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Health risk assessment of toxic elements in Kashan drinking water reservoirs using Monte Carlo simulation and sensitivity analysis

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In today's world, given the industrialization of societies and the water scarcity crisis, the issue of water resource protection has gained attention. Among water pollutants, toxic elements are among the most significant. Therefore, this study was conducted with the aim of assessing the health risk posed by exposure to toxic elements in the drinking water of Kashan, Iran. In this study, 39 water samples were collected from 13 active water reservoirs. The concentrations of toxic elements including arsenic (As), lead (Pb), and cadmium (Cd) were determined using ICP-MS and compared with national and international standards. Ultimately, human health risk assessment was calculated using the United States Environmental Protection Agency (USEPA) index, carcinogenic and non-carcinogenic risks were evaluated for three age groups—children, teenagers, and adults—using a Monte Carlo simulation-based method with the help of Crystal Ball (Oracle) software. The average concentrations of As, Pb, and Cd in the drinking water reservoirs of Kashan city were 3.94 μg/L, 0.86 μg/L and 0.35 μg/L, respectively. The hazard quotient (HQ) and hazard index (HI) for all age groups were below the safety limit (HQ < 1). The cumulative excess lifetime carcinogenic risk (ELCR) values for Pb and Cd were below the safety limit; however, for As, the ELCR values in children and teenagers were 1.73×10^{-4} and 1.59×10^{-4}, respectively, exceeding the permissible limit. This indicates that these two age groups may be at risk in the long term. A sensitivity analysis was conducted and confirmed that there is a potential risk to the health of children. It is recommended that continuous monitoring and risk management be implemented to protect public health, particularly for the age group of children and teenagers. Also, more comprehensive studies in different seasons of the year are recommended.

Keywords Carcinogenic, Health risk assessment, Monte Carlo simulation, Non-carcinogenic, Toxic elements, Water reservoirs

The contamination of drinking water with hazardous substances, particularly toxic elements, is a growing global concern that poses serious health risks to millions of people. toxic elements such as arsenic (As), lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) are of particular concern due to their toxic effects even at low concentrations[1]. These metals are introduced into water bodies through both natural processes and anthropogenic activities, such as industrial emissions, mining, waste disposal, and agricultural runoff. As toxic elements do not degrade easily, they accumulate in water reservoirs, making long-term exposure through drinking water a critical health issue[2]. The accumulation of these contaminants in the human body over time can lead to chronic diseases, including cancer, kidney dysfunction, and developmental issues, making their regulation and monitoring in water sources a public health priority[3,4]. Heavy metals are classified as persistent pollutants, meaning they remain in the environment for extended periods, posing a long-term threat to ecosystems and human health. In drinking water reservoirs, these metals can come from a variety of sources, including leaching from natural mineral deposits, industrial waste discharges, and agricultural chemicals that

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seep into groundwater[5]. Once in the water supply, these metals are difficult to remove through conventional water treatment methods, which increases the risk of human exposure. Exposure to toxic elements through drinking water has been linked to numerous adverse health outcomes, including neurological damage, reproductive toxicity, and an increased risk of cancer[3]. Pb, for instance, is well known for causing cognitive impairment and developmental delays in children, while Cd exposure has been associated with kidney damage and osteoporosis. In response to these concerns, the assessment of health risks associated with toxic elements in drinking water has become a critical aspect of environmental health studies[1].

Risk assessment methods provide a structured approach to quantifying the potential impact of toxic element exposure on human populations. These assessments typically involve identifying the specific contaminants present, determining their concentrations in the water supply, and estimating the level of human exposure based on water consumption patterns. However, traditional risk assessment methods often rely on fixed values for exposure parameters, which can limit their ability to account for the inherent variability and uncertainty in environmental data[6,7]. This is where advanced techniques, such as Monte Carlo simulation and sensitivity analysis, come into play, offering more robust tools for evaluating health risks[8].

Monte Carlo simulation is a powerful probabilistic method for assessing uncertainties related to health risks. This approach provides a distribution of potential risks by simulating thousands of scenarios instead of relying on a single fixed estimate. Consequently, it offers a more comprehensive understanding of the range of possible outcomes, taking into account factors such as metal concentrations and water consumption rates[9]. In the context of drinking water contamination, this simulation can predict the likelihood of adverse health effects resulting from toxic elements like As and Pb. For example, it can be examined how fluctuations of these pollutants in a reservoir over time may impact the long-term health of consumers[10]. Additionally, sensitivity analysis plays a crucial role in risk assessment by identifying key variables that influence risk. This analysis shows how factors such as metal concentrations or exposure duration affect the risk estimate. This information is essential for improving predictions and prioritizing risk reduction measures[11]. The combination of Monte Carlo simulation and sensitivity analysis offers a flexible and comprehensive approach to risk assessment. It aids researchers and policymakers in examining the complexities of environmental exposures and developing more effective strategies for managing water quality[5].

These techniques are particularly valuable in areas with high toxic element pollution, where traditional methods may not be sufficient for accurate assessments. For instance, in regions where groundwater is the primary source of drinking water coupled with prevalent industrial activities, probabilistic models can forecast changes in pollution levels and provide strategies for risk mitigation[11]. Furthermore, in facing challenges such as climate change, these methods become even more significant. Changes in precipitation, temperature, and land use can affect the movement and concentration of toxic elements. By considering these variables, the future quality of water and its impacts on public health can be better predicted[10].

The need for effective water management practices has never been greater, especially in regions experiencing rapid industrialization and urbanization. As human activities continue to release toxic elements and other pollutants into water systems, the burden of ensuring safe drinking water falls on both regulatory agencies and the scientific community[10]. Health risk assessments based on advanced modeling techniques offer a pathway toward more accurate and reliable predictions of contamination risks, enabling timely and targeted responses to water quality issues[12]. By integrating Monte Carlo simulation and sensitivity analysis into these assessments, we can better understand the complexities of environmental health risks and take proactive measures to safeguard public health. The World Health Organization (WHO) and other health agencies have established guidelines for permissible levels of toxic elements in drinking water. However, in many areas, these guidelines are exceeded, putting millions of people at risk[13]. Kashan city is very poor in terms of surface water resources due to its location in arid and desert areas, with its only water source coming from underground aquifers[14,15]. Considering that the quality of water resources in this area faces challenges such as salinity and pollution from human activities, it is essential to assess the effects of water pollution in this region on the health of consumers. This study focuses on assessing the health risks posed by the presence of As, Pb, and Cd in the drinking water of Kashan, Iran. By employing risk assessment methods and analyzing water quality data, this study seeks to contribute to a better understanding of the potential health impacts of toxic elements contamination and to inform policies aimed at safeguarding public health.

Materials and methods

Study area

Kashan is situated in northern Isfahan province, positioned between the Karkas Mountains and the Central Iranian Desert. Kashan has a hot and dry climate. This characteristic is due to its geographical location and the influence of the central mountains of Iran, as well as the lack of sufficient water resources. The annual precipitation and average humidity in Kashan is approximately 120 to 220 mm and 40% respectively. Rainfall mostly occurs in the fall and winter months, while summers are generally dry and without precipitation. Its water sources include rivers, deep and semi-deep wells, and springs. This city is located near the central desert of Iran and is located at 33° 99’ 10” N and 51° 42’ 35” E (Fig. 1). With a history of approximately 7000 years and an elevation of 945 m above sea level, the city has a hot and dry climate. Kashan has a population of over 300,000 residents.

Sample collection and analysis

In this study, sampling was done from all drinking water tanks in Kashan (13 Reservoir). After ensuring water drainage for 5 min, samples were taken from the valves on the main pipe installed at the bottom of the tanks. 39 samples were taken from 13 reservoirs during one season. After collecting the sample and adding 1 to 2 ml of concentrated nitric acid per liter to stabilize the metals, the samples were placed on a shaker at a speed of 85 rpm

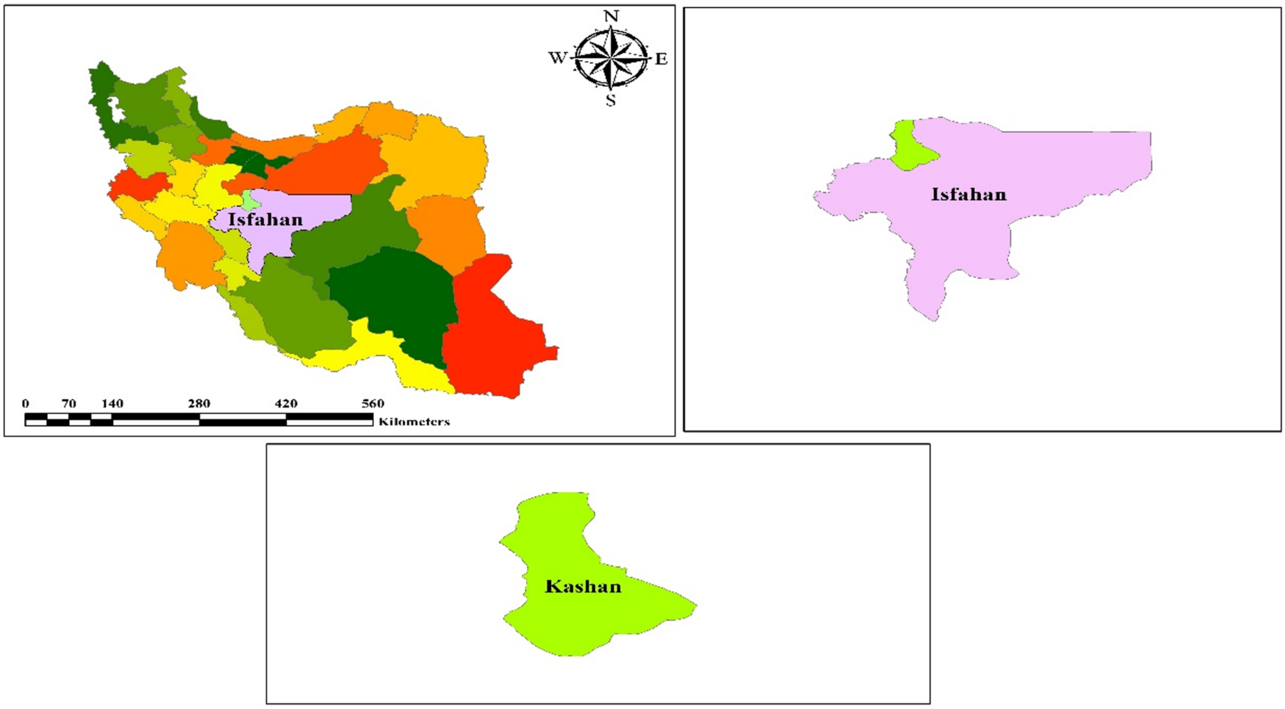

Fig. 1. Geographic location of the study area.

for 10 min, after which the solution was filtered using Whatman filter paper (42 micron) and stored at 4 °C. All sample containers were labeled at the sampling site. Date, time, weather conditions, sampling location and other necessary information were recorded on the sticker.

Then the samples were sent to the reference laboratory and measured by the ICP-MS device model ELAN DRC-E manufactured by Perkin Elmer device. In order to confirm the reliability of the analytical data and increase confidence in the relationship of the obtained responses, quality assurance and quality control (QA/QC) evaluations were conducted. In this regard, linear regression showed a good fit ($R^2 \geq 0.98$) with high precision (≤ 12.9% RSD). The limit of detection (LOD) and limit of quantification (LOQ) for various elements were determined as follows: for Pb: 0.1 µg/L and 2.2 µg/L, Cd: 0.1 µg/L and 0.72 µg/L, As: 1 µg/L and 4.2 µg/L, respectively. The R^2 and precision (% RSD) values for the elements were obtained as follows: Pb: 0.98 and 8.2%, Cd: 0.99 and 6.1%, As: 0.99 and 6.6%, respectively. This study received approval from the ethics committee of the relevant institution. Additionally, all methods adhered to the applicable guidelines and regulations.

Human health risk assessment

The health risk evaluation process is essential for understanding the adverse effects of exposure to contaminants in polluted environments. It serves as the initial step in protecting public health and safety. Contaminants can enter the human body through three main pathways: inhalation, ingestion, and dermal absorption, with drinking water being the most significant route of exposure[16]. According to the USEPA guidelines, there are various techniques for assessing health risk, based on which the assessment is performed. Risk assessment in this study was calculated based on water consumption conditions per day throughout human life and for the three age groups of children, teenagers and adults[17].

Non-carcinogenic risk

To achieve a non-carcinogenic risk assessment, the average daily intake of a specific parameter through consumption for three subpopulations—children, teenagers and adults—was calculated using the following Eq. (1):

$$CDI = \frac{\mathrm{CW} \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

CDI (mg kg^{-1} day^{-1}) is the chronic daily intake. The parameters C_w, EF, BW, IR, ED, and AT represent the following: C_w denotes the average concentration of toxic elements in drinking water (mg L^{-1}), EF is the exposure frequency (day yr^{-1}), BW refers to body weight (kg), IR indicates the ingestion rate (L day^{-1}), ED represents the exposure duration (years), and AT stands for the average lifetime (days). The hazard quotient (HQ) is obtained using Eq. 2. The values of these parameters are listed in Table 1.

Parameter	Unit	Age group (years)			Ref.
		Children (2–6 years)	Teenagers (7–16 years)	Adults (> 16 years)	
IR	L d^{-1}	0.51 ± 0.14	1.12 ± 0.27	1.23 ± 0.27	[21]
EF	Day $year^{-1}$	365	365	365	[22]
ED	Year	4	13	40*	[23]
		–	–	70*	[24]
BW	Kg	16.41 ± 3.78	39.83 ± 10.16	77.45 ± 13.6	[25]
AT	Day	1460	4745	14,600 (For carcinogenic:25550)	[23]

*ED for adults: Non-carcinogenic (40 year); Carcinogenic (70 year).

Table 1. Parameter values for health risk assessment of drinking water reservoirs.

Toxic elements	Unit	RfD	CSF	Ref.
As	mg kg^{-1} day^{-1}	0.0003	1.5	[26]
Pb	mg kg^{-1} day^{-1}	0.0035	0.0085	[17]
Cd	mg kg^{-1} day^{-1}	0.001	0.38	[26]

Table 2. Reference dose (RfD) and cancer slope factor (CSF) for the contaminants studied.

$$HQ = \frac{CDI}{RfD} \tag{2}$$

HQ is the hazard quotient, and RfD is the reference dose (mg kg^{-1} day^{-1})[17]. Table 2 shows the values related to RfD of toxic elements.

To assess the non-carcinogenic risk associated with all the studied metals, the Hazard Index (HI) was calculated using Eq. 3, based on the assigned HQ values for each metal.

$$HI = \sum_{i=1}^{n} HQ_i \tag{3}$$

Here, HQi represents the HQ value for pollutant i, and n denotes the total number of metals[18].

Carcinogenic risk

Carcinogenic risk refers to the potential risk of developing cancer as a result of exposure to substances or agents that are known or suspected to be carcinogenic. However, the assessment of carcinogenic risk involves other considerations, such as identifying the type and level of cancer risk, estimating the incidence or mortality rate, and evaluating potential cancer risks over a lifetime of exposure. Carcinogenic risks substances are mostly determined using criteria such as the excess lifetime cancer risk (ELCR), which estimates the additional risk of developing cancer over a lifetime due to exposure to a specific substance[19].

ELCR is calculated for different age groups using Eq. 4.

$$\mathrm{ELCR} = \mathrm{CDI} \times \mathrm{CSF} \tag{4}$$

CSF is the cancer slope factor of the contaminant (mg kg^{-1} day^{-1}). Table 2 shows the CSF values related to As, Pb and Cd.

The quantity is determined by adding together the values of ELCR associated with each of the pollutants being studied. According to the guidelines set by the USEPA, the acceptable or tolerable limit for carcinogenic risk ranges from 10^{-6} to 10^{-4}. In accordance with this, ELCR values below 10^{-6} are considered a negligible risk of causing cancer, while ELCR values greater than 10^{-4} are deemed unacceptable in terms of cancer risk[20].

Monte Carlo simulation technique and sensitivity analysis

There is a significant level of unpredictability in the deterministic method of risk calculation as a result of disparities in personal attributes and environmental factors[27,28]. To address this limitation, the Monte-Carlo simulation method was utilized by employing the Oracle Company's software, Crystal Ball (Oracle® Crystal Ball software). In the present investigation, the Monte Carlo technique with 10,000 iterations was employed to assess the non-carcinogenic risk associated with exposure to toxic elements exposure in children, teenagers, and adults. The sensitivity analyses were conducted using the Monte-Carlo technique to identify the input parameters that have the most significant influence on the output of the risk assessment model. In the field of health risk assessment, Monte Carlo simulation can be utilized to replicate different situations of exposure to harmful substances, such as toxic elements in water, and determine the probability of various health effects occurring based on the distribution of exposure levels. By conducting multiple simulations, the software generates a wide range of potential outcomes, enabling a thorough analysis of the associated health risks[29,30].

Results and discussion

Concentration of toxic elements

The first step in assessing the level and severity of toxic elements pollution in water reservoirs is to determine the concentration of metals in these reservoirs. The concentrations of trace elements and their comparison with WHO standards, EPA standards and national standards are presented in Table 3.

The average concentrations of As (3.94 µg/L), Pb (0.86 µg/L), and Cd (0.35 µg/L) in the drinking water of Kashan were found to be below the acceptable limits set by Iranian national and international standards (WHO, EPA). This is a positive outcome as it indicates that the current concentration levels of these metals do not immediately violate safety standards, suggesting that Kashan's water supply, at this point, is within regulatory compliance. The absence of toxic element concentrations exceeding the standards suggests minimal immediate exposure risks. The geology of Kashan (being located near the central desert) likely plays a role in maintaining low contamination levels, as the limited industrial activity reduces potential sources of pollution. However, while the concentrations are currently within safe limits, the variability in environmental conditions (e.g., seasonal changes, water source changes) warrants continuous monitoring[31]. According to the information in Table 3, the highest concentration among the elements studied in the water reservoirs of Kashan city was related to As (As > Pb > Cd). This could be due to the geological composition and deposits present in the area or the pollution introduced along the water transfer line from the source to the storage tank. Human exposure to inorganic As primarily occurs through the consumption of naturally contaminated drinking water[32]. As is found in surface waters and in areas where iron metal mines exist, and it often enters water as a result of the use of pesticides and insecticides that contain As. This element is recognized as one of the most toxic and dangerous substances soluble in natural waters[33].

Research by Geen et al. revealed that toxic element concentrations change over time, and it was found that wells in a given location can have widely varying concentrations of metals. In fact, the concentration of toxic elements in wells is related to both the location and the depth of the wells, and higher concentrations typically found in shallower wells in specific geological areas[34]. Studies conducted by Alighadr et al. as well as Shahryari et al., on the concentration of toxic elements in the drinking water distribution networks of Ardabil and Birjand have shown that the levels of these metals do not exceed standard limits[35,36]. Other studies have also shown that toxic element concentrations in drinking water reservoirs are below the standards set by international authorities, and our findings are consistent with these results[8,19,37].

Health risk assessment

Overall, researchers believe that assessing the adverse effects of toxic elements on human health requires more than just focusing on the concentrations of harmful elements. It is essential to evaluate water quality and the impact of the metal content in water in conjunction with other factors[38]. Therefore, in this study, the health risk assessment from exposure to the metals under investigation through drinking was calculated for three age groups: children, teenagers, and adults.

Non-carcinogenic health risk assessment (HQ and HI)

Table 4 revealed that the HQ for each element, along with the HI for the combined impact of all elements, fell below the 1 threshold across all age groups (children, teenagers, and adults). This suggests that there is no significant non-carcinogenic health risk from As, Pb, and Cd in the drinking water of Kashan for any age group. While the HQ for As was the highest, it still remained within acceptable limits. Conversely, the HQ values for Pb and Cd were much lower, indicating minimal non-carcinogenic risks.

Specifically, the HI values were 0.434 for children, 0.394 for teenagers, and 0.227 for adults—all under 1. This is an important finding, as it shows that the population, including vulnerable groups like children, is not at risk of non-carcinogenic effects from exposure to these toxic elements. These results are consistent with research from other semi-arid regions, where non-carcinogenic risks have also been assessed as low, primarily due to controlled industrial pollution levels. A study by Malakoutian et al. investigated drinking water sources in Lake Urmia, northwest Iran, and similarly found no non-carcinogenic risk from As, Cd, and Pb in that area[39]. Another study on water sources in Yazd province, central Iran, also indicated negligible risk for all age groups regarding toxic elements[40]. These findings align with our study's outcomes.

In contrast, The results of the study by Shahriyari et al. on the drinking water of Zabol city showed that the concentrations of As and Cd were higher than the permissible levels of international standards. The total non-carcinogenic risk (HI) was 9.62 for children and 4.12 for adults. Their findings indicate a significant risk of non-cancerous diseases for local residents due to long-term exposure[41]. The high concentration of elements in the

Toxic elements concentration (µg/L)	As	Pb	Cd
This study	3.94 ± 3.72	0.86 ± 0.08	0.35 ± 0.08
National Standard (1053)	10	10	3
WHO Standard (2017)	10	10	3
EPA Standard (2018)	10	15	5

Table 3. Average concentration of toxic elements and comparison with standards.

Toxic elements		HQ·children	HQ·teenagers	HQ·adults
As	Mean	4.31E−01	3.93E−01	2.15E−01
	SD	1.55E−01	1.40E−01	6.17E−02
Pb	Mean	8.12E−03	7.37E−03	4.03E−03
	SD	2.99E−03	2.63E−03	1.13E−03
Cd	Mean	2.30E−02	2.12E−02	1.16E−02
	SD	8.35E−03	7.63E−03	3.28E−03
$\sum$ **HQ**(HI)	Mean	4.34E−01	3.94E−01	2.27E−01
	SD	1.56E−01	1.41E−01	6.61E−02

Table 4. Results of non-carcinogenic risk calculations of toxic elements in the reservoirs.

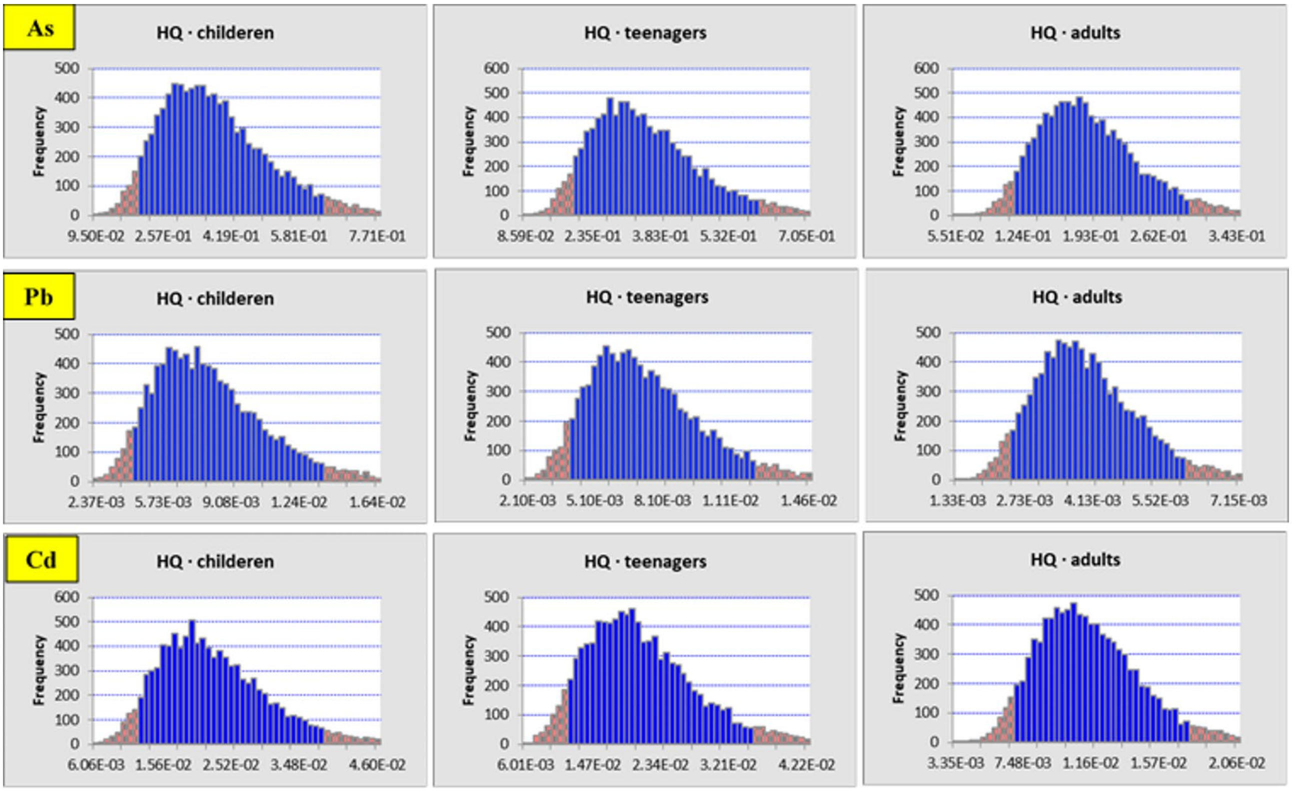

Fig. 2. Probabilistic risk assessment of HQ values for all three age groups (children, teenagers and adults).

water of Zabol city may be due to the fact that the surface water resources of Zabol are limited to the Hirmand River, the majority of whose watershed is located in Afghanistan. To transfer excess water from the Hirmand River, four reservoirs (lakes) have been connected outside the river's path and are filled with water[42]. This water travels a long distance to reach its final consumption point. Natural materials washed from the soil, runoff from agricultural activities, sewage discharge, effluent from nearby areas along the water flow path, and potential leakage from landfills can each contribute to the pollution of this water.

The findings were further supported by a Monte Carlo simulation, which provided a probabilistic assessment confirming their reliability. Using the Monte Carlo simulation, the non-carcinogenic risks of As, Pb, and Cd were evaluated for different age groups. Figure 2 showcases the predicted non-carcinogenic risk (HQ) associated with these three toxic elements in Kashan's drinking water reservoirs.

Additionally, research by Tarviji et al. suggested that the cumulative risk from total metals, including As, chromium (Cr), Cd, Pb, and nickel (Ni) through drinking, remained within safe limits, confirming that the non-carcinogenic risk values were acceptable and safe[43]. However, findings by Fallahzadeh et al. revealed that the carcinogenic risk from Cr in Birjand's drinking water exceeds 1, indicating a hazardous range for children and teenagers[44]. Due to their higher water consumption relative to body weight, children face greater risks than adults through ingestion[45,46]. Yüksel et al.'s study highlighted that all sampling stations showed suitable water quality, except for one near a Garbage Disposal Facility (GDF), which posed significant non-carcinogenic risks for children[47]. Such findings emphasize the need for vigilant monitoring of water quality, particularly concerning the proximity of water sources to landfills and mining sites. Effective resource management and innovative strategies—such as relocating landfills and utilizing water sources upstream from potential pollutants—are vital for maintaining water safety.

Carcinogenic risk assessment

In carcinogenic risk assessment, the long-term effects of exposure to pollutants are evaluated. The results of the carcinogenic risk assessment are presented in the Table 5. There are various methods for assessing the risk of carcinogenesis, including calculating the ELCR. In this method, the carcinogenic risk is calculated using information related to per capita water consumption, pollutant concentration, and body weight in different age groups. According to WHO guidelines, a carcinogenic risk within the range of 10^{-6} to 10^{-4} is considered acceptable, while a risk greater than 10^{-4} is deemed unacceptable.

The ELCR values for Pb and Cd were within safe limits across all age groups, indicating no long-term carcinogenic threat from these metals. However, the ELCR for As was 1.92×10^{-4} and (CI: 4.66×10^{-5}–6.60×10^{-4}) for children and 1.71×10^{-4} (CI: 4.24×10^{-5}–6.07×10^{-4}) for teenagers, both of which exceed the acceptable range (10^{-6} to 10^{-4}), suggesting a potential long-term cancer risk for these two age group (Table 3). As, classified as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), is well known for its association with increased carcinogenic risk, particularly through long-term exposure via drinking water[48]. In this study, both the excess lifetime cancer risk and the cumulative carcinogenic risk (total risk) were greater than 10^{-4}. Consequently, the risk is not acceptable, and actions must be taken to mitigate it. The contamination from As has both natural and anthropogenic sources. Natural As contamination in water has been reported in over 73 countries worldwide, with approximately 153 million people in Southwestern Asia alone being exposed to severe As water contamination[41].

The elevated ELCR values for children and teenagers in this study highlight their higher vulnerability due to higher water intake relative to body weight, combined with the potential cumulative effects of As exposure over time (Fig. 3). This aligns with other studies from arid regions of Iran, where children and teenagers were identified as at-risk populations for As-related carcinogenesis. In 2017, a study was conducted on the drinking water of Sistan and Baluchistan province. The results of this study showed that Pb was not carcinogenic for consumers and its levels were lower than national and international standards[49]. The results of studies conducted on drinking water in the cities of Rafsanjan and Bam have shown that the risk of As-induced carcinogenesis from drinking water is higher than the WHO standard[50,51] and is consistent with the results of this study. The study by Shahriyari et al. showed that the overall carcinogenic risk index in the drinking water of Zabol city was 1.79×10^{-3}, which exceeds the permitted limit and poses a high cancer risk for consumers[41]. In the study by Dashtizadeh et al. which assessed the health risk of heavy metals in drinking water in the city of Zahedan, the average concentrations of the studied heavy metals (arsenic, cadmium, chromium, nickel, lead, boron, aluminum, mercury, manganese, zinc, copper, iron, selenium, and barium) were reported to be within the national and international standards. Additionally, the total cancer risk assessment yielded a value of 4.28×10^{-5}, which is considered acceptable[38], indicating that, contrary to the results of the present study, there was no health risk to the local population.

In the study by Islam et al. which investigated groundwater contamination by As and assessed the risk of water consumption in the Chapai-Nawabganj region of Bangladesh, the health risk assessment for As similarly indicated that children are at a higher risk[52], consistent with the findings of the present study. In other studies that evaluated the carcinogenic risk of heavy metals in the drinking water of Khoramabad and Mahneshan, the risk index was found to be below the established standards[53,54], and contrary to the results of this study, consumers were not threatened by any significant risk. Other studies have been conducted that indicate an increased risk of

Toxic elements		ELCR.Children	ELCR.Teenagers	ELCR.Adults
As	Mean	1.92E−04	1.71E−04	9.70E−05
	SD	6.97E−05	6.50E−05	2.76E−05
	CI	4.66E−5-6.60E−4	(4.24E−5-6.07E−4)	(6.24E−5-4.63E−4)
	P5%	1.02E−04	9.57E−05	1.03E−04
	P95%	3.24E−04	2.95E−04	2.59E−04
Pb	Mean	2.41E−07	2.19E−07	2.10E−07
	SD	8.90E−08	7.82E−08	5.95E−08
	CI	(6.68E−8-8.33E−7)	(8.86E−8-6.73E−7)	(7.78E−8-6.17E−7)
	P5%	1.26E−07	1.16E−07	1.29E−07
	P95%	4.06E−07	3.63E−07	3.19E−07
Cd	Mean	7.25E−05	6.68E−05	6.39E−05
	SD	2.63E−05	2.40E−05	1.82E−05
	CI	(1.78E−5-2.66E−4)	(1.78E−5-2.45E−4)	(1.96E−5-1.92E−4)
	P5%	3.83E−05	3.53E−05	3.87E−05
	P95%	1.21E−04	1.12E−04	9.69E−05
$\sum ELCR$	Mean	2.64E−04	2.38E−04	1.61E−04
	SD	9.60E−05	8.91E−05	4.58E−05

Table 5. The results of carcinogenic risk calculations in three sub-groups ages.

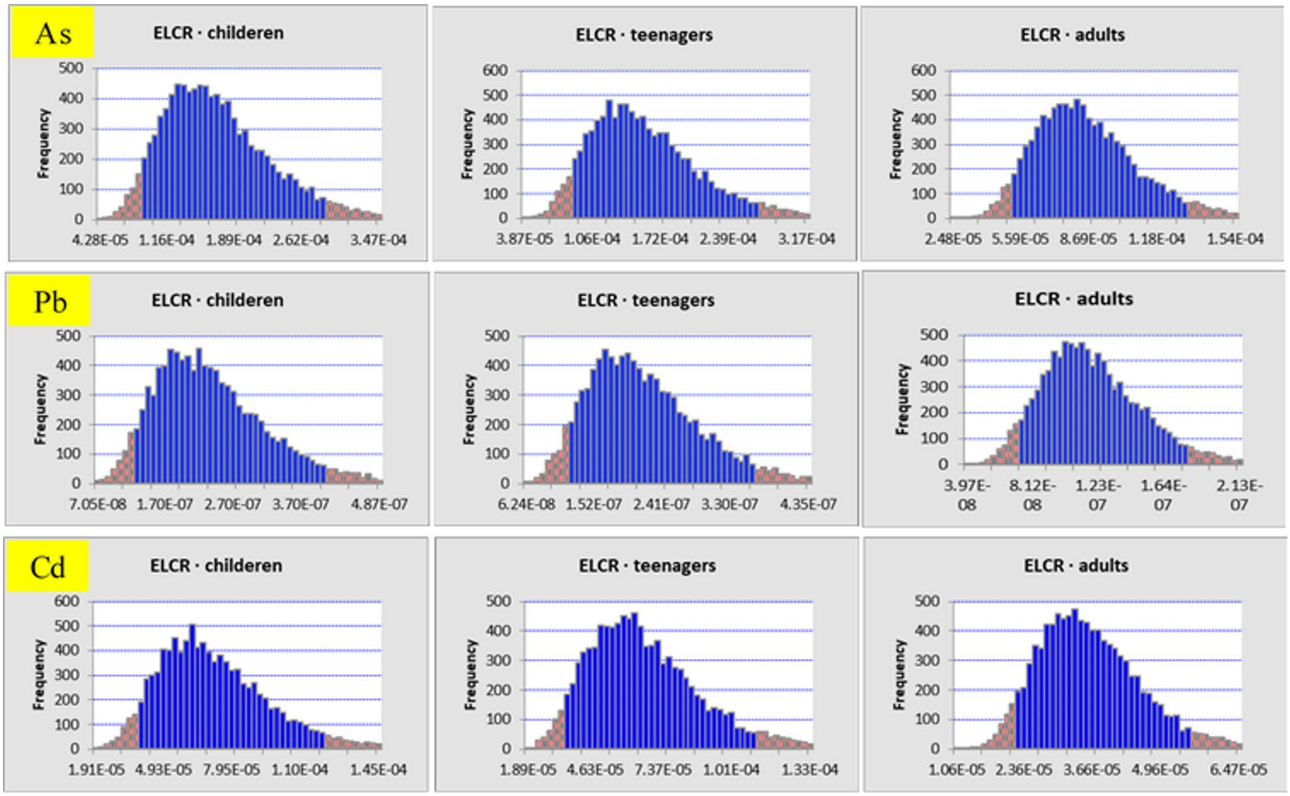

Fig. 3. Probabilistic risk assessment of ELCR values for all three age groups (children, teenagers and adults).

As carcinogenicity. These studies identify the sources of As in water predominantly as anthropogenic activities such as mining[55,56].

Monte Carlo simulation results

The Monte Carlo simulation played a critical role in confirming the probabilistic risk associated with the non-carcinogenic and carcinogenic health impacts. By running 10,000 iterations, the study provided a detailed distribution of risks under various exposure scenarios, which confirmed that the overall non-carcinogenic risks are low, but carcinogenic risks for As in children and teenagers require attention. Monte Carlo simulations offer a robust approach to deal with uncertainties in exposure assessments. They provide a probabilistic understanding of risks, which is particularly valuable for policymaking. In this case, it justifies the need for targeted interventions for vulnerable groups (children and teenagers), such as improving water treatment methods specifically for As removal.

Sensitivity analysis

Sensitivity analysis is a quantitative technique that explores the relationship between input variables and the output of a model. This analysis is essential for understanding model stability, identifying key factors, and making informed decisions. By examining how changes in input variables impact the output, sensitivity analysis provides valuable insights into the model's behavior[57]. The sensitivity analysis in this study identifies the most influential parameters affecting the health risk outcomes, providing valuable insights into the key drivers of both non-carcinogenic and carcinogenic risks. In this case, the analysis revealed that the IR of water was the most significant factor influencing both the HQ and ELCR for all age groups (Fig. 3).

IR had the highest impact on non-carcinogenic risk, contributing over 61% to the variability in the results. This is expected, as children and teenagers tend to consume more water per unit body weight compared to adults, increasing their exposure to contaminants. The ingestion rate indicates the level of toxic substances that may directly enter the body through the consumption of water. Therefore, any change in the ingestion rate can directly affect risk estimation. For carcinogenic risk, As and Cd concentrations were the most significant contributors, with As being the primary driver of the elevated ELCR values in children and teenagers. The importance of the IR highlights that population-specific water consumption habits are crucial in determining exposure risks. For example, children's higher water intake per body weight puts them at greater risk, which is particularly evident in the elevated carcinogenic risk of As for this group. This finding underscores the need for more detailed population studies that account for age-specific behaviors when assessing health risks. The analysis also shows that even though Cd and Pb were within safe limits, the presence of As remains a critical concern due to its high carcinogenic potential. This suggests that public health strategies should prioritize As

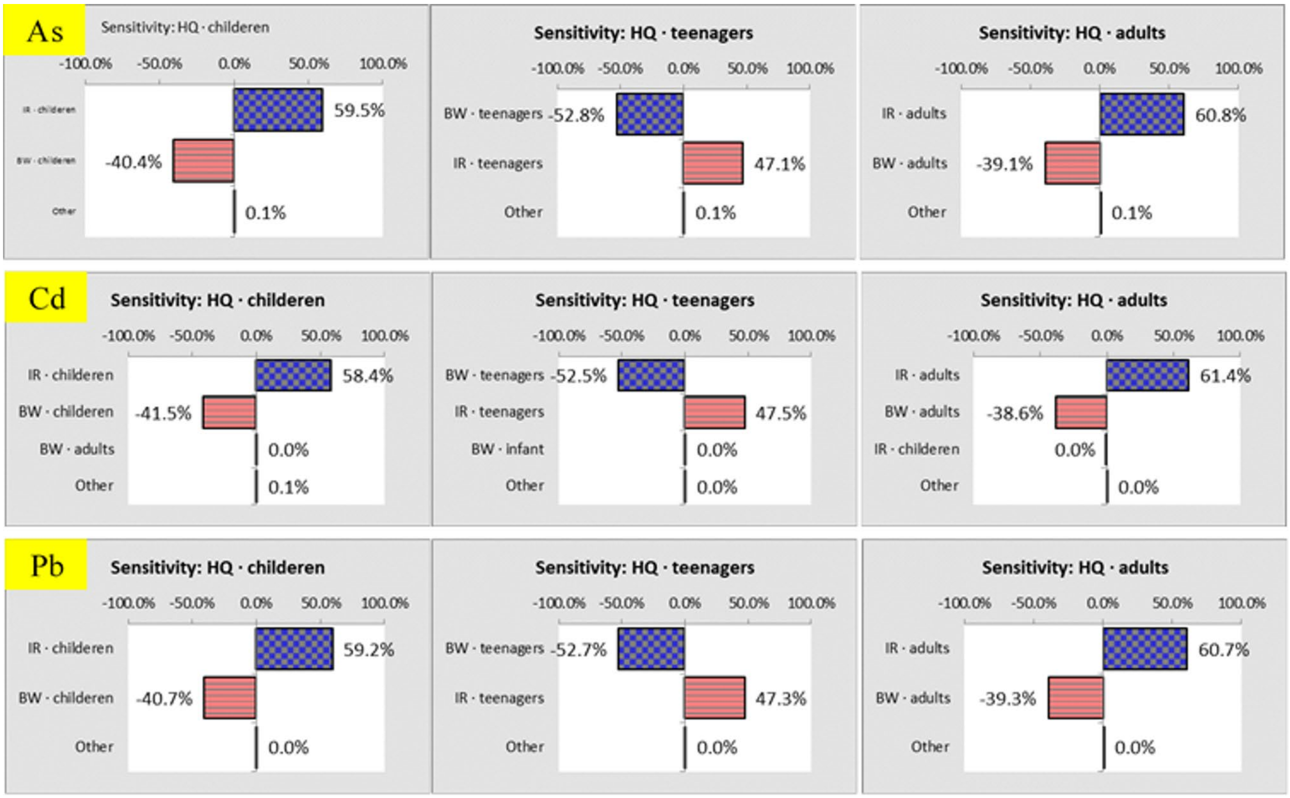

Fig. 4. Sensitivity analysis of the effect of input parameters on the non-carcinogenic risk of toxic elements in drinking water reservoirs.

mitigation in water sources, particularly in regions like Kashan with limited water resources and reliance on groundwater, where As contamination can persist.

Given the sensitivity of As and IR, it would be prudent to implement age-specific monitoring programs for toxic elements in water supplies. Monitoring children's exposure more closely can provide early warnings of rising health risks. The sensitivity analysis suggests that reducing IR (via public awareness on safe water consumption practices) and implementing advanced water treatment technologies (such as As filtration systems) could significantly lower both non-carcinogenic and carcinogenic risks, especially for vulnerable populations. The results of the sensitivity analysis in current study are consistent with other health risk assessments that also found IR to be a dominant factor in determining risk levels, especially among children and teenagers (Figs. 4 and 5). Additionally, the high impact of As concentration is aligned with findings from regions with similar geological profiles where As naturally occurs in groundwater.

Conclusion

This study investigated the concentrations of toxic elements— As, Pb, and Cd—in the drinking water of reservoirs in Kashan City, Iran. Additionally, it assessed the associated carcinogenic and non-carcinogenic risks for children, teenagers, and adults using a Monte Carlo simulation approach. The results of this study demonstrated that, the concentrations of these toxic elements in the drinking water were found to be below both national and international standards. The health risk assessment revealed no potential non-carcinogenic risks for any age group, and the HI was below the safe threshold. Additionally, no potential carcinogenic risks for Pb and Cd were observed in any age group. However, concerning As, the ELCR for children and teenagers exceeded the permissible limits, indicating a potential long-term carcinogenic risk. Monte Carlo simulation and sensitivity analysis confirmed that the overall risk of carcinogenic and non-carcinogenic hazards for adults is within an acceptable range. However, the carcinogenic risk for children and teenagers requires immediate attention. The findings of this study suggest that while the current concentrations of toxic elements in the water reservoirs of Kashan are generally safe for consumers, continuous monitoring and stringent regulations are crucial to mitigate potential health risks, especially for vulnerable populations.

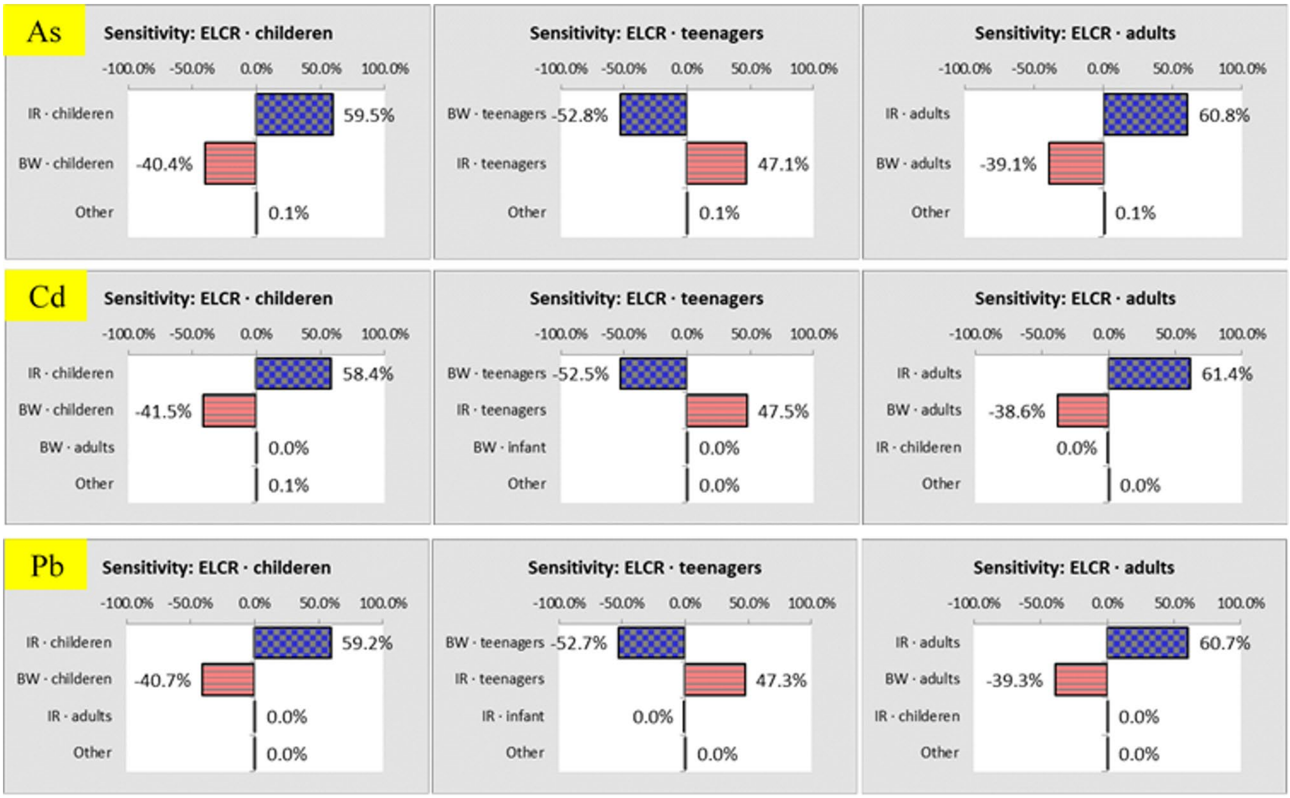

Fig. 5. Sensitivity analysis of the effect of input parameters on the carcinogenic risk of toxic elements in drinking water reservoirs.

Data availability

Data supporting the findings of this study are available from the corresponding authors.

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B.N. and S.F. Methodology, Conceptualization, Investigation, Writing – original draft. GH.R.M. and M.B.M.Z Methodology, supervision, writing – review & editing.

Declarations

Competing interests
The authors declare no competing interests.

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