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Research Article

Assessment of Human Health Risk from Chromium in Drinking Water in the Northeast of Iran Using the Monte Carlo Simulation

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Abstract

Background: Despite technological advancements, heavy metal concentrations in water sources remain above the safe limits set by regulatory standards worldwide. Contaminated drinking water containing heavy metals poses significant public health concerns globally.

Objectives: This study aims to examine the non-carcinogenic and carcinogenic risks for adults and children exposed to chromium (Cr) in drinking water through ingestion and dermal pathways.

Methods: Health risk assessments were conducted on 60 samples collected from ten active wells and ten stations within the drinking water distribution network sections in Fariman, Iran. The Superfund risk assessment model from the US Environmental Protection Agency (EPA) was employed to evaluate health risks. Crystal Ball software was used to perform Monte Carlo simulations and sensitivity analyses to reduce uncertainties and assess the impact of each variable on the risk assessment results.

Results: The hazard quotient (HQ) values for Cr from ingestion pathways exceeded the safety level threshold (HQ > 1) for both adults and children in all sampling sites, while for dermal exposure, the HQ was lower than the safe limit for both populations. The mean cancer risk (CR) values for children and adults via ingestion were 4.58×10^{-4} and 7.9×10^{-5}, respectively. However, the CR associated with dermal exposure for both groups was deemed negligible.

Conclusions: The health risk of Cr exposure from drinking water exceeds the acceptable safety level for children and adults. This indicates that drinking water is the primary source of Cr exposure for residents in Fariman. It is essential to implement more control measures and suitable purification systems to reduce Cr levels in the water supply in Fariman.

Keywords: Health Risk Assessment, Chromium, Drinking Water

1. Background

Access to safe drinking water is a basic human right and essential for health and welfare. Governments must establish adequate infrastructure and ensure effective water quality monitoring. Contamination by chemical pollutants and pathogens poses serious public health risks, even at low concentrations (1, 2). Heavy metal contamination in water sources, particularly by chromium (Cr), is a significant global environmental issue with serious implications for human health (1, 3). Chromium in water is classified by its oxidation states, specifically hexavalent chromium [Cr (VI)] and trivalent chromium [Cr (III)]. Prolonged exposure to hexavalent Cr is classified as a human carcinogen and is associated with significant health risks, particularly lung and stomach cancer (4). The Agency for toxic substances and disease registry ranks Cr as the seventh most hazardous substance. Studies indicate that waterborne hexavalent Cr significantly contributes to global cancer rates. The environmental protection agency (EPA) and WHO set the drinking water limits for total chromium (Cr III and Cr VI) at 0.1 mg/L and 0.05 mg/L, respectively (5).

Chromium can enter water sources through natural processes, such as the interaction of water with ultramafic rocks, as well as through agricultural runoff and human activities like mining, coal burning, and industrial waste disposal (6). Additionally, Cr can leach into water sources from the corrosion of cast iron when exposed to disinfectants (7, 8).

Fariman city faces significant water challenges, including limited surface water availability, which places considerable stress on underground water sources. Furthermore, the groundwater in the area is contaminated with heavy metals such as Cr and iron, originating from ophiolitic sources (9). Numerous studies have examined the levels of heavy metals in surface water sources and soil surrounding Fariman. Findings indicate that Cr levels are significantly higher than those of other metals and exceed permissible consumption limits (10). This is likely due to geological conditions and chromite mining activities near the city. These findings suggest a high probability of Cr contamination in Fariman's drinking water.

A comprehensive study is required to measure Cr levels in the city's drinking water sources and distribution system and assess potential health risks. The available information regarding Cr contamination levels in Fariman, its potential sources, and associated health risks is limited. It remains unclear whether drinking water quality in this region meets safety standards and adequately protects human health from potential hazards. Regular monitoring of Cr levels in Fariman's water supply is essential to assess contamination and implement prompt remediation measures.

2. Objectives

The study aimed to: (1) Determine the concentrations of chromium [Cr (VI)] in treated piped water and well water to monitor the quality of drinking water; and (2) assess the non-carcinogenic and carcinogenic risks for both adults and children exposed to chromium [Cr (VI)] in drinking water through ingestion and dermal contact.

3. Methods

3.1. Study Area

This study investigates the quality of drinking water in Fariman, focusing on contamination by chromium hexavalent [Cr (VI)], which is recognized as both a carcinogenic and mutagenic substance. Fariman is located in the northeast of Iran at the coordinates of 35°42' latitude and 59°50' longitude (Figure 1). Fariman covers an area of approximately 3,232 km^2 and has a population of 32,344 residents (11).

3.2. Samples Collection and Chemical Analysis

Health risk assessments were conducted on 60 samples collected from 10 active wells and 10 stations within the drinking water distribution network, based on the system's structure and population distribution. This study included 20 sampling stations and 3 replications, resulting in a total of 60 samples. Before collecting the samples, the water tap was allowed to run for one minute to eliminate any stagnant water in the pipes. The samples were collected in high-quality, dark 500 ml polyethylene containers, which were rinsed with distilled water before use.

To stabilize the heavy metals and prevent crystallization or absorption into the sampling containers, 5 mL of 65% nitric acid was added to all containers. The samples were filtered and acidified before being analyzed for Cr using EPA Method 6020, employing an inductively coupled plasma mass spectrometer (ICP-MS, 7700 series). The device was calibrated with standard solutions to ensure accurate measurements of Cr. Standard solutions and a blank for Cr ions were used to create the calibration graph. The correlation coefficients of the calibration line were greater than 0.99. The limit of detection for Cr ions was 0.06, and all samples were measured in triplicate to check the reproducibility of the tests. Recovery values for Cr ranged within acceptable limits, from 88.2% to 109%.

3.3. Health Risk Assessment

3.3.1. Problem Formulation

The US EPA states that Cr intake from drinking water can lead to health risks, including both carcinogenic and non-carcinogenic effects. This evaluation involves hazard identification, dose-response assessment, exposure assessment, and risk characterization (12). In this study, two age groups were evaluated for the risk of Cr exposure through ingestion and dermal contact with drinking water: Children, as a sensitive population, and adults, representing the general population. All parameters and their values in the health risk assessment are detailed in the attached Table 1.

3.3.2. Exposure Assessment

The average daily dose (ADD) of Cr exposure through skin absorption and direct ingestion was measured using Equations 1-3 based on the US EPA method (13).

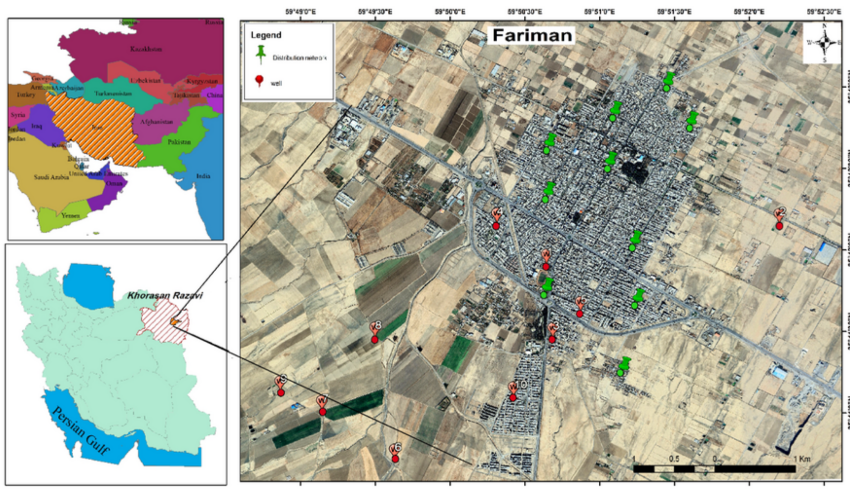

Figure 1. Map of the study area

Table 1. Parameters and Input Assumptions for Health Risk Assessment of Chromium (12-16)

Variables	Definition	Values	Reference
ADD $_{ing}$ (mg/kg/d)	Average daily dose of elements through ingestion	-	Equation 1, Table 2
DAD (mg/kg/d)	Dermal absorbed dose	-	Equation 2, Table 2
DA $_{event}$ (mg/cm ^{3}/event)	Absorbed dose per event	-	Chemical-specific, Equation 3
C (mg/cm ^{3})	Concentration of elements in drinking water	-	Site-specific, Table 2
EV (events/d)	Event frequency	1	-
IR $_d$ (L/d)	Drinking water daily ingestion rate	Adult = 2, child = 1.8	Cite specific
EF (d/y)	Exposure frequency	Ingestion = 365, dermal = 350	-
ED (y)	Exposure duration	Adult = 70, child = 6	
BW (kg)	Body weight	Adult = 70, child = 32	-
AT (d)	Average time	Noncarcinogenic effects (ED × 365)/carcinogenic effects 70 y × 365 d/y	-
SA (m ^{2})	Skin surface area available for contact	Adult = 1.8, child = 6.6	-
Kp (cm/h)	Dermal permeability constant	Cr = 0.002	-
RFD (mg/kg/d)	Reference dose	Cr = 0.0009	-
CSF (mg/kg/d)	Cancer slope factor	Cr = 0.27	-
HQ	Hazard quotient	-	Equation 4, Table 1
T $_{event}$ (h/event)	Event duration	Adult = 0.33, child = 0.25	
CR	Cancer risks	-	Equation 5, Table 1

$$ADDing = \frac{C \times IRd \times EF \times ED}{BW \times AT} \tag{1}$$

$$DAD = \frac{DA_{event} \times SA \times EV \times ED \times EF}{BW \times AT} \tag{2}$$

$$DA_{event} = K_p \times C_w \times t_{event} \tag{3}$$

3.3.3. Non-carcinogenic Risks

We estimated non-carcinogenic health risks based on the hazard quotient (HQ) using Equation 4. The HQ is

Table 2. Descriptive Statistics of Carcinogenic and Non-carcinogenic Risks Associated with Chromium in Drinking Water (via Ingestion and Dermal Exposure) for Both Children and Adults

Code	Risk Assessment-Ingestion				Risk Assessment-Dermal			
	HQ		CR		HQ		CR	
	Adults	Children	Children	Adults	Children	Adults	Children	Adults
1	1.8095	3.6515	4.40E-04	7.61E-05	1.07E-03	6.70E-03	2.61E-07	1.395E-07
2	1.8095	3.6515	4.40E-04	7.61E-05	1.07E-03	6.70E-03	2.61E-07	1.395E-07
3	1.5238	3.0750	3.70E-04	6.4E-05	9.05E-04	5.64E-03	2.2E-07	1.175E-07
4	1.6825	3.3953	4.09E-04	7.07E-05	9.99E-04	6.23E-03	2.43E-07	1.297E-07
5	1.2698	2.5625	3.09E-04	5.34E-05	7.54E-04	4.70E-03	1.83E-07	9.791E-08
6	1.9683	3.9718	4.78E-04	8.27E-05	1.17E-03	7.29E-03	2.84E-07	1.518E-07
7	1.8413	3.7156	4.47E-04	7.74E-05	1.09E-03	6.82E-03	2.66E-07	1.420E-07
8	1.6825	3.3953	4.09E-04	7.07E-05	9.99E-04	6.23E-03	2.43E-07	1.297E-07
9	2.2540	4.5484	5.48E-04	9.47E-05	1.34E-03	8.34E-03	3.25E-07	1.738E-07
10	2.0635	4.1640	5.01E-04	8.67E-05	1.23E-03	7.64E-03	2.98E-07	1.591E-07
11	2.1270	4.2921	5.17E-04	8.94E-05	1.26E-03	7.87E-03	3.07E-07	1.640E-07
12	1.7143	3.4593	4.17E-04	7.21E-05	1.02E-03	6.35E-03	2.47E-07	1.322E-07
13	1.9365	3.9078	4.71E-04	8.14E-05	1.15E-03	7.17E-03	2.8E-07	1.493E-07
14	1.6508	3.3312	4.01E-04	6.94E-05	9.81E-04	6.11E-03	2.38E-07	1.273E-07
15	2.0000	4.0359	4.86E-04	8.41E-05	1.19E-03	7.40E-03	2.89E-07	1.542E-07
16	2.0635	4.1640	5.01E-04	8.67E-05	1.23E-03	7.64E-03	2.98E-07	1.591E-07
17	2.0000	4.0359	4.86E-04	8.41E-05	1.19E-03	7.40E-03	2.89E-07	1.542E-07
18	2.0000	4.0359	4.86E-04	8.41E-05	1.19E-03	7.40E-03	2.89E-07	1.542E-07
19	2.0000	4.0359	4.86E-04	8.41E-05	1.19E-03	7.40E-03	2.89E-07	1.542E-07
20	2.2222	4.4843	5.40E-04	9.34E-05	1.32E-03	8.23E-03	3.21E-07	1.713E-07
Mean ± SD	1.8810 ± 0.2431	3.7956 ± 0.4905	0.000458 ± 5.89E-05	7.91E-05 ± 1.02E-05	0.001117 ± 0.000145	0.006963 ± 0.000899	2.72E-07 ± 3.51E-08	1.45E-07 ± 1.87E-08

Abbreviations: HQ, hazard quotient; CR, cancer risk.

defined as the ratio of the ADD of a given element to its reference dose (RfD) for a specific exposure pathway (ingestion or dermal contact). The RfD represents the daily exposure level for humans over a lifetime that is unlikely to cause significant adverse effects. When the HQ is less than 1, the population is considered safe from non-carcinogenic risks.

$$HQ = \frac{ADD}{RfD} \quad (4)$$

3.3.4. Carcinogenic Risks

The US EPA defines carcinogenic risk as the likelihood of developing cancer from exposure to a carcinogen. Their acceptable risk levels range from 10^{-4} to 10^{-6}, with risks above 10^{-4} considered unacceptable and requiring action. We estimated the level of carcinogenic risk using Equation 5 as follows:

$$CR = ADD \times CSF \quad (5)$$

3.4. Statistical Analysis

The analysis of data was conducted using SPSS version 25 and Microsoft Excel 2016. Descriptive statistics, including frequency, mean, and standard deviation, were utilized to summarize the data, while bivariate analysis, including an independent t-test, was employed to assess variations in variables across different groups. Traditional risk assessments often provide a single-point value, limiting the understanding of uncertainty. To address this limitation, the US EPA recommends the Monte Carlo simulation method, which employs random sampling and probability distributions to model uncertainties. Therefore, we applied the Monte Carlo simulation using Crystal Ball software (version 11.1.24), running 10,000 replications to create a 90% confidence interval, focusing on the 95th percentile of the risk index and estimating carcinogenic risk. A sensitivity analysis was also performed to evaluate the influence of each variable on the risk assessment.

4. Results

The Kolmogorov-Smirnov test yielded a P-value of 0.2, confirming that the data follows a normal distribution.

Table 3. Descriptive Statistics of Estimated Average Daily Dose of Chromium for Adults and Children Through Ingestion and Dermal Intake of Drinking Water

Sources and Codes	Cr (μg/L)	ADD (Ingestion Intake)		ADD (Dermal Absorption)	
		ADD_{ing} Child	ADD_{ing} Adult	ADD_{derm} Child	ADD_{derm} Adult
Well					
1	57	3.29E-03	1.63E-03	6.95E-04	4.19E-05
2	57	3.29E-03	1.63E-03	6.95E-04	4.19E-05
3	48	2.77E-03	1.37E-03	5.85E-04	3.53E-05
4	53	3.06E-03	1.51E-03	6.46E-04	3.89E-05
5	40	2.31E-03	1.14E-03	4.88E-04	2.94E-05
6	62	3.57E-03	1.77E-03	7.56E-04	4.56E-05
7	58	3.34E-03	1.66E-03	7.07E-04	4.26E-05
8	53	3.06E-03	1.51E-03	6.46E-04	3.89E-05
9	71	4.09E-03	2.03E-03	8.66E-04	5.22E-05
10	65	3.75E-03	1.86E-03	7.93E-04	4.78E-05
Water supply					
11	67	3.86E-03	1.91E-03	8.17E-04	4.92E-05
12	54	3.11E-03	1.54E-03	6.59E-04	3.97E-05
13	61	3.52E-03	1.74E-03	7.44E-04	4.48E-05
14	52	3.00E-03	1.49E-03	6.34E-04	3.82E-05
15	63	3.63E-03	1.80E-03	7.68E-04	4.63E-05
16	65	3.75E-03	1.86E-03	7.93E-04	4.78E-05
17	63	3.63E-03	1.80E-03	7.68E-04	4.63E-05
18	63	3.63E-03	1.80E-03	7.68E-04	4.63E-05
19	63	3.63E-03	1.80E-03	7.68E-04	4.63E-05
20	70	4.04E-03	2.00E-03	8.54E-04	5.14E-05
Mean ± SD	59.25 ± 7.6563	3.42E-03 ± 4.40E-04	1.69E-03 ± 2.19E-04	7.23E-04 ± 9.34E-05	4.35E-05 ± 5.63E-06

Abbreviations: ADD, average daily dose; Cr, cancer risk.

An independent *t*-test was conducted to analyze the significant difference between Cr concentrations in well water and the distribution network. The *t*-test showed a mean difference of -4.19 (SE = 3.39), t = -1.235, df = 18, P = 0.233, with a 95% confidence interval of [-11.32, 2.94]. Thus, there is no significant difference in Cr concentrations between the well water and the supply water ($P > 0.05$).

Table 3 shows that Cr concentrations ranged from 40 to 71 μg/L, with an average of 59.25 ± 7.65 μg/L, often exceeding the 50 μg/L limit set by national standards and the WHO. The average Cr intake through ingestion was measured at $3.4 \times 10^{-4} \pm 4.40 \times 10^{-4}$ for children and $1.69 \times 10^{-4} \pm 2.19 \times 10^{-4}$ for adults. The average dermal contact intakes were $7.3 \times 10^{-7} \pm 9.34 \times 10^{-5}$ for children and $4.25 \times 10^{-7} \pm 5.63 \times 10^{-6}$ for adults (Table 3).

4.1. Non-carcinogenic and Carcinogenic Risk

The HQ and carcinogenic risk values for ingestion and dermal exposure in adults and children are shown in Table 2. The mean HQ for ingestion was 3.79 ± 0.49 in children and 1.88 ± 0.24 in adults, both exceeding the concern level (HQ > 1) for their respective groups. In contrast, the mean HQ for dermal contact was notably low, measured at 0.0069 ± 0.0008 in children and 0.0011 ± 0.0001 in adults, both falling below the US EPA threshold (HQ < 1).

The mean CR values for children and adults via ingestion were measured at $4.58 \times 10^{-4} \pm 5.89 \times 10^{-5}$ and $7.9 \times 10^{-5} \pm 1.02 \times 10^{-5}$, respectively. For dermal exposure, the CR values for children and adults were $2.7 \times 10^{-7} \pm 3.51 \times 10^{-7}$ and $1.45 \times 10^{-7} \pm 1.87 \times 10^{-7}$, respectively. Both values are below the standard threshold recorded by the US EPA of 10^{-6}, indicating a negligible risk associated with dermal contact.

4.2. Uncertainty and Sensitivity Analysis

The carcinogenic and non-carcinogenic risks were assessed at a 95% confidence level using 10,000 simulations in Crystal Ball software. As shown in Figure 2, the HQ index for children from ingestion ranges from

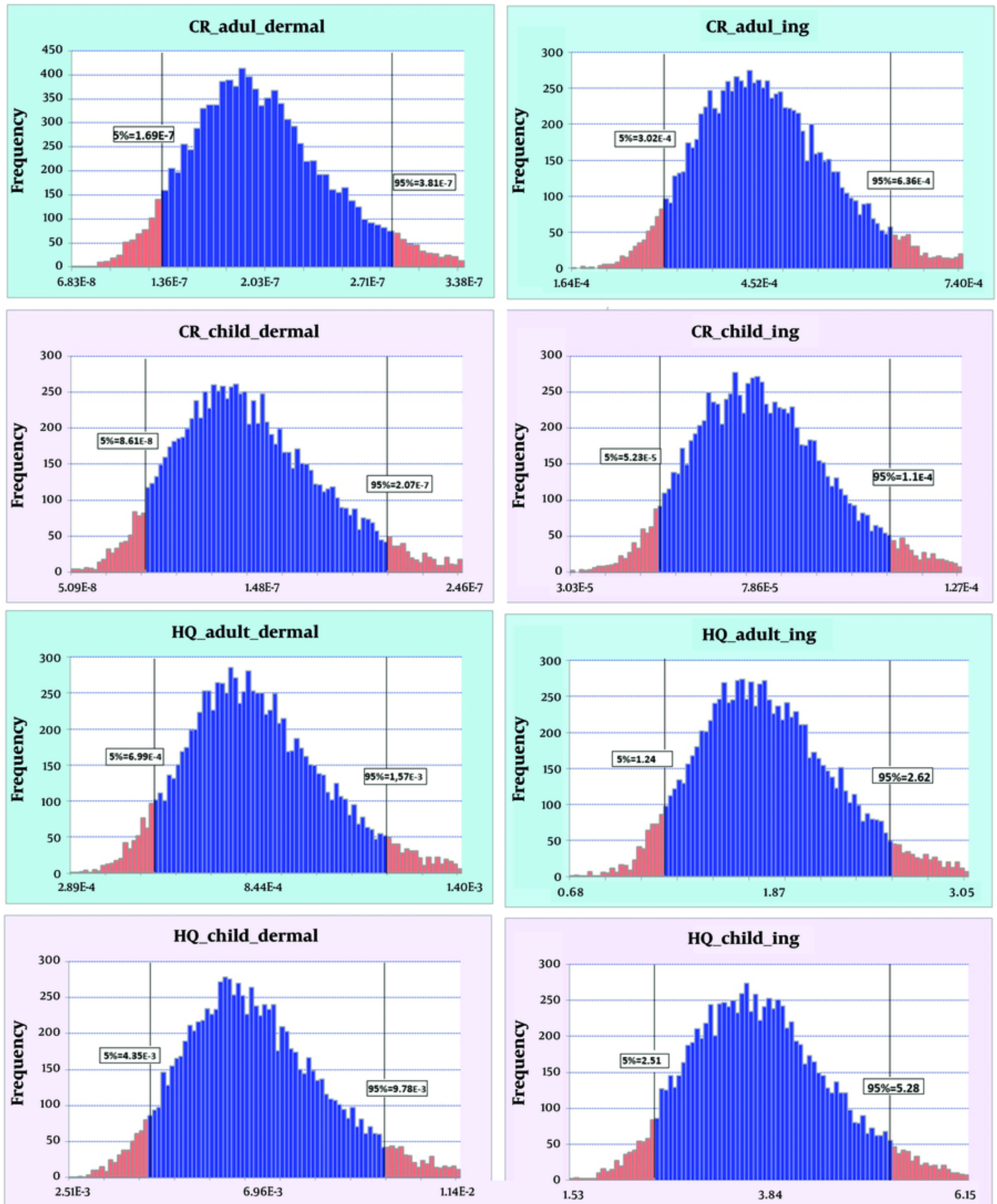

Figure 2. The cumulative distribution of hazard quotient (HQ) and cancer risk (CR) values of chromium (Cr) through ingestion and dermal exposure for both children and adults

2.51 to 5.28 (mean: 3.76), while for adults, it ranges from 1.24 to 2.62 (mean: 1.87), both values exceeding the US EPA safe level (HQ > 1). The HQ for children from dermal contact ranges from 0.00435 to 0.00978, and for adults, it ranges from 0.000699 to 0.00157, both below the EPA safe level (HQ < 1). The CR for Cr from ingestion for children ranges from 3.02×10^{-4} to 6.36×10^{-4} (mean: 5.52×10^{-4}), and for adults, it ranges from 5.23×10^{-5} to 1.1×10^{-4} (mean: 7.78×10^{-5}), which falls within the moderate EPA range (10^{-4} to 10^{-6}). For dermal contact, the CR for children ranges from 1.69×10^{-7} to 3.81×10^{-7}, and for

Figure 3. The effect of different variables on hazard quotient (HQ) and cancer risk (CR) caused by chromium (Cr) through ingestion and dermal exposure for both children and adults

adults, it ranges from 8.67×10^{-8} to 2.07×10^{-7}, both below the EPA threshold (10^{-6}).

As illustrated in Figure 3, the sensitivity analysis reveals that for both children and adults, the HQ values from ingested drinking water and dermal contact are influenced in the following order: CR > IR > BW > AT > EF > ED. Chromium concentrations, IR, and BW exhibited the highest contributions, whereas AT, EF, and ED contributed less than 10%. Sensitivity analysis for cancer risk (CR) reveals that in both adults and children, the health risk associated with dermal exposure and ingestion pathways to Cr is influenced in the following order: Cr > BW > SA > KP > EF > CSF. According to the results, Cr and BW have the most significant impact on CR, while other parameters contributed less than 10% (Figure 3).

5. Discussion

This study assessed health risks related to Cr in Fariman city's drinking water using Monte Carlo simulations. The results revealed that Cr concentrations exceeded the EPA's recommended limit of 50 μg/L in many samples. High Cr levels in water may arise from mining activities, inadequate purification, and pipeline corrosion. Research has indicated significant Cr and Fe contamination near the Kosar chromite mine in Fariman city (6, 10). Numerous studies have reported exposure to Cr pollutants in drinking water both in Iran and globally. Similar findings were observed in Birjand, Iran, by Fallahzadeh et al. (17), as well as by Shi et al. in Iceland (18). These studies reported that exposure to Cr pollution through ingestion or dermal contact with drinking water is a public health concern.

Since no data was previously available regarding the carcinogenic and non-carcinogenic risks linked to Cr in Fariman's water sources, the average daily intakes of Cr as a toxic heavy metal were determined through ingestion and dermal absorption pathways. The average daily intake of Cr from ingestion was found to be approximately 3.88 to 4.72 times greater than that from dermal contact for both population groups. This finding emphasizes ingestion as the main route of exposure. Thus, exposure to Cr through water ingestion is the significant pathway for Cr absorption, aligning with recent research highlighting ingestion as the primary route of exposure to Cr in drinking water. Additionally, children were found to be about twice as exposed to Cr through drinking water compared to adults, consistent with findings by Alidadi et al. (19).

This study indicates that ingestion hazard coefficients (HQ > 1) for both children and adults signify serious lifelong health risks from Cr. Therefore, the non-carcinogenic risk from Cr via ingestion was not within the safe range for either population group. This result aligns with findings from other studies conducted in Iran, Malaysia, and Pakistan (20, 21). In contrast, dermal contact hazard coefficients for both groups were well below the threshold (HQ < 1), suggesting minimal long-term risks for residents. These findings are consistent with research by Nyambura et al. in Kenya (22) and Moradian et al. in Isfahan (8). This study demonstrates that the non-HQ from ingestion is greater than that from dermal contact and that children are at greater risk than adults because of their lower body weight, higher dose per unit of weight, and increased susceptibility to environmental influences during developmental stages. Similar findings were reported by Shams et al. in Iran (23) and by Shi et al. in Iceland (18).

The CR from dermal contact is below the safety threshold (1×10^{-4}) for both populations in Fariman, suggesting it is acceptable. However, the potential CR via ingestion of drinking water for both populations was observed, indicating that the consumption of drinking water may warrant action under Superfund guidelines and pose detrimental health hazards to the exposed population in this region. The study concluded that the carcinogenic risk associated with Cr from dermal exposure is below the EPA-established minimum threshold of 10^{-6} and therefore does not constitute a threat to the local population. In the study titled "Cancer and Non-Cancer Risk Assessment of Heavy Metals in Ground Water Resources of Varamin Plain", conducted by Movafaghi Ardestani and Pardakhti, it was similarly reported that the carcinogenic risk associated with Cr from dermal exposure remains within acceptable limits (24, 25).

The results of the sensitivity analysis indicated that certain parameters significantly affect the carcinogenic and non-carcinogenic risks associated with drinking water in Fariman for both populations. The analysis revealed that Cr concentration, body weight, skin surface area, and daily water consumption are the most critical variables impacting these risk levels. These findings can guide resource allocation and decision-making, leading to timely treatment and intervention programs aimed at improving the water supply in the region.

This study provides comprehensive information for decision-makers regarding concerns about Cr exposures and their potential risks to the child and adult populations in Fariman. Based on risk analysis, all water supplies, distribution networks, and wells in Fariman require intervention with targeted remediation and control measures to reduce Cr contamination. Suitable intervention programs should include remediation of contaminated sites through advanced water treatment technologies (e.g., filtration and chemical precipitation) and improvements to water supply infrastructure.

5.1. Conclusions

In the study area, for dermal exposure, there is no health risk concern from Cr for either population. However, drinking water ingestion was identified as the primary route of Cr exposure for the child and adult populations in Fariman. Therefore, residents in this city may face significant non-carcinogenic and carcinogenic risks. Greater attention is required to reduce Cr levels in the water supply, such as through continuous monitoring of water resources and the implementation of effective treatment solutions.

Footnotes

Authors' Contribution: Study concept and design: R. V.; Analysis and interpretation of data and drafting of the manuscript: M. P.; Critical revision of the manuscript for important intellectual content: B. T.

Conflict of Interests Statement: The authors have no conflicts of interest to declare.

Data Availability: The dataset presented in the study is available on request from the corresponding author during submission or after publication.

Ethical Approval: This study is approved under the ethical approval code of IR.MUMS.FHMPM.REC.1403.189 .

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