

The effectiveness of household water treatment and safe storage in improving drinking water quality: a disinfection by-product (DBP) perspective

Rong Xiao, Youli Duan and Wenhai Chu 

ABSTRACT

Serving as the last barrier to secure drinking water safety, household water treatment and safe storage (HWTS) is perceived as an interim measure for removing pathogens from drinking water and reducing disease risk. In recent years, the application of HWTS has shown a growing trend, and its performance in controlling chemicals has also received much attention. Disinfection by-products (DBPs) are formed by the reaction of chemical disinfectants and precursors, and are present at sub- $\mu\text{g}\cdot\text{L}^{-1}$ or low-to-mid- $\mu\text{g}\cdot\text{L}^{-1}$ levels in drinking water. Although precursor control and disinfection operation modification could contribute to DBP mitigation to some degree, DBP removal after their formation emerges as an important strategy due to the ubiquitous existence of DBPs in distribution systems and tap water. In order to figure out how DBP concentrations vary during the residence time of drinking water in households, this review summarizes the effectiveness and mechanism of HWTS and combination technologies for DBP control in municipal tap water, and makes a comparison with regard to technologies implementing different removal mechanisms as well as DBPs possessing different natures. Based on these results, this article provides an insight into DBP risk assessment and human health protection.

Key words | boiling water, disinfection by-products, filtration, household water treatment, municipal tap water, safe storage

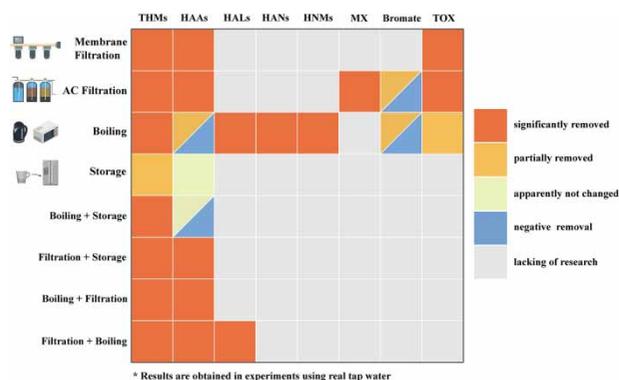
HIGHLIGHTS

- The performances and mechanisms of household treatment for DBP control were reviewed.
- Point-of-use filtration, boiling and relevant combination technologies could remove DBPs significantly.
- Different technologies showed varying removal rates regarding different DBPs species.
- DBPs formation, transformation and removal could occur simultaneously during household treatment.

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GRAPHICAL ABSTRACT



ABBREVIATIONS

AC	activated carbon	LOQ	limit of quantification
AOBr	adsorbable organic bromine	MBAA	monobromoacetic acid
AOCl	adsorbable organic chlorine	MCAA	monochloroacetic acid
AOI	adsorbable organic iodine	MF	microfiltration
AOX	adsorbable organic halogen	MW	molecular weight
BCAA	bromochloroacetic acid	MX	3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone
BDCM	bromodichloromethane	NDMA	<i>N</i> -nitrosodimethylamine
BP	boiling point	NOM	natural organic matter
C-DBPs	carbonaceous disinfection by-products	N-DBPs	nitrogenous disinfection by-products
DBAA	dibromoacetic acid	PoU	point-of-use
DBAN	dibromoacetonitrile	RO	reverse osmosis
DBCM	dibromochloromethane	TBM	tribromomethane
DBPs	disinfection by-products	TCAA	trichloroacetic acid
DCAA	dichloroacetic acid	TCAL	trichloroacetaldehyde
DCAN	dichloroacetonitrile	TCM	trichloromethane
DWDS	drinking water distribution system	TCNM	trichloronitromethane
DWTPs	drinking water treatment plants	THM ₄	sum of TCM, BDCM, DBCM and TBM
DXAAs	sum of dihalogenated HAAs	THMs	trihalomethanes
GAC	granular AC	TOCl	total organic chlorine
HAA ₅	sum of MCAA, DCAA, TCAA, MBAA and DBAA	TOBr	total organic bromine
HAAs	haloacetic acids	TOX	total organic halogen
HALs	haloacetaldehydes	TXAAs	sum of trihalogenated HAAs
HAMs	haloacetamides	WHO	World Health Organization
HANs	haloacetonitriles	UNICEF	United Nations Children's Fund
HNMs	halonitromethanes	USEPA	US Environmental Protection Agency
HWT	household water treatment	UV	ultraviolet light
HWTS	household water treatment and safe storage		
log <i>K</i> _{ow}	logarithmic octanol-water partitioning coefficient		

INTRODUCTION

According to recent reports published by the World Health Organization (WHO) and United Nations Children's Fund (UNICEF), although 90% of the global population uses a basic drinking water source, over two billion people worldwide lack access to safely managed drinking water services, and approximately 485,000 diarrheal deaths in low- and middle-income countries are attributable to unsafe drinking water annually, accounting for over half of the diarrheal disease burden all over the world (WHO 2019; WHO/UNICEF 2019). Drinking water safety risks associated with the disease could be minimized from catchment to consumer, and within this framework, household water treatment and safe storage (HWTS) serves as an important interim measure used for waterborne pathogen removal and disease risk reduction (WHO 2012). The main types of household water treatment (HWT) methods include disinfection with chemicals, disinfection with heat, disinfection with solar light or ultraviolet light (UV), filtration as well as flocculation-disinfection. Rosa & Clasen (2010) extracted data on reported HWT practices from 67 national surveys and supposed that the actual number of people practicing HWT in low- and middle-income countries might exceed 1.5 billion. On the one hand, HWT is an effective intervention in households where continuous access to safe piped-in water is not available, on the other hand, the employment of HWTS shows an increasing trend in institutional settings such as schools and health care facilities (WHO 2019). The microbiological performance of HWTS technologies has been investigated in different countries or regions (Brown & Sobsey 2012; Lantagne & Clasen 2012) and evaluated globally based on WHO criteria (WHO 2016, 2019). The effectiveness of HWTS in removing chemical contaminants (e.g., trace organic compounds, metals, nitrates, residual chlorine, and other inorganics) also raises concern (Anumol *et al.* 2015; Brown *et al.* 2017). However, there is a current paucity of studies reviewing the performance of HWTS in controlling disinfection by-products (DBPs), which are regarded as a series of important emerging contaminants in drinking water (Richardson & Ternes 2011).

Disinfection of drinking water supplies commenced early in the 20th century with the purpose of deactivation

of waterborne pathogens and has been rightly hailed as one of the greatest achievements in public health (Li & Mitch 2018). Nevertheless, disinfection could result in an unintended hazard concerning human health: DBP formation caused by the reaction of chemical disinfectants (chlorine, chloramines, ozone, chlorine dioxide, etc.) with natural organic matter (NOM), halide and anthropogenic contaminants (Richardson & Ternes 2011). It has been demonstrated that DBPs exhibit toxicological properties (e.g., cytotoxicity and genotoxicity) and are potentially responsible for an increase in the risk of cancer and other adverse outcomes, including reproductive and developmental effects (Cantor *et al.* 1998; Richardson *et al.* 2007; Nieuwenhuijsen *et al.* 2009). The occurrence (Krasner *et al.* 2006; Templeton & Chen 2010; Bei *et al.* 2016), analytical methods (Yang & Zhang 2016; Ding & Chu 2017), precursors and formation mechanisms (Shah & Mitch 2011; Bond *et al.* 2012; Ding *et al.* 2019a), health effects (Hrudey 2009; Wagner & Plewa 2017), as well as control technologies (Singer 1994; Chu *et al.* 2015; Hu *et al.* 2018) of DBPs in drinking water have gained considerable attention since the first discovery of DBPs in the mid-1970s (Bellar *et al.* 1974; Rook 1974).

The strategies for DBP mitigation include precursor control (source control and precursor removal), disinfection operation modification as well as DBP removal after their generation (Singer 1994; Sun *et al.* 2019). However, DBP precursors are present in drinking water inevitably and residual disinfectants is required to maintain microbial safety, thus formation of DBPs will further occur in drinking water distribution systems (DWDS) and plumbing systems (Dion-Fortier *et al.* 2009; Chowdhury *et al.* 2011; Li *et al.* 2019), making it significant to consider removal of DBPs just before human ingestion. Serving as the last barrier to ensure drinking water safety, HWT methods (boiling, filtering, UV treatment, etc.) combined with storage have been reported to result in DBP variations (Weinberg *et al.* 2006; Chowdhury *et al.* 2010), and the related processes include: (1) DBP formation due to thermal cleavage of larger halogenated species and additional reactions between precursors and residual disinfectants; (2) DBP transformation mainly through hydrolysis and decarboxylation; and (3) DBP removal by means of membrane rejection, physical adsorption, UV photolysis, volatilization, and so on.

With the purpose of understanding the effectiveness of HWTS in managing drinking water quality risks from a DBP perspective and improving the assessment accuracy of human exposure to DBPs by ingestion, this paper attempts to provide a review of the DBP concentration variations during HWTS processes. First, the microbial performance and worldwide application status of HWT methods as well as the occurrence level and regulation (or guideline) of DBPs are briefly introduced. Then, the effects of HWTS on DBP concentrations and the mechanisms relevant to DBP variations are presented. The final part gives a summary of HWTS performance for DBP control, provides insight about DBP exposure assessment and human health protection, and makes a conclusion.

HOUSEHOLD WATER TREATMENT

Microbial performance

Based on the mechanism of pathogen removal or inactivation, HWT can be classified into filtration methods, thermal methods, photolytic methods and chemical methods (Smieja 2011). Table 1 summarizes the microbial performances of typically used HWT methods in households or small public facilities.

Application status

Another important aspect about HWT technologies is their application across the globe. Figure 1 shows the application status of several typical HWT methods (including the proportion of individual methods used in households and the percentage of population treating drinking water at home) in six selected regions with low- and middle-income families surveyed by Rosa & Clasen (2010). In general, 33% of households were reported to treat water at home, with the practice being widespread in the Western Pacific region (66.8%) while less common in the Eastern Mediterranean (13.6%) and Africa (18.2%). Boiling was reported to be the most dominant HWT method and was described by approximately one-fifth of households in these countries (Rosa & Clasen 2010). Moreover, in early 2015, the WHO commissioned a rapid market assessment of commercial HWT

products using literature review, interview, and field visits. A strong growth in filter markets in parts of Asia (e.g., Vietnam, China, South Korea) was found, which might be associated with consumers' growing awareness of drinking water quality and human health, and the wide availability and affordability of HWT products (WHO 2016). Different from people who use HWT mainly for pathogen control, North Americans are more familiar with point-of-use (PoU) treatment (i.e., HWT) for taste and odor control, or less commonly for removal of metals or organics (Berg 2015). It was estimated that ~40% of the population in the United States used water purifiers at home (Anumol *et al.* 2015).

DBPS IN DRINKING WATER

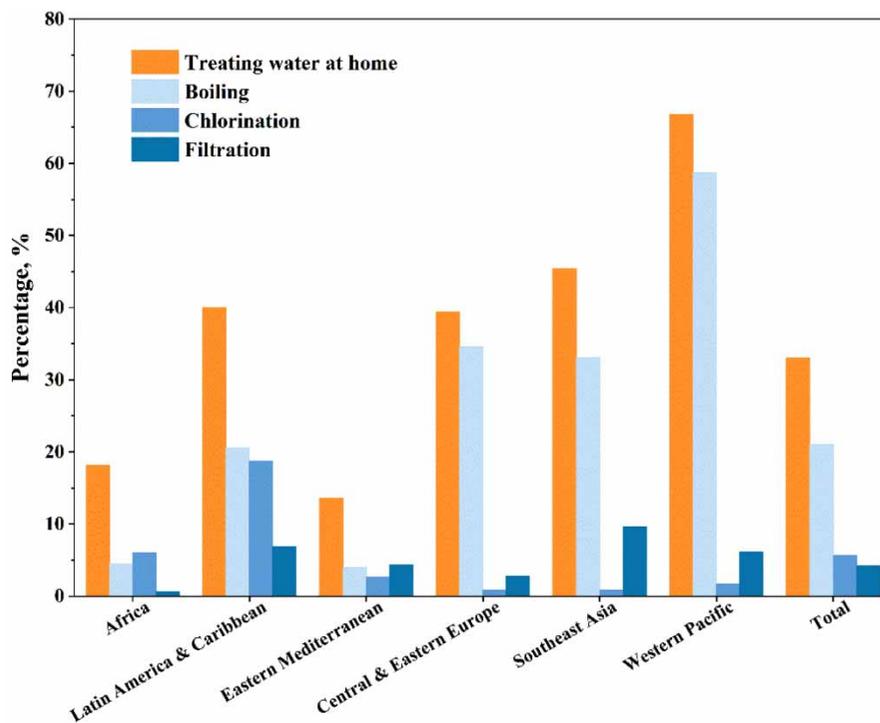
Chemical constituents of drinking water may come from source waters, treatment process, distribution system, and consumers' plumbing (Ministry of Health 2018). Since DBPs are formed after the addition of disinfectants and their concentrations might change during delivery (Fang *et al.* 2019a; Li *et al.* 2019), research relevant to DBP occurrence mostly collected water samples from drinking water treatment plants (DWTPs) outlet, DWDS, and water faucets. Standards or guidelines for drinking water quality proposed by different countries, regions, and organizations generally provide regulatory compliance for DBPs, including their regulatory limits or guideline values, as well as corresponding monitoring requirements (sampling sites, monitoring frequencies, etc.).

Occurrence levels

Organic halogenated DBPs commonly occurring in drinking water include carbonaceous DBPs (C-DBPs), such as trihalomethanes (THMs), haloacetic acids (HAAs), haloacetaldehydes (HALs) and nitrogenous DBPs (N-DBPs), such as halonitromethanes (HNMs), haloacetonitriles (HANs) and haloacetamides (HAMs). These DBPs possess a similar CX₃R structure (X = H, Cl, Br or I, R = functional group) and exhibit significantly higher concentration or higher toxicity, thus are classified as CX₃R-type DBPs (Ding *et al.* 2019b; Fang *et al.* 2019b). CX₃R-type DBPs are generally present in drinking

Table 1 | Summary of selected HWT methods and their microbial performances (WHO 2015, 2016, 2017)

HWT technology	Microbial performance
<i>Filtration method</i>	
Ultrafiltration	Effective against viruses (depending on the integrity of the membrane), bacteria and protozoa
Porous ceramic filtration	Effective against bacteria and protozoa Limited effectiveness against viruses
<i>Thermal method</i>	
Boiling	Effective in inactivating bacteria, viruses and protozoa
<i>Photolytic methods</i>	
UV disinfection	Effective against viruses, bacteria and protozoa
Solar disinfection	Potentially effective against viruses, bacteria, and protozoa depending on the container material and climatic and weather conditions
<i>Chemical method</i>	
Flocculation-disinfection	Effective against viruses, bacteria, and protozoa
Chlorination	Effective against bacteria and some viruses Ineffective against protozoan cysts (e.g., <i>Cryptosporidium parvum</i>)

**Figure 1** | Percentage of the population using HWT in low- and middle-income countries. Data source: Rosa & Clasen (2010).

water at sub- $\mu\text{g}\cdot\text{L}^{-1}$ or low-to-mid- $\mu\text{g}\cdot\text{L}^{-1}$ levels, and THMs and HAAs are two major classes on a weight basis. The levels of representative CX_3R -type DBPs in finished water of DWTPs,

DWDS water, and tap water are summarized in Table 2. The concentrations and speciation of DBPs in drinking water are dependent on several factors, including nature and

Table 2 | Occurrence levels of CX₃R-type DBPs in drinking water (median value, µg/L)

Location	THMs	HAAs	HALs	HANs	HAMs	HNMs	Reference
<i>Finished water</i>							
China	10.53	10.95		1.11		0.05	Ding <i>et al.</i> (2013)
United Kingdom	20	48		2.7	1	0.2	Bond <i>et al.</i> (2015)
United States	31	34	4	3	1.4	1	Krasner <i>et al.</i> (2006)
North Carolina, USA	35	64		4.6		0.28	Singer <i>et al.</i> (1995)
<i>DWDS water</i>							
Shenzhen, China	19.9		3.4	2	1.5		Huang <i>et al.</i> (2017)
Pearl River Delta, China	17.7	8.6	2.1	1.8		0.2	Gan <i>et al.</i> (2013)
Barcelona, Spain	85	~35		~6			Goslan <i>et al.</i> (2014)
United Kingdom	28	52		2.8	1.4	0.2	Bond <i>et al.</i> (2015)
United Kingdom		20.6					Zhang <i>et al.</i> (2011)
North Carolina, USA	46	81		5.1		0.43	Singer <i>et al.</i> (1995)
<i>Tap water</i>							
Zhejiang, China	23.2	15.3		2.2		0.7	Zhou <i>et al.</i> (2019)
Seoul, Korea	23.9	15.8					Lee <i>et al.</i> (2013)
Spain	26.4	26.4		5.7			Villanueva <i>et al.</i> (2012)
Cyprus	66						Charisiadis <i>et al.</i> (2015)

concentration of DBP precursors (Westerhoff & Mash 2002; Chow *et al.* 2005; Chow 2006), disinfection scenarios (e.g., disinfectant type, disinfectant dose, disinfectant contact time) (Barrott 2004; Hua & Reckhow 2007), and other characteristics of water quality such as pH and water temperature (Yang *et al.* 2007; Hua & Reckhow 2008).

Physicochemical properties

Physicochemical properties are of significance when assessing the behavior of DBPs in natural waters, DWTPs, DWDS, as well as households. For instance, logarithmic octanol-water partitioning coefficient ($\log K_{ow}$) is acknowledged to be associated with polarity and water solubility, and the substances with high $\log K_{ow}$ values tend to be more readily adsorbed on organic matter owing to their low affinity to water. Furthermore, boiling point (BP) and Henry's law constant are related to DBP volatilization, which is a predominant process for volatile DBP reduction during boiling treatment and can also occur in DWTPs (Wu *et al.* 2001; Qiu *et al.* 2019). As suggested by Krasner

& Wright (2005), although Henry's law constants are not determined for boiling water at 100 °C, DBPs which are not volatile (Henry's law constant at 25 °C $<10^{-7}$ atm·m³/mol) would still be considered relatively non-volatile in boiling water. Table 3 lists some physicochemical properties of commonly occurring CX₃R-type DBPs.

Regulations and guidelines

Numerous countries in Asia, Europe, America, Oceania, as well as Africa have included DBPs in their standards or guidelines for drinking water quality (European Union 1998; Ministry of Health of the People's Republic of China 2006; WHO 2006; USEPA 2009; National Health & Medical Research Council & National Resource Management Ministerial Council 2011; Ministry of Health Labour & Welfare 2015; South African National Standard 2015; England & Wales 2016; WHO 2017; Ministry of Health 2018; Health Canada 2019), and the regulatory limits or guideline values of different organic DBPs in selected standards or guidelines are listed in Table 4. THMs and HAAs are regulated in the

Table 3 | Physicochemical properties of commonly occurring CX₃R-type DBPs (Krasner & Wright 2005; US National Library of Medicine 2020)

Halogenated compounds	Abbr.	MW	BP (°C)	log K _{ow}	Henry's law constant at 25 °C (atm·m ³ /mol)
<i>Trihalomethane</i>	THM				
Trichloromethane	TCM	119.378	61.1	1.97	3.67×10^{-03}
Bromodichloromethane	BDCM	163.829	90	2	2.12×10^{-03}
Dibromochloromethane	DBCM	208.28	120	2.16	7.83×10^{-04}
Tribromomethane	TBM	252.731	149.1	2.4	5.35×10^{-04}
<i>Haloacetic acid</i>	HAA				
Monochloroacetic acid	MCAA	94.497	189.3	0.22	9.42×10^{-09}
Dichloroacetic acid	DCAA	128.942	194	0.92	3.52×10^{-07}
Trichloroacetic acid	TCAA	163.387	196.5	1.33	1.35×10^{-08}
Monobromoacetic acid	MBAA	138.948	208	0.41	6.31×10^{-08}
Dibromoacetic acid	DBAA	217.844	233	0.70	7.27×10^{-09}
Bromochloroacetic acid	BCAA	173.393	215	0.61	2.22×10^{-08}
<i>Haloacetaldehyde</i>	HAL				
Trichloroacetaldehyde	TCAL	147.388	97.8	0.99	2.91×10^{-09}
<i>Haloacetonitrile</i>	HAN				
Dichloroacetonitrile	DCAN	109.943	112.5	0.29	3.79×10^{-06}
Dibromoacetonitrile	DBAN	198.845	168	0.47	4.06×10^{-07}
<i>Halonitromethane</i>	HNM				
Trichloronitromethane	TCNM	164.375	112	2.09	2.05×10^{-03}

majority of cases, while only a few standards or guidelines consider N-DBPs such as HANs and N-nitrosodimethylamine (NDMA), which are of greater perceived health risk than regulated C-DBPs (Muellner *et al.* 2007; Bond *et al.* 2011).

With respect to drinking water quality monitoring, the WHO (2017) proposed that sampling locations should include points near the extremities of DWDS and taps connected directly to the mains in houses when the concentrations of target constituents can change during distribution, while sampling at DWTPs or at the head of the DWDS may be sufficient for constituents whose concentrations do not change during delivery. In mainland China, samples aimed at monitoring regulated DBPs should be collected from the outlet of DWTPs and extremities of DWDS (Ministry of Construction of the People's Republic of China 2005; Ministry of Health of the People's Republic of China 2006). In the case of the USA, USEPA (2006) provided different monitoring locations for different DBPs and the requirements are as follows: THM₄/HAA₅ (several points

in DWDS), bromate (one point at entry point to DWDS), and chlorite (one point at entry point to DWDS and three points in DWDS). As for the UK, the points of compliance set for THMs and bromate are consumers' taps (England & Wales 2016).

DBP VARIATIONS IN HOUSEHOLD TREATMENT PROCESS

Water purification with PoU filters (filtration method)

A PoU filter attached directly to the consumer's tap or pitchers is perceived as an effective solution to DBP issues, and its performance for DBP removal may vary depending on the features of the filter (e.g., filter technique, filter manufacturer, aging condition) and the characteristics of water to be treated (Egorov *et al.* 2003; Leuesque *et al.* 2006; Wright *et al.* 2006). To our knowledge, much work on DBP removal through membrane rejection (size exclusion, charge

Table 4 | Regulatory limits or guideline values of DBPs in different countries, region, and organization ($\mu\text{g/L}$)

	TCM	BDCM	DBCM	TBM	THM ₄	MCAA	DCAA	TCAA	HAA ₅	TCAL	DCAN	DBAN	NDMA
<i>Asia</i>													
China	60	60	100	100	1 ^a		50	100		10			
Japan	60	30	100	90	100	20	30	30		20 ^b	10 ^b	60 ^c	0.1 ^c
<i>Europe</i>													
European Union					100								
United Kingdom					100								
<i>America</i>													
United States					80				60				
Canada					100				80				0.04
<i>Oceania</i>													
Australia					250	150	100	100		100			0.1
New Zealand	400	60	150	100	1 ^a	20	50	200			20	80	
<i>Africa</i>													
Egypt					100					10	90	10	
South Africa	300	60	100	100	1 ^a								
WHO	300	60	100	100	1 ^a	20	50	200			20	70	0.1

THM₄: sum of TCM, BDCM, DBCM, and TBM.

HAA₅: sum of MCAA, DCAA, TCAA, MBAA, and DBAA.

^aThe sum of the ratio of the concentration of each THM to its respective regulatory limit/guideline value.

^bComplementary items to set the targets for water quality management in drinking water quality standards in Japan.

^cItems for further study in drinking water quality standards in Japan.

repulsion, and hydrophobic interaction effects) or physical adsorption has been carried out (Tung *et al.* 2006; Fujioka *et al.* 2013; Wang *et al.* 2018). Most of these studies focused on removal mechanisms and influencing factors, thus solutions merely containing one or several DBP compounds with extremely high concentration were employed in these experiments to avoid interference caused by other matters and amplify the removal effect. However, since drinking water is a complex mixture comprising various substances, this section mainly takes into account the results obtained in experiments involving commercially available PoU filters and real tap water, which seems to be more practical and representative. Filtering systems consisting of activated carbon (AC) and ion exchange resin, reverse osmosis (RO) filters, microfiltration (MF) filters, as well as non-membrane pressure filters have been used to investigate the impact of domestic filtering devices on DBPs in municipal tap water (Gibbons & Laha 1999; Egorov *et al.* 2003; Ahmedna *et al.* 2004; Leuesque *et al.* 2006; Weinberg *et al.* 2006; Chowdhury *et al.* 2010; Rahman *et al.* 2011; Carrasco-Turigas *et al.*

2013; Stalter *et al.* 2016). The tested filters, target DBPs, and key findings are shown in Table 5.

Gibbons & Laha (1999) conducted an investigation into water purification systems employed for treating municipal water, and reported that the home water filtration system involving AC and ion exchange resin performed an almost 50% reduction in total THMs while commercial filter units did not contribute to a water quality improvement, which was likely owing to the improper operation. The removal efficiency of THMs, HAAs, and 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone (MX) with three commercially available home filters was assessed by Egorov *et al.* (2003). In this study, the removal rate of MX (up to >99%) and TCM by tested filters was consistently higher than that of HAAs, and TCM removal efficiency of 90% by Brita filters and 95% by Aquaphor filters was reported after 150 L of use, which was the manufacturer-recommended capacity of both filters. As Aquaphor filter use increased from 1 to 150 L, reductions of 97 and 59% for DCAA as well as 95 and 63% for TCAA were observed.

Table 5 | DBPs control with filtration method

No.	Filter technique and filter media	Target DBPs	Key findings	Reference
1	Residential filter containing AC and ion exchange resin; Commercial system using RO, MF and UV	THMs	Residential filter produced an almost 50% reduction in total THMs	Gibbons & Laha (1999)
2	Brita filters containing AC and ion exchange resin; Aquaphor filters containing AC; Rodnik filter containing AC	THMs, HAAs, MX	TCM removal efficiency of 90% by Brita filters and 95% by Aquaphor filters were achieved after 150 L of use As Aquaphor filter use increased from 1 to 150 L, reductions of 97 and 59% for DCAA as well as 95 and 63% for TCAA were observed Removal rate of MX (up to >99%) and THM by tested filters was consistently higher than that of HAAs	Egorov <i>et al.</i> (2003)
3	AC filters and RO/deionized water system	THMs, HAAs	Four AC PoU devices reduced THM ₄ (93–99%) and HAA ₉ (68–95%) levels RO/deionized water system removed 48% of THMs and 100% of HAAs	Weinberg <i>et al.</i> (2006)
4	Brita devices with AC and ion exchange resin	THMs, HAAs	The average removal rate of THMs was up to ~90% HAAs were reduced when using new filters (72%) or used filters (54%)	Leuesque <i>et al.</i> (2006)
5	GAC unit and RO unit	THMs	Properly functioning GAC and RO units both removed ~70% of total THMs	Smith & El Komos (2009)
6	Brita Classic Pitcher	THMs, HAAs	THMs were reduced by 84–89% using new and used filters HAAs were removed significantly using new and used filters (71 and 58%, respectively)	Chowdhury <i>et al.</i> (2010)
7	Domestic jug fitted with ion exchange and AC filtration	THMs, HAAs	Significant reductions in THMs (93%) and HAAs (82%) were reported	Rahman <i>et al.</i> (2011)
8	Pitcher filter containing GAC and ion exchange resin; Household RO filtering system	THMs, MX, bromate	RO led to the highest THM ₄ reduction (97%), with almost a 99% reduction for the bromine-containing species TCM had higher removal rate when using a pitcher filter (91% for the new filter) in comparison to the RO system (56%) Bromate concentration decreased after pitcher filtration with 1 L of usage but increased after 75 L MX concentration decreased below the LOQ after filtration	Carrasco-Turigas <i>et al.</i> (2013)
9	RO filters; Non-membrane pressure filters; Gravity filters	AOX	6 out of 11 filters effectively removed AOCl and AOBr by >60% RO and gravity filter containing AC removed >94% of AOCl, AOBr and AOI	Stalter <i>et al.</i> (2016)

However, a negative TCAA removal (–19%) by a Brita filter after 150 L of use demonstrated that longer use of a cartridge in filters might result in the elution of previously accumulated HAAs, which was probably attributed to HAA replacement by compounds with higher affinity to binding sites (Egorov *et al.* 2003).

The claim that effectiveness of DBP removal by pitcher-PoU devices depended on DBP physicochemical properties was suggested by Weinberg *et al.* (2006) according to the observation that pitcher-PoU devices had poorer average removal efficiency of TCM, DCAA, and TCAA than their bromine-containing counterparts; this might be because the latter possessed lower aqueous solubility and polarity, making them more amenable to carbon adsorption. In this study, reduction in THMs (93–99%) and HAAs (68–95%) by four different AC PoU devices were reported. In addition, 48% reduction in THM and 100% removal of HAAs was achieved in this research with the use of RO/deionized water system; the considerably high removal rate of HAAs could be explained by the fact that HAAs are in an anionic state at the pH of tap water and thus could be amenable to removal on the deionization resins through ion exchange (Weinberg *et al.* 2006). With regard to filters' artificial aging, it has been found that there was no real differences in THM reduction when using new filters (91%) or used filters (89%) for Brita pitchers, while the artificial aging of the filter had some effect on HAA removal, and HAA reduction was approximately 72 and 54% for new filters and used filters, respectively (Leuesque *et al.* 2006). Average reduction of HAAs by filter involved in this study was lower than that obtained for THMs, which might be because HAAs have a higher affinity to water than THMs, and thus THMs could be more easily adsorbed on the carbon particles contained in the filter.

Smith & El Komos (2009) evaluated the treatment performance of several PoU units with respect to various water quality parameters and reported that both properly functioning granular AC (GAC) units and RO units could remove about 70% of THMs. With the intention of developing models to predict the effects of indoor handling strategies on DBPs, Chowdhury *et al.* (2010) collected water samples and found that using commercial filters could reduce THMs and HAAs by 84–89% and 58–71%, respectively. Another study examining the effects of tap

water processing on DBPs revealed that jug filter containing AC and ion exchange resin could produce substantial and statistically significant reductions in THMs (93%) and HAAs (82%) (Rahman *et al.* 2011).

In addition to the aforementioned organic DBPs, inorganic DBP such as bromate was also considered and bromate showed a less consistent pattern (Carrasco-Turigas *et al.* 2013). In the same study, RO appeared to be a good method for brominated THM elimination (99%) while TCM had higher removal rate using pitcher filter (91% for new filter) compared to a RO system (56% reduction), and MX concentration decreased below the limit of quantification (LOQ) after filtration (Carrasco-Turigas *et al.* 2013). In contrast with previous researchers who mainly focused on specific DBP species, Stalter *et al.* (2016) selected adsorbable organic halogen (AOX), which is also known as TOX, as a sum parameter for all halogenated DBPs, and examined the effect of 11 filters on AOX level. Of the filters examined, RO and a gravity filter containing AC removed >94% of AOX, and the removal efficacy of adsorbable organic bromine (AOBr) was generally higher than that of adsorbable organic chlorine (AOCl) and adsorbable organic iodine (AOI) for most filters. Also, the results of toxicity assays showed that 7 out of the 11 filters tested reduced cytotoxicity, oxidative stress response, and genotoxicity by >60% (Stalter *et al.* 2016).

Water treatment with boiling devices (thermal method)

DBP variations during water boiling might be associated with several processes, including DBP removal through volatilization, hydrolysis or destruction, DBP further formation as a result of cleavage of larger halogenated intermediate species or accelerated reactions between residual disinfectants and corresponding precursors, as well as DBP transformation from one species to another, including base-catalyzed hydrolysis (e.g., DCAN to dichloroacetamide) and thermal decarboxylation (e.g., TCAA to TCM) (Li & Sun 2001; Reckhow *et al.* 2001; Wu *et al.* 2001; Zhang & Minear 2002; Krasner & Wright 2005; Pan *et al.* 2013; Zhang *et al.* 2015; Ma *et al.* 2017; Shi *et al.* 2017). Several documented variation mechanisms of CX₃R-type DBPs during boiling water are shown in Figure 2. Therefore, DBPs possessing different volatility or thermo-stability may

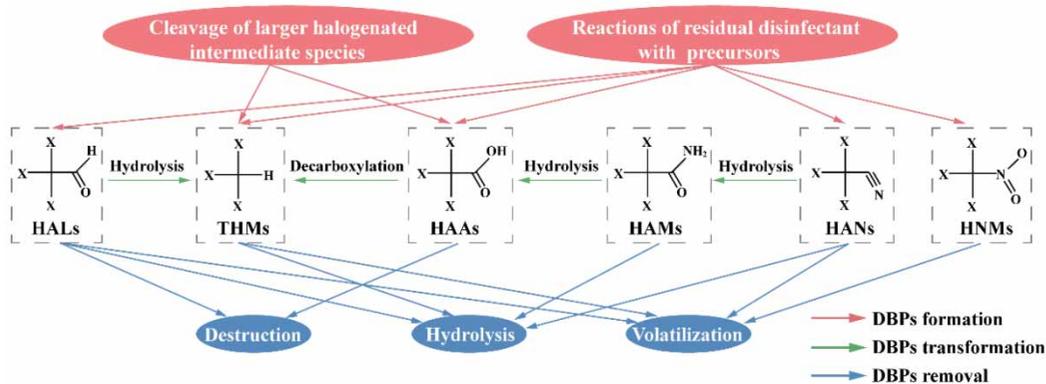


Figure 2 | Documented variation mechanisms of CX₃R-type DBPs upon boiling.

behave in different ways under the same conditions, making it critical to consider individual species when estimating thermal effects on DBPs.

In order to provide a more realistic and intensive understanding about the effect of boiling water on DBPs in drinking water, and distinguish boiling water discussed in this section from heating water since water temperature has been proven as a significant factor influencing DBP volatilization (Batterman *et al.* 2000), what follows will focus on DBP variations in real tap water during the process of boiling, and the experimental conditions and a series of key findings are detailed in Table 6. Although volatilization occurring during tap water boiling could potentially increase airborne DBP concentrations and thus inhalation exposures, small impacts were expected given the large amount of dilution in most indoor environments (Batterman *et al.* 2000).

The effect of boiling water on concentrations of 21 target DBPs and TOX in chlorinated tap water was explored by Wu *et al.* (2001) using glass beakers covered with watch glasses. As boil time increased from 1 to 5 min, reductions of 68 and 83% for TCM as well as 74 and 95% for BDCM were observed, along with a decrease in TCAA (31–46%) and an increase in MCAA (27–30%). Moreover, a two-fold increase of DCAA levels upon boiling was worth noting, and other identifiable DBPs declined dramatically. With regard to TOX, boiling of tap water reduced TOX by 28 and 44% after 1 and 5 min, respectively. THM variations upon boiling was dominated by volatilization reactions in an open system, where THMs were almost completely removed, while the volatilization

of HAAs could be ignored during boiling. It has also been suggested that HAA destruction reactions took over at higher temperatures and for more highly halogenated species, while HAA formation was more important for less halogenated species (Wu *et al.* 2001).

Since different residual disinfectants would contribute to DBPs formation to varying degrees and overall DBP variations would depend on the competition of formation rate and removal rate, Krasner & Wright (2005) employed a tea kettle on a stovetop to determine the impact of boiling on DBP concentrations in both chloraminated and chlorinated tap waters with a boiling time of 1, 2, and 5 min. As for HAAs in chloraminated water, no significant change was detected in the concentrations of the DXAAs (sum of dihalogenated HAAs) upon boiling, whereas the levels of the TXAAs (sum of trihalogenated HAAs) decreased over time (e.g., 9–37% for TCAA, 32–61% for TXAAs). However, increased DXAA concentrations (58–68%) were detected in the boiled chlorinated sample while TCAA concentration was unchanged after boiling chlorinated water for 1 min, but a 30% reduction was observed after 5 min. Furthermore, THM concentrations were reduced in both chloraminated (74–98%) and chlorinated (64–98%) waters upon boiling, and the reduction of 75% for TCM in chloraminated water as well as the reduction of 34% for TCM in chlorinated water after a 1 min boil indicated that simultaneous formation and volatilization of TCM was occurring. Most of the remaining DBPs (e.g., TCAL, HAN, HNM) were removed by at least 90% after 1 min of boiling in both samples.

Tests have also been performed with the utilization of an electric kettle that automatically cut off when boiling began

Table 6 | DBP control with water boiling

No.	Residual disinfectant	Boiling device or procedure	Target DBPs	Key findings	Reference
1	Free chlorine	Water samples were boiled for 1 or 5 min in glass beakers covered with watch glasses	THMs, HAAs, HANs, HALs, HNMs, TOX	As boil time increased from 1 to 5 min, reductions of 68 and 83% for TCM as well as 74 and 95% for BDCM were observed. DCAA levels showed a two-fold increase, and TCAA decreased (31–46%) while MCAA increased (27–30%) upon boiling. Other identifiable DBPs declined dramatically upon boiling, and TOX was reduced by 44% after 5 min of boiling.	Wu <i>et al.</i> (2001)
2	Free chlorine or chloramine	Water samples were boiled using a tea kettle on a stovetop for 1, 2, and 5 min	THMs, HAAs, HANs, HALs, HNMs	DXAAs were seemingly unchanged upon boiling chloraminated water, whereas TXAA levels decreased over time (e.g., 9–37% for TCAA). In the chlorinated samples, DXAA concentrations increased over time (58–68%) while TCAA levels decreased by 30% after 5 min of boiling. THM concentrations were reduced in both chloraminated (74–98%) and chlorinated (64–98%) waters upon boiling. Most remaining DBPs (e.g., TCAL, HANs, HNM) were removed by at least 90% after 1 min of boiling in both water samples.	Krasner & Wright (2005)
3	Free chlorine	Water was heated for ~5 min in an electric kettle that automatically cut off when boiling began	THMs	Boiling cold tap water could remove more than 98% of the THM ₄ .	Weinberg <i>et al.</i> (2006)
4	Free chlorine	Water was boiled using a plastic kettle which was turned off 30 s after onset of boiling and water was left to cool in the kettle for 5 min	THMs, HAAs	THMs reduction by boiling water for 30 s averaged 83%. Average total concentrations of HAAs were apparently unchanged upon boiling, while boiling resulted in an increase in DCAA level (35%) and a decrease in TCAA level (42%).	Leuesque <i>et al.</i> (2006)
5	Free chlorine	Boiling was performed in a plastic kettle, which was turned off 30 s after onset of boiling and the water was left to cool in the kettle for 5 min	THMs, HAAs	Boiling of tap water reduced THMs by 82–83%. DCAA increased by 22–49% while TCAA decreased by 34–62%.	Chowdhury <i>et al.</i> (2010)
6	Chloramine	Boiling experiment was carried out using a domestic electric kettle which kept water at a rolling boil for 10–15 s and an instant boiling water unit	THMs, HAAs	The mean concentrations of THMs were consistently and substantially reduced by boiling (86–94%). Kettle boiling did not reduce total HAAs but instant boiling did (28%).	Rahman <i>et al.</i> (2011)

(continued)

Table 6 | continued

No.	Residual disinfectant	Boiling device or procedure	Target DBPs	Key findings	Reference
7	Free chlorine and chloramine	Boiling experiment was performed using a lidded electric kettle, a saucepan and a microwave oven. Once the water reached boiling point, heat source was immediately turned off	THMs, MX, bromate	BCAA was reduced in instant boiled water (53%) but not in kettle Boiling removed TCAA (25% for kettle and 94% for instant unit) but increased DCAA levels (12% for kettle and 17% for instant unit) Among the three devices, microwave oven performed the highest THM ₄ reduction (97%) and kettle showed the lowest (48%) Bromate concentration increased in saucepan tests (21%) but decreased in kettle tests (40%) MX concentration decreased below the LOQ during boiling	Carrasco-Turigas <i>et al.</i> (2013)
8	Free chlorine	Samples were heated to boiling (at 100 °C) in open 5 L glass beakers, and kept boiling for 5 min	TOX	TOCl and TOBr in one sample were reduced by 39 and 44%, respectively, and in the other sample were reduced by 52 and 38%, separately	Liu <i>et al.</i> (2015)

(Weinberg *et al.* 2006). This study found that boiling of cold tap water with free chlorine residual removed more than 98% of the THM₄ concentration. Leuesque *et al.* (2006) evaluated the extent to which boiling water influenced DBP concentration under a relatively different condition, where chlorinated tap water was boiled using a plastic kettle which was turned off 30 s after the onset of boiling. THM reduction alone by boiling water for 30 s averaged 83% while average total concentrations of HAAs apparently did not change during boiling. Regarding individual species of HAAs, boiling resulted in a statistically significant increase in DCAA levels (on average 35%, p value <0.001) and a statistically obvious decrease in TCAA levels (on average 42%, p value <0.001) (Leuesque *et al.* 2006). A reduction of 82–83% for THMs and a decrease of 34–62% in TCAA upon boiling was found in another study, as well as an increase of 22–49% in DCAA (Chowdhury *et al.* 2010).

Even though the aforementioned studies provided a detailed description about the effect of boiling water on DBP concentrations in tap water, other research attempted to make a comparison among the performances of various household boiling devices. A domestic electric

kettle keeping water at a rolling boil for 10–15 s and an instant boiling water unit were compared for treating DBPs in chloraminated water (Rahman *et al.* 2011). In general, the mean concentrations of THMs were consistently and substantially reduced by boiling (86–94%) while HAAs showed a different behavior. Kettle boiling did not reduce total HAAs but instant boiling produced an average reduction of approximately 28%. Furthermore, boiling appeared to reduce mean TCAA concentrations (25% for kettle and 94% for instant unit) but increase mean DCAA concentrations (12% for kettle and 17% for instant unit), and bromochloroacetic acid (BCAA) concentrations were substantially reduced in instant boiled water (averaging 53%) but not in kettle-boiled water, suggesting that a longer time at a high temperature was required for BCAA breakdown (Rahman *et al.* 2011).

Interestingly, Carrasco-Turigas *et al.* (2013) took lidded electric kettle, saucepan, and microwave oven into consideration and made a systematical comparison. Among the three boiling devices, the highest THM reduction was observed for the microwave oven (97%) with a very high decrease of the brominated forms, and the kettle experienced the lowest

reduction in THM₄ levels (48%). In addition, TCM presented a higher percentage of removal than brominated analog in a saucepan, where bromate concentration increased after boiling water. As for MX, the concentration of MX decreased after all boiling experiments. Possible explanations for these results included: (1) the presence of a lid created a semi-sealed environment for kettle experiments; (2) in a microwave, big bubbles were created when water started boiling and 'hot spots' could occur due to faster temperature rise and homogeneously dissipated energy; and (3) when water was boiled using a saucepan, the heat source was not very powerful and it took longer for water to boil, leading to the formation of very small bubbles as well as little agitation (Carrasco-Turigas *et al.* 2013).

Since the adverse health effects of halogenated DBPs in humans have been proven to be associated with tap water ingestion (Li & Mitch 2018), the effect of boiling water on DBP concentration as well as developmental toxicity of water has been explored by Liu *et al.* (2015). The concentrations of total organic chlorine (TOCl) and total organic bromine (TOBr) in the two tap waters tested substantially reduced after 5 min boiling in open glass beakers. TOCl and TOBr in tap water 1 were reduced by 39 and 44%, respectively, and TOCl and TOBr in tap water 2 were reduced by 52 and 38%, respectively. Another important result was that 5 min boiling could significantly decrease the toxicity of tap water based on the data of developmental toxicity against the polychaete *Platynereis dumerilii* (Liu *et al.* 2015).

Water disinfection with UV light (photolytic method)

Most household water treatment technologies employ low-pressure lamps that emit UV radiation at 254 nm to inactivate microorganisms, and the effectiveness of UV disinfection is dependent on the delivered UV fluence, which is associated with intensity and exposure time (WHO 2019). Compared with other typical HWT methods, the home use of UV light for water disinfection might be limited due to its requirement of power sources, professional maintenance, and relatively higher cost. Very few studies have explored the performance of household UV treatment in removing DBPs in municipal drinking water; however, UV treatment is regarded as an effective method for DBP

elimination at reuse facilities as well as swimming pools (Mitch *et al.* 2003; Hansen *et al.* 2013).

Chuang *et al.* (2016) investigated the UV direct photolysis of 26 halogenated DBPs and presented their corresponding photolysis rate constants as well as quantum yields under low pressure UV irradiation at 254 nm. Considering the lack of research relevant to UV photolysis of iodinated N-DBPs, Zhang *et al.* (2019) reported the direct UV photolysis degradation rate constants of 40 halogenated DBPs with the use of a low-pressure mercury vapor lamp emitting irradiation at 254 nm and established a quantitative structure–activity relationship model based on the experimental results. Both of these studies focused on the fluence-based UV photolysis rate constants of DBPs (unit: $\text{cm}^2 \text{mJ}^{-1}$), which depend on DBP molar extinction coefficients and their quantum yields. It has been found that the fluence-based photodegradation rate constants of DBPs by UV₂₅₄ alone are affected by DBP halogen substitution patterns including halogen substituents species and halogenation degrees, and the rate constants follow the trend of iodo- > bromo- > chloro-DBPs and tri- > di- > monohalogenated DBPs; besides, DBP classes with more functional groups and larger molecular volume are more susceptible towards UV photolysis (Chuang *et al.* 2016; Wang *et al.* 2017; Zhang *et al.* 2019).

Water storage

In addition, water storage was also considered as a handling scenario to explore DBPs variations during the residence time of drinking water in households. In a study where tap water was refrigerated at 4 °C in a high density polypropylene bottle overnight for 12 h, Weinberg *et al.* (2006) reported that refrigeration of cold tap water in an open container appeared to have negligible impact on the THM levels, with a removal rate of only ~8%. Considering that DBP removal by volatilization during storage might be influenced by the seal condition of containers, experiments storing tap water in covered or uncovered polypropylene pitcher in refrigerators at about 4 °C for 4 and 48 h was conducted by Leuesque *et al.* (2006). Average THM reduction of 17% by the storage of water in a covered pitcher was observed in this study. In addition, a reduction of 61% for THMs was found in the uncovered container after 48 h

from the moment the water was stored in the refrigerator. As for HAAs which are not volatile compounds, average HAA concentrations remained practically the same during the time of storage regardless of the presence of a lid, suggesting that there was no further formation of HAAs even if the water contained appreciable concentrations of residual chlorine and precursors at the time of storage in refrigeration (Leuesque *et al.* 2006).

However, an increase in THMs between 4 and 48 h storage of tap water was observed when the storage treatment was performed in a closed pitcher in the refrigerator at about 4 °C, which might be attributed to the extended reactions between disinfectant and THM precursors (Chowdhury *et al.* 2010). Consistent with the previously obtained results, reduction of THMs continued from 27% to 61% after 4 to 48 h of storage in the case of open pitcher, and no significant changes in HAAs were reported during storage in the refrigerator regardless of the seal condition (Chowdhury *et al.* 2010). Similarly, Rahman *et al.* (2011) proposed that refrigerating tap water at 4 °C in closed containers with about 5% air space for 5 h resulted in no or little change in DBP concentrations, although all the levels were decreased.

Combination technologies

Besides previously noted results, Leuesque *et al.* (2006) also assessed the effect of combined household treatment technologies on DBP variations in tap water, including boiling water followed by storage as well as filtering water followed by storage (in the refrigerator at 4 °C). Results showed that the reduction of THMs by boiling and subsequently storing water was considerable, with an average total removal rate of 83 and 90% observed for further storage in a covered and uncovered pitcher, respectively, and a subsequent THM reduction during storage emerged in the case of the uncovered pitcher (85% reduction after 48 h storage). Filtration of tap water followed by storage resulted in slightly higher reductions of THMs compared to filtration alone, and the average total removal rate of 92 and 91% was found for the employment of a new filter and a used filter, respectively, with a significant additional reduction associated with water storage after filtering (34–39%). Moreover, average HAA reduction was about 72 and 60% in the case

of new and used filters followed by storage, respectively (Leuesque *et al.* 2006).

The result that further variations of THMs during storage after boiling depended on the seal condition of containers was also reported by Chowdhury *et al.* (2010). In this study, boiling followed by storage decreased THMs by 82 and 97% in the case of storage for 48 h in a closed pitcher and an open pitcher, respectively, while HAAs showed varying results under the same conditions. With regard to the combination of filtration and storage, THMs were reduced by 90 and 93% when tap waters were filtered with new and used filters followed by storage for 48 h in a refrigerator, respectively. In addition, reductions of HAAs were observed using new and used filters followed by storage under identical conditions (71 and 59%, respectively) (Chowdhury *et al.* 2010).

Rahman *et al.* (2011) treated tap water with an instant boiling water unit followed by a jug fitted with ion exchange and AC filtration, and found that there were relatively large reductions for total THMs (88%) and HAAs (81%) in instant boiled-filtered water. A facility consisting of a polypropylene cotton filter, two GAC filter cartridges, and a boiler was used to determine DBP removal by PoU facility (Wang *et al.* 2019). Based on the data obtained in the one-year-long survey, the new PoU facility removed 40–60% of THMs and its efficiency gradually decreased with time, and the treated water occasionally contained higher THMs than untreated water in the summer. Furthermore, this study demonstrated that HALs and residual chlorine were completely removed regardless of old or new PoU facilities, and the removal efficiency of HAAs (84% in summer and 58% in autumn) was higher than that of THMs (Wang *et al.* 2019).

SUMMARY AND INSIGHT

Table 7 and Figure 3 summarize the performance of HWTS and combination technologies in controlling DBPs in municipal tap water. Generally, PoU filters could substantially reduce regulated DBP levels, while diverse DBP classes have different fates. Compared with HAAs, the filters which contain AC could perform higher THM reduction, which could be explained by the fact

Table 7 | Summary of DBP removal rate with the use of HWTS and combination technologies in real tap water

	THMs	HAAs	HALs	HANs	HNMs	MX	Bromate	TOX
Membrane filtration	50% ^a ; 48% ^b ; 68% ^c ; 97% ^d	100% ^b	NA	NA	NA	NA	NA	>94% ^e
AC filtration	93–99% ^b ; 73% ^c ; 74–89% ^d ; 77–96% ^f ; 89–91% ^g ; 84–89% ^h ; 93% ⁱ	68–95% ^b ; (–19)–97% ^b ; 54–72% ^g ; 58–71% ^h ; 82% ⁱ	NA	NA	NA	60–99% ^f	(–7)–12% ^d	>94% ^e
Boiling	98% ^b ; 48–97% ^d ; 83% ^g ; 82–82% ^h ; 86–94% ⁱ ; 83% ^j ; 98% ^k	MCAA: –30% ^j ; –35% ^k ; DCAA: –35% ^g ; –49% ^h ; –17% ⁱ ; –130% ^j ; –76% ^k ; TCAA: 42% ^g ; 34–62% ^h ; 25–94% ⁱ ; 46% ^j ; 30–37% ^k ; BCAA: 53% ⁱ ; 7% ^j ; –49% ^k ; HAAs: –17% ^h ; 28% ⁱ ; –41% ^j ; (–11)–23% ^k	100% ⁱ ; 85–100% ^k	100% ^{i,k}	100% ^{i,k}	NA	(–21)–40% ^d	TOX: 44% ^j TOCl: 39–52% ^l ; TOBr: 38–44% ^l
Storage	8% ^b ; 17–61% ^g ; 14–61% ^h	NC ^{g,h}	NA	NA	NA	NA	NA	NA
Boiling + Storage	83–90% ^g ; 82–97% ^h	NC ^g ; –17% ^h	NA	NA	NA	NA	NA	NA
Filtration + Storage	91–92% ^g ; 90–93% ^h	60–72% ^g ; 59–71% ^h	NA	NA	NA	NA	NA	NA
Boiling + Filtration	88% ⁱ	81 ⁱ	NA	NA	NA	NA	NA	NA
Filtration + Boiling	40–60% ^m	58–84% ^m	100% ^m	NA	NA	NA	NA	NA

NC: Total concentrations of HAAs not changed apparently; NA: not enough information available.

^aGibbons & Laha (1999).

^bWeinberg *et al.* (2006).

^cSmith & El Komos (2009).

^dCarrasco-Turigas *et al.* (2013).

^eStalter *et al.* (2016).

^fEgorov *et al.* (2003).

^gLeuesque *et al.* (2006).

^hChowdhury *et al.* (2010).

ⁱRahman *et al.* (2011).

^jWu *et al.* (2001).

^kKrasner & Wright (2005).

^lLiu *et al.* (2015).

^mWang *et al.* (2019).

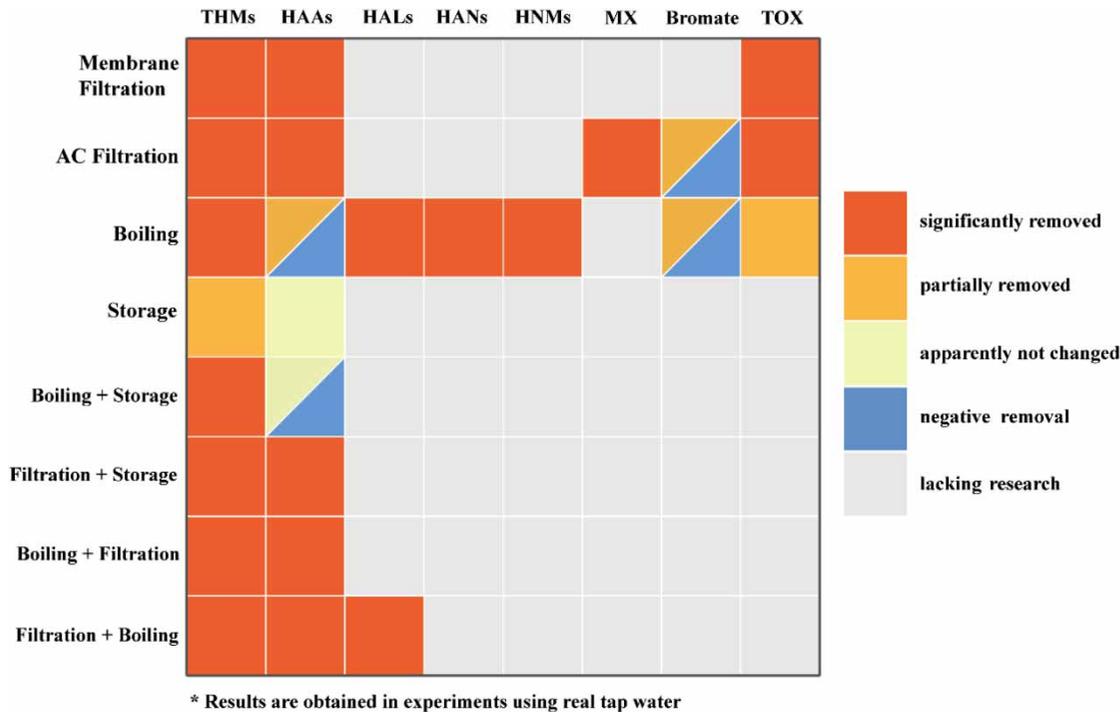


Figure 3 | The performance of HWTS and combination technologies for DBP removal in real tap water.

that THMs possess higher log K_{ow} values (see Table 3) and exhibit lower aqueous solubility and polarity, making them more amenable to carbon adsorption. Similarly, filters containing AC showed poorer average removal efficiency of TCM, DCAA, and TCAA than their bromine-containing counterparts, since the latter have a lower affinity to water and tend to be more readily adsorbed on the carbon particles. As for filters in which ion exchange happens, DBPs existing in an anionic state could be easily eliminated in these filters. Furthermore, most filters showed higher removal rate of AOB_r than AOCI and AOI. Different from PoU filters, boiling treatment might increase the concentration of HAA species, especially MCAA and DCAA in chlorinated tap water, leading to an unpredictable change of total HAA levels. However, it has been reported that boiling could eliminate a series of DBPs through volatilization, hydrolysis, or destruction, including THMs, HALs, HANs, and HNMs, while the removal rate of TOX by boiling was lower than the case of PoU filtration. Storage did contribute to DBP removal to some extent, while the effect was not clear when the target DBPs were not volatile (see Table 3, DBPs with

Henry's law constant at 25 °C $<10^{-7}$ atm·m³/mol are considered not volatile) or the storage was performed in a closed system. Also, combination technologies including filtration followed by storage, boiling followed by storage, as well as boiling coupled with filtration all showed unnegligible removal effect on DBPs in municipal tap water.

Although domestic water purifiers fitted with UV lamp are rarely studied for their effect on DBP control, the processes and rate constants of UV direct photolysis for DBPs have been explored. As for household chemical disinfection, there is no doubt that chlorination as well as flocculation followed by chlorination would cause DBP formation, and DBP yields might depend on characteristics of water to be treated as well as the dosage of disinfectant. Smith *et al.* (2010) compared DBP formation from iodine-based disinfectants at their recommended dosages for point of use to chlorination, and reported that iodoform with high toxicity was the predominant THM formed during iodination and total organic iodine concentrations during iodination with lower oxidant dosage exceeded TOCl concentrations during chlorination on a molar basis.

As mentioned above, HWTS has a significant impact on DBP levels before drinking water ingestion, which could have important implications for DBP exposure assessment and public health protection. In terms of DBP exposure assessment, on the one hand, studies conducted for occurrence survey or regulatory purposes mainly obtained monitoring data of DBPs in DWTP effluent, DWDS or tap water, which may not adequately represent DBP exposure and risks to human health since the population is not necessarily exposed directly to these waters (Dion-Fortier *et al.* 2009; Liu & Reckhow 2013; Chowdhury 2016). On the other hand, in epidemiological studies, researchers mostly used average DBP concentrations in water systems to estimate individual-level exposures, or used tap water consumption as a surrogate for DBP exposures to understand the dose–response relationships, which may lead to inaccuracy and misclassification in exposure assessment (Waller *et al.* 1998; Weinberg *et al.* 2006; Wright *et al.* 2006; Hamidin *et al.* 2008; Evans *et al.* 2013). Owing to the important role played by HWTS in DBP control, the variations of DBPs during the residence time of drinking water in households should be taken into account when studies of exposure characterization are conducted for DBPs in drinking water.

Also, HWTS is related to drinking water quality improvement, and consequently, human health protection. For emergencies in which tap water contains DBPs with a high level, HWTS seems to be an interim and useful solution to DBP elimination. Household treatment including filtration (especially in the case of AC filter), boiling water, storage in an open system as well as relevant combination technologies could help vulnerable populations who are exposed to THMs with high level. As for involatile HAAs, indoor treatment that favors DBP volatilization, including boiling and storage, are not recommended for HAA removal, while the filters could contribute to HAA control, and notably the filters contain ion exchange resins. From a perspective of TOX which is a surrogate for all halogenated DBPs and has been proven to be associated with toxicity (Yang *et al.* 2014), both filtration and boiling could reduce TOX levels in drinking water. However, what should be noted is that the efforts to reduce DBP concentrations must not compromise the effectiveness of pathogen removal by HWTS. For instance,

storage in an open system could favor removal of some volatile DBPs, while the treated water may be susceptible to recontamination under such conditions. Microbial contamination in filters could occur when regular cleaning of filters and frequent replacement of spare parts are not carried out. On the other hand, it is well known that membrane filtration could remove some minerals and nutrients, resulting in another trade-off associated with pollutants and nutrients in drinking water.

CONCLUSION

In this study, the research in the field of HWTS in DBP control have been reviewed, and the involved technologies include filtration, boiling, photolytic method, storage in refrigerators, as well as combination technologies. Generally, HWTS could remove DBP to some extent, and the performances of different methods are dependent on the removal mechanisms performed by HWTS, the physico-chemical properties of target DBPs as well as the characteristics of water to be treated. However, DBP concentration might show an increased trend, which could be attributable to accelerated DBP formation at high temperature as well as DBP elution from filter cartridges. Understanding the link between HWTS and DBPs will help improve the assessment accuracy of human exposure to DBPs and provide some interim advice for humans exposed to DBPs with a high level. Similarly, a trade-off between microbial and chemical risks also exists during household treatment, but pathogen removal should not be compromised in attempting to control DBPs as well. Future research relevant to DBP control by means of HWTS should take into account more DBP species possessing higher toxicity and other types of domestic devices used for drinking water purification.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- Ahmedna, M., Marshall, W. E., Hussein, A. A., Goktepe, L. & Rao, R. M. 2004 The use of nutshell carbons in drinking water filters for removal of chlorination by-products. *J. Chem. Technol. Biotechnol.* **79** (10), 1092–1097.
- Anumol, T., Clarke, B. O., Merel, S. & Snyder, S. A. 2015 Point-of-use devices for attenuation of trace organic compounds in water. *J. Am. Water Works Assoc.* **107** (9), E474–E485.
- Barrott, L. 2004 Chloral hydrate: formation and removal by drinking water treatment. *J. Water Supply Res. Technol.-AQUA* **53** (6), 381–390.
- Batterman, S., Huang, A. T., Wang, S. G. & Zhang, L. 2000 Reduction of ingestion exposure to trihalomethanes due to volatilization. *Environ. Sci. Technol.* **34** (20), 4418–4424.
- Bei, E., Shu, Y., Li, S., Liao, X., Wang, J., Zhang, X., Chen, C. & Krasner, S. 2016 Occurrence of nitrosamines and their precursors in drinking water systems around mainland China. *Water Res.* **98**, 168–175.
- Bellar, T. A., Lichtenberg, J. J. & Kroner, R. C. 1974 The occurrence of organohalides in chlorinated drinking waters. *J. Am. Water Works Assoc.* **66** (12), 703–706.
- Berg, P. A. 2015 The world's need for household water treatment. *J. Am. Water Works Assoc.* **107** (10), 36–44.
- Bond, T., Huang, J., Templeton, M. R. & Graham, N. 2011 Occurrence and control of nitrogenous disinfection by-products in drinking water – A review. *Water Res.* **45** (15), 4341–4354.
- Bond, T., Templeton, M. R. & Graham, N. 2012 Precursors of nitrogenous disinfection by-products in drinking water—A critical review and analysis. *J. Hazard. Mater.* **235**, 1–16.
- Bond, T., Templeton, M. R., Kamal, N. H. M., Graham, N. & Kanda, R. 2015 Nitrogenous disinfection byproducts in English drinking water supply systems: Occurrence, bromine substitution and correlation analysis. *Water Res.* **85**, 85–94.
- Brown, J. & Sobsey, M. D. 2012 Boiling as household water treatment in Cambodia: a longitudinal study of boiling practice and microbiological effectiveness. *Am. J. Trop. Med. Hyg.* **87** (3), 394–398.
- Brown, K. W., Gessesse, B., Butler, L. J. & MacIntosh, D. L. 2017 Potential effectiveness of point-of-use filtration to address risks to drinking water in the United States. *Environ. Health Insights* **11**, 1–8.
- Cantor, K. P., Lynch, C. F., Hildesheim, M. E., Dosemeci, M., Lubin, J., Alavanja, M. & Craun, G. 1998 Drinking water source and chlorination byproducts I. Risk of bladder cancer. *Epidemiology* **9** (1), 21–28.
- Carrasco-Turigas, G., Villanueva, C. M., Goni, F., Rantakokko, P. & Nieuwenhuijsen, M. J. 2013 The effect of different boiling and filtering devices on the concentration of disinfection by-products in tap water. *J. Environ. Public Health* **2013**, 959480.
- Charisiadis, P., Andra, S. S., Makris, K. C., Christophi, C. A., Skarlatos, D., Vamvakousis, V., Kargald, S. & Stephanou, E. G. 2015 Spatial and seasonal variability of tap water disinfection by-products within distribution pipe networks. *Sci. Total Environ.* **506**, 26–35.
- Chow, A. T. 2006 Comparison of DAX-8 and XAD-8 resins for isolating disinfection byproduct precursors. *J. Water Supply Res. Technol.-AQUA* **55** (1), 45–55.
- Chow, A. T., Gao, S. & Dahlgren, R. A. 2005 Physical and chemical fractionation of dissolved organic matter and trihalomethane precursors: a review. *J. Water Supply Res. Technol.-AQUA* **54** (8), 475–507.
- Chowdhury, S. 2016 Effects of plumbing systems on human exposure to disinfection byproducts in water: a case study. *J. Water Health* **14** (3), 489–503.
- Chowdhury, S., Rodriguez, M. J. & Serodes, J. 2010 Model development for predicting changes in DBP exposure concentrations during indoor handling of tap water. *Sci. Total Environ.* **408** (20), 4733–4743.
- Chowdhury, S., Rodriguez, M. J., Sadiq, R. & Serodes, J. 2011 Modeling DBPs formation in drinking water in residential plumbing pipes and hot water tanks. *Water Res.* **45** (1), 337–347.
- Chu, W., Li, D., Gao, N., Templeton, M. R., Tan, C. & Gao, Y. 2015 The control of emerging haloacetamide DBP precursors with UV/persulfate treatment. *Water Res.* **72**, 340–348.
- Chuang, Y.-H., Parker, K. M. & Mitch, W. A. 2016 Development of predictive models for the degradation of halogenated disinfection byproducts during the UV/H₂O₂ advanced oxidation process. *Environ. Sci. Technol.* **50** (20), 11209–11217.
- Ding, S. & Chu, W. 2017 Recent advances in the analysis of nitrogenous disinfection by-products. *Trends Environ. Anal. Chem.* **14**, 19–27.
- Ding, H., Meng, L., Zhang, H., Yu, J., An, W., Hu, J. & Yang, M. 2013 Occurrence, profiling and prioritization of halogenated disinfection by-products in drinking water of China. *Environ. Sci.-Process Impacts* **15** (7), 1424–1429.
- Ding, S., Deng, Y., Bond, T., Fang, C., Cao, Z. & Chu, W. 2019a Disinfection byproduct formation during drinking water treatment and distribution: a review of unintended effects of engineering agents and materials. *Water Res.* **160**, 313–329.
- Ding, S., Wang, F., Chu, W., Fang, C., Du, E., Yin, D. & Gao, N. 2019b Effect of reduced sulfur group on the formation of

- CX3R-type disinfection by-products during chlor(am)ination of reduced sulfur compounds. *Chem. Eng. J.* **361**, 227–234.
- Dion-Fortier, A., Rodriguez, M. J., Serodes, J. & Proulx, F. 2009 Impact of water stagnation in residential cold and hot water plumbing on concentrations of trihalomethanes and haloacetic acids. *Water Res.* **43** (12), 3057–3066.
- Egorov, A. I., Tereschenko, A. A., Altshul, L. M., Vurtiainen, T., Samsonov, D., LaBrecque, B., Maki-Paakkanen, J., Drizhd, N. L. & Fordb, T. E. 2003 Exposures to drinking water chlorination by-products in a Russian city. *Int. J. Hyg. Environ. Health* **206** (6), 539–551.
- England and Wales 2016 *Water Supply (Water Quality) Regulations 2016*.
- European Union 1998 *COUNCIL DIRECTIVE 98/83/EC of 3 November 1998 on the Quality of Water Intended for Human Consumption*. Brussels, Belgium.
- Evans, A. M., Wright, J. M., Meyer, A. & Rivera-Nunez, Z. 2013 Spatial variation of disinfection by-product concentrations: exposure assessment implications. *Water Res.* **47** (16), 6130–6140.
- Fang, C., Ding, S., Gai, S., Xiao, R., Wu, Y., Geng, B. & Chu, W. 2019a Effect of oxoanions on oxidant decay, bromate and brominated disinfection by-product formation during chlorination in the presence of copper corrosion products. *Water Res.* **166**, 115087–115087.
- Fang, C., Hu, J., Chu, W., Ding, S., Zhao, T., Lu, X., Zhao, H., Yin, D. & Gao, N. 2019b Formation of CX3R-type disinfection by-products during the chlorination of protein: the effect of enzymolysis. *Chem. Eng. J.* **363**, 309–317.
- Fujioka, T., Khan, S. J., McDonald, J. A., Roux, A., Poussade, Y., Drewes, J. E. & Nghiem, L. D. 2013 N-nitrosamine rejection by nanofiltration and reverse osmosis membranes: the importance of membrane characteristics. *Desalination* **316**, 67–75.
- Gan, W., Guo, W., Mo, J., He, Y., Liu, Y., Liu, W., Liang, Y. & Yang, X. 2013 The occurrence of disinfection by-products in municipal drinking water in China's Pearl River Delta and a multipathway cancer risk assessment. *Sci. Total Environ.* **447**, 108–115.
- Gibbons, J. & Laha, S. 1999 Water purification systems: a comparative analysis based on the occurrence of disinfection by-products. *Environ. Pollut.* **106** (3), 425–428.
- Goslan, E. H., Krasner, S. W., Villanueva, C. M., Carrasco Turigas, G., Toledano, M. B., Kogevinas, M., Stephanou, E. G., Cordier, S., Grazuleviciene, R., Parsons, S. A. & Nieuwenhuijsen, M. J. 2014 Disinfection by-product occurrence in selected European waters. *J. Water Supply Res. Technol.-AQUA* **63** (5), 379–390.
- Hamidin, N., Yu, Q. J. & Connell, D. W. 2008 Human health risk assessment of chlorinated disinfection by-products in drinking water using a probabilistic approach. *Water Res.* **42** (13), 3263–3274.
- Hansen, K. M. S., Zortea, R., Pickett, A., Rodriguez Vega, S. & Andersen, H. R. 2013 Photolytic removal of DBPs by medium pressure UV in swimming pool water. *Sci. Total Environ.* **443**, 850–856.
- Health Canada 2019 *Guidelines for Canadian Drinking Water Quality Summary Table*. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Ottawa, Canada.
- Hrudey, S. E. 2009 Chlorination disinfection by-products, public health risk tradeoffs and me. *Water Res.* **43** (8), 2057–2092.
- Hu, J., Chu, W., Sui, M., Xu, B., Gao, N. & Ding, S. 2018 Comparison of drinking water treatment processes combinations for the minimization of subsequent disinfection by-products formation during chlorination and chloramination. *Chem. Eng. J.* **335**, 352–361.
- Hua, G. & Reckhow, D. A. 2007 Comparison of disinfection byproduct formation from chlorine and alternative disinfectants. *Water Res.* **41** (8), 1667–1678.
- Hua, G. & Reckhow, D. A. 2008 DBP formation during chlorination and chloramination: effect of reaction time, pH, dosage, and temperature. *J. Am. Water Work Assoc.* **100** (8), 82–95.
- Huang, H., Zhu, H., Gan, W., Chen, X. & Yang, X. 2017 Occurrence of nitrogenous and carbonaceous disinfection byproducts in drinking water distributed in Shenzhen, China. *Chemosphere* **188**, 257–264.
- Krasner, S. W. & Wright, J. M. 2005 The effect of boiling water on disinfection by-product exposure. *Water Res.* **39** (5), 855–864.
- Krasner, S. W., Weinberg, H. S., Richardson, S. D., Pastor, S. J., Chinn, R., Scrimanti, M. J., Onstad, G. D. & Thruston Jr., A. D. 2006 Occurrence of a new generation of disinfection byproducts. *Environ. Sci. Technol.* **40** (23), 7175–7185.
- Lantagne, D. S. & Clasen, T. F. 2012 Use of household water treatment and safe storage methods in acute emergency response: case study results from Nepal, Indonesia, Kenya, and Haiti. *Environ. Sci. Technol.* **46** (20), 11352–11360.
- Lee, J., Kim, E.-S., Roh, B.-S., Eom, S.-W. & Zoh, K.-D. 2013 Occurrence of disinfection by-products in tap water distribution systems and their associated health risk. *Environ. Monit. Assess.* **185** (9), 7675–7691.
- Leuesque, S., Rodriguez, M. J., Serodes, J., Beaulieu, C. & Proulx, F. 2006 Effects of indoor drinking water handling on trihalomethanes and haloacetic acids. *Water Res.* **40** (15), 2921–2930.
- Li, X.-F. & Mitch, W. A. 2018 Drinking water disinfection byproducts (DBPs) and human health effects: multidisciplinary challenges and opportunities. *Environ. Sci. Technol.* **52** (4), 1681–1689.
- Li, X. Z. & Sun, J. M. 2001 Further formation of trihalomethanes in drinking water during heating. *Int. J. Environ. Health Res.* **11** (4), 343–348.
- Li, R. A., McDonald, J. A., Sathasivan, A. & Khan, S. J. 2019 Disinfectant residual stability leading to disinfectant decay and by-product formation in drinking water distribution systems: a systematic review. *Water Res.* **153**, 335–348.
- Liu, B. & Reckhow, D. A. 2013 DBP formation in hot and cold water across a simulated distribution system: effect of incubation time, heating time, pH, chlorine dose, and incubation temperature. *Environ. Sci. Technol.* **47** (20), 11584–11591.

- Liu, J., Zhang, X. & Li, Y. 2015 Effect of boiling on halogenated DBPs and their developmental toxicity in real tap waters. In: *Recent Advances in Disinfection by-Products* (T. Karanfil, B. Mitch, P. Westerhoff, & Y. Xie, eds). American Chemical Society, Washington DC, USA, pp. 45–60. <https://pubs.acs.org/doi/10.1021/bk-2015-1190>.
- Ma, S., Gan, Y., Chen, B., Tang, Z. & Krasner, S. 2017 Understanding and exploring the potentials of household water treatment methods for volatile disinfection by-products control: kinetics, mechanisms, and influencing factors. *J. Hazard. Mater.* **321**, 509–516.
- Ministry of Construction of the People's Republic of China 2005 *CJ/T 206-2005 Water Quality Standards for Urban Water Supply*. Beijing, China.
- Ministry of Health 2018 *Drinking-water Standards for New Zealand 2005 (Revised 2018)*. Ministry of Health, Wellington, New Zealand. <https://www.health.govt.nz/publication/drinking-water-standards-new-zealand-2005-revised-2018>.
- Ministry of Health Labour and Welfare 2015 *Drinking Water Quality Standards in Japan*. Tokyo, Japan.
- Ministry of Health of the People's Republic of China 2006 *GB5749–2006 Standards for Drinking Water Quality*. Standards Press of China, Beijing, China.
- Mitch, W. A., Sharp, J. O., Trussell, R. R., Valentine, R. L., Alvarez-Cohen, L. & Sedlak, D. L. 2003 N-nitrosodimethylamine (NDMA) as a drinking water contaminant: a review. *Environ. Eng. Sci.* **20** (5), 389–404.
- Muellner, M. G., Wagner, E. D., McCalla, K., Richardson, S. D., Woo, Y.-T. & Plewa, M. J. 2007 Haloacetonitriles vs. regulated haloacetic acids: are nitrogen-containing DBPs more toxic? *Environ. Sci. Technol.* **41** (2), 645–651.
- National Health and Medical Research Council & National Resource Management Ministerial Council 2011 *Australian Drinking Water Guidelines Paper 6 National Water Quality Management Strategy*. NHMRC, NRMCC, Commonwealth of Australia, Canberra.
- Nieuwenhuijsen, M. J., Grellier, J., Smith, R., Iszatt, N., Bennett, J., Best, N. & Toledano, M. 2009 The epidemiology and possible mechanisms of disinfection by-products in drinking water. *Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci.* **367** (1904), 4043–4076.
- Pan, Y., Zhang, X., Wagner, E. D., Osiol, J. & Plewa, M. J. 2013 Boiling of simulated tap water: effect on polar brominated disinfection byproducts, halogen speciation, and cytotoxicity. *Environ. Sci. Technol.* **48** (1), 149–156.
- Qiu, Y., Bei, E., Xie, S., Li, S., Wang, J., Zhang, X., Krasner, S. & Chen, C. 2019 Contributions of volatilization, photolysis, and biodegradation to N-nitrosodimethylamine removal in conventional drinking water treatment plants. *Sci. Total Environ.* **697**, 133993.
- Rahman, M. B., Driscoll, T., Clements, M., Armstrong, B. K. & Cowie, C. T. 2011 Effects of tap water processing on the concentration of disinfection by-products. *J. Water Health* **9** (3), 507–514.
- Reckhow, D. A., Platt, T. L., MacNeill, A. L. & McClellan, J. N. 2001 Formation and degradation of dichloroacetonitrile in drinking waters. *J. Water Supply Res. Technol.-AQUA* **50** (1), 1–13.
- Richardson, S. D. & Ternes, T. A. 2011 Water analysis: emerging contaminants and current issues. *Anal. Chem.* **83** (12), 4614–4648.
- Richardson, S. D., Plewa, M. J., Wagner, E. D., Schoeny, R. & Demarini, D. M. 2007 Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: a review and roadmap for research. *Mutat. Res.-Rev. Mutat. Res.* **636** (1–3), 178–242.
- Rook, J. J. 1974 Formation of haloforms during chlorination of natural waters. *Water Treat. Exam.* **23**, 234–243.
- Rosa, G. & Clasen, T. 2010 Estimating the scope of household water treatment in low- and medium-income countries. *Am. J. Trop. Med. Hyg.* **82** (2), 289–300.
- Shah, A. D. & Mitch, W. A. 2011 Halonitroalkanes, halonitriles, haloamides, and N-nitrosamines: a critical review of nitrogenous disinfection byproduct formation pathways. *Environ. Sci. Technol.* **46** (1), 119–131.
- Shi, W., Wang, L. & Chen, B. 2017 Kinetics, mechanisms, and influencing factors on the treatment of haloacetonitriles (HANs) in water by two household heating devices. *Chemosphere* **172**, 278–285.
- Singer, P. C. 1994 Control of disinfection by-products in drinking water. *J. Environ. Eng.-ASCE* **120** (4), 727–744.
- Singer, P. C., Obolensky, A. & Greiner, A. 1995 DBPs in chlorinated North Carolina drinking waters. *J. Am. Water Works Assoc.* **87** (10), 83–92.
- Smieja, J. A. 2011 Household water treatments in developing countries. *J. Chem. Educ.* **88** (5), 549–553.
- Smith, E. & El Komos, S. 2009 Tap water quality and performance of point-of-use treatment devices in Cairo, Egypt. *Water Environ. J.* **23** (2), 119–127.
- Smith, E. M., Plewa, M. J., Lindell, C. L., Richardson, S. D. & Mitch, W. A. 2010 Comparison of byproduct formation in waters treated with chlorine and iodine: relevance to point-of-use treatment. *Environ. Sci. Technol.* **44** (22), 8446–8452.
- South African National Standard. 2015 *SANS 241 Drinking Water Part 1: Microbiological, Physical, Aesthetic and Chemical Determinands*.
- Stalter, D., O'Malley, E., von Gunten, U. & Escher, B. I. 2016 Point-of-use water filters can effectively remove disinfection by-products and toxicity from chlorinated and chloraminated tap water. *Environ. Sci.-Wat. Res. Technol.* **2** (5), 875–883.
- Sun, X., Chen, M., Wei, D. & Du, Y. 2019 Research progress of disinfection and disinfection by-products in China. *J. Environ. Sci.* **81**, 52–67.
- Templeton, M. R. & Chen, Z. 2010 NDMA and seven other nitrosamines in selected UK drinking water supply systems. *J. Water Supply Res. Technol.-AQUA* **59** (4), 277–283.
- Tung, H.-H., Unz, R. F. & Xie, Y. F. 2006 HAA removal by GAC adsorption. *J. Am. Water Works Assoc.* **98** (6), 107–112.
- USEPA 2006 *Stage 2 Disinfectant and Disinfection Byproduct Rule*. USEPA, Washington DC, USA.

- USEPA 2009 *National Primary Drinking Water Regulations*. USEPA, Washington DC, USA.
- US National Library of Medicine 2020 *ChemIDplus: A TOXNET Database*. <https://chem.nlm.nih.gov/chemidplus/>. (accessed 27 July 2020).
- Villanueva, C. M., Castano-Vinyals, G., Moreno, V., Carrasco-Turigas, G., Aragones, N., Boldo, E., Ardanaz, E., Toledo, E., Altzibar, J. M., Zaldua, I., Azpiroz, L., Goni, F., Tardon, A., Molina, A. J., Martin, V., Lopez-Rojo, C., Jimenez-Moleon, J. J., Capelo, R., Gomez-Acebo, I., Peiro, R., Ripoll, M., Gracia-Lavedan, E., Nieuwenhuijsen, M. J., Rantakokko, P., Goslan, E. H., Pollan, M. & Kogevinas, M. 2012 Concentrations and correlations of disinfection by-products in municipal drinking water from an exposure assessment perspective. *Environ. Res.* **114**, 1–11.
- Wagner, E. D. & Plewa, M. J. 2017 CHO cell cytotoxicity and genotoxicity analyses of disinfection by-products: an updated review. *J. Environ. Sci.* **58**, 64–76.
- Waller, K., Swan, S. H., DeLorenze, G. & Hopkins, B. 1998 Trihalomethanes in drinking water and spontaneous abortion. *Epidemiology* **9** (2), 134–140.
- Wang, L., Niu, R., Chen, B., Wang, L. & Zhang, G. 2017 A comparison of photodegradation kinetics, mechanisms, and products between chlorinated and brominated/iodinated haloacetic acids in water. *Chem. Eng. J.* **330**, 1326–1333.
- Wang, L., Sun, Y. & Chen, B. 2018 Rejection of haloacetic acids in water by multi-stage reverse osmosis: efficiency, mechanisms, and influencing factors. *Water Res.* **144**, 383–392.
- Wang, L., Chen, Y., Chen, S., Long, L., Bu, Y., Xu, H., Chen, B. & Krasner, S. 2019 A one-year long survey of temporal disinfection byproducts variations in a consumer's tap and their removals by a point-of-use facility. *Water Res.* **159**, 203–213.
- Weinberg, H. S., Pereira, V., Singer, P. C. & Savitz, D. A. 2006 Considerations for improving the accuracy of exposure to disinfection by-products by ingestion in epidemiologic studies. *Sci. Total Environ.* **354** (1), 35–42.
- Westerhoff, P. & Mash, H. 2002 Dissolved organic nitrogen in drinking water supplies: a review. *J. Water Supply Res. Technol.-AQUA* **51** (8), 415–448.
- WHO 2006 *A Compendium of Drinking-Water Quality Standards in the Eastern Mediterranean Region*. World Health Organization, Geneva, Switzerland.
- WHO 2012 *Status of National Household Water Treatment and Safe Storage Policies in Selected Countries*. World Health Organization, Geneva, Switzerland.
- WHO 2015 *Boil Water*. World Health Organization, Geneva, Switzerland.
- WHO 2016 *Results of Round I of the WHO International Scheme to Evaluate Household Water Treatment Technologies*. World Health Organization, Geneva, Switzerland.
- WHO 2017 *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum*. World Health Organization, Geneva, Switzerland.
- WHO 2019 *Results of Round II of the WHO International Scheme to Evaluate Household Water Treatment Technologies*. World Health Organization, Geneva, Switzerland.
- WHO/UNICEF 2019 *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2017: Special Focus on Inequalities*. United Nations Children's Fund (UNICEF) and World Health Organization, New York, USA.
- Wright, J. M., Murphy, P. A., Nieuwenhuijsen, M. J. & Savitz, D. A. 2006 The impact of water consumption, point-of-use filtration and exposure categorization on exposure misclassification of ingested drinking water contaminants. *Sci. Total Environ.* **366** (1), 65–73.
- Wu, W. W., Benjamin, M. M. & Korshin, G. V. 2001 Effects of thermal treatment on halogenated disinfection by-products in drinking water. *Water Res.* **35** (15), 3545–3550.
- Yang, M. & Zhang, X. 2016 Current trends in the analysis and identification of emerging disinfection byproducts. *Trends Environ. Anal. Chem.* **10**, 24–34.
- Yang, X., Shang, C. & Westerhoff, P. 2007 Factors affecting formation of haloacetonitriles, haloacetones, chloropicrin and cyanogen halides during chloramination. *Water Res.* **41** (6), 1193–1200.
- Yang, Y., Komaki, Y., Kimura, S. Y., Hu, H. Y., Wagner, E. D., Marinas, B. J. & Plewa, M. J. 2014 Toxic impact of bromide and iodide on drinking water disinfected with chlorine or chloramines. *Environ. Sci. Technol.* **48** (20), 12362–12369.
- Zhang, X. & Minear, R. A. 2002 Decomposition of trihaloacetic acids and formation of the corresponding trihalomethanes in drinking water. *Water Res.* **36** (14), 3665–3673.
- Zhang, Y., Martinez, D., Collins, C., Graham, N., Templeton, M. R., Huang, J. & Nieuwenhuijsen, M. 2011 Modelling of haloacetic acid concentrations in a United Kingdom drinking water system. *J. Water Supply Res. Technol.-AQUA* **60** (5), 275–285.
- Zhang, X., Yang, H., Wang, X., Karanfil, T. & Xie, Y. F. 2015 Trihalomethane hydrolysis in drinking water at elevated temperatures. *Water Res.* **78**, 18–27.
- Zhang, Y., Xiao, Y., Zhang, Y. & Lim, T.-T. 2019 UV direct photolysis of halogenated disinfection byproducts: experimental study and QSAR modeling. *Chemosphere* **235**, 719–725.
- Zhou, X., Zheng, L., Chen, S., Du, H., Raphael, B. M. G., Song, Q., Wu, F., Chen, J., Lin, H. & Hong, H. 2019 Factors influencing DBPs occurrence in tap water of Jinhua Region in Zhejiang Province, China. *Ecotoxicol. Environ. Saf.* **171**, 813–822.

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