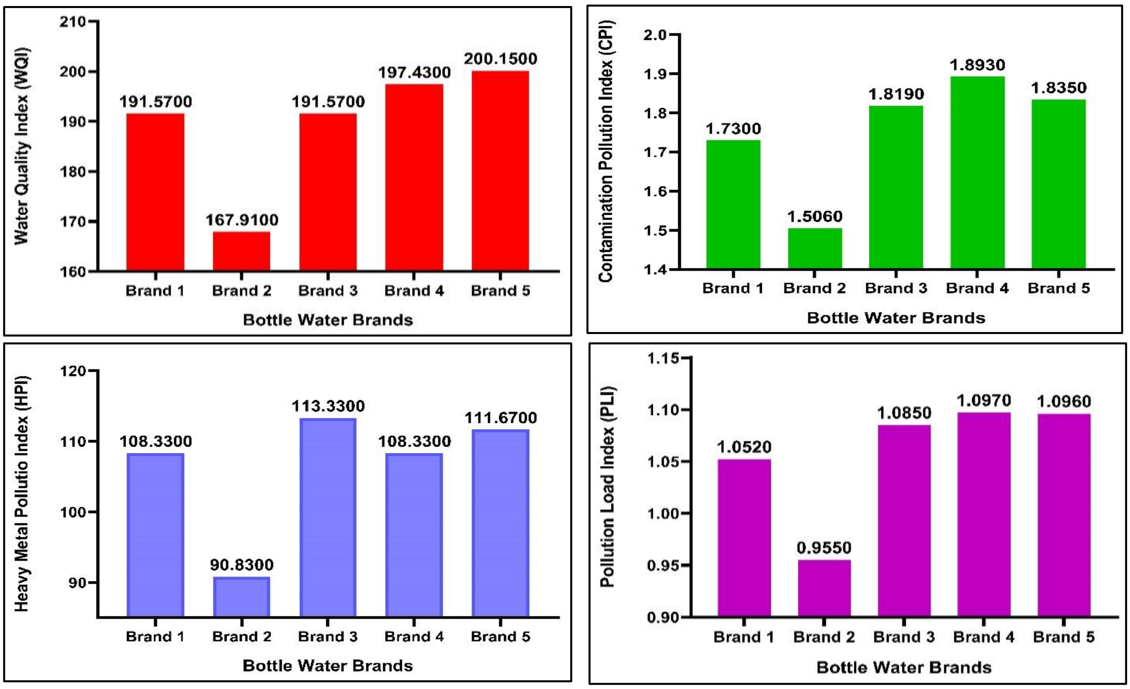

Figure 2: Water quality indices across different bottled water brands

Table 4: Hazard Quotient values across different bottled water brands

Metal	Lead	Cadmium	Arsenic	Mercury
Brand 1	0.09	0.09	1.05	0.1
Brand 2	0.07	0.08	0.86	0.09
Brand 3	0.09	0.09	1.24	0.1
Brand 4	0.09	0.09	1.05	0.1
Brand 5	0.09	0.09	1.05	0.1

Note: Hazard Quotient (HQ) values were calculated to assess potential non-carcinogenic health risks associated with heavy metal exposure from bottled water consumption**.**

Health Risk Assessment

The Chronic Daily Intake (CDI) values for Pb, Cd, As. The highest CDI for lead was observed in Brand 5 (0.0000343 ± 0.000001 mg/kg/day), whereas Brand 3 showed the highest CDI for mercury (0.00000371 ± 0.0000001 mg/kg/day). Arsenic demonstrated consistent CDI values (0.0000314 ± 0.000001 mg/kg/day), indicated steady exposure risks across brands.

The calculated Hazard Quotient (HQ) values for Pb, Cd, As, and Hg in the bottled water brands indicated that arsenic (As) posed the greatest potential risk. Brand 1 showed HQs of 0.09 (Pb), 0.09 (Cd), 1.05 (As), and 0.10 (Hg), while Brand 2 recorded the lowest values (0.07, 0.08, 0.86, and 0.09, respectively). Brand 3 had the highest HQ for arsenic (1.24), whereas Brands 4 and 5 displayed identical HQs (Pb

= 0.09, Cd = 0.09, As = 1.05, Hg = 0.10) (*Table 4*). The calculated Hazard Index (HI) values, shown in *Figure 3, 4*, ranged from 1.1 to 1.52, reflecting differences in cumulative non-carcinogenic risk among the brands. Brand 2 had the lowest HI (1.1), suggesting minimal potential risk, while Brand 3 showed the highest value (1.52), indicating greater overall exposure to heavy metals. Brands 1, 4, and 5 shared similar HI values (1.33). Because all HI values exceeded 1, the findings imply possible non-carcinogenic health effects from long-term consumption, with Brand 3 posing the highest concern due to elevated arsenic levels contributin. most to the overall risk. The Incremental Lifetime Cancer Risk (ILCR) exceeded acceptable limits (1.0E-06) for cadmium and arsenic across all brands (*Figure 5, 6*). Cadmium showed the highest cancer risk (5.04E-05 to 5.76E-05), followed by arsenic (3.86E-05 to 4.71E-05). Lead and mercury posed negligible carcinogenic risks, with ILCR values well below 10^{-7}.

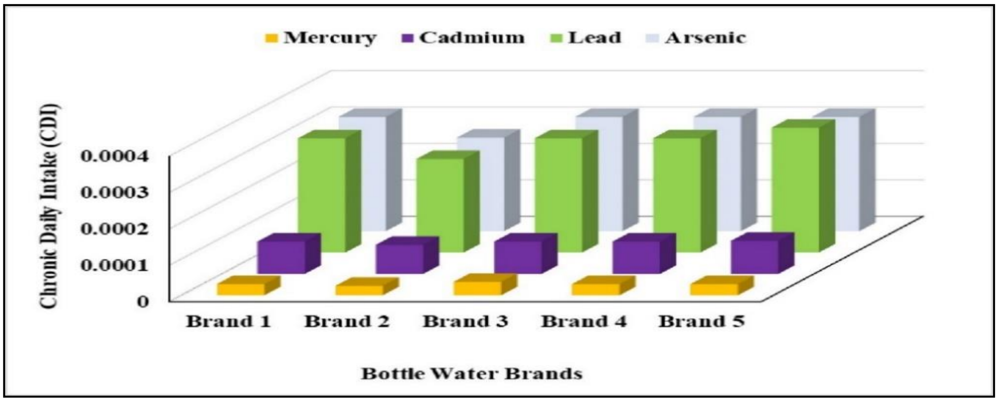

Figure 3: Chronic Daily Intake of different bottled water brands

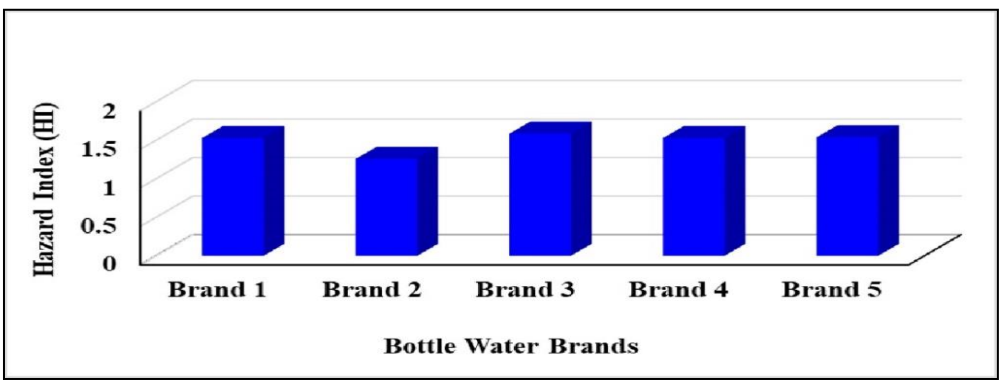

Figure 4: Hazard Index values across different brands of bottled water

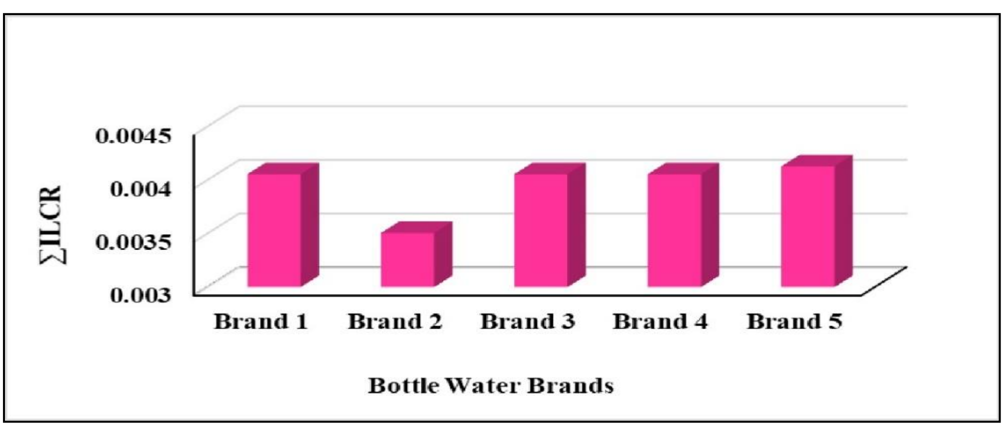

Figure 5: Sum of Incremental Lifetime Cancer Risk (∑ILCR)

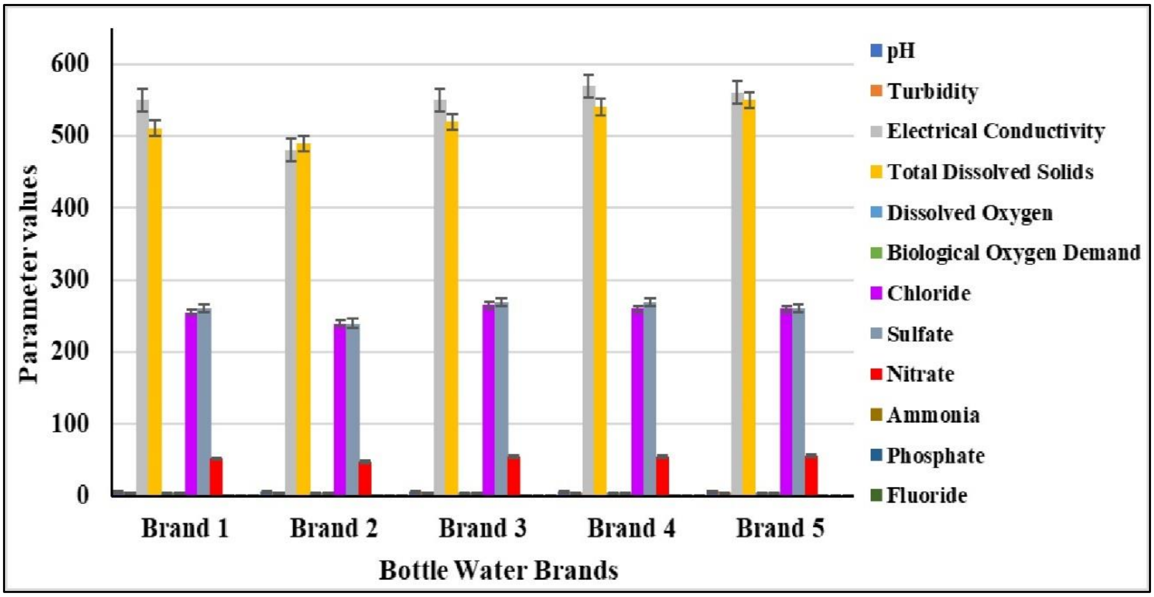

Figure 6: Comparison of Key Physicochemical Parameters Across Bottled Water Brands.

Discussion

The analysis of physico-chemical parameters across different bottled water brands demonstrated significant variations in key water quality indicators, reflecting potential differences in source water characteristics and treatment processes. The pH values ranged from 6.6 to 7.1, with Brand 2 indicated the highest mean value (7.1), whereas Brands 1 and 5 recorded the lowest (6.6). Although the differences were not statistically significant ($p = 0.082$), the observed range remained within the WHO-recommended limits for drinking water (Organization, 2024). Electrical conductivity values varied significantly ($p = 0.045$), with Brand 4 reporting the highest value (570 µS/cm), indicating higher dissolved ionic content compared to Brand 2, which exhibited the lowest (480 µS/cm). These findings aligned with those of Bityukova and Petersell (2010) and Peh et al. (2010), who observed EC variations in bottled water brands due to differences in geological water sources. The total dissolved solids (TDS) values ranged from 490 to 550 mg/L, with statistically significant differences ($p = 0.048$), indicating possible variations in mineral content among brands, which agreed with the findings of Reyes-Toscano et al. (2020)

Turbidity levels revealed significant differences ($p = 0.031$), with Brand 5 displaying the highest value (5.4NTU) and Brand 2 the lowest (4.9NTU). Higher turbidity indicates inadequate filtration or the presence of suspended particles, similar to the results reported by Neukermans et al. (2012) and Yao et al. (2014). The concentrations of nitrate varied significantly ($p = 0.038$), with Brand 5 recording the highest value (57 mg/L), exceeding that of Brand 2 (48 mg/L). Elevated nitrate levels in drinking water have been associated with potential health risks, particularly for infants, as noted by Richard et al. (2014). Ammonia concentrations also reported notable differences ($p = 0.067$), with Brands 4 and 5 (0.70 mg/L) showing higher values compared to Brand 2 (0.48 mg/L). These results corroborated those of Sasakova et al. (2018), who reported that ammonia presence in bottled water often originated from microbial activity or contamination from agricultural runoff.

Phosphate concentrations showed significant differences ($p = 0.041$), with Brand 4 containing the highest levels (1.3mg/L), while Brand 2 had the lowest (0.9mg/L). Similar phosphate concentrations have been reported by Fang et al. (2009), who reported that excessive phosphate in bottled water could contribute to biofilm formation, affecting water quality during storage. Chloride concentrations were not significantly different among brands ($p = 0.089$), with values ranging from 240 to 265 mg/L, which aligned with acceptable drinking water limits. Fluoride concentrations showed minor variations ($p = 0.071$), with Brands 1, 4, and 5 containing the highest concentration (1.6 ± 0.04 mg/L), in agreement with WHO recommendations for dental health benefits Organization (2024).

Sulphate levels were comparable across brands ($p = 0.092$), with Brands 3 and 4 reported the highest concentrations (270mg/L), indicated differences in mineral composition, similar to the observations of Lanjwani et al. (2022). Dissolved oxygen varied significantly ($p = 0.054$), with Brand 2 (5.1mg/L) demonstrated the highest value and Brand 5 (4.5 ± 0.11 mg/L) the lowest. These findings were similar to those of Lopes et al. (2009), who reported that variations in DO levels could result from differences in storage conditions and bottle permeability to atmospheric oxygen. Similarly, biochemical oxygen demand (BOD5) exhibited significant variations (p = 0.038), with Brand 4 (5.4mg/L) showing the highest levels, revealed the possible presence of organic matter, as previously observed by Latif and Dickert (2014).

Heavy metal concentrations varied across brands, with lead levels reaching their highest in Brand 5 (12µg/L), although differences were not statistically significant (p = 0.065). Cadmium levels differed significantly (p = 0.079), with Brand 5 (3.2µg/L) having the highest concentration. Arsenic was notably higher in Brands 1, 3, 4, and 5 (11µg/L), whereas Brand 2 recorded the lowest level (9µg/L), though the difference was not significant (p = 0.073). Mercury levels showed significant differences (p = 0.051), with Brand 3 demonstrating the highest concentration (1.3µg/L), which was consistent with contamination sources such as industrial discharge Sullivan and Leavey (2011) (Vardè et al., 2019, Muzhda, 2025, Qader et al., 2025). This study was limited by the small number of bottled water brands (n=5) and single-season sampling, which may not reflect temporal variation. Additionally, microbial contamination was not assessed. However, the study's strength lies in its comprehensive integration of physicochemical, heavy metal, and quantitative health risk analyses, providing the first systematic evaluation of bottled water safety in Erbil.

Conclusion

This study demonstrated that bottled water sold in Erbil generally meets international drinking-water quality standards, with most physicochemical parameters falling within WHO acceptable limits. Nevertheless, nitrate and fluoride levels slightly exceeded recommended values, and arsenic concentrations were occasionally above the 0.01 mg/L threshold. Corrected health-risk assessment revealed that arsenic was the major contributor to total hazard, with HQ values above 1 and cumulative HI values exceeding unity, indicating potential non-carcinogenic health risks upon prolonged consumption. Lead, cadmium, and mercury remained within safe exposure limits. These findings emphasize the need for regular surveillance of bottled water quality, enforcement of production and labeling standards, and adoption of preventive measures to reduce trace metal and nitrate contamination in water sources. Continuous health-risk assessment and periodic review of bottled-water quality are essential to protect public health in the Kurdistan Region of Iraq.

Statements and Declarations

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Competing Interests The authors declare no conflict of interest.

Ethics Statement This study was reviewed and approved by the Medical Ethics Committee of Hawler Medical University, Erbil, Iraq, during their eighth meeting (Paper Code: 8C) on 1/9/2025. All procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki.

Data Availability Statement The data that support the findings of this study are available from the corresponding author upon reasonable request.

Clinical trial registration This study did not constitute a clinical trial and therefore did not require registration.

Transparency Statement The lead author Muzhda Q. Qader affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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Permission to reproduce material from other sources There are no reproduced materials in the current study.

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