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RESEARCH PAPER

Monitoring of Trihalomethanes and its Cancer Risk Assessment in Drinking Water of Delhi City, India

Mohd. Aamir Mazhar[1*], Sirajuddin Ahmed[1*], Azhar Husain[1] and Rahisuddin[2]

[1] Department of Civil Engineering, Jamia Millia Islamia, New Delhi-110025, India
[2] Department of Chemistry, Jamia Millia Islamia, New Delhi-110025, India

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Abstract
The current study determines the concentrations of trihalomethanes (THMs), and the cancer risk associated with them. The tap water sampling was done from the command area of nine water treatment plants (WTPs) of Delhi, India. THMs levels in the water samples from eighteen distribution points were investigated for one year. The cancer risk (CR) related to THMs by different exposure routes i.e., ingestion, dermal absorption, and inhalation, was assessed for males and females. The THM levels varied between 11.41 µg/L to 175.54 µg/L in the distribution system, having a mean level of 77.58 µg/L. The average concentrations of THMs exceeded the maximum permissible limit given by Indian Standards. The concentration of chloroform was maximum, followed by bromodichloromethane, dibromochloromethane, and bromoform. For males and females, the mean value of total CR was 5.09E-05 5.70E-05, respectively. As the THMs levels were high, the total CR value was also more than the negligible level of risk i.e., 1.0 x 10^{-6} through all exposure routes.

Keywords: Chlorination, Trihalomethanes, Drinking Water, Cancer Risk Assessment

INTRODUCTION

In developing countries, one of the most significant challenges is to provide safe drinking water to its population. There is a higher health risk associated with the microbial contamination present in water (Madhav et al., 2021). To protect human beings from pathogens and waterborne diseases, disinfection is done during water treatment (Al-Otoum et al., 2016). Chlorine is a highly viable and economical disinfectant used in India. Disinfection by-products (DBPs) are generated when chlorine reacts with organic matter during disinfection. Trihalomethanes (THMs) and Haloaceticacids (HAAs) are the mainly formed DBPs (Golea et al., 2017; Ioannou et al., 2016; Mazhar et al., 2020). Various researchers have shown its variability depending on factors like a source of water, pH, temperature, residence time, chlorine dose, disinfectant type, operating conditions of the treatment plant, bromide concentration, applied chlorine dose, residual chlorine, etc, (Ates et al., 2020; Kalankesh et al., 2021; Liu et al., 2017). Various researchers studied their toxicology and epidemiology to establish a relation between DBPs and cancer (Espejo-Herrera et al., 2015; Evlampidou et al., 2020; Font-Ribera et al., 2018; Inoue-Choi et al., 2015; Jones et al., 2019; Quist et al., 2018)

THMs were the first regulated group of DBPs having four species: chloroform (CF), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform (BF). The permissible limit given by the United States Environmental Protection Agency (USEPA) is 80 mg/L for total THMs (USEPA, 2018), and by World Health Organization (WHO) the individual limit for CF, BDCM, DBCM, and BF is given as 300 mg/L, 60 mg/L, 100 mg/L and

* Corresponding author Email: er.aamirmazhar@gmail.com, suahmed@jmi.ac.in

100 mg/L respectively (WHO, 2017). The Bureau of Indian Standards also regulated CF, BDCM, DBCM, and BF individually as 200 mg/L, 60 mg/L, 100 mg/L, and 100 mg/L respectively in 2012 (IS:10500, 2012). Human beings use water in their daily life for drinking, bathing, showering, cooking, washing, cleaning, etc. As a result, for humans, the exposure routes to THMs are oral ingestion, dermal absorption, and inhalation. Therefore, it is essential to detect and monitor THMs in municipal water supplies to safeguard humans against their carcinogenic risk. Recently several studies around the world on THMs studied their health risk through different routes of exposure (Cadwallader & VanBriesen, 2019; Genisoglu et al., 2019; Kujlu et al., 2020; Wang et al., 2019).

In India, several researchers studied THMs, but it is still not regularly being monitored at the water treatment plants (Hasan et al., 2010; Kumari and Gupta, 2015; Mishra and Dixit, 2013; Sharma and Goel, 2007). Delhi is in the north of India, and all the water treatment plants (WTPs) in Delhi use chlorination processes considering the regrowth of pathogens in the water supply pipes. As the THMs are probable carcinogens, there is a need to quantify the health risks. The goal of this study is to monitor the THMs levels in the tap water coming out from the distribution system of nine WTPs of Delhi, India, and to assess the cancer risk. To achieve this, the THM levels in tap water were determined, and cancer risk was evaluated for THMs through oral ingestion, dermal absorption, and inhalation for the urban area under study.

MATERIALS AND METHODS

The study area was New Delhi which is a densely populated metropolitan city in India, having a population of 19.43 million. In recent decades there has been an increase in water demand because of the rapid growth of industries and people in Delhi. For this study, nine water treatment plants (WTP), namely Chandrawal WTP (CWTP), Wazirabad WTP (WWTP), Haiderpur WTP (HWTP), Bhagirathi WTP (BWTP), Bawana WTP (BAWTP), Nangloi WTP (NWTP), Sonia Vihar WTP (SVWTP), Okhla WTP (OWTP), Dwarka WTP (DWTP) were selected as shown in **Figure 1**. The WTPs under study are supplied with surface water coming from Yamuna River and Ganga River and are using chlorine for disinfection.

Two sampling sites were selected from the command area (CA) of each facility, and the

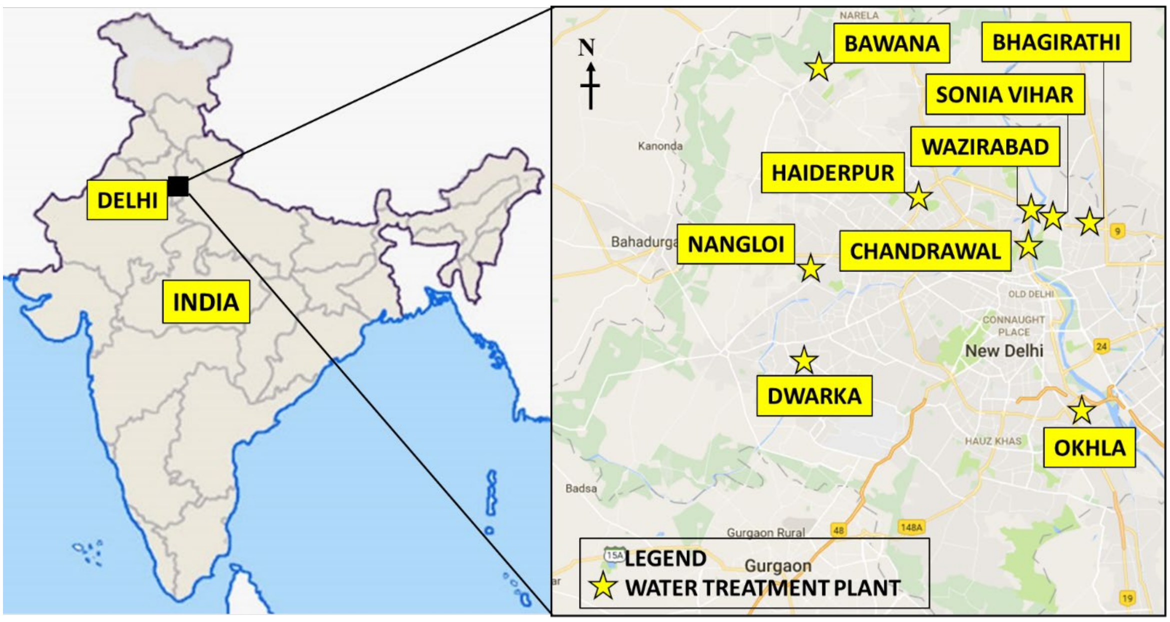

Fig. 1. Map showing locations of Water Treatment Plants in Delhi

Fig. 2. Map showing sampling locations in the command area of Water Treatment Plants

samples were collected in duplicate. Thirty-six samples from 18 sampling sites were collected for a one-year sampling program carried out between January 2019 to December 2019. The sampling points are shown in **Figure 2**. In 40 mL glass vials, the drinking water samples were collected and pre-treated with sodium thiosulfate to stop the formation of THMs (APHA, 2017). The samples were stored below 4°C before the laboratory analysis. Separate sampling was done to study temperature, pH, total organic carbon (TOC), and residual chlorine (res. Cl).

The THMs (CF, BDCM, DBCM, and BF) were analyzed by liquid-liquid extraction USEPA Method 551.1 using gas chromatography-mass spectrometry (GC-MS) (USEPA, 1995). The THMs samples were separated using HP-5 column, size 30m x 0.25mm x 0.25µm (Agilent Technologies). A volume of 1 µL was injected into the column, and at a flow rate of 1 mL/min, helium was used as a carrier gas. The chemicals used were of the analytical grade from Merck, India. The GC-MS grade solvents and standards were from Sigma-Aldrich. De-ionized water from a Milli-Q system was used for all experimental purposes. The temperature and pH were measured by pH meter (8603 Mettler Toledo). TOC was analyzed by a TOC analyzer (TOC-5000, Shimadzu, Japan) following the Standard method 5310C. The residual chlorine (in mg/L) was analyzed by DPD titrimetric Standard method 4500-Cl-G (APHA, 2017).

Cancer risk (CR) assessment from THMs is based on their concentrations in the tap water collected from the command areas of nine WTPs of Delhi. The primary route of exposure is ingestion or oral exposure. However, bathing is considered for dermal exposure, and showering is considered for inhalation exposure (Téllez Tovar & Rodríguez Susa, 2021; Wang et al., 2019; Zeng et al., 2014). For this assessment, activities like drinking water, bathing, showering were considered for ingestion, dermal, and inhalation exposure, respectively. Carcinogenic risk assessment was applied as per USEPA guidelines (USEPA, 2005), previously adopted in various studies (Kujlu et al., 2020; Pan et al., 2014; Pardakhti et al., 2011; Wang et al., 2019). The input parameters were based on the Indian conditions taken from the Indian Council of Medical Research (ICMR), also from Integrated Risk Information System (IRIS) and Risk Assessment Information System (RAIS), as summarized in **Table 1**.

Table 1. Parameters used for assessment of cancer risk

Input parameters	Symbol	Values	Units	References
Oral ingestion				
THMs concentration in water	C_w	See Table 3	μg/L	Current Study
Exposure duration	ED	Male: 68.2	year	(ICMR, 2018)
		Female: 70.7		
Exposure frequency	EF	365	days/year	(Kujlu et al., 2020)
Ingestion rate	IR_w	3	L/day	(Basu et al., 2011)
Dermal absorption				
Surface area of skin	SA	Male: 1.76	m^2	(ICMR, 2018)
		Female: 1.64		
Chemical specific dermal Permeability constant	Kp	CF: 0.00683	m/h	(RAIS, 2021)
		BDCM: 0.00402		
		DBCM: 0.00289		
		BF: 0.00235		
Inhalation exposure				
Contaminant concentration in air	C_a	Model calculations	mg/L	(Little, 1992)
Inhalation rate	IR	Male: 0.95	m^3/h	(USEPA, 2015)
		Female: 0.88		
Airflow rate	Q_G	50	L/min	(B. K. Mishra et al., 2014)
Water flow rate	Q_L	5	L/min	
Bathroom Volume	V_S	5	m^3	
Dimensionless Henry's law constant	H	CF: 0.15	Unit less	(RAIS, 2021)
		BDCM: 0.0656		
		DBCM: 0.0321		
		CF: 0.0219		
Overall mass transfer coefficient	$K_{OL}A$	CF: 7.4	L/min	(Genisoglu et al., 2019)
		BDCM: 5.9		
		DBCM: 4.6		
		BF: 3.7		
Exposure time	ET	0.25	h/event	(Legay, Rodriguez, Sadiq, et al., 2011)
Exposure frequency	EF	1	event/day	(Ahmed et al., 2019)
Exposure duration	ED	Male: 365 x 68.2	days	
		Female: 365 x 70.7		
Body weight	BW	Male: 65	kg	(ICMR, 2018)
		Female: 55		
Average time (AT)	AT	Male: 365 x 68.2	days	
		Female: 365 x 70.7		

Chronic daily intake (CDI) for each exposure pathway was used to calculate the cancer risks from THMs expressed as follows (USEPA, 2005):

CR from ingestion route: $CR_{ingestion} = CDI_{ingestion} \times SF_{ingestion}$

where, $$CDI_{ingestion}\left(\frac{mg}{\frac{kg}{day}}\right)=\frac{C_w\left(mg/L\right)*IR_w\left(L/day\right)*EF\left(day/year\right)*ED\left(years\right)}{BW\left(kg\right)*AT\left(days\right)}$$

Similarly,
CR from dermal absorption route: $CR_{dermal} = CDI_{dermal} \times SF_{dermal}$

where,
$$CDI_{dermal}\left(mg/kg/day\right)=\frac{C_w\left(mg/L\right)*SA\left(cm2\right)*Kp\left(cm/h\right)*ET\left(h/event\right)*EF\left(day/year\right)*ED\left(years\right)*CF}{BW\left(kg\right)*AT\left(days\right)}$$

where,
CF = Conversion factor of cm^3 to L (10^{-3} L/cm^3)
and

CR from inhalation route: $CR_{inhalation} = CDI_{inhalation} \times SF_{inhalation}$

where,

$$CDI_{inhalation}\left(mg/kg/day\right)=\frac{C_a\left(mg/m3\right)*IRa\left(m3/h\right)*ET\left(h/event\right)*EF\left(day/year\right)*ED\left(years\right)}{BW\left(kg\right)*AT\left(days\right)}$$

For the inhalation exposure route, the major contributors are volatile compounds generated from showering. For showering volatilizing of THMs depends on the temperature of the water, which is 40°C. Among other THMs, chloroform has the lowest boiling point; therefore, it is supposed to be the highest contributor to cancer risk through inhalation (Lee et al., 2004). Few researchers have directly assessed the concentration of chloroform in the air by using the volatilization factor resulting in an underestimated cancer risk (Ioannou et al., 2016; Legacy et al., 2011a; Wang et al., 2019). Littles two resistance theory was applied to calculate volatilized THMs concentration in air i.e., C_a from C_w (Little, 1992).

For inhalation, C_a is calculated by:

C_a = (Ysi + Ys(t)) /2

where,
Ysi = initial THM concentration assumed to be 0 mg/L in the bathroom.
Ys(t) = THM concentration in the bathroom at time t (min) assumed to be 30 min.
And

Ys (t) = [1 – exp(-bt)] (a/b)
a = {$Q_L C_W$ [1 - exp(-N)]}/V_S
b = {(Q_L/H) [1- exp(-N)] + Q_G} /V_S
N = (K_{OL}A) /Q_L

where,
Q_L = Flow rate of water during shower (L/min)
Q_G = Flow rate of air in the bathroom (L/min)
V_S= Volume of the bathroom (m^3)

Table 2. Slope factor of THMs for cancer risk assessment

THMs	SF (mg/kg/day)			References
	Ingestion	Dermal	Inhalation	
CF	0.0061	0.0305	0.081	RAIS (2021)
BDCM	0.062	0.062	0.13	IRIS (2021), CalEPA (2021)
DBCM	0.084	0.084	0.094	IRIS (2021), CalEPA (2021)
BF	0.0079	0.0079	0.0039	RAIS (2021), IRIS (2021)

H = Henry's Law constant of THMs
$K_{OL}A$ = Overall mass transfer coefficient of THMs (L/min)
N = dimensionless coefficient calculated from $K_{OL}A$
The CR from all three exposure routes was summed up to get the total cancer risk (CR_{Total}):

$$CR_{Total} = CR_{ingestion} + CR_{dermal} + CR_{inhalation}$$

The corresponding slope factor (SF) values as shown in **Table 2** for a specific compound were taken from IRIS, RAIS, and California Environmental Protection Agency (CalEPA).

RESULTS AND DISCUSSION

Water quality analysis was conducted for pH, temperature, TOC, residual chlorine, and the results are shown in **Table 3**. In the distribution system, the pH at the sampling points was in the range of 6.65 to 7.85, with an average of 7.29. The pH values were found to be in the normal range as per Indian Standard. The temperature varies between 12.6 °C to 31.6 °C having a mean concentration of 21.51 °C. The TOC was in the range of 0.57 mg/L to 12.92 mg/L with a mean of 5.48 mg/L. The samples from the command areas of CWTP, WWTP, HWTP, BWTP, SVWTP showed higher TOC concentrations than the BAWTP, NWTP, OWTP, and DWTP command areas. Higher TOC levels in the tap water reflect the infestation of wastewater into the distribution network (Gunnarsdottir et al., 2020; Turner et al., 2021). The residual chlorine was in the range of 0.14 mg/L to 2.17 mg/L, having a mean concentration of 0.94 mg/L, and was found to be greater than the permissible limit given by India Standards, i.e., 0.2 mg/L to 1 mg/L (IS:10500, 2012). The samples from the command areas of CWTP, WWTP, HWTP, BWTP, NWTP, SVWTP showed higher residual chlorine concentrations than the samples from BAWTP, OWTP, and DWTP command areas. Error in estimating the post-chlorine dose or infestation of wastewater into the water supply network can be the main reason for higher residual chlorine values. In the distribution network the increase in residual chlorine advocates higher THMs formation.

In this study, the THMs are measured in the command areas of nine WTPs of Delhi. The average values of THMs were found to be varying from plant to plant, and the results are shown in **Table 3**. The CF concentration ranges between 7.53 μg/L to 66.80 μg/L for the study period with an average of 34.62 ± 13.09 μg/L. The BDCM concentration ranges between 3.88 μg/L to 56.46 μg/L for the study period with an average of 25.39 ± 11.75 μg/L. The DBCM concentration ranges between 0 μg/L to 45.68 μg/L for the study period with an average of 15.83 ± 9.66 μg/L. The concentration of BF ranges between 0 μg/L to 6.6 μg/L for the study period with an average of 1.74 ± 1.51 μg/L. The concentrations of BF were found to be below the detection level. The presence of BF in treated water indicates the existence of bromide in raw water. The tap water from the command area of CWTP had the highest THM concentration, and from the command area of OWTP had the lowest THM concentration. The THM concentrations measured in the

Table 3. Concentration of water quality parameters and THMs at various locations

Location	pH	Temp (°C)	TOC (mg/L)	Res. Cl (mg/L)	CF (µg/L)	BDCM (µg/L)	DBCM (µg/L)	BF (µg/L)	TTHM (µg/L)
CWTP	7.26±0.21	21.46±5.92	8.07±2.35	1.41±0.25	49.89±7.65	39.87±5.70	26.27±6.88	3.51±1.54	119.53±20.51
WWTP	7.29±0.22	21.62±6.04	7.27±2.55	1.25±0.25	43.06±8.43	33.94±6.64	23.09±7.06	2.48±0.94	102.57±21.94
HWTP	7.29±0.26	21.43±6.03	6.75±2.94	1.17±0.35	41.31±11.22	30.39±9.61	20.95±7.89	2.14±1.21	94.80±28.92
BWTP	7.33±0.19	21.45±6.00	6.44±2.76	1.17±0.38	39.58±10.87	30.27±10.07	20.33±8.53	2.38±1.52	92.56±30.26
BAWTP	7.35±0.25	21.63±6.18	3.79±1.44	0.60±0.14	24.26±4.57	16.14±3.81	9.26±2.56	0.99±0.52	50.65±10.39
NWTP	7.38±0.24	21.47±6.14	5.52±1.94	0.94±0.20	35.03±7.41	25.82±6.18	16.09±4.63	1.61±0.84	78.55±17.86
SVWTP	7.30±0.24	21.53±6.08	6.48±2.12	1.10±0.23	40.38±6.26	30.35±5.80	19.06±4.97	2.38±1.40	92.16±16.59
OWTP	7.20±0.20	21.43±6.13	2.49±1.10	0.40±0.16	18.52±6.49	10.63±4.32	3.85±1.98	0.06±0.18	33.05±12.58
DWTP	7.21±0.20	21.57±6.08	2.54±0.91	0.42±0.12	19.58±5.33	11.09±3.66	3.56±1.82	0.10±0.28	34.34±10.01
Overall	7.29±0.23	21.51±5.95	5.48±2.85	0.94±0.43	34.62±13.09	25.39±11.75	15.83±9.66	1.74±1.51	77.58±35.30

Note: n=24 for each WTP, ± SD (Standard Deviation)

command area of CWTP, WWTP, HWTP, BWTP, NWTP, and SVWTP surpassed the WHO and USEPA guideline values, while THM concentrations at BAWTP, OWTP, and DWTP command area were within the prescribed guidelines. The highest THM concentration was found in CWTP command area 119.53 ± 19.57 µg/L, and the lowest was found in OWTP command area 33.04 ± 10.04 µg/L.

Cancer risk assessment was conducted across different exposure routes. The concentration of THMs measured in drinking water samples from the studied region is given in **Table 3** were taken for evaluating the cancer risk assessment.

Through ingestion, the cancer risk for males and females is represented in **Figure 3**. The cumulative CR for male and female through ingestion were found to be highest: Chandrawal WTPCA: 2.31E-05, 2.73E-05 (which is 0.23 and 0.27 times higher than the USEPA limit) > Wazirabad WTPCA: 2.00E-05, 2.36E-05 (which is 0.2 and 0.23 times higher) > Haiderpur WTPCA: 1.81E-05, 2.13E-05 (which is 0.18 and 0.21 times higher) > Bhagirathi WTPCA: 1.77E-05, 2.10E-05 (which is 0.17 and 0.21 times higher) > Sonia Vihar WTPCA: 1.73E-05, 2.04E-05 (which is 0.17 and 0.20 times higher) > Nangloi WTPCA: 1.47E-05, 1.73E-05 (which is 0.14 and 0.17 times higher) > Bawana WTPCA: 8.93E-06, 1.06E-05 (which is 0.089 and 0.10 times higher) > Dwarka WTPCA; 5.11E-06, 6.04E-06 (which is 0.05 and 0.06 times higher)

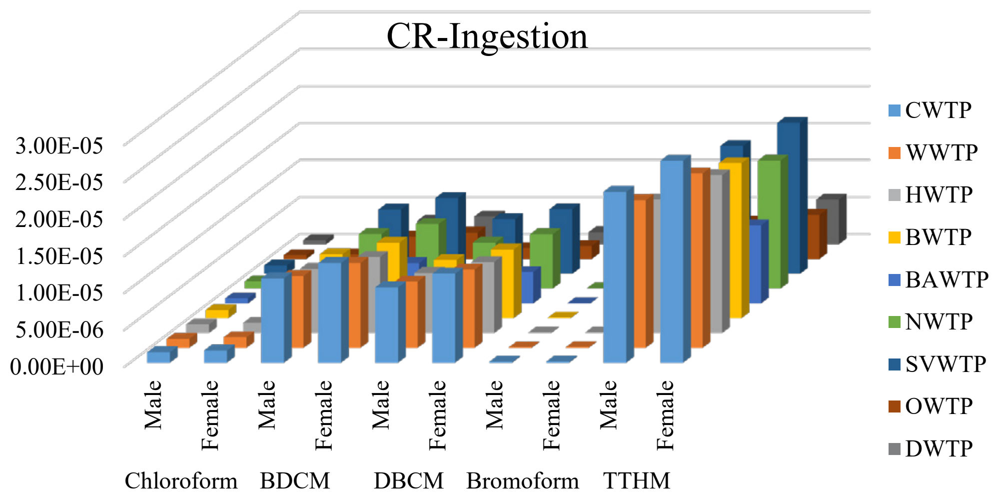

Fig. 3. Cancer Risk of THMs for males and females through ingestion

> Okhla WTPCA: 5.06E-06, 5.98E-06 (which is 0.05 and 0.06 times higher). The higher risk factor by the THMs species revealed that their concentrations in the water samples exceed the permissible limit given by IS:10500, WHO, and USEPA. The average total contribution in cancer risk through ingestion is: BDCM 50% > DBCM 43% > chloroform 7% > bromoform 0%. The high-risk factor due to BDCM and DBCM can be due to higher slope factors even when their concentrations were lesser than the chloroform. The outcome revealed that the BDCM and DBCM had more cancer risk. All WTPs showed higher lifetime cancer risk by ingestion (> 10^{-6} USEPA limit). The average lifetime CR for males and females by ingestion in all water supply water is 1.44E-05 and 1.71E-05, which is about 0.144 and 0.171 times higher than the acceptable risk given by USEPA, respectively. Through ingestion, the female has a higher cancer risk than the male due to higher exposure duration.

By dermal absorption, the pollutants present in the contaminated water can penetrate the body by bathing, swimming, laundry, washing, etc., contributing to risk exposure. The dermal exposure by THMs directly depends upon the skin's surface area. The CR for males and females through dermal absorption is represented in **Figure 4**. The cumulative cancer risk for males and females by dermal absorption were found to be: Chandrawal WTPCA: 1.81E-05, 2.00E-05 (which is 0.18 and 0.2 times higher than the USEPA limit) > Wazirabad WTPCA: 1.56E-05, 1.72E-05 (which is 0.15 and 0.17 times higher) > Haiderpur WTPCA: 1.44E-05, 1.59E-05 (which is 0.14 and 0.15 times higher) > Bhagirathi WTPCA: 1.41E-05, 1.55E-05 (which is 0.14 and 0.15 times higher) > Sonia Vihar WTPCA: 1.40E-05, 1.54E-05 (which is 0.14 and 0.15 times higher) > Nangloi WTPCA: 1.20E-05, 1.32E-05 (which is 0.12 and 0.13 times higher) > Bawana WTPCA: 7.68E-06, 8.46E-06 (which is 0.077 and 0.084 times higher) > Dwarka WTPCA; 5.22E-06, 5.75E-06 (which is 0.052 and 0.057 times higher) > Okhla WTPCA: 5.04E-06, 5.55E-06 (which is 0.050 and 0.055 times higher). The higher risk factor by the THMs species revealed that their concentrations in the water samples are more than the permissible limit given by IS:10500, WHO and USEPA. The average total contribution in cancer risk by Chloroform is 42% > by BDCM is 36% > by DBCM is 22% > by bromoform is 0%. The highest cancer risk was shown by chloroform than the other THMs species. All WTP showed higher lifetime cancer risk by dermal absorption (> 10^{-6} USEPA limit). The average lifetime CR by dermal absorption for males and females in the studied region is 1.18E-05 and 1.30E-05, which is about 0.118 and 0.13 times higher than the limit given by USEPA, respectively. Regardless of a male having a higher surface area, the females have a higher

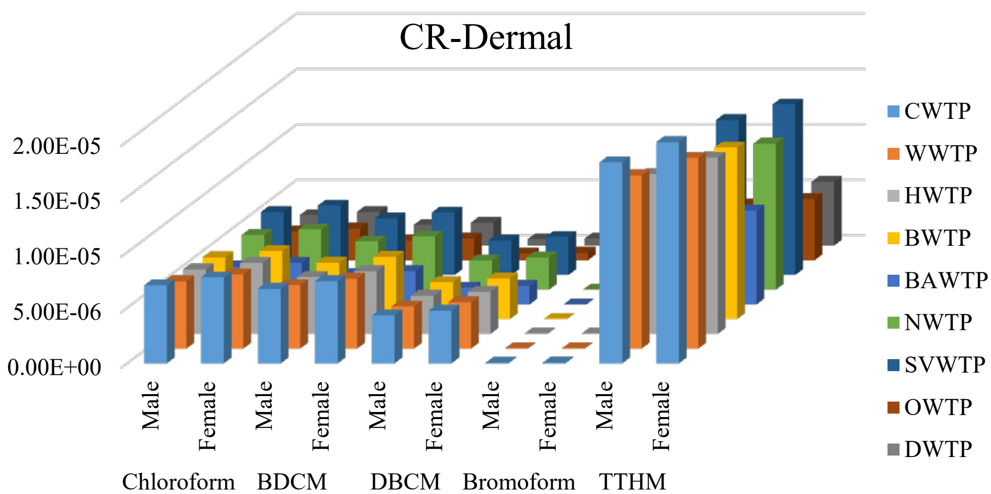

Fig. 4. Cancer Risk of THMs for males and females through dermal absorption

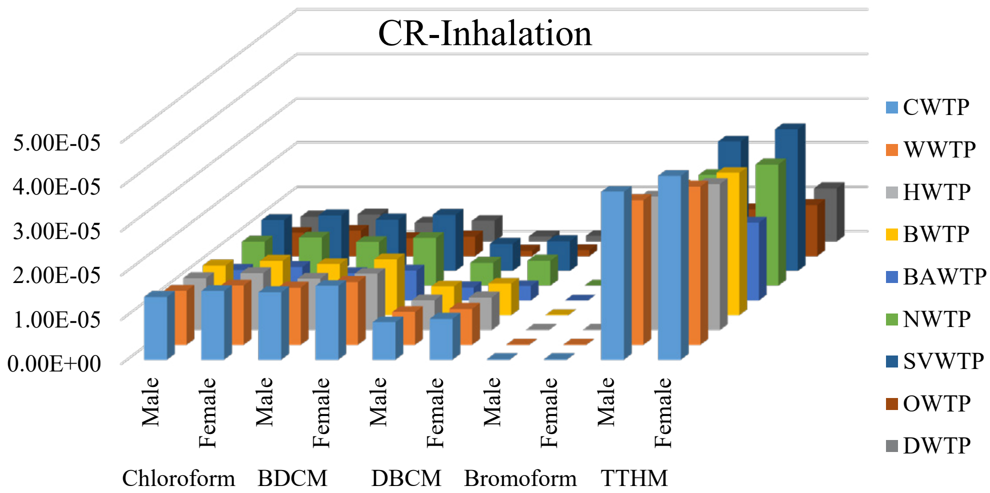

Fig. 5. Cancer Risk of THMs for males and females through inhalation

cancer risk than the males through dermal exposure.

The compounds present in the water get volatilized during activities like bathing, washing, showering, cooking, etc., and are exposed to humans by inhalation. Through inhalation exposure, showering activity is the highest contributor to volatile compounds. Chloroform is the major contributor through inhalation as it has a low boiling point. The cancer risk for male and female by inhalation are represented in **Figure 5**. The cumulative cancer risk for male and female through inhalation were found to be: Chandrawal WTPCA: 3.79E-05, 4.15E-05 (which is 0.37 and 0.41 times higher than the USEPA limit) > Wazirabad WTPCA: 3.27E-05, 3.58E-05 (which is 0.32 and 0.35 times higher) > Haiderpur WTPCA: 3.01E-05, 3.30E-05 (which is 0.30 and 0.33 times higher) > Bhagirathi WTPCA: 2.94E-05, 3.22E-05 (which is 0.29 and 0.32 times higher) > Sonia Vihar WTPCA: 2.92E-05, 3.20E-05 (which is 0.29 and 0.32 times higher) > Nangloi WTPCA: 2.50E-05, 2.74E-05 (which is 0.25 and 0.27 times higher) > Bawana WTPCA: 1.60E-05, 1.76E-05 (which is 0.16 and 0.17 times higher) > Dwarka WTPCA: 1.09E-05, 1.20E-05 (which is 0.10 and 0.12 times higher) > Okhla WTPCA: 1.06E-05, 1.16E-05 (which is 0.10 and 0.11 times higher). The higher risk factor by the THMs species revealed that their concentrations in the water samples exceed the permissible limit given by IS:10500, WHO, and USEPA. The average total contribution in cancer risk through dermal absorption is Chloroform 40% > BDCM 39% > DBCM 21% > bromoform 0%. The BDCM had the highest cancer risk than the other THMs species. All WTP showed higher lifetime cancer risk by dermal absorption (>10^{-6} USEPA limit). The average lifetime CR by dermal absorption for males and females in the studied region is 2.46E-05 and 2.70E-05, which is about 0.246 and 0.27 times more than the acceptable risk given by USEPA, respectively. Through inhalation exposure, the females have a higher cancer risk than the males indicating higher CDI of THMs through an inhalation route.

The total CR was estimated by adding CR factors through ingestion, dermal absorption, and inhalation exposure of individual THMs. The cancer risk is categorized into four classes i.e. negligible risk (CR < 10^{-6}), acceptable low risk (10^{-6} < CR < 5.1×10^{-5}), acceptable high risk (5.1×10^{-5} ≤ CR < 10^{-4}), and unacceptable risk (CR ≥ 10^{-4}) (Legay, Rodriguez, Sadiq, et al., 2011). The different categories of CR are shown in **Table 4** highlighted with different colors. The CR in the studied region exceeds the acceptable risk by 0.050 to 0.415 times for both males and females. On analyzing the total cancer risk, the population living in the command area of Chandrawal WTP, Wazirabad WTP, Haiderpur WTP, Bhagirathi WTP, Sonia Vihar WTP, Nangloi WTP were found to be having an acceptable high risk for cancer. In contrast, the population living in

Table 4. Total CR of THMs for males and females

WTPs Command Area	CR Ingestion		CR Dermal		CR Inhalation		Total CR	
	Males	Females	Males	Females	Males	Females	Males	Females
CWTP	2.31E-05	2.73E-05	1.81E-05	2.00E-05	3.79E-05	4.15E-05	7.91E-05	8.88E-05
WWTP	2.00E-05	2.36E-05	1.56E-05	1.72E-05	3.27E-05	3.58E-05	6.83E-05	7.66E-05
HWTP	1.81E-05	2.13E-05	1.44E-05	1.59E-05	3.01E-05	3.30E-05	6.26E-05	7.02E-05
BWTP	1.77E-05	2.10E-05	1.41E-05	1.55E-05	2.94E-05	3.22E-05	6.12E-05	6.87E-05
BAWTP	8.93E-06	1.06E-05	7.68E-06	8.46E-06	1.60E-05	1.76E-05	3.27E-05	3.66E-05
NWTP	1.47E-05	1.73E-05	1.20E-05	1.32E-05	2.50E-05	2.74E-05	5.16E-05	5.79E-05
SVWTP	1.73E-05	2.04E-05	1.40E-05	1.54E-05	2.92E-05	3.20E-05	6.05E-05	6.78E-05
OWTP	5.06E-06	5.98E-06	5.04E-06	5.55E-06	1.06E-05	1.16E-05	2.06E-05	2.31E-05
DWTP	5.11E-06	6.04E-06	5.22E-06	5.75E-06	1.09E-05	1.20E-05	2.13E-05	2.38E-05
Color Code	**Negligible Risk**		**Acceptable Low Risk**		**Acceptable High Risk**		**Unacceptable Risk**	

the command area of Bawana WTP, Okhla WTP, and Dwarka WTP were found to be having an acceptable low risk for cancer.

The total cancer risk due to BDCM was the highest when added risk by all three exposure routes was estimated, followed by DBCM and CF, BF showed negligible risk in the water supplied. The total CR for THMs was highest at Chandrawal WTPCA (7.91E-05, 8.88E-05) and lowest at Okhla WTPCA (2.06E-05, 2.31E-05) for males and females, respectively. In all the cases, females showed a higher CR than males. The highest contribution in terms of percentage was made by BDCM (42%) in total cancer risk, followed by CF (31%), DBCM (27%).

CONCLUSION

In this study, the formation of THMs in the command areas of nine WTPs of Delhi was assessed for one year. THMs were higher than the permissible limits given by Indian Standards and USEPA. The annual mean THM levels ranged between 77.58 ± 35.30 μg/L. While the minimum THM concentration was 11.41 μg/L and the maximum THM concentration was 175.54 μg/L in the distribution system. On an average concentration basis, the most abundant species measured was chloroform, followed by BDCM, DBCM, and BF in the tap water samples. Cancer risk assessment of THMs was evaluated for each exposure route, and the highest carcinogenic risk was found through oral ingestion. The cancer risk exceeds the acceptable risk by 0.050 to 0.415 times in the studied region. The total cancer risk in the Chandrawal WTP command area was the highest (7.91E-05, 8.88E-05) and lowest at the Okhla WTP command area (2.06E-05, 2.31E-05) for males and females, respectively. Cancer risk by inhalation and dermal absorption was also higher than the acceptable limit given by USEPA, i.e., 10^{-6}. Females showed higher cancer risks through all exposure routes than males.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

ABBREVIATIONS

BDCM	Bromodichloromethane
BF	Bromoform
CA	Command Area
CalEPA	California Environmental Protection Agency
CDI	Chronic Daily Intake
CF	Chloroform
CR	Cancer Risk
DBCM	Dibromochloromethane
DBPs	Disinfection Byproducts
DPD	N, N-diethyl-p-phenylenediamine
GC-MS	Gas Chromatography-Mass Spectrometry
HAA	Haloaceticacid
ICMR	Indian Council of Medical Research
IRIS	Integrated Risk Information System
RAIS	Risk Assessment Information System
Res. Cl	Residual Chlorine
SF	Slope Factor
THM	Trihalomethane
TOC	Total Organic Carbon
TTHM	Total Trihalomethane
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WTP	Water Treatment Plant
WTPCA	Water Treatment Plant Command Area

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