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Emerging disinfection byproducts: a review on their occurrence and control in drinking water treatment processes

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Abstract

The occurrence of disinfection byproducts (DBPs) is related both to drinking water treatment (DWT) processes and to raw water's characteristics. Emerging pollutants typically occur in low concentrations and are not removed by conventional DWT processes. Emerging DBPs appear within the DWT or in the distribution system due to the combination of disinfection agents (especially chlorine) with precursors as: natural organic matter (NOM), algal organic matter (AOM), anthropogenic contaminants (pesticides, pharmaceuticals, detergents etc.), brominated and iodinated compounds.

This study has as main goal a consistent analysis of the major problems caused by emerging DBPs to drinking water supplies. It presents a comprehensive review of the research efforts related to emerging DBPs considering three viewpoints: 1. an overview of their classification, legislative framework, methods of analysis, disinfection operational conditions and removal processes; 2. their occurrence, fate, health effects and impacts; 3. the analysis of the advanced DWT processes that might be used for the removal and control of precursors and DBPs with a focus on pilot and full-scale installations. All presented case studies considered pollutants removed, process conditions and efficiencies, and a critical assessment of processes based on membranes, advanced oxidation and adsorption on activated carbon or other materials. The main challenges of the control and removal of emerging DBPs are their low concentrations and the technical and economic sustainability of the application at full-scale of the AOPs, which need to be carefully adapted to local boundary conditions.

Keywords: disinfection byproducts, emerging pollutants, drinking water, water treatment process

Contents

List of abbreviations

Abbreviations/ Chemical formulas	Complete name
ADWT	Advanced Drinking Water Treatment
AOM	Algal Organic Matter
AOPs	Advanced Oxidation Processes
BCAA	Bromochloroacetic acid
BDCAA	Bromodichloroacetic acid
BDCM	Bromodichloromethane
Br-DBPs	Brominated-Disinfection byproducts
C/F	Coagulation/Flocculation
C-DBPs	Carbonaceous disinfection byproducts
$CHCl_3$	Chloroform
Cl-DBPs	Chlorinated-Disinfection byproducts
DBAN	Dibromoacetonitrile
DBCM	Dibromochloromethane
DBPs	Disinfection byproducts
DCAA	Dichloroacetic acid
DCAcAm	2,2-dichloroacetamide
DCAN	Dichloroacetonitrile
DWT	Drinking Water Treatment
EDCs	Endocrine Disrupting Chemicals
EPs	Emerging pollutants
GAC	Granular Activated Carbon
GC-ECD	Gas Chromatography- Electron Capture Detector
GC-MS	Gas Chromatography- Mass Spectrometry
HAA5	Haloacetic Acids
HNM	Halonitromethane
HPLC	High-Performance Liquid Chromatography
HS-SPME	Solid-phase Microextraction in the Headspace
IC-MS/MS	Ion Chromatography-tandem Mass Spectrometry
I-DBPs	Iodinated disinfection byproducts
IER	Ion-exchange Resin
LLE-ETAC	Liquid-Liquid Extraction with Ethyl Acetate
MCAA	Monochloroacetic acid
MCL	Maximum Concentration Level
MLLE	Micro Liquid-Liquid Extraction
N-DBPs	Nitrogenous disinfection byproducts
NDMA	N-nitrosodimethylamine
NOM	Natural Organic Matter
PAC	Powdered Activated Carbon
PIE	Precursor Ion Elimination
TBAA	Tribromoacetic acid
TCAA	Trichloroacetic acid
TCAcAm	Trichloroacetamide
TCAN	Trichloroacetonitrile
TCNM	Trichloronitromethane
THM	Trihalomethane
TTHM	Total Trihalomethanes
UPLC	Ultra-Performance Liquid Chromatography

1. Introduction

A major accomplishment for human health is the production of safe drinking water from raw surface and ground waters. Drinking water sources have thus become a priority for environmental communities worldwide. Water disinfection plays a pivotal role in reducing serious illnesses associated with waterborne diseases. Disinfection is used to eliminate pathogenic microorganisms during the drinking water treatment (DWT) and to ensure in the distribution network the quality parameters for a safe drinking water consumption (Chau et al., 2015). DWT plants' managers and water suppliers must assume the responsibility for water safety and at the same time for the implementation of the most efficient technologies to warrant that all qualitative indicators are below the limits imposed by the regulations.

Most common chemical disinfectants are chlorine-based (e.g. chlorine, chlorine dioxide, hypochlorite salts), having the advantages of low cost and easy manipulation, high efficiency towards different pathogens, taste improvement and persistence in the distribution network. However, disinfection byproducts (DBPs) often occur after chlorine-based disinfection processes (Gupta and Ali, 2013), implying possible adverse effects and risks to human health. Many precursors, as natural organic matter (NOM), algal organic matter (AOM), anthropogenic contaminants (e.g. pesticides, pharmaceuticals, detergents, etc.), brominated and iodinated compounds, as well as upstream wastewater discharges, and DWT operational parameters (disinfection agent type and/or dose, pH, contact time, temperature) may contribute to the development of DBPs (Alexandrou et al., 2018). Precursors' presence and amount could be subjected to seasonal variations (e.g. for AOM or contaminants related to agricultural activities, as ammonium and pesticides). DBPs are classified "harmful for human health" and their occurrence in raw water sources imposes special monitoring and efforts for the water suppliers (WHO, 2017).

In order to avoid DBPs formation, new disinfection processes and technologies were developed (e.g. ozone, ultraviolet, silver ion, electrochlorination, ferrate), involving high costs related to equipment and energy consumption (Zainudin et al., 2018). However, DBPs occurrence was demonstrated also for disinfection processes using non-chlorinated reagents (Ding et al., 2019).

Many members of the drinking water protection community have been actively working to clearly understand the possible negative effects of DBPs on human health. Meanwhile, state and federal governments have taken steps to protect the public from the potential health risks of DBPs by conducting research on their toxicological effects, strengthening drinking water regulations and supporting improvements in water treatment technology (Bereskie et al., 2017). Many authors focused their research on DBPs and disinfection processes under the following directions: (i) occurrence and removal of DBPs precursors deriving from raw water sources and optimization of DWT operational parameters and (ii) improved removal of DBPs and residual microorganisms at the end of DWT process and within the distribution network. Advanced drinking water treatment (ADWT) technologies are commonly implemented for the removal of emerging pollutants (including DBPs) and to reduce the concentrations of organic/inorganic precursors (Teodosiu et al., 2018).

This study has as main goal a consistent analysis of the major problems caused by emerging DBPs to drinking water supplies, providing a foundation for future research and highlighting the strengths and weaknesses of DBPs' control processes. To our knowledge, most research focused so far on the identification of DBPs and their precursors rather than on removal technologies. This study has the aim to present a comprehensive review of the research efforts related to emerging DBPs considering three objectives: 1) an overview of their classification, legislative framework, methods of analysis, disinfection operational conditions and removal processes; 2) their occurrence, fate, health effects and impacts; 3) a critical assessment of the ADWT processes that might be used for the removal and control of emerging DBPs and their precursors with a specific focus on pilot and full-scale installations.

2. Methodology

The analysis of the scientific literature considered for this review was based on the following selection criteria:

- ✓ *The relevance of articles and international information databases*. This study was based on 202 documents: articles found in Science Direct, Scopus, Web of Science, Springer, Wiley Online Library, and reports downloaded from the European Commission or other international reference databases (162 scientific papers, 23 review papers, 17 books/technical reports/regulations);
- ✓ *Publication period*. The references are mostly from 2010-2020 (93.77 %);
- ✓ *Relevant keywords*. The following keywords have been used in different combinations: *drinking water treatment, disinfection, disinfection byproducts, treatment technologies, pilot scale, full scale, analysis of disinfection by products from drinking water, regulations*;

- ✓ *Selection of references based on content analysis*. On the grounds of the above-mentioned criteria, 202 references were finally analysed as abstracts or full text documents.

3. Emerging DBPs of concern for drinking water treatment processes

DBPs are formed in drinking water from the reaction of disinfection agents with other compounds (*precursors*) occurring in raw water as: NOM, bromide and iodide, anthropogenic compounds (pharmaceuticals, antibacterial agents, textile dyes, pesticides, surfactants and cyanotoxins, etc.) (Papageorgiou et al., 2016; Barcelo, 2012). In recent years, great efforts were made to study the fate, occurrence and ecotoxicology of byproducts of drinking water disinfection processes. During chlorination, a large number and variety of DBPs are formed (Bond et al., 2014), as trihalomethanes (THMs), haloacetic acids (HAAs), haloacetonitriles, halophenols and halopropanoles (Farré et al., 2008, Liu et al., 2017; Young et al., 2018). Some DBPs, like THMs, HAAs, chlorites and bromates, are acknowledged by USEPA, WHO and international regulations as they are considered to have high impacts on human health. However, other DBPs (Table 1) are unregulated, even if their presence was detected during disinfection (with chloramines, chlorine, chlorine dioxide, ozone or ferrate) or if raw water contains natural bromide (Jiang et al., 2016). Unregulated DBPs are less known and studied, having very low concentrations, but they can be more toxic for humans and can rapidly increase the risks for cancer or other diseases (Li et al., 2015).

3.1. Definition, classifications and regulations

Most DBPs could be defined *emerging pollutants* (EPs) (see Table 1), according to the Norman Network classification (Norman Network, 2016). EPs are chemical compounds with risks to human health, which appear in drinking water as a consequence of disinfection treatment (Table 1). Over 600 DBPs were identified (Richardson and Postigo, 2011), however the studies concerning their occurrence and formation mechanisms, human health effects and treatment alternatives (Hebert et al., 2010; Kimura and Ortega-Hernandez, 2019; Chaukura et al., 2020; Sorlini et al., 2014) are much less. Usually, DBPs are related to the use of chlorine-based disinfectants (chlorine gas, chloramines, chlorine dioxide, hypochlorite/hypochlorous acid) or ozone and to the raw water physicochemical features. The most common DBPs classes, their sources and health effects are presented in Table 1.

Table 1. DBPs classes, sources and health effects

DBPs Classes	**Recognized as EPs**	**Sources**				**Effects**	**References**
		Cl	**NH_2Cl**	**ClO_2**	**O_3**		
Total Trihalomethanes (**TTHMs or THM4**)							
Bromodichloromethane	yes	**x**	**x**	**x**		Possible carcinogenic for liver, kidney, intestine; central nervous and reproductive system diseases; also causing bladder, colon, rectal, or pancreatic cancer	Hebert et al., 2010; Pardakhti et al., 2011; Kogevinas et al., 2016; Lodhi et al., 2017; Han et al., 2017
Bromoform							
Dibromochloromethane							
Chloroform							
Haloacetic acids (HAAs or HAA5)							
Dichloroacetic acid		**x**	**x**			Possible carcinogenic for liver, kidney, lung, causing leukaemia; effects on reproductive system, skin and eyes irritation	Chowdhury et al., 2011; Dad et al., 2018
Trichloroacetic acid							
Chloroacetic acid	yes						
Bromoacetic acid							
Dibromoacetic acid							
Bromate				**x**	**x**	Possible carcinogenic for thyroid, kidney and breast	Dongmei et al., 2015; Xiao et al., 2017
Chlorite				**x**		Anaemia, thyroid gland and kidney diseases; mutagenic and teratogenic effects on nervous system	Feretti et al., 2008; Garcia-Villanova et al., 2010; Chhetri et al., 2017
Chlorate	yes			**x**		Possible carcinogenic for thyroid; immune system hypersensitivity	Feretti et al., 2008; Hebert et al., 2010; Ibrahim and Abu-Shanab, 2013
Hydrazine	yes		**x**			Possible effects upon the nervous and cardiovascular system, liver and kidneys; causing vomiting and hepatotoxicity; carcinogenic and with chronic toxicity	Bond et al., 2011; Matsumoto et al., 2016; Guyton et al., 2018;

DBPs Classes	**Recognized as EPs**	**Sources**				**Effects**	**References**
		Cl	**NH_2Cl**	**ClO_2**	**O_3**		
Nitrosamines (NDMA) N-Nitrosodimethylamine N-Nitrosopyrrolidine N-Nitrosomorpholine N-Nitrosopiperidine N-Nitrosodiphenylamine N-nitrosomethylethylamine N-nitrosodiethylamine N-nitroso-di-n-butylamine	yes	**x**	**x**			Possible carcinogenic for liver, stomach, esophagus, bladder, lung, breast and brain	Hebert et al., 2010; Hanigan et al., 2017 Linge et al., 2017;
Aldehydes Chloroacetaldehyde Dichloroacetaldehyde Bromochloroacetaldehyde Tribromoacetaldehyde	yes	**x**		**x**	**x**	Possible carcinogenic for stomach and lung; reproductive system toxicity; causes depression and DNA damage	Hebert et al., 2010; Xie et al., 2016
Unregulated THMs Dibromomethane Bromochloromethane Tetrachloromethane Dibromodichloromethane	yes	**x**	**x**			Possible carcinogenic for liver, kidney, intestine; central nervous and reproductive systems diseases;	Hebert et al., 2010 Yang et al., 2019
Unregulated HAAs Bromochloroacetic acid Bromodichloroacetic acid Dibromochloroacetic acid Tribromoacetic acid	yes	**x**	**x**			Possible carcinogenic for liver, lungs, kidney and reproductive system diseases; leukemia	Richardson et al., 2007; Hebert et al., 2010; Zhang et al., 2011
Tribromopyrrole/ Halopyrole	yes	**x**	**x**	**x**	**x**	Possible carcinogenic for breast	Hebert et al., 2010; Yang and Zhang, 2014
Cyanogen chloride	yes	**x**	**x**		**x**	Possibly causes eyes and skin irritation, respiratory and cardiovascular deficiencies; may be lethal at high concentration	Hebert et al., 2010; Weng and Blatchley, 2013;
Haloanisoles 2,4,6-trichloroanisol 2,4,6-tribromoanisole 2,4-dibromoanisole 2,4-dichloroanisole 2,6-dichloroanisole 2-bromoanisole 4-bromoanisole	yes	**x**				N/A	Hebert et al., 2010; Barceló and Alastuey, 2012; Xie et al., 2016
Chlorophenols 2-chlorophenol 2,4-Dichlorophenol 2,4,6-Trichlorophenol 2,3,4,6-Tetrachlorophenol 2,4,5-Trichlorophenol 4-chlorophenol	yes	**x**	**x**			Possible carcinogenic for liver, lymphoma and lungs; immune system hypersensitivity; hepatic and renal toxicity	Gopal et al., 2007; Hebert et al., 2010; Igbinosa et al., 2013; Zhai et al., 2014
Haloamides Dichloroacetamide Bromochloroacetamide Dibromoacetamide Bromoiodoacetamide Trichloroacetamide Diiodoacetamide Tribromoacetamide	yes	**x**	**x**			Possible carcinogenic effects on reproductive system, liver or leukemia	Hebert et al., 2010; Bull et al., 2011; Shah et al., 2012

DBPs Classes	**Recognized as EPs**	**Sources**				**Effects**	**References**
		Cl	**NH_2Cl**	**ClO_2**	**O_3**		
Halonitromethanes Chloronitromethane Bromonitromethane Dichloronitromethane Dibromonitromethane Bromochloronitromethane Trichloronitromethane Dibromochloronitromethane Tribromonitromethane	yes	**x**	**x**	**x**	**x**	Possible carcinogenic for breast	Liviac et al., 2009; Hebert et al., 2010; Ceretti et al., 2016;
Haloacetonitriles (HANs) Chloroacetonitrile Bromoacetonitrile Dichloroacetonitrile Bromochloroacetonitrile Trichloroacetonitrile Iodoacetonitrile Dibromoacetonitrile	yes	**x**	**x**	**x**	**x**	Reproductive system toxicity; possible carcinogenic for breast	Richardson et al., 2007; Hebert et al., 2010; Ileka-Priouzeau et al., 2015;
Haloketones Hexachloropropanone 1,1-Dibromopropanone 1,1,3-Trichloropropanone 1,1,1,3-Tetrachloropropanone 1,1,3,3 Tetrachloropropanone 1,1,1,3,3Pentachloropropanone	yes	**x**	**x**			Possible carcinogenic or mutagenic effects	Hebert et al., 2010; Linge et al., 2013; Zhai et al., 2014
Iodoacids	yes		**x**			Possible cytotoxic and genotoxic effects, causing breast cancer	Hebert et al., 2010; Xiao et al., 2016
IodoTHMs Dichloroiodomethane Bromochloroiodomethane Bromodiiodomethane Dibromoiodomethane Chlorodiiodomethane Iodoform	yes	**x**	**x**	**x**		Possible genotoxic and cytotoxic effects, causing bleeder cancer and endocrine diseases	Hebert et al., 2010; Luo et al., 2014; Han et al., 2017
HEX & TEX Hexachlorocyclopentadiene Tetrachlorocyclopentadiene	yes		**x**			Possible carcinogenic for liver, causing skin and eyes irritation	Hebert et al., 2010; TOXNET, 2018
MX & halofuranones Mutagen X Mucochloric acid	yes	**x**	**x**	**x**		Possible carcinogenic for thyroid, bile duct, pancreas and lungs	Hebert et al., 2010; Richardson and Postigo, 2016

Note: N/A – not applicable/not available

Apart of the identification of DBPs and their adverse health effects, international regulations and guidelines also defined maximum amounts of DBPs allowed in drinking water. The World Health Organization (WHO) introduced Drinking Water Guidelines with maximum contaminant levels for DBPs (WHO, 2006; WHO, 2008; WHO, 2017). The Environmental Protection Agency (USEPA, 2009) regulates DBPs like THMs, HAAs, bromate and chlorite. USEPA specifically regulates five HAAs, defined HAA5 (Table 1). In Europe, only THM4

(Table 1) and bromate are regulated as DBPs through the Drinking Water Directive, but there are standards and guidelines for each species of THMs (Karanfil et al., 2008). Wang et al. (2015) compared the maximum contaminant levels (MCL, expressed as µg L^{-1}) for regulated DBPs in drinking water according to international regulations and guidelines (Table 2). However, MCL values do not characterize DBPs from the point of view of toxicity, carcinogenicity and occurrence (Hebert et al., 2010).

Table 2. Maximum contaminant levels for DBPs as in current directives and guidelines (adapted from Wang et al., 2015)

DBPs	**MCL (µg L^{-1})**							
	WHO guidelines (a)	USA Guidelines (b)	Canadian Guidelines (c)	Australian guidelines (d)	EU Directive (e)	Japanese standards (f)	Chinese regulations (g)	Egyptian standards (k)
TTHM(h)	**1000**	**80**	**100** LRAA(i)	**250**	**100**	**100**	**1000**	**100**
Cloroform(l)	**300**	-	-	-	-	**60**	**60**	**1000**
BDCM (n)	**60**	-	**16**	-	-	**30**	**60**	**500**
DBCM (n)	**100**	-	-	-	-	**100**	**100**	**500**
Bromoform (l,n)	**100**	80	-	-	-	**90**	**100**	**200**
HAA5(j)	**60**	**60**	**80** LRAA	-	-	-	-	-
MCAA	20	-	-	**150**	-	**20**	-	-
DCAA	50	-	-	**100**	-	**30**	**50**	
DCAN(k)	20	-	-	N.D.	-	-	-	**1000**
DBAN	70	-	-	N.D.	-	-	-	**1000**
TCAA	200	-	-	**100**	-	**30**	**100**	-
TCAN	-	-	-	-	-	-	-	**100**
CH (k)	-	-	-	**100**	-	-	**10**	**200**
Bromate (l,p)	10	**10**	**10**	20	**10**	**10**	**10**	-
Formaldehyde	-	-	-	**500**	-	**80**	**900**	-
Chlorite (l,m)	700	**1000**	**1000**	800	-	-	**700**	-
Chlorate (m)	700	700	**1000**	N.D.	-		**700**	-
CHCl (as CN) (l)	-	-	-	80	-	**10**	**70**	-
2-chlorophenol (o)	-	-	-	**300**	-	-	-	-
2,4-dichlorophenol (o)	-	-	**900**	**200**	-	-	-	-
2,4,6-dichlorophenol (o)	200	-	2	**20**	-	-	**200**	-
2,3,4,6-Tetrachlorophenol(o)	-	-	**100**	-	-	-	-	-
NDMA (nitrosamines)	0.1	-	**0.04**	0.1	-	-	-	-
Chloropicrin (q)	-	-	-	-	-	-	-	**500**
1,1,1-Trichloropropane (q)	-	-	-	-	-	-	-	**500**

Notes and abbreviations: (a) World Health Organization guidelines – (*WHO*, 2017); (b) United States of America guidelines– (*US EPA*, 2006); (c) Canadian Guidelines 2019 - (*Canadian DWQ*, 2019); (d) Australian guidelines – (*NWQMS*, 2016); (e) Drinking Water Directive of European Council 2012 - (*Directive 98/83/EC*, 1998); (f) Ministry of Health, Labour and Welfare (*Japanese Standards*, 2016, *JWWA*, 2016); (g) Chinese regulation (*GB 5749-2006*, 2007); (h) TTHM - Sum of all THMs contaminants; (i) LRAA - Local Running Annual Average; (j) HAA5 - Haloacetic Acids (k) Ibrahim and Abu-Shanab, 2013; (l) Richardson, 2005; (m) Al-Otoum *et al.*, 2016; (n) Pérez Pavón *et al.*, 2008; (o) Hebert *et al.*, 2010; (p) Winid, 2015; (q) Ali, 2013

Explanation: Values in bold refer to DBPs included in the international guidelines, regulations, standards and directives specified in brackets from point (a) to (g) and (k). Notes in brackets as (h), (i) and (j) are abbreviations explained. The rest are references for DBPs not included in the international regulations/guidelines.

3.2. DBPs sources and occurrence

To state the importance of the disinfection processes in providing safe drinking water for human consumption, the disinfectants used, with their main characteristics and effectiveness should be considered, along with the byproducts formed and consequent health risks. Figure 1 presents the sources and technologies that may remove both precursors and already formed-DBPs, these technologies being largely influenced by the outline of the DWT process scheme and of the distribution system.

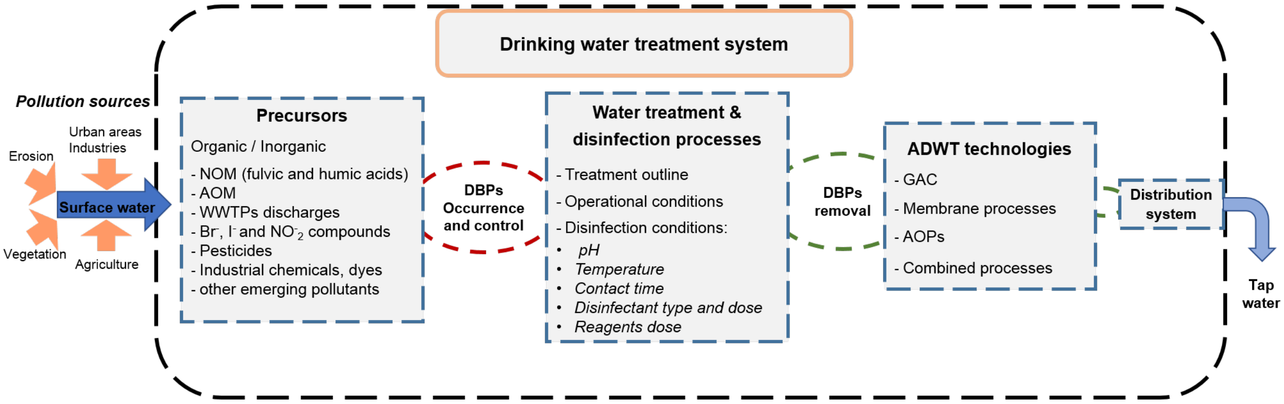

Fig. 1. Disinfection byproducts in a DWT system – from occurrence to removal.

DBPs formation mechanisms are strongly influenced by operational parameters such as: type of disinfectant used, dose and contact time, and by the physico-chemical features of raw water (pH, temperature, NOM, ammonium, metals) (Shahi et al., 2019; Jiang et al., 2018; Gougoutsa et al., 2016; Ibrahim and Abu-Shanab, 2013; Wei et al., 2010). Raw water characteristics are crucial, and many substances were identified as DBPs precursors: NOM (Sillanpää, 2014; Neale et al., 2019), pharmaceuticals (Ternes and von Gunten, 2010; Zhou et al., 2016), antibacterial agents (Barceló, 2012), textile dyes (Alves de Lima et al., 2007), pesticides (Duirk and Collette, 2006; Mehrsheikh et al., 2006), bisphenol A (Hu et al., 2002), alkylphenol ethoxylate surfactants (Petrovic et al., 2010) and cyanotoxins (Lee et al., 2017; Corbe et al., 2014). It is more effective to remove DBPs precursors before disinfection or to control its operational parameters than removing the already formed DBPs (Lin et al., 2016). NOM (especially humic substances), AOM, bromide, iodide and anthropogenic pollutants have been widely investigated in raw water sources as precursors (López-Roldán et al., 2016; Chaukura et al., 2020).

Water sources are often affected by industrial discharges, agriculture runoffs, algal blooms, municipal wastewater discharges, storm water runoffs, wildfires and elevated bromine and iodine concentration, each with high or moderate impact on DBPs occurrence (Sgroi et al., 2018). Pharmaceuticals reach drinking water due to inadequate wastewater treatment, exaggerated human consumption and veterinary use, even through leaks from the agricultural lands. Even if they are present in low concentrations, pharmaceuticals can resist conventional DWT (e.g. flocculation, sedimentation, filtration) and chemical disinfection (through chlorine, chloramines, ozone or chlorine dioxide) (Kaplan, 2013) and produce DBPs (Postigo and Richardson, 2014; Kimura and Ortega-Hernandez, 2019). Advanced DWT systems that use UV or UV/H_2O_2 disinfection processes can interact with pharmaceutical substances and form NDMA or increased levels of DBPs after the addition of chloramine (Radjenovic et al., 2012; Postigo and Richardson, 2014).

Disinfectants like chlorine, chlorine dioxide, chloramine, sodium hypochloride or ozone interact with NOM, microorganisms or bromide/iodide to produce a different class of DBPs with a high toxicity (Zhao et al., 2012; Jiang et al., 2018).

In the following subsections an overview of the main disinfection agents used in DWT processes and the generated DBPs will be presented.

3.2.1. Chlorine

Within chlorine disinfection, TCAA and DCAA are the major DBPs formed, followed by THMs (Zhai et al., 2017; Di Cristo et al., 2015). NOM presence in raw water has a high potential to generate THMs and HAAs during the chlorination process and it is correlated with seasonal variations and water quality parameters (Alver et al., 2018). AOM is a precursor as well and during chlorination leads to C-DBPs and N-DBPs (Qi et al., 2016; Goslan et al., 2017), depending both on AOM concentration and on the chlorine dose and contact time.

Coagulation/flocculation process is essential to achieve high NOM and AOM removal efficiencies, while a well-adjusted coagulant dose influences the performances of suspended solids removal (Gad-Allah et al., 2012; Zaleschi et al., 2012). Recent studies indicated that chlorine might attack NOM and form intermediate DBPs (including nonhalogenated and halogenated aromatic DBPs) (Jiang et al., 2017), and finally form halogenated aliphatic DBPs (including regulated THMs and HAAs) (Jiang et al., 2020, Li et al., 2020). Similarly, nitrogenous DBPs formed during chlorination depend on disinfectant dose and pH (5 to 6), while the high temperature increases the formation potential of TCNM (Chen et al., 2017).

A study involving water disinfection with chlorine, UV, UV/chlorine and UV/H_2O_2 (Wang et al., 2015), showed that DBPs formation during UV/chlorine AOPs depended on chlorine dose, exposure time and quality of water sources. The formation of THM and HAA during disinfection was low and constant for the three types of disinfection processes and depended on pH, temperature and season.

Chlorine used as disinfection agent in special conditions (seasonal variation, temperature, dose or drinking water quality) can form Haloacetamides (Kimura et al., 2019) or Dimethylamine (de Vera et al., 2017). The formation of $CHCl_3$ or N-DBPs during UV/chlorine disinfection occurred, as demonstrated by a study of Kimura et al. (2019). HAAs as TCAA, hydroquinone, DCAA presented a high formation potential during chlorination under short-term and long-term contact time conditions (Cordero et al.,2020). N-nitrosodimethylamine formation occurred when chlorination was applied to a surface DWT plant (Orak et al., 2019). Also, dichloroacetonitrile (DCAN) and dichloroacetamide (DCAcAm) occurred after the chlorination process (Chen et al., 2019). AOM is a major precursor of halogenated carbonaceous and nitrogenous byproducts (C-DBPs and N-DBPs) in the chlorination process (Wu et al., 2020; Maeng et al., 2019).

3.2.2. Chlorine dioxide

The increased application of chlorine dioxide in DWT, particularly for surface water, avoids the formation of THMs but can generate other DBPs: chlorite and chlorate, both supposed to act as endocrine disruptors affecting human thyroid (Snyder et al., 2009). Chlorite (ClO_2^-) and chlorate (ClO_3^-) are well-known degradation products of hypochlorite solutions. Hypochlorite ion (OCl^-) is unstable and naturally undergoes two independent paths of self-decomposition: one generating oxygen and chloride (Eq. 1), and the other chlorate and chloride ions (Eq. 2):

$$2OCl^- \rightarrow O_2 + 2\ Cl^- \qquad \text{(Eq. 1)}$$

$$3OCl^- \rightarrow ClO_3^- + 2\ Cl^- \qquad \text{(Eq. 2)}$$

Chlorite is rapidly formed as an intermediate between hypochlorite and chlorate in (Eq. 2) (Snyder et al., 2009). Chlorine dioxide (ClO_2), in contact with organic and inorganic oxidizable substances (DBPs precursors), degrades to chlorite, chlorate and chloride ions, thus reducing the subsequent possibility of THMs and HAAs developing in the distribution networks (Al-Otoum et al., 2016; Ye et al., 2019). Chlorite levels may vary between 10-20 % of ClO_2 dose in winter and 40-70 % in summer, while chlorate levels usually are between 10 and 30 % of the ClO_2 dose (Gates et al., 2009). Chlorine dioxide, in the presence of hypochlorite, may undergo a disproportionation reaction to form chlorate (Eq. 3) (Gates et al., 2009):

$$2ClO_2 + HClO + H_2O \Leftrightarrow 2ClO_3^- + Cl^- + 3H^+ \qquad \text{(Eq. 3)}$$

The factors commonly assumed to be of main influence in chlorite and chlorate generation are: temperature and sunlight, which may catalyze the reactions presented in Eqs. 1- 3; hypochlorite and chlorine dioxide doses; characteristics of raw water, particularly the presence of transition metals and other oxidizable substances (Gates et al., 2009; Snyder et al., 2009; Garcia-Villanova et al., 2010). It was found that DBPs occurrence during sodium hypochlorite disinfection was affected by bromide ions (Rong et al., 2018).

DBPs formation (anhydroerythromycin, N-desmethyl clarithromycin and N-desmethyl clarithromycin), occurred after chlorine dioxide treatment in the raw water of a DWT plant located in Barcelona. Anhydroerythromycin was removed by both conventional (ozonisation) and advanced (reverse osmosis) processes, and N-desmethyl clarithromycin was removed only after ADWT (Rubirola et al., 2019).

3.2.3. Chloramination

NOM is considered the main precursor of DBPs, it is usually associated with surface waters and interacts with chloramine forming THMs, HAAs and HANs. Dissolved fractions of organic nitrogen and carbon (DON and DOC) play an essential role in the formation of C-DBPs and N-DBPs in the pre-chloramination stage during summer (Chu et al., 2011). NOM with higher aromaticity in the reaction with chloramine increased phenolic I-DBPs and decreased polar aliphatic I-DBPs (Pan et al., 2016).

I-DBPs formation in the presence of zero-valent iron (ZVI) during chloramination is strongly influenced by the same operational parameters (initial pH, IO_3 concentrations and disinfectant dose). However, ZVI presence, iron corrosion scale, phosphate concentration and Br-/IO3- molar ratio accelerated the formation potential of I-THMs (Xia et al., 2017). THMs and HAAs are the most abundant DBPs generated by hypochlorite, while HANs may derive from chloramines.

ADWT systems that use UV or UV/H_2O_2 disinfection processes can interact with pharmaceutical substances and form NDMA or increased concentrations of DBPs after the addition of chloramine (Radjenovic et al., 2012; Postigo and Richardson, 2014). During the chloramination process used for DWT some DBPs are formed, especially Nitrosamines (Selles et al., 2018), N-DBPs and Chloroform (Kimura et al., 2019) or NDMA (Ding et al., 2019). Chloramine disinfection reagent contribute to the formation of NDMA and THMs, respectively, both of which are defined as disinfection byproducts (Orak et al., 2019). Iodo-THMs (DCIM, DBIM, BCIM, CDIM and TIM) occurred in 65 water treatment systems in Canada during drinking water disinfection process with chloramine, and their concentration ranged from 0.02 µg/L to 21.66 µg/L, due to various water quality parameters, seasonal variations and relevant precursors content (DOC, bromide, iodide and iodine) (Tugulea et al., 2018).

3.2.4. Ozone

When ozonation is followed by chlorination, the concentration of brominated and iodinated THMs and HAAs increases, but nitrosamines formation is inhibited at high concentrations of bromide (Zha et al., 2014). It was reported that in surface waters, bromides converted to brominated DBPs has a potential hazardous impact on living organisms, especially on the endocrine system, and on the aquatic environment (Watson et al., 2015; Winid, 2015).

In the presence of chlorine, chloramine or ozone, bromide and iodide halogenated ions influence the amount of Cl-DBPs, Br-DBPs or I-DBPs and not only THMs, HAAs and N-nitrosodimethylamine (Pan et al., 2015). Iodide compounds form hypoiodous acid/iodine by disinfection processes with chlorine, monochloramine and ozone, or iodine-radicals by chlorine dioxide. Bromate formation can be inhibited during water treatment process by adapting ozonation to electro-peroxone process by a carbon-based cathode and production of H_2O_2 from O_2. In this case, Br-DBP is reduced, while NOM removal in the drinking water treatment process increases (Li et al., 2015).

Carboxylic acids may occur after disinfection, especially when chlorine and ozone are used (Richardson et al., 2000), their amount varying due to raw water quality and DWT processes. Jurado-Sánchez et al. (2014) detected 35 aliphatic and aromatic acids in two DWT plants characterized by different process outlines. The first plant used chlorination/ chloramination while the second one used ozonation and chlorination; the presence of the carboxylic acids being 6 times higher in the second plant, the number of generated carboxylic acids increasing especially in autumn and winter seasons. NDMA (Kimura et al., 2019) and Hydroxylamine (Heeb et al., 2017) are some DBPs formed during drinking water disinfection with ozone especially under various conditions (ozone dosages, pH) and different components in water (bromide ion (Br^-), bicarbonate ion (HCO_3^-), sulfate ion (SO_4^{2-}), and humic acid (HA), as well as NOM from a lake (Shen et al., 2019).

3.2.5. Ferrate

A new disinfection agent is ferrate (Fe IV), which can successfully be applied on DWT processes given its oxidation, coagulation (Prucek et al., 2013) and disinfection (Alsheyab et al., 2009) abilities. It also limits DBPs generation and contributes to NOM and EPs elimination (Jiang, 2013). DBPs formation through chlorine dioxide or ferrate used for surface water treatment show that the production of THM, haloketones, haloacetonitriles and trichloronitromethane is higher for chlorine dioxide (Yang et al., 2013, Liu et al., 2020). Few studies regarding DBPs formation reported that high doses of ferrate (21 mg/L) can reduce nitrosamines up to 84 % (Lee et al., 2008) or react with amino acids, resulting in aldehydes (Sharma, 2010). Halogenated DBPs (including THMs, HAAs, haloketones, chloral hydrate, haloacetonitriles and trichloronitromethane) are the byproducts resulted from the disinfection of water with ferrate in presence of an important precursor such as AOM (Dong et al., 2019).

3.2.6. Multi stage disinfection processes and the influence of the distribution system

Other crucial issues about DBPs generation refer to the type and dose of disinfectants, related to raw water quality and size of DWT plant. While in small DWT plants, particularly those dedicated to groundwater treatment, a single-phase disinfection is usually adopted, large DWT plants generally perform multi-stage disinfection processes. In such systems, primary disinfection targets the removal of pollutants and pathogens (usually by means of ozone or chlorine dioxide). While secondary disinfection has the main goal of assuring drinking water quality along the water distribution network up to the final users. As a result, primary and secondary disinfectants are both considered DBPs’ potential sources and their interaction should be taken into account. Hypochlorite is usually employed as secondary disinfectant because of its persistence in the distribution network, therefore most international regulations call for a residual chlorine concentration in drinking water (e.g. EU requires 0.2 mg/L through Directive 98/83/CE) (EC, 1998). Another relevant factor that can influence DBPs formation is the seasonal variation of the surface water characteristics. Higher temperature determines the use of an increased dose of disinfectant (aimed to control the increase in pathogens growth) and supports its reaction with NOM, leading to high DBPs formation in summer and autumn (Ibrahim and Abu-Shanab, 2013; Guilherme and Rodriguez, 2014), while HAAs concentration is higher in the cold season (Wei et al., 2010). The occurrence of DBPs in the drinking water network is variable, and their concentration range does not depend on the size of the network itself (Guilherme and Rodriguez, 2015). At the same time, DBPs concentration can fluctuate within the DWT, so the difficulty of their removal consists in choosing an appropriate process outline, taking into account: spatial location of the treatment system, raw water extraction quality, seasonal and short-term variations (Mercier-Shanks, et al., 2013). The fluctuating levels of THMs and HAAs across the treatment system show a temporal and spatial variability of their concentrations, which hinders the monitoring process and makes it difficult to choose a period or point of sampling (Guilherme and Rodriguez, 2015). Recent studies emphasized the role of different chemical agents and treatment/piping materials of the DWT or distribution system on DBPs formation. Besides additional DBPs precursors (phenolic structures, amino acids, oligopeptides and nitrogen-containing contaminants), another concern is that certain treatment stages have the potential to transform DBPs into more toxic compounds. For example, activated carbon, ion-exchange resins or membrane treatments can increase the ratios of Br-DBPs to Cl-DBPs, resulting in higher mammalian cell cytotoxicity and genotoxicity, although the overall DBPs concentrations decrease (Ding et al., 2019). Also, in the distribution systems the main challenges include the maintenance of stable concentrations of residual disinfectant and the control of microbial content that may form DBPs as consequence of residual decay processes. Microbial activity is a complex process and many factors (temperature, water age, piping material, corrosion products, nutrients, natural organic matter, hydraulic condition and disinfectant residual type and dosage) could influence it. Disinfectant types and dose were found to be among the most important factors driving the occurrence of DBPs in distribution networks (Li et al., 2019).

3.3. Methods of analysis

Most common methods for DBPs analysis include (Table 3): LC/ESI-MS/MS (liquid chromatography-electrospray ionization tandem mass spectrometry) for determination of chlorinated and brominated DBPs (Nollet and De Gelder, 2014) and also used to detect polar halogenated DBPs, especially aromatic DBPs (Yang et al., 2019); capillary electrophoresis (CE) (Kubáň et al., 2012) and high-field asymmetric waveform ion mobility spectrometry (FAIMS-MS) for HAA analysis (Barceló et al., 2012); membrane-introduction mass spectrometry (MIMS) for CNX (cyanogen halide) (Barceló et al., 2012); FT-ICR MS (Fourier transform ion cyclotron resonance mass spectrometry) for bromate and brominated DBPs (Yang and Zhang, 2016); SPE-LC-MS/MS (solid phase extraction-liquid chromatography-tandem mass spectrometry) for haloquinones investigation from WTPs (Li et al., 2011). Gas chromatography coupled with Orbitrap-based on mass spectrometry was used for I-DBPs analysis (Cojocariu et al., 2016), GC-ECD was reported to identify the DBPs formed by UV/chlorine disinfection (Huang et al., 2017) and GC-MS was able to detect specific DBPs with low molecular weight (Yang and Zhang, 2016). Other specific analytical methods for emerging DBPs detection include: High-Resolution Mass Spectrometry (HR-MS) (Richardson and Postigo, 2016); Ion Chromatography-Mass Spectrometry (Bruzzoniti et al., 2019), combined SPE, DCLCHR-LCMS and PIE (Zulkifli et al., 2018). HNMs HANs, HAcAms, NDMAs and other emerging N-DBPs (Ding and Chu, 2017) are commonly analyzed using GC (Pozzi et al., 2011; Chen et al., 2015; Ma et al., 2014; Montesinos and Gallego, 2012), HPLC (Chu et al., 2012; Kodamatani et al., 2016) and UPLC (Müller et al., 2012; Ripollés et al., 2011).

Table 3. Analytical techniques used for DBPs measurement

Analysis method	DBPs analyzed	Reference
SPE-HPLC-MS/MS	I-HAAs and aromatic I-DBPs	Hu et al., 2018
FT-ICR MS	Br-DBP	Yang and Zhang, 2016
GC-O/MS	I-DBP	Cojocariu et al., 2016
GC MS	HNMs HANs, HAcAms, NDMAs and emerging N-DBPs	Ding and Chu, 2017; Pozzi et al., 2011; Chen et al., 2015; Ma et al., 2014; Montesinos and Gallego, 2012
HPLC MS		Chu et al., 2012; Kodamatani et al., 2016
UPLC		Müller et al., 2012; Ripollés et al., 2011
LC/ESI-MS/MS	Chlorinated and Brominated DBPs	Nollet and De Gelder, 2014
	halogenated DBPs	Yang et al., 2019
MIMS	CNX HAA	Barceló et al., 2012
CE		
FAIMS-MS		
HPLC-MS	Hydrazine	Susinskis et al., 2018
IC-MS/MS	Nine HAAs, bromate, dalapon and I-HAAs	Wu et al., 2017
UHPLC/QTOF-MS	NDMA	Hanigan et al., 2017
GS-ECD	THMs, THAs, HANs and HKs	Huang et al., 2017
LLE-ETAC	DCAcAm	Lin et al., 2016
HS-SPME/GC-MS	Haloketones	Serrano, M., et al., 2015
LC/HR-MS	N-DBPs	Kolkman et al., 2015
MLLE	Haloketones	Serrano, M., et al., 2014
UPLC/ESI–MS–MS	Halobenzoquinones (HBQs)	Huang et al., 2013
SPE-LC-MS/MS	Haloquinones	Li et al., 2011

3.4. Environmental and health impacts

Human organisms can be exposed to DBPs through three conventional pathways: dermal contact, ingestion or inhalation (Nieuwenhuijsen et al., 2009; Chowdhury et al., 2011; Chaves et al. 2019; Chowdhury et al., 2020; Gonsioroski et al. 2020). The presence of DBPs in drinking water became a human health concern because some epidemiological studies demonstrated associations between DBPs exposure and increased risk of cancer development, liver, kidney defects and central nervous system problems, adverse reproductive outcomes (Legay et al., 2010; Chowdhury et al., 2017; Chen et al., 2019; Wang et al.,2019; Gonsioroski et al., 2020) and endocrine disruption (Chaves et al., 2020). Urinary bladder cancer has been the health risk most consistently associated with chlorination DBPs

(Hrudey et al., 2015; Regli et al.,2015; Chaves et al. 2019; Diana et al., 2019). Another study (Jones et al., 2019) evaluated the association between high DBPs levels with increased risk of colon and rectal cancer, however positive associations with individual THMs and HAAs, most consistent for rectal cancer, require further investigations.

Emerging DBPs formed in distribution system during chlorination and chloramination (THMs, HAA and HANs) have been reported to cause symptoms such as liver, kidneys and nervous system diseases and health risks associated with these regulated DBPs can be spontaneous abortions, births defects, stillbirths and negative reproductive effects (Quintiliani et al., 2018). Recent research focused on maternal exposure to emerging DBPs (THMs and TCAA) during pregnancy, and some DNA anomalies were observed in cord blood (Yang et al., 2017; Salas et al., 2015) causing foetal growth restriction (Cao et al., 2016) or other adverse reproductive outcomes (Wang et al., 2016; Holmes et al., 2017). Rivera-Nunez et al. evaluated the association between maternal exposure to THMs and DCAA. In a study of 2460 cases in Massachusetts from 1997 to 2004, chloroform, BDCM (Lodhi et al., 2017) and DCAA exposures (Dad et al., 2018) were associated with stillbirths (Rivera-Nunez et al., 2018). In a study of 7438 singleton term babies in United Kingdom, THMs and HAA% exposure during pregnancy was associated with reduced birth weight, but suggested differences by ethnicity (Smith et al., 2016). Halomethanes, iodo-trihalomethanes, nitrosamines, halobenzoquinones, NDMA, DCAN, DBAN exposure has been shown to be more genotoxic and cytotoxic than some regulated compounds, reinforcing their potential toxicological effect to humans (Chaves et al., 2020), and posing higher cancer risks for children than for adults (Luo et al., 2020).

Emerging DBPs may be classified as carcinogenic substances (Di Cristo et al., 2015; Ng et al., 2016) or may affect human health due to effects like: alteration of pregnancy duration, menstrual cycle or pregnancy loss, foetal development and congenital malformations or cancer (Villanueva et al., 2015). Long-term human exposure to various types of DBPs triggers many forms of cancer or other diseases (as presented in Table 1) (Hebert et al., 2010; Yang and Zhang, 2014; Xiao et al., 2017; Chhetri et al., 2017). The risk to develop cancer (López-Roldán et al., 2016) or diseases caused by THMs ingestion is higher than the risk caused by inhalation during shower or dermal exposure (Dyck et al., 2015). Therefore, water contaminated with DBPs (mostly THMs and HAAs) is highly dangerous for human health and can present high risks if the raw water originates from surface water, and less risks if the source is mixed (e.g., surface water and groundwater or only groundwater). The variety of DBPs known today, caused by the multitude of sources that influence their formation and occurrence, is reflected in the variety and complexity of the negative effects they can have on the environment and humans (Table 1). Some DBPs are considered EPs due to their persistence, low biodegradability and although they can be found in low concentrations, they may have the most devastating effects as compared to other contaminants (Yang and Zhang, 2016).

Because emerging N-DBPs resulted after chlorination or chloramination present cytotoxicity and genotoxicity risks, treatment processes should be applied as described in section 4 (Hu et al., 2018; Chen et al., 2017). With the same toxic characteristics, Br-DBPs resulting during water chlorination and chloramination in the presence of bromide, have a high potential to generate illnesses as compared to Cl-DBPs (Zhang and Yang, 2018). Some classes of DBPs (N-nitrosamines) are classified at international level as substances with a potential risk to develop cancer if the daily ingestion rate is exceeded (Fan and Lin, 2018).

Recent studies focused on formation mechanisms, concentrations and adverse health effects have been conducted those I-aldehydes, cyanides, halonitromethanes, haloketones, haloacetamides, iodinated-DBPs and N-nitrosamines presented in drinking waters are harmful for human health being more cytotoxic, genotoxic and mutagenic than their brominated and chlorinated equivalents (Chen et al., 2018; Andersson et al., 2019, Chaukura et al., 2020). Among N-DBPs, NDMA have received significant attention because low ng/L levels in drinking water are associated with 10^{-6} lifetime excess cancer risks. Epidemiological studies highlight that exposure via inhalation and dermal contact may be more dangerous than via ingestion of drinking water, because many emerging DBPs are sufficiently volatile such that skin absorption or inhalation during showering can be harmful (Li et al., 2018, Li et al., 2020).

4. Advanced DWT technologies for DBPs prevention and control

Given the number of known DBPs and its continuous growth, to prevent their occurrence and development, operational parameters and drinking water characteristics should be carefully monitored. Implementing technologies that have the ability to remove DBPs and to prevent their re-emergence in the distribution network is highly necessary (López-Roldán et al., 2016). Conventional DWT processes needs to be completed with ADWT processes (Du et al., 2017; Ohar et al., 2014; Chaukura et al., 2020) and/or the use of a strong oxidant as final disinfectant (Zainudin et al., 2018). In order to mitigate DBPs formation, dissemination activities oriented to a reduction of precursors or unnecessary pharmaceuticals use among the population could also be effective (Plewa et al., 2010).

Recent studies at pilot and full-scale showed the high performances of ADWT technologies (Hu et al., 2018; Wang et al., 2015; Jurado-Sanchez et al., 2014) (see Table 4), such as: membrane processes, advanced oxidation processes or adsorption on activated carbon and other materials, which were studied from the points of view of: technological performances (mechanism, pollutants removal efficiency), economic, social and environmental performances (Zainudin et al., 2018; Bui et al., 2016). From the chemical, biological and technological point of views, the prevention of DBPs formation may be possible through preventive actions (disinfectant agents used/ removing DBPs precursors through adequate DWT processes) or treatment actions (removing DBPs after their formation). Each treatment stage, like adsorption (GAC, PAC, CNTs, IER), coagulation/flocculation- C/F, AOPs, membrane filtration or integrated technologies), has its own contribution to the ADWT process efficiency. However, combined technologies ensure better drinking water quality, while preventing the development of certain risks from the recurrence of DBPs.

Table 4. Overview of DBPs removal by ADWT at pilot and full-scale

Treatment process	DBPs monitored	Operational parameters (PS/FS)	Removal efficiency (%)	References
C/F; S; SF	THMs, CH; DCAcAm; TCAcAm; TCNM and DCAN	**(FS)** pH: 6.5 ± 0.2 Contact time: 24 h		Hu J. et al., 2018
PO ($KMnO_4$/O_3/K_2FeO_4/ ClO_2); C/F; S; SF			17.6%, 23.6%, 19.6%, and 14.5%;	
PO ($KMnO_4$/O_3/K_2FeO_4/ ClO_2); C/F; S; SF; GAC filtration/O_3-GAC advanced treatment			45.3%, 51.1%, 49.3%, and 46.1%;	
UV/TiO_2 UV/Pt/TiO_2 Fe(0)/Cu(II) UV-L UV-M	Bromate	**(PS)** Reaction time/pH: 90-150 min/1.5-13.5 90 min/ 8.1; 30 min/6-6.5; 60 min/5.1-9.2; 50 min/ 6.8	50-60%; 95-99%; 100%; 35%–45%; 100%	Xiao et al., 2017
1. PO (Cl_2); C/F; SF (sand/anthracite) 2. PO (Cl_2); C/F; GAC filtration	36 DBPs	**(PS)** Contact time: 7.5/15 min; Cl_2 dose:3-6 mg/L	THMs 20%; Halonitroalkanes-58.50%; Haloaldehydes 33.62%; HAAs 28.13%; Haloalkanes 20.46%; Haloketones 13.46%; Nitrosamines 10.23%; Halonitriles -8.82%; Haloalkenes -9.84%; N-DBPs 4.82%; Chlorite 84.95% (GAC), Chlorite 19.55 % (SF)	Fu et al., 2017
Membrane nanofiltration: ESNA 1-LF2; TS80; NF270	NDMA, HNM, and THM	**(PS)** pH: 6-9; Ionic strength: 0.005-0.05 M; Ca^{2+}: 6-60 mg/L	57-83%; 48-87% and 72-97%	Ersan et al., 2016
RWE, PO, pH adjustment (H_2SO_4); C/F ($Al2(SO_4)_3$); SF; O_3, GAC filtration; Cl_2; pH adjustment (H_2SO_4)	THMs ($CHCl_3$ and BDCM); HAAs (MCAA, MBAA, DCAA, DBAA, BCAA, BDCAA, TCAA, TBAA, H)	**(FS)** O_3 dose: 5 - 0.8 mg/L; T: 7.4°C to 21°C; pH 8.02 - 8.8;	79% for $CHCl_3$; 21%for BDCM; 71% for DCAA and TCAA	Papageorgiou et al., 2016
1) C; S; SF; Cl_2 2) C; S; SF; O_3, BAC, Cl_2	DCAcAm	**(FS)** pH: 8,5; Cl_2 dose: 25.5 mg/L; Disinfection time: 24 h	9% in CDWT plant and 76% in ADWT plant	Lin et al., 2016
1) RWE, PO (ClO_2), C,F,S,SF; UF, RO,REM, Cl_2, Tanks, Cl_2 2) RWE, PO (ClO_2), C,F,S,SF; O_3, GAC filtration, Cl_2, Tanks, Cl_2	THMs	**(FS)**	-	López-Roldán et al., 2016
RWE; F ($Al_2(SO_4)_3$); pH adjustment and activated silica; S; SF (anthracite/sand); NH_2Cl; pH correction and Fl	TTHM and HAA5	**(FS)** Contact time 20 min; Bed layer: anthracite 0.56m and sand 0.3m	75%overall reduction for TTHM and HAA5	Delatolla et al., 2015
RWE; PO (Cl_2); C/F (Al_2Cl_3); S; SF; NH_2Cl	10 THMs, 13 HAAs, 6 HNMs, 6 HANs and 11 aldehydes	**(FS)** Cl_2 dose: 0.6–1.0 mg/L); NH_2Cl dose: 2.1–2.6 mg/L; Contact time 24/48 h; pH 3.0–3.5 (H_2SO_4)	Increased concentration in summer seasons along the distribution network: 50% for HAAs and 350% for THMs. Cl_2 , NH_2Cl dose, C/F, and S steps increase DBPs level in warmer seasons	Serrano et al., 2015
RWE; PO (Cl_2); C/F (Al_2Cl_3); S; SF (sand/anthracite); UV (Cl_2; UV; UV/Cl_2;UV/H_2O_2)	THM, HAA, DCAN, BCAN; AOX	**(FS)** Cl_2 dose: 5–10 mg L^{-1}as free chlorine; UV dose: 1800Mj/m^2; Contact time: 30/40	UV/Cl_2: 27 µg L^{-1} for THM and HAA; < 6 µg L^{-1} for DCAN and BACN; 70 µg Cl $L^{-1}$for AOX.	Wang et al., 2015
RWE; C/F (Al2Cl3); S; SF			UV/Cl2: 50 µg L^{-1} for	

Treatment process	DBPs monitored	Operational parameters (PS/FS)	Removal efficiency (%)	References
(sand/anthracite); UV (Cl_2; UV; UV/Cl_2;UV/H_2O_2)		seconds; pH: 6.5-8.5	THM and 19-24 for HAA; 20-70 µg Cl L^{-1} for AOX	
RWE, PO (O_3), pH adjustment, C/F, SF, O_3, GAC filtration, Cl, pH adjustment	Carbonyl compounds	**(FS)** T: 7.4 - 17.7°C; pH: 8.02 – 8.80 O_3 dose: 0.29-0.52 mg/L;	~80% (15 - 62% on GAC filtration)	Papageorgiou et al., 2014
RWE, PO ($KMnO_4$), C (Al_xCl_3), S, SF (sand + anthracite), NH_2Cl, Tanks, Cl+Fl	35 Carboxylic acids	**(FS)** T:9-28°C; NH_2Cl dose 0.7 mg/L; Contact time 20 min; pH 6-8	6.3 µg/L	Jurado-Sanchez et al., 2014
RWE, C, O_3, UF (ceramic membrane), GAC filtration, Cl	4 THMs, 6 HAAs	**(FS)** Cl_2 dose 1.5 mg/L; O_3 dose 2–5 mg/L; Contact time 120 min;	73% for THMs and 75% for HAAs	Fan et al., 2014
4 DWTPs: RWE; PO (Cl_2), C/F, S, SF, Cl_2	THM4, HAA5	**(FS)** pH: 7.4-8.1;	64.38, 43.94, 52.41 and 51.72 µg/L for THM4; HAA5;	Gad-Allah et al., 2012

Notes and abbreviations: RWE – raw water extraction; PO – pre-oxidation; pH adjustment; C/F – coagulation/flocculation; SF – sand filtration; O_3 – ozonisation; GAC filtration; Cl – chlorination; S – sedimentation; Fl – fluorination; NH_2Cl – chloramination; UF – ultrafiltration; Cl_2 – Chlorination; BAC – Biological Activated Carbon; REM – Remineralisation; RO - Reverse Osmosis; UV - Ultraviolet Disinfection; PS – Pilot scale; FS – Full scale.

Adsorption is often applied due to its low cost and operational simplicity, providing a high quality of treated water. The majority of DWT processes (Table 4), applied at pilot or full scale, include adsorption on GAC with high removal efficiencies for DBPs. For nitrosamines removal from DW sources, GAC filtration shows an increased efficiency of DBPs precursor removal or DBPs formed after the disinfection process (Leavey-Roback et al., 2016; Zhang and Yang, 2018). A new approach has been studied to control the formation of THMs, HAAs, and total organic halogen (TOX) in chlorinated drinking water by targeting intermediate aromatic halogenated DBPs instead of NOM by using GAC adsorption, the applicability of this method being influenced by the source water matrices and disinfection conditions. With different bromide levels in source waters and different chlorination contact times, the TOX removals with this new approach (chlorine disinfection prior to GAC adsorption) were always doubled or more than doubled as compared to those of the traditional approach (GAC adsorption prior to chlorine disinfection) (Jiang et al., 2018). However, the potential to remove some DBPs through GAC obviously decreases with the saturation of the adsorbent

(Zainudin et al., 2018). Another disadvantage consists in the need to manage the wastewater resulting from back-washing the GAC filters (Bhatnagar and Sillanpaa, 2017).

In a recent study, Lin et al. (2016) showed that biological activated carbon (BAC) filtration is the most popular technology in DWT process, followed by ozonation. They proved that combined advanced processes (O_3+BAC) significantly improve DCAcAm removal. Few full-scale studies on control and removal of DBPs through BAC processes show that HAAs and THMs formation potential was minimized at 57 % and 45 %, respectively, since bromide concentration was higher after biofiltration. This required a higher capacity to inactivate the microorganisms responsible for the DBPs occurrence (Liu et al., 2017). Different coagulation/flocculation processes ($KMnO_4$, O_3, K_2FeO_4, and ClO_2) applied after pre-treatment resulted in DCAN removal efficiencies higher with 12.9 %, 18.0 %, 16.3 % and 10.1 %, respectively, compared to conventional DWT. When O_3-GAC was added to the DWT process, the removal efficiencies increased to 48.6 %, 53.0 %, 51.0 %, and 48.5 %, respectively (Hu et al, 2018).

Photocatalytic technologies applied for bromate degradation from post-ozonation showed good reduction efficiency, stable performance and easy combination with UV disinfection techniques (UV/TiO_2; UV/SO_3^{2-}; UV/Pt/TiO_2) (Xiao et al., 2017). AOPs with ozone (O_3), hydrogen peroxide (H_2O_2), UV radiation or combinations of these are often used for DBPs removal and recording positive results in DWT processes. Advanced disinfection techniques such as UV or UV/hydrogen peroxide can interact with pharmaceuticals and form hydroxylated compounds and NDMA or can increase some levels of DBPs after chloramine addition (Postigo and Richardson, 2014; Radjenovic et al., 2012).

Membrane filtration is often applied for DBPs removal due to the high removal efficiency especially towards THMs precursors (Sutherland et al., 2015). Ultrafiltration (UF), reverse osmosis (RO), advanced oxidation water treatment by post-ozonation and biological activated carbon (BAC) were demonstrated to have a significant contribution in THMs and HAAs removal from drinking water (Lou et al., 2010; Fan et al., 2014). The removal of DBP precursors is influenced by the presence of bacteria, micropollutants and membrane characteristics. For example, chloroform is easily removed using a UF membrane rather than NF or RO membranes (Bodzek et al., 2002). Different membrane technologies (MF, NF, UF, RO) (Fan et al., 2014; Ersan et al., 2016; López-Roldán et al., 2016) proved their efficiency in DBPs removal (see Table 4), however there is a lack of data regarding the application of membrane processes at pilot or full scale and the operational costs (imposed by the rapid fouling of the membranes), high electricity consumption etc. are not available (Zainudin et al., 2018).

Considering a critical assessment of the ADWT processes analysed (see Table 4), integrated technologies involving membrane processes present higher removal rates for DBPs or precursors compared to single DWT processes. In the case of THM removal, the efficiency sequence follows the order: O_3/BGAC > GAC; O_3/UF > UF and GAC/SF > SF (Zainudin et al., 2018). However, as a general principle, the benefits of a particular technology applied in a DWT process outline are related to the operational parameters adopted. Once applied a certain technology, a number of challenges arise, especially regarding the quality of water supplied to consumers, which must comply with legislation. At the same time, the performance of a treatment technology may be different from plant to plant. Depending on where any specific technology is implemented within the treatment process, it may influence positively or negatively the quality of the water required for human consumption.

5. Conclusions

DWT plants monitoring and management may not fully cover the regulated DBPs occurrence and the further exposure of humans through drinking water consumption. DBPs and their precursors removal from treated water is the key to supply safe drinking water. Unlike the removal of commonly known precursors, which has been greatly developed, up-to-date treatment processes may be not efficient in removing emerging DBPs because of the lack of data on their trace concentrations and the risks associated with these compounds. DBPs removal using a single treatment technology is likely not the best approach for their removal from drinking water. It is necessary to investigate the use of coupled/integrated systems, which can improve the effectiveness of single technologies for the removal of these complex contaminants. The key findings of this study are summarised below.

Firstly, operational parameters such as pH, temperature, disinfectant dose, reagents used, and raw water quality should be carefully analysed and optimized to reduce or remove emerging DBPs in order to comply with current standards and regulations. Secondly, the occurrence of DBPs in drinking water due to their persistence, low biodegradability and concentrations, and the pathways related to population exposure may have the most devastating effects against the human body (particularly, the nervous and reproductive systems) for a long time.

This study represents a solid foundation for further research, and it highlights the strengths and weaknesses of DWT systems, according to their operational parameters. Due to the multitude of DBPs known and their newly discovered health effects, the analytical methods must be continuously improved. A particularity of this review paper is that only the ADWT technologies for DBPs removal from drinking water sources applied at the pilot or full-scale were considered. It was found that a limited number of studies have been performed in this direction. Various treatment technologies, including membrane processes, advanced oxidation processes and adsorption on activated carbon or other materials have found application at pilot and full-scale, and their selection among available existing mature technologies was mainly based on technical operation conditions and economic considerations. According to the studied literature, the treatment processes that are efficient for DBPs removal from drinking water sources are ADWTs combining different treatment technologies, because every raw water source has individual characteristics and from this point of view, the technological treatment scheme should be specifically adapted to improve the DBPs’ removal efficiencies.

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