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Article

Evaluating the occurrence of trihalomethanes in drinking water and their implications for human health risk

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Abstract
Trihalomethanes (THMs) are a group of volatile organic compounds that can be easily found in drinking water, especially in municipal water distribution systems supplied by water treatment stations as a result of the chlorination process. This study investigates the THMs presence in various sources across Romania and conducts a human health risk assessment in order to determine the potential danger the population is exposed to. Using a gas-chromatography coupled mass-spectrometry (GC-MS) analysis method, water samples collected over the course of a year were analysed and revealed the cumulative sum of all trihalomethanes (ΣTHMs) saw a maximum concentration of 90.6 µg/L, with an average of 25.6 µg/L and a median of 22.2 µg/L with chloroform and bromoform being the most abundant. The analysis of carcinogenic and non-carcinogenic risks associated with THMs in drinking water reveals women exhibit higher risk levels than men across both categories. The total non-carcinogenic risks for women range from 5.14×10^{-4} to 4.30×10^{-1}, while for men, the risks range from 4.78×10^{-4} to 3.78×10^{-1}. Carcinogenic risk assessments indicate a similar trend, with total risks for women varying between 1.37×10^{-6} and 1.88×10^{-4}, and for men between 2.22×10^{-7} and 1.66×10^{-4}. comparable values for cancer risk that exceed the minimum or negligible risk threshold established by the USEPA (1.00×10^{-6}).

Keywords: *THMs, drinking water, water quality, human health risk, carcinogenic risk*

INTRODUCTION

Volatile organic compounds (VOCs) represent a class of chemicals consisting of several thousands of man-made compounds employed in a superabundance of industries making them virtually omnipresent around us. From fuels, solvents, cooling agents, and cleaning solutions or as a byproduct of various industrial processes, there is no denying that VOCs are everywhere and many of them are soluble and persistent enough to ultimately make their way into groundwater systems and from there into the drinking water supplies [1, 2].

Among the many VOCs that can contaminate the water supply, THMs are the most frequently detected compounds especially when testing tap water or generally chemically treated water. THMs consist of chloroform ($CHCl_3$), bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$), and bromoform ($CHBr_3$) [3]. Their presence is explained by the use of chlorine and chlorinated compounds as disinfectants in water treatment stations in the process called chlorination, an effective and economically viable method used essentially everywhere around the world. Chlorination provides the optimum amount of residual chlorine for water distribution systems to protect against microbial pollution. By getting in contact with various organic and inorganic

compounds, the residual chlorine can react in water resulting what is called disinfection byproducts, among which are the aforementioned THMs [4, 5].
People get exposed to THMs through ingestion, inhalation, and dermal adsorption during any activity that involves water such as drinking, washing, cleaning, showering, swimming, and so on. The adverse health effects following exposure to THMs include nephrotoxicity, hepatotoxicity, neurotoxicity, and reproductive toxicity [2, 6, 7]. Because of the potential health hazard, the THMs concentration in drinking water has been regulated in most of the world. According to the World Health Organisation (WHO), the individual maximum admitted values for THMs are 300 μg/L for chloroform, 100 μg/L for bromoform, 100 μg/L for dibromochloromethane, and 60 μg/L for bromodichloromethane [8]. Romanian legislation follows the EU regulations according to which the maximum admitted concentration for THMs is 100 μg/L for the sum of all four compounds [9].
Following the introduction of regulations water treatment processes have been optimized to control the concentration of THMs, however, despite of because of the contamination of sources in combination with the continuous use of chlorination, eliminating these compounds has proved to be impossible. As such, human exposure to THMs is unfortunately inevitable.
Water source contamination levels depend on the intensity and nature of the human activity in the region. Generally speaking, urban areas with large populations and industrial activity will experience a larger exposure to THMs compared to rural areas. Hence, it is of utmost importance to monitor the pollution levels in these areas periodically to avoid putting human lives in danger.
In this study, sixty samples collected over a year from multiple sources across Romania have been investigated to assess the extent of THMs presence in Romanian drinking water distribution systems. Furthermore, a human health risk assessment has been conducted to determine the potential danger the population is exposed to.

MATERIALS AND METHODS

Chemicals and reagents

In this study, the THMs were analyzed according to the ISO 20595:2018 international standard using a 60-component VOC mixture standard solution purchased from CPA Chem. Standard stock solutions of VOCs were prepared using chromatographic-grade methanol and stored in a 4 ˚C refrigerator to prevent VOCs degradation. Fresh working solutions were used to prepare spike solutions for aqueous calibration standards. Chromatographic-grade methanol, as well as 2-bromo-1-chloro-propane internal standard, were purchased from ChemLab.

Sample collection and preparation

Sixty samples were collected between January and December 2023 across Romania. The samples were collected in duplicates directly from water distribution systems in 1L glass containers filled to the top leaving no headspace to avoid photolysis and exudation, stored at 4 ˚C, and analysed within one week from sampling.

Instrumental analysis

Quantitative analysis of THMs was carried by headspace gas-chromatography coupled with mass-spectrometry (HS/GC-MS) using an Agilent 7890B Gas-Chromatograph combined with an Agilent 7010B Triple-Quad Mass Spectrometer and a PAL3 automatic sampler equipped with a headspace module. GC conditions: Agilent VF-1701 capillary column, dimensions: 30m × 0.25 mm × 1μm, carrier is helium, column flow rate of 1mL/min. Injector port was set to 200˚C working in split mode with a 5:1 split ratio. Oven temperature program was: initial temperature 35˚C for 15 minutes then ramped at 5˚C/min up to 145˚C, no hold time, ramped at 20˚C/min to 185˚C hold time 4 minutes.
MS conditions: the triple-quadrupole mass spectrometer was equipped with an ionization source at 70 eV and operated as follows: ion source temperature, 230 ◦C; and transfer line temperature, 250 ◦C.

Analysis and quality control

Each analysis was conducted by taking a 10 mL aliquot from each sample which was transferred into 20 mL screw-top glass vials containing 2g of NaCl. 50 μL of internal standard solution was added to each vial by pipetting beneath the water surface and closing the vials using metal screw-caps provided with silicone/PTFE septa. NaCl is added to remove the matrix effect. The concentration of each compound is calculated by comparing the MS response of the quantifier ion of the analyte with the MS response of the quantifier ion of the internal standard. The retention time (RT) as well as the quantifier ions of the THMs are presented in table 1.

Table 1. Retention times and quantifier ions of the analyzed THMs

Compound	Chemical Formula	RT (min)	Quantifier Ion (m/z)
Chloroform	$CHCl_3$	9.27	83
Bromodichloromethane	$CHBrCl_2$	18.56	83
Dibromochloromethane	$CHBr_2Cl$	24.98	129
Bromoform	$CHBr_3$	29.69	173

Human risk assessment

To evaluate health risks, models utilized by the U.S. EPA are often employed, assessing both carcinogenic and non-carcinogenic risks associated with exposure pathways including inhalation, ingestion, and dermal contact [10, 11]. Similar methodologies have been adopted in various studies, including that of Zhang et al. 2021 and Zhu et al. 2023 [12, 5].

The primary route of exposure to organic pollutants for individuals is ingestion, and the non-carcinogenic risk is typically quantified using a Hazard Index (HI). This index is calculated according to equation (1).

$$HI = CDI \times RfD \quad (1)$$

where RfD represents the reference dose (expressed in mg / (kg x day)). For evaluating carcinogenic risk (R), two equations are employed based on the calculated chronic daily intake (CDI, μg / (kg x day):

$$R = CDI \times SF, R < 0.01 \quad (2)$$

$$R = 1 \times \exp(- CDI \times SF), R \geq 0.01 \quad (3)$$

Here, SF denotes the slope factor (measured in kg·day/μg), and CDI is calculated using two distinct exposure pathways:

Ingestion (CDIin): $CDIin = MEC \times IR \times EF \times ED \times BW \times AT$ (4)

Dermal absorption (CDIder): $CDIder = MEC \times SA \times Kp \times ET \times EF \times ED \times BW \times AT$ (5)

In these equations, IR is the ingestion rate (L/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the average body weight (kg), and AT is the average time (days). Additionally, SA represents the exposed skin area (dm^2), Kp is the dermal permeability coefficient (dm/h), and ET refers to the exposure time during bathing and showering (h/day).

To compute the cumulative non-carcinogenic risk from multiple chemicals, the individual Hazard Indices are summed to yield a total HI:

$$HItotal = HI1 + HI2 + \cdots + Him \quad (6)$$

Similarly, the total carcinogenic risk is assessed by summing the individual R values:

$$Rtotal = R1 + R2 + \cdots + Rm \quad (7)$$

The parameters used in these calculations—such as IR, EF, ED, BW, AT, SA, RfD, SF, Kp, and ET - are derived from recognized reference values from the U.S. EPA and other agencies [13÷16]. This comprehensive approach to risk assessment enables a better understanding of the potential impacts of THMs on human health and the environment, ultimately informing more effective regulatory measures for water quality management.

RESULTS AND DISCUSSION

Occurrence of trihalomethanes in drinking water samples

In examining the results presented in Table 2 regarding the concentration levels of various trihalomethanes in drinking water samples, several noteworthy observations emerge that merits a thorough discussion. THMs are byproducts formed during the chlorination of drinking water, and their presence is of significant concern due to their potential health risks, including carcinogenic effects.

Table 2. Statistical analysis of trihalomethanes concentration level determined in the drinking water samples

Compounds	Min	Max	Median	Average
	µg/L ± RsD (n = 3)			
$CHCl_3$	<0.1	81.1 ± 5.03	17.9 ± 1.11	19.6 ± 1.21
$CHBr_3$	<0.1	32.8 ± 1.90	7.88 ± 0.46	9.19 ± 0.53
$CHBrCl_2$	<0.1	8.77 ± 0.47	2.40 ± 0.13	3.09 ± 0.17
$CHClBr_2$	<0.1	73.2 ± 4.10	0.97 ± 0.05	5.98 ± 0.34
ΣTrihalomethanes	<0.1	90.6 ± 5.62	22.2 ± 1.38	25.6 ± 1.58

Starting with the individual compounds, $CHCl_3$ appears to have a minimum concentration below detectable limits (<0.1 µg/L) and a maximum level reaching 81.1 µg/L, with an average concentration of 19.6 µg/L. The median value is 17.9 µg/L, indicating that half of the samples exceed this concentration. The relatively high maximum concentration suggests that in some drinking water sources, chloroform levels can significantly exceed what is typically expected, raising concerns for public health, especially since the average and median values are positioned on either side of the midpoint. The relative standard deviation (RsD) of 5.03% also illustrates a degree of consistency among the samples. However, the presence of outliers cannot be ruled out, which potentially skews the mean higher. In the case of $CHBr_3$, we note that the maximum concentration is considerably lower than that of chloroform, peaking at 32.8 µg/L, while the average concentration stands at 9.19 µg/L. The median of 7.88 µg/L falls below the mean, suggesting a positively skewed distribution possibly influenced by a few higher concentrations. Such a pattern may indicate localized sources of contamination or differing chlorination practices resulting in varying THM formation.

Considering other lesser-known THMs such as $CHBrCl_2$ and $CHClBr_2$, the data reveals lower maximum values of 8.77 µg/L and 73.2 µg/L, respectively. The average concentrations for $CHBrCl_2$ and $CHClBr_2$ were determined to be 3.09 µg/L and 5.98 µg/L, respectively. This distribution suggests that while these compounds are present, they form in considerably lower concentrations compared to chloroform and bromoform. The RSD values of 0.47% for $CHBrCl_2$ and 4.10% for $CHClBr_2$ showcase a lesser variation among samples for dibromochloromethane but highlight the variability of the chlorinated forms, particularly for $CHClBr_2$, which could be tied to sampling conditions or chlorination processes. When examining the cumulative sum of all trihalomethanes (ΣTHMs), we see a maximum concentration of 90.6 µg/L, with an average of 25.6 µg/L and a median of 22.2 µg/L. The presence of a collective measurement provides valuable insight into water quality, as it aggregates the potential risks associated with each of the individual compounds. The considerable difference between the maximum and average values emphasizes the degree of variability across the samples, suggesting that certain water sources may pose a much higher risk than others.

The analysis of the trihalomethanes in the drinking water samples reveals a significant presence of these compounds, with varying levels that appear to be influenced by different factors such as geographic location, chlorination practices, and possible contamination sources fig. 1. While certain samples demonstrate acceptable levels within safety guidelines, the sporadic spikes in concentration—particularly for chloroform and bromoform—warrant attention and further investigation. Addressing these findings through improved water treatment methodologies and ongoing monitoring will be essential to protect public health and ensure the safety of drinking water supplies. The results indicate an urgent need for a nuanced understanding and intervention, particularly in areas with traditionally high concentrations of these harmful byproducts.

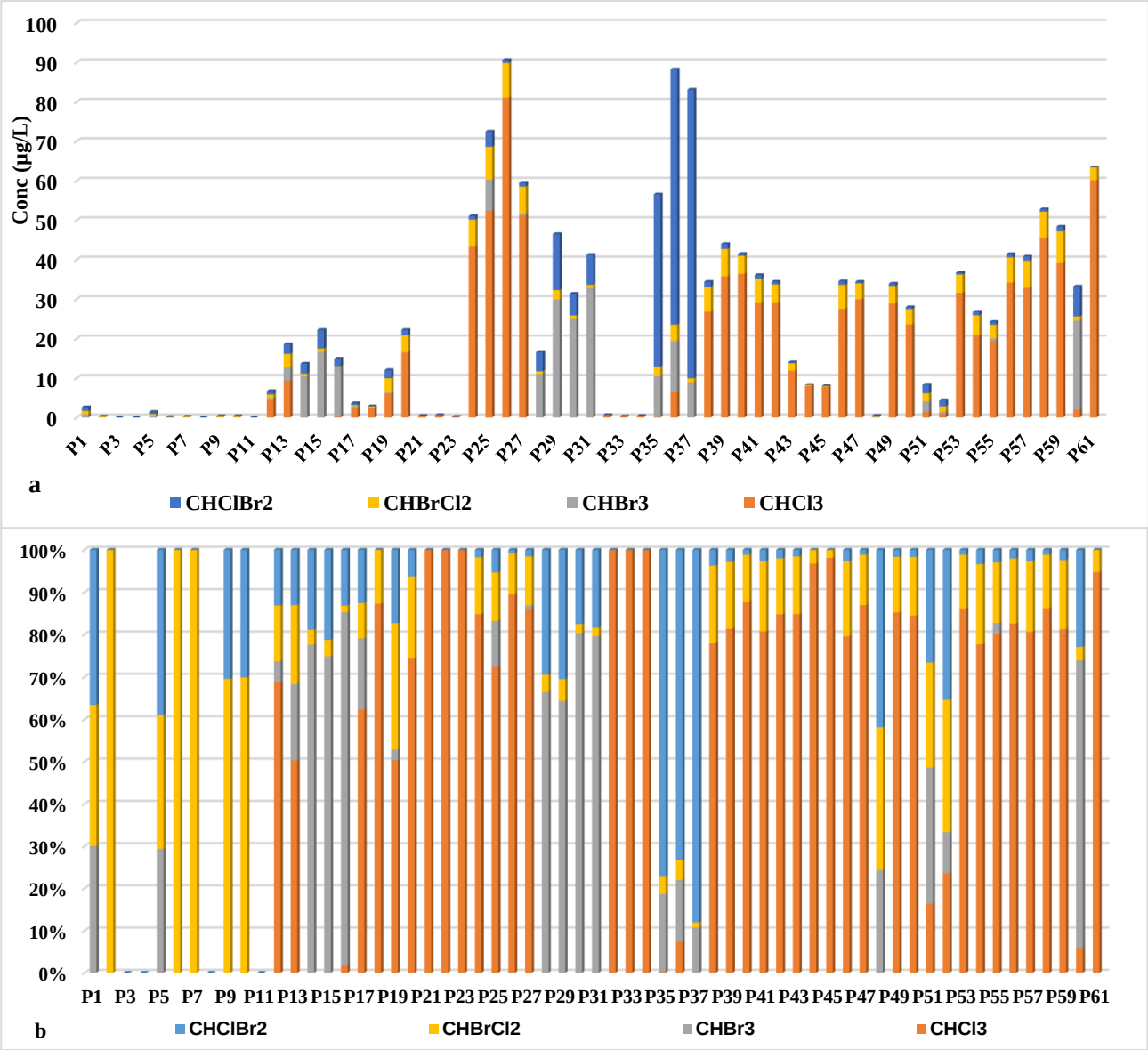

Fig. 1. The concentrations (a) and the percentage distribution (b) of detected THMs in the drinking water samples.

The analysis of the THM concentrations in the drinking water samples yields critical insights regarding water quality and regulatory compliance. Among the tested samples, 6.6% exhibited total THM values that fell below the method's limit of quantification. This observation signifies the effectiveness of water treatment processes in certain sources where THM formation is minimal, perhaps due to careful chlorination practices or the use of alternative disinfection methods.

Furthermore, 39% of the samples were classified within the range of <0.1 to 20 µg/L, indicating that a notable portion of the tested drinking water demonstrates relatively low levels of THMs. This is encouraging, as it corresponds to safer water conditions for consumers. It also reflects positively on the water supply management practices that likely emphasize maintaining low disinfection byproduct levels, contributing to public health safety. The data further reveals that 31% of the samples reported THM concentrations within the 20 to 50 µg/L range. While this category still represents compliance with health regulations, it suggests that specific mitigation strategies may be necessary to reduce these levels further. Enhanced monitoring and adjustments to chlorination methods or treatment protocols may help lower these concentrations, especially in areas consistently approaching the higher limits. Additionally, the 23% of samples that fell within the 50 to 100 µg/L range indicate that substantial attention is warranted. Although all sampled water sources remained below the maximum allowable

limit of 100 µg/L as stipulated in Ordinance 7 of January 18, 2023 [9], the presence of this proportion of samples in the upper range underscores the need for ongoing vigilance. Monitoring and regulatory adherence in these cases become critical, as consistently high THM levels within drinking water could pose health risks and might lead to public concern regarding water safety.
The fact that none of the analyzed drinking water samples exceeded the regulatory threshold of 100 µg/L is a promising indicator of water quality management. This compliance reflects the effectiveness of existing water treatment practices and monitoring systems. However, the variability in THM levels necessitates continued diligence to ensure that public health is maintained and improved. Regular assessments and the implementation of proactive measures to minimize THM concentrations, especially in the higher ranges, will be essential in the ongoing efforts to provide safe drinking water to the community. Continued research and technological advancements in water treatment should also be explored to further reduce the formation of these potentially harmful compounds, thereby enhancing consumer confidence in drinking water safety.

Correlation between concentrations of THMs
The percentage distribution of the four THMs in the examined drinking water samples, as shown in figure 2, provides valuable insights into the composition and potential sources of these compounds in the water supply.

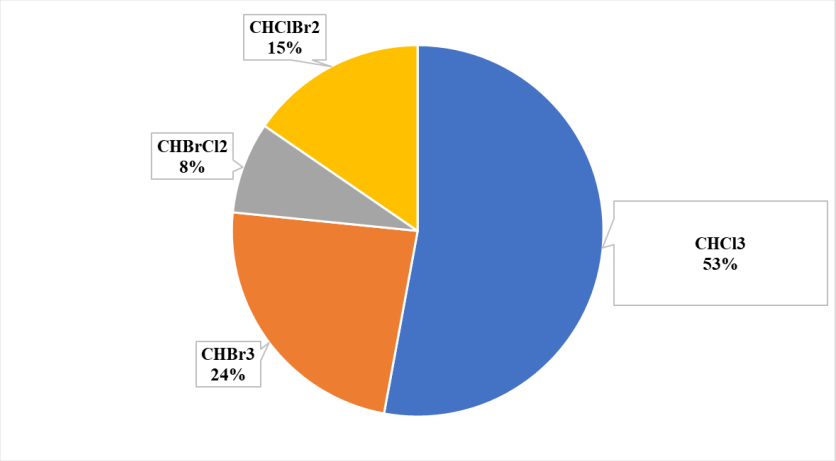

Fig. 2. The composition of THMs in the drinking water samples

The data reveals a dominance of $CHCl_3$ at 53%, followed by $CHBr_3$ at 24%, $CHClBr_2$ at 15%, and $CHBrCl_2$ at 8%. This distribution pattern elucidates several important considerations related to water quality management and public health. The prominent prevalence of chloroform, which makes up more than half of the total THMs detected, suggests that it is the primary byproduct of the chlorination process employed in water treatment. Chloroform is known to form during the reaction of chlorine with organic matter present in water, and its significant concentration raises concerns since it has been associated with various health risks, including potential carcinogenic effects. The strategies employed in source water management, such as reducing organic load before chlorination, should be evaluated to minimize chloroform levels. Bromoform, accounting for 24% of the THMs, is also noteworthy. Its presence may be indicative of the bromine content in the source water or the use of chlorinated oxidants in the treatment process. Higher levels of bromoform can arise in waters with elevated concentrations of bromide, which may be a concern for specific water sources. Continued monitoring of this compound is necessary, as its documented association with health issues, similar to chloroform, necessitates attention and possible mitigation strategies. The lower concentrations of dibromochloromethane and dibromochloromethane represent 15% and 8% of the THMs, respectively. While these levels are comparatively lower, they are still relevant from a regulatory perspective. The formation of these compounds typically reflects the interaction of chlorine with more complex organic structures, and their presence highlights the importance of analyzing the water treatment procedures to minimize their formation.

The overall THM profile indicates notable variances that could inform future water treatment practices. Recognizing the specific compounds and their respective concentrations may guide water treatment facilities to adopt more tailored approaches, such as optimizing chlorination levels or integrating alternative disinfection methods (e.g., UV treatment or ozone treatment) that may mitigate the occurrence of harmful byproducts like THMs.
The results of the Spearman's correlation analysis provided in table 3 reveal intriguing relationships between the concentrations of various trihalomethanes (THMs) in the drinking water samples. Correlation analysis is a useful tool for identifying potential associations between variables, and the significant correlations observed here can offer insights into the formation mechanisms and interdependencies of these important drinking water contaminants.

Table 3. Spearman's correlation analysis between THM concentrations*

Compound	Test	DW (n=61)		
		$CHBr_3$	$CHBrCl_2$	$CHClBr_2$
$CHCl_3$	Spearman Corr.	-0.313	0.797	0.094
	p value	0.014	0.000	0.473
$CHBr_3$	Spearman Corr.		0.041	0.765
	p value		0.751	0.000
$CHBrCl_2$	Spearman Corr.			0.550
	p value			0.000

*the results were considered significant correlations at 5% level ($p < 0.05$).

Starting with $CHCl_3$, the negative correlation with $CHBr_3$ shows a Spearman correlation coefficient of -0.313 (p=0.014). This suggests that as the concentration of chloroform increases, the concentration of bromoform tends to decrease, which could indicate an inverse relationship in their formation pathways or a competition between these two THMs during the chlorination process. Such dynamics may be influenced by varying concentrations of organic precursors or differences in disinfection practices applied at the water treatment facilities. Interestingly, there is a strong positive correlation between $CHCl_3$ and $CHClBr_2$, with a correlation coefficient of 0.797 ($p < 0.001$). This significant association may imply that both compounds are forming concurrently as a result of similar reactions involving chlorine and organic matter. The strong correlation could indicate that strategies to mitigate chloroform levels may also inadvertently impact the levels of dibromochloromethane, thus warranting an integrated approach to THM reduction.
The relationship between chloroform and $CHBrCl_2$ appears to be weak and not statistically significant, with a correlation coefficient of 0.094 ($p = 0.473$). This lack of correlation indicates that the concentration of dibromo-chloromethane does not have a predictable relationship with chloroform levels, suggesting that its formation may be driven by different precursors or conditions in the water treatment process that do not overlap with those influencing chloroform concentrations. Regarding $CHBr_3$, the correlation with $CHBrCl_2$ shows a strong positive association (correlation coefficient of 0.765, $p < 0.001$). This significant correlation indicates that as the concentration of bromoform increases, so does the concentration of dibromochloromethane. This could suggest that both compounds arise from similar brominated precursor substances in the water, underscoring the need for monitoring and managing bromide levels in source waters. Lastly, there is a strong positive correlation between $CHClBr_2$ and $CHBrCl_2$, with a correlation coefficient of 0.550 ($p < 0.001$). This indicates that the formation of these two compounds may share common precursors or conditions in the water treatment processes, highlighting the complexity of THM formation and the importance of understanding these relationships for effective management.
In summary, Spearman's correlation analysis elucidates significant relationships among the concentrations of various THMs in drinking water, particularly the strong positive correlation between chloroform and dibromochloromethane, as well as between bromoform and dibromochloromethane. These findings suggest important implications for water treatment practices aimed at reducing THM levels, highlighting the need for a comprehensive approach that addresses the intricate relationships among these compounds. Further research is warranted to explore the

underlying mechanisms of THM formation and to develop targeted strategies for minimizing their concentrations in drinking water, thus safeguarding public health.

Human health risk assessment

As urban populations expand and industrial activities intensify, the quality of surface water is being increasingly compromised, prompting a surge in global research focused on the detection of THMs in aquatic environments [17, 18]. In response to growing concerns regarding THMs, relevant environmental management agencies must carry out risk assessments and implement emission control measures based on the existing pollution levels of THMs within water bodies. Historically, many studies have benchmarked THM concentrations against various standards, including those set by the China National Standards, the World Health Organization, and the U.S. Environmental Protection Agency [18, 19]. Although THMs are classified as priority pollutants, their potential risks and long-term effects remain inadequately understood. Therefore, there is a pressing need for additional risk data and information on environmental concentrations of THMs to establish a comprehensive understanding of their hazards [20].

In recent years, researchers have embraced more holistic evaluation methodologies to better investigate the hazards associated with pollutants, considering both ecological and human health risks [21, 22]. As global water quality standards advance, it has become increasingly important to also examine the sensory aspects of drinking water, such as odors attributed to THMs [23, 24].

The provided toxicity data, specifically the slope factor (SF) values for trihalomethanes (THMs) listed in table 4, highlight the recognized carcinogenic potential of these contaminants in drinking water.

Table 4. Toxicological parameters and OTC the THM compounds [25]

Toxicological parameters	Units	$CHClBr_2$	$CHCl_3$	$CHBrCl_2$	$CHBr_3$
BCF		12	9.3	9.7	18
ChV	(μg/L)	30000	24000	28000	31000
SF	(kg·d/mg)	0.084	0.031	0.062	0.0079
RfD	(mg/(kg·d))	0.02	0.01	0.02	0.02
Kp	(cm/h)	0.00289	0.00683	0.00402	0.00235
OTC	(μg/L)	-	7500 a	-	-

Given the increasing presence of THMs due to industrial activities and population growth, understanding their human health implications is of paramount importance. Input parameters for human health risk assessment are listed in table 5.

Table 5. Input parameters for human health risk assessment

Input parameters	Units	Men/Women	Values	References
Ingestion rate (IR)	L/day	-	1.85	[14]
Exposure frequency (EF)	Day/year	-	365	
Exposure duration (ED)	year	Man	74	
		Woman	78	
Body weight (BW)	kg	Man	67.7	
		Woman	59.6	
Average time (AT)	day	Man	27 010	
		Woman	28 470	
Exposed skin area (SA)	dm^2	Man	166	[12]
		Woman	153	
Exposure time during bathing and showering (ET)	h/day	-	0.5	[13]
Dermal permeability coefficient (K_P)	dm/h	-	BDCM 0.000402, DBCM 0.000289, 0.0001 for $CHCl_3$ and $CHBr_3$	[15] [14]

The U.S. Environmental Protection Agency (EPA) utilizes specific benchmarks to evaluate human health risks associated with contaminants in drinking water. A carcinogenic risk value of less than 10^{-6} is generally considered negligible and indicates that the likelihood of developing cancer as a result of exposure is exceedingly low. Conversely, a risk value in the range of 10^{-6} to 10^{-4} suggests that while the risk may be acceptable for the general population, it could still pose a threat to vulnerable groups, including children, the elderly, or individuals with pre-existing health conditions [26]. A value exceeding 10^{-4} raises alarm bells, indicating a considerable potential for serious carcinogenic risks, which necessitates urgent intervention and regulatory measures.
The analysis of Chronic daily intake of THMs exposure from drinking water samples to men and woman, as presented in table 6.

Table 6. Chronic daily intake of THMs in the drinking water samples to men and women through ingestion and dermal routes

THMs	Woman ingestion		Woman dermal		Man ingestion		Man dermal	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$CHCl_3$	2.517	0.607	0.010	0.010	2.216	0.534	0.010	0.002
$CHBr_3$	1.018	0.285	0.004	0.004	0.896	0.251	0.004	0.001
$CHBrCl_2$	0.272	0.096	0.005	0.004	0.240	0.084	0.004	0.002
$CHClBr_2$	2.272	0.186	0.029	0.026	2.000	0.163	0.026	0.002

The table 6 provided presents the chronic daily intake (CDI) of THMs in drinking water samples to men and women through ingestion and dermal routes. The CDI values are calculated using the maximum and mean concentrations of THMs in the drinking water samples. The data shows that the CDI values for men and women are generally similar, with some differences in the magnitude of exposure. The maximum CDI values for women range from 2.517 μg/kg/day for $CHCl_3$ to 0.272 μg/kg/day for $CHBrCl_2$, while for men, the maximum CDI values range from 2.216 μg/kg/day for $CHCl_3$ to 0.240 μg/kg/day for $CHBrCl_2$. The mean CDI values for women are slightly lower than those for men, with a range of 0.607÷0.096 μg/kg/day for $CHCl_3$ and $CHBrCl_2$, respectively. For men, the mean CDI values range from 0.534÷0.084 μg/kg/day for $CHCl_3$ and $CHBrCl_2$, respectively. It is also notable that the dermal route of exposure contributes significantly to the total CDI values, particularly for $CHCl_3$ and $CHBr_3$. For example, the dermal CDI values for $CHCl_3$ are approximately 0.010-0.002 μg/kg/day, which is comparable to the ingestion CDI values.
The data suggests that exposure to THMs through both ingestion and dermal routes is a significant concern, particularly for $CHCl_3$ and $CHBr_3$. These compounds are known to have potential carcinogenic and non-carcinogenic effects, and their presence in drinking water can pose a risk to human health. The results also highlight the importance of considering both ingestion and dermal routes of exposure when assessing the risks associated with THMs in drinking water. This is particularly important for vulnerable populations, such as children and the elderly, who may be more susceptible to the effects of THMs due to their developing or compromised immune systems.
In this study, the non-carcinogenic risks associated with various THMs in drinking water samples for both men and women were assessed based on ingestion and dermal exposure routes (table 7).

Table 7. Non-carcinogenic risk of THMs in the drinking water samples to men and women through ingestion and dermal routes

THMs	Woman ingestion		Woman dermal		Man ingestion		Man dermal	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$CHCl_3$	2.52E-01	6.07E-02	1.04E-03	2.51E-04	2.22E-01	5.34E-02	9.94E-04	2.40E-04
$CHBr_3$	5.09E-02	1.43E-02	2.22E-04	6.22E-05	4.48E-02	1.26E-02	2.01E-04	5.63E-05
$CHBrCl_2$	1.36E-02	4.80E-03	2.38E-04	8.40E-05	1.20E-02	4.22E-03	2.16E-04	7.62E-05
$CHClBr_2$	1.14E-01	9.28E-03	1.43E-03	1.17E-04	1.00E-01	8.17E-03	1.30E-03	1.06E-04

The analysis reveals that $CHCl_3$ presents the highest non-carcinogenic risk for both genders, with maximum ingestion risks of 2.52E-01 for women and 2.22E-01 for men. Corresponding mean values suggest similar trends, with women averaging at 6.07E-02 and men at 5.34E-02, highlighting that $CHCl_3$ is a significant health concern in both cases. In addition, $CHBr_3$ emerges as another critical compound, with maximum ingestion risks of 5.09E-02 for women and 4.48E-02 for men, indicating that this compound also poses a considerable non-carcinogenic risk, albeit lower than $CHCl_3$. The dermal exposure risks for $CHBr_3$ are notably lower, showing values of 2.22E-04 and 2.01E-04 for women and men, respectively, reflecting a more significant risk through ingestion compared to dermal contact. The data also show that $CHBrCl_2$ contributes to non-carcinogenic risk, particularly through ingestion routes, with maximum risks of 1.36E-02 for women and 1.20E-02 for men. The mean ingestion risks of 4.80E-03 for women and 4.22E-03 for men further substantiate that $CHBrCl_2$ is less hazardous than $CHCl_3$ and $CHBr_3$ but still warrants attention. Lastly, $CHClBr_2$ shows a non-carcinogenic risk profile similar to that of $CHBr_3$, although still substantial with maximum ingestion risks of 1.14E-01 for women and 1.00E-01 for men. Mean values further indicate that while risks through dermal exposure are lower, the ingestion pathway remains a key concern.
Table 8 presents the carcinogenic risk of THMs in drinking water samples for both men and women, considering ingestion and dermal exposure routes. The results reveal varying levels of risk associated with each compound, highlighting the potential health implications for both genders.

Table 8. Carcinogenic risk of THMs in the drinking water samples to men and women through ingestion and dermal routes

THMs	Woman ingestion		Woman dermal		Man ingestion		Man dermal	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$CHCl_3$	7.80E-05	1.88E-05	3.23E-07	3.08E-07	6.87E-05	1.66E-05	3.08E-07	7.43E-08
$CHBr_3$	3.16E-05	8.84E-06	1.38E-07	1.25E-07	2.78E-05	7.78E-06	1.25E-07	3.49E-08
$CHBrCl_2$	8.44E-06	2.97E-06	1.48E-07	1.34E-07	7.43E-06	2.62E-06	1.34E-07	4.72E-08
$CHClBr_2$	7.04E-05	5.76E-06	8.87E-07	8.04E-07	6.20E-05	5.07E-06	8.04E-07	6.57E-08

$CHCl_3$ shows the highest carcinogenic risk values among the analyzed THMs. For women, the maximum carcinogenic risk through ingestion is 7.80E-05, while for men, it is slightly lower at 6.87E-05. These values, while below the risk threshold of 10^{-4}, indicate a notable risk that warrants attention, particularly as they approach the upper limit of acceptable exposure. Mean values for both sexes reflect a similar trend, with women at 1.88E-05 and men at 1.66E-05 through ingestion, again suggesting an inherent risk. The dermal exposure risks for $CHCl_3$ are significantly lower, at 3.23E-07 for women and 3.08E-07 for men. This finding indicates that while dermal absorption contributes to overall exposure, the risk through ingestion is predominant. Bromodichloromethane also presents considerable carcinogenic risks, especially through ingestion, with maximum values of 3.16E-05 for women and 2.78E-05 for men. The mean values further underscore this risk, with women experiencing 8.84E-06 and men 7.78E-06. The dermal exposure values are comparatively lower, indicating that ingestion is the more significant route for this compound as well. Dibromochloromethane and chlorinated bromomethane exhibit lower carcinogenic risk levels when compared to $CHCl_3$ and $CHBr_3$. For example, the maximum risk for women via ingestion of $CHBrCl_2$ is 8.44E-06, while the male counterpart is 7.43E-06. The dermal risk for this compound remains low across both genders. The same trend is observed for $CHClBr_2$, where the ingestion maximums are 7.04E-05 for women and 6.20E-05 for men. Overall, the carcinogenic risks for the assessed THMs do not exceed the 10^{-4} threshold indicating substantial concern. However, the values do suggest potential health risks that could be particularly relevant to vulnerable groups. Specifically, the risks for $CHCl_3$ and $CHBr_3$ approach levels that could justify further investigation.
The analysis of carcinogenic and non-carcinogenic risks associated with THMs in drinking water reveals a notable gender disparity, with women exhibiting higher risk levels than men across both categories. The total non-carcinogenic risks for women range from 5.14×10^{-4} to 4.30×10^{-1}, while for men, the risks range from 4.78×10^{-4} to 3.78×10^{-1}. This consistent pattern points to a greater

vulnerability in women, which may be attributable to physiological differences, including body composition and metabolism, as well as behavioral factors such as dietary habits and exposure scenarios. Carcinogenic risk assessments indicate a similar trend, with total risks for women varying between 1.37×10^{-6} and 1.88×10^{-4}, and for men between 2.22×10^{-7} and 1.66×10^{-4}. comparable values for cancer risk that exceed the minimum or negligible risk threshold established by the USEPA (1.00×10^{-6}) have also been published by different studies [5, 27]. The elevated risks for women within this context underline an urgent need for targeted health interventions and risk communication strategies in populations with a predominantly female demographic, particularly since these values approach critical thresholds for health impact.

In one of the most detailed studies examining direct relationships, Cantor et al., 2010 [28] identified that a variant in the GSTT1 gene—a crucial enzyme involved in the metabolism of trihalomethanes—affected the link between THMs and bladder cancer risk. While the accumulated evidence suggests a potential connection, there remains a gap in large-scale cohort studies to definitively establish this association.

Furthermore, the findings illustrate that both carcinogenic and non-carcinogenic risks via ingestion were approximately 150 times higher than those from dermal exposure. This stark contrast highlights the importance of prioritizing ingestion pathways in public health discussions and regulatory efforts concerning THM contamination in drinking water. The relative insignificance of dermal contact risks suggests that while it is a relevant exposure route, the primary concern should lie within the ingestion route, necessitating measures to reduce contamination or improve water treatment processes.

The consistency of these findings with previous research conducted by Zhang et al. (2021) [12] reinforces the reliability of the results and suggests that the observed risks are not isolated incidents but part of a broader pattern in public health data concerning THM exposure. This alignment with earlier studies provides a compelling argument for continued monitoring of THM levels in drinking water, particularly in vulnerable populations, and emphasizes the need for regulations and guidelines that specifically address the disparities in risk between genders.

Limitations of the study

The study examining the carcinogenic and non-carcinogenic risks of THMs in drinking water may have several inherent limitations that need to be acknowledged. Firstly, the assessment relies heavily on existing data, which may not fully capture the variations in THM concentrations across different geographical regions, seasonal fluctuations, or changes in water treatment practices over time. If the samples collected do not adequately represent the broader water quality conditions experienced by the populations, the risk assessments may not accurately reflect actual exposure levels. Additionally, the study's focus on ingestion and dermal exposure routes, while important, does not consider other potential exposure pathways such as inhalation or dietary sources, which may also play significant roles in overall exposure to THMs. For instance, individuals may be exposed to THMs through the vaporization of contaminated water when bathing or showering, and ignoring this route could lead to an underestimation of the total risk associated with THM exposure. Another limitation lies in the assumption of uniform susceptibility across genders and among different age groups. The study indicates that women experience higher risks than men, yet it does not delve deeply into how various life stages, hormonal differences, or pre-existing health conditions may further influence these risks. This lack of stratification may mask significant disparities in risk assessment and health outcomes among different subpopulations. Moreover, the methodology used to quantify carcinogenic risks could also present limitations. The use of certain modeling approaches or risk assessment models may incorporate assumptions that cannot capture the complexity of human health responses to long-term exposure to THMs. For instance, the linear extrapolation of risk from short-term exposure data to predict long-term health outcomes can be contentious and may not accurately reflect the biological reality of chronic exposure. Furthermore, the study focuses on a limited number of compounds, which means that other relevant compounds often found in drinking water, such as other volatile organic compounds (VOCs) or disinfection byproducts, are not considered. This omission could result in an

incomplete understanding of the overall health risks associated with water quality, as interactions among various contaminants might exacerbate or modify individual risks.

CONCLUSIONS

In conclusion, this study provides critical insights into the carcinogenic and non-carcinogenic risks associated with exposure to THMs in drinking water, revealing significant gender differences that warrant attention. The findings demonstrate that women experience higher risk levels compared to men, underscoring the need for tailored public health strategies that address these disparities. The marked elevation of ingestion-related risks—approximately 150 times greater than those associated with dermal contact—highlights the importance of mitigating risks through rigorous monitoring and regulation of drinking water quality. While the study aligns with previous research, it is imperative to acknowledge the limitations present in the methodology, including potential gaps in the representation of exposure routes, population susceptibility, and the consideration of other contaminants. These limitations emphasize the importance of ongoing research to better understand the comprehensive effects of THMs and related substances on public health. Overall, our findings advocate for the refinement of risk assessment practices and the implementation of effective water treatment standards to protect at-risk populations, particularly women, from the adverse health effects associated with THM exposure. Future studies should aim to expand the scope of risk evaluation to include additional exposure pathways, a broader array of contaminants, and more nuanced demographic analyses to enhance our understanding of the potential health impacts of THMs and contribute to informed regulatory practices. Through such efforts, we can better safeguard community health and ensure safer drinking water for all.

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