Review

Disinfection Byproducts and Their Precursors in Drinking Water Sources: Origins, Influencing Factors, and Environmental Insights

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ABSTRACT

Tracing the contamination origins in water sources and identifying the impacts of natural and human processes are essential for ecological safety and public health. However, current analysis approaches are not ideal, as they tend to be laborious, time-consuming, or technically difficult. Disinfection byproducts (DBPs) are a family of well-known secondary pollutants formed by the reactions of chemical disinfectants with DBP precursors during water disinfection treatment. Since DBP precursors have various origins (e.g., natural, domestic, industrial, and agricultural sources), and since the formation of DBPs from different precursors in the presence of specific disinfectants is distinctive, we argue that DBPs and DBP precursors can serve as alternative indicators to assess the contamination in water sources and identify pollution origins. After providing a retrospective of the origins of DBPs and DBP precursors, as well as the specific formation patterns of DBPs from different precursors, this article presents an overview of the impacts of various natural and anthropogenic factors on DBPs and DBP precursors in drinking water sources. In practice, the DBPs (i.e., their concentration and speciation) originally present in source water and the DBP precursors determined using DBP formation potential tests—in which water samples are dosed with a stoichiometric excess of specific disinfectants in order to maximize DBP formation under certain reaction conditions—can be considered as alternative metrics. When jointly used with other water–quality parameters (e.g., dissolved organic carbon, dissolved organic nitrogen, fluorescence, and molecular weight distribution) and specific contaminants of emerging concern (e.g., certain pharmaceuticals and personal care products), DBPs and DBP precursors in drinking water sources can provide a more comprehensive picture of water pollution for better managing water resources and ensuring human health.

1. Introduction

Pollution occurs globally in natural and engineered water systems, and contamination of drinking water sources challenges ecological safety and public health. According to a report by the United Nations Children's Fund (UNICEF) and the World Health Organization (WHO), although 90% of the global population has access to a basic drinking water source, water contamination is widespread, and at least 2 billion people are using drinking water sources that are contaminated with feces [1]. To protect aquatic environments and safeguard drinking water safety, the potential origins of pollutants in drinking water sources and their resultant contamination occurrences should be recognized [2,3]. Among different water contaminants, harmful chemical constituents in raw water can be primarily classified in terms of their origins, such as naturally occurring chemicals, chemicals of industrial origin, chemicals due to human dwellings, and chemicals from agricultural activities [2]. Both natural processes (e.g., climate change (a process that is natural in its progression, despite its anthropogenic sources), and natural disasters such as floods, drought, and wildfire) and human activities (e.g., urbanization, mining, domestic/farm/industrial wastewater discharge, and hydraulic fracturing) may affect the availability and quality of source water and even finished water at drinking water treatment plants (DWTPs) [4–6].

Efforts have been made to develop numerous methods for identifying potential sources of water contamination on a watershed

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scale, such as inventory analysis of pollutant discharge, hydrological modeling, stable isotope tracing, and multivariate statistics [7]. Several specific pollutants are viewed as contamination indicators of different pollution origins. For example, the presence of primidone and carbamazepine suggests possible wastewater-discharge-induced pollution [8]. Caffeine is likely related to fecal and untreated wastewater contamination, while a high ratio of caffeine to carbamazepine may be indicative of a major proportion of raw or insufficiently treated sewage in surface water [9,10]. Sucralose—an artificial sweetener that is extensively found in aqueous environments—is consistently absent in natural waters without wastewater impacts but is constantly detected in wastewater-impacted waters [11]. Therefore, sucralose has been suggested to serve as a tracer for wastewater contamination [11,12].

Disinfection byproducts (DBPs) are a family of secondary contaminants generated during water disinfection. They are formed by the unintended reactions of chemical disinfectants with certain water matrix constituents, known as DBP precursors (e.g., natural organic matter (NOM), anthropogenic contaminants, and halides) [13,14]. Since the first discovery of DBPs in chlorinated drinking water in the 1970s, DBPs have gained a great deal of attention due to their potential adverse health effects [15]. A variety of chemical constituents can serve as DBP precursors, with varied origins such as terrestrial or natural aquatic systems, atmospheric systems, wastewater treatment plants (WWTPs), industrial discharge, human dwellings, aquaculture, and agricultural activities [16–18]. In general, water pollution is directly linked to human activities of urban, industrial, or agricultural origin, and a series of natural events have been found to lead to degradation in surface water quality [4,19–22]. Thus, considerable interest has been directed to the impacts of natural processes and human activities on DBPs and DBP precursors in drinking water sources. For example, tropical storms can dramatically alter the quantity and quality of dissolved organic matter (DOM) in natural water bodies, including those serving as drinking water sources, and thus change the concentration and speciation of DBPs formed during subsequent disinfection at DWTPs [23]. Inappropriate disposal and leakage of bromide- and iodide-containing wastewater from hydraulic fracturing can lead to an increase in these unwanted halides in raw water and further promote the production of DBPs, especially highly toxic brominated and iodinated DBPs [24]. Furthermore, because disinfection typically acts as the last barrier in wastewater treatment, the discharge of WWTP effluent and treated farm and industrial wastewater can potentially introduce the produced DBPs to natural waters [25,26].

Given that source water is a highly complex matrix, it is technically infeasible to identify and quantify all the water constituents. However, studies on DBPs and DBP precursors—where the latter are determined using DBP formation potential (FP) tests—in water sources may open up a new opportunity, due to a greater understanding of the contributions of different pollution origins to specific DBP precursors, the distinct DBP formation patterns from different precursors, and the theoretical absence of formed DBPs in water sources without disinfected wastewater impacts. Here, we hypothesize that DBPs and DBP precursors can potentially serve as alternative indicators to assess the pollution status of drinking water sources, identify the pollution origins, and evaluate changes in source water quality due to natural processes or human activities.

To this end, this study is organized as follows: ① Firstly, we review the origins of DBPs and DBP precursors in drinking water sources and the formation traits of DBPs from different precursors; ② we then summarize natural and human-induced impacts on DBP precursors and produced DBPs in source water; ③ we discuss the feasibility of using formed DBPs and DBP precursors as contamination indicators for drinking water sources; and, finally,

④ we recognize environmental insights and future research needs.

2. DBPs, DBP precursors, and their origins

Since the first discovery of trihalomethanes (THMs) in the mid-1970s, a series of DBPs have been detected in disinfected water all over the world (Fig. 1 [13,16,18,27–53]), including in drinking water, reclaimed wastewater, disinfected hospital wastewater, desalinated seawater, treated produced water from oil and gas extraction, discharge from industrial facilities, and farm wastewater [25,37,54–58]. In general, common organic DBPs include carbonaceous DBPs (C-DBPs), such as haloacetaldehydes (HALs) and widely regulated THMs and haloacetic acids (HAAs); and nitrogenous DBPs (N-DBPs), such as nitrosamines (NAs), haloacetonitriles (HANs), haloacetamides (HAMs), and halonitromethanes (HNMs) [37]. Among these DBPs, THMs, HAAs, HALs, HANs, HAMs, and HNMs share a similar CX_3R structure (where X = H, Cl, Br or I, and R = functional group) and thus have been classified as CX_3R-type DBPs (Fig. S1 in Appendix A) [18,59]. With regard to DBP precursors, as shown in Fig. 1, dominant investigations on DBP precursors in source water have gradually evolved from a focus on naturally occurring chemicals to investigations into anthropogenic contaminants, due to increasing concern over human-related activities on the watershed scale, where drinking water sources are situated.

2.1. Existing DBPs in aquatic environments and their origins

Studies investigating DBPs mostly focus on DBPs in disinfected drinking water, since people are directly exposed to drinking water DBPs, which have been reported to have potentially adverse effects on human health [13]. Moreover, in order to mitigate biofouling and limit the discharge of invasive aquatic organisms and pathogens to receiving water bodies (e.g., surface water, groundwater, and marine water), wastewater is always subject to disinfection treatment, leading to the formation of DBPs [58,60,61]. Since DBPs also pose risks to ecological safety [62–64], the generation of DBPs in disinfected wastewater that is then discharged to the aquatic environment raises considerable concern. Interestingly, after estimating the inputs of DBPs to the marine environment from various industrial activities, based on the volumes of treated water and DBP concentrations in corresponding wastewater types, Grote et al. [65] concluded that cooling water was the predominant anthropogenic source of DBPs, followed by desalination brine and ballast water. Table 1 [60,65–68] presents a summary of DBPs detected in disinfected wastewater, some of which may be important origins of existing DBPs in water sources.

2.2. DBP precursors in water sources and their origins

Fig. 2 provides a schematic of the origins of DBP precursors that are present in natural water sources, as well as general DBP formation pathways via the reactions of inorganic and organic DBP precursors with different disinfectants. In general, certain halide ions (i.e., bromide and iodide), various fractions of NOM or effluent organic matter (EfOM), and specific anthropogenic contaminants, which are derived from various origins (e.g., natural, domestic, industrial, and agricultural sources), can all serve as DBP precursors. Commonly used disinfectants include free chlorine, chloramines, chlorine dioxide, ozone, ultraviolet (UV) treatment, and disinfectant combinations. The formation of DBPs from various disinfection agents has been previously compared [69,70]. In general, each disinfectant tends to form its own suite of DBPs, with some overlap of DBPs among different disinfectants [13]. Free chlorine
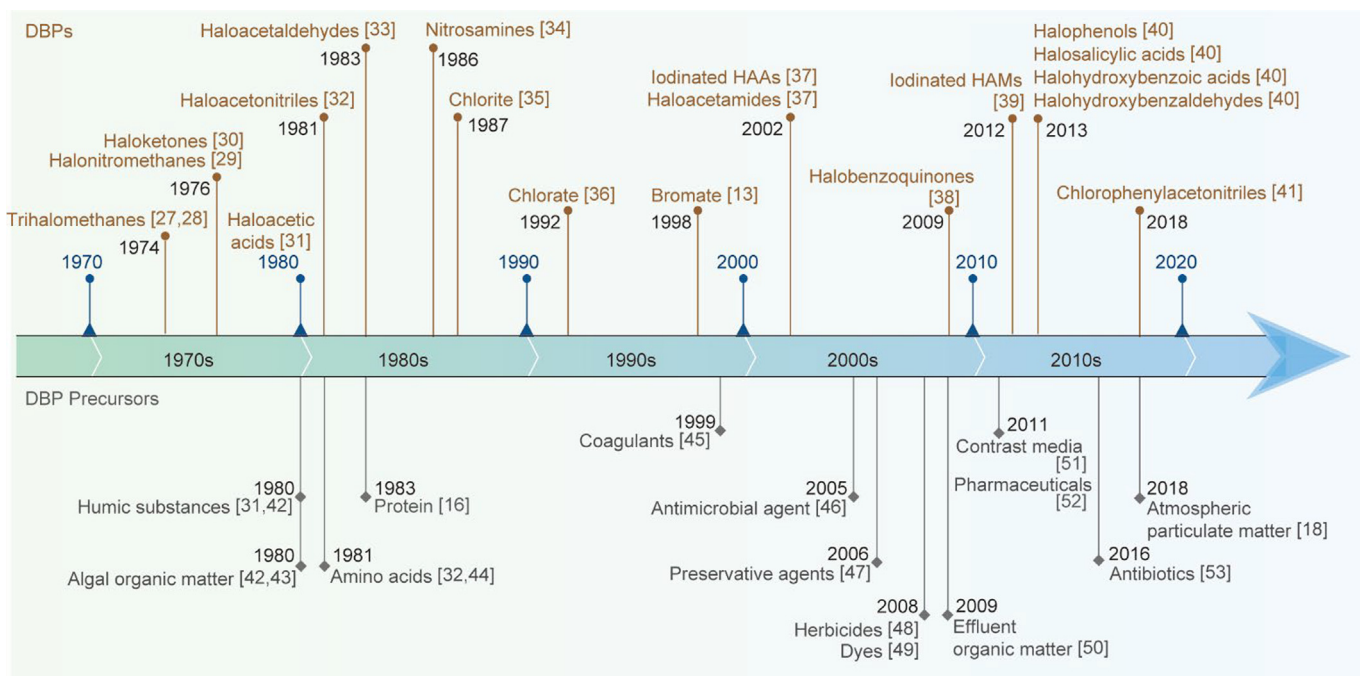
Fig. 1. Chronology of DBPs and DBP precursors reported in the literatures.

mainly produces THMs and HAAs, and chloramines could also lead to the formation of iodinated DBPs and NAs. Chlorine dioxide does not produce halogenated DBPs to any significant degree, except for chlorite and chlorate, and ozone disinfection is generally associated with issues concerning bromate and aldehydes. The sources, characteristics, and DBP formation patterns of representative DBP precursors in water sources have been systematically reviewed elsewhere [16,71–75], and a brief overview is presented below.

2.2.1. Bromide and iodide

Bromide is generally present in fresh water at concentrations ranging from a few micrograms per liter to several milligrams per liter [74], and iodide levels in source water are reported to range from 0.5 to 200 $\mu g \cdot L^{-1}$ [76]. Both natural processes (e.g., seawater intrusion and geologic mineral dissolution) and anthropogenic activities (e.g., seawater desalination, mining, discharge of treated wastewater and industrial effluents, and hydraulic fracturing) can increase the levels of bromide and iodide in aquatic environments [73,77,78]. As for the impacts of bromide and iodide on DBP formation, the presence of bromide increases the total concentration of halogenated DBPs while shifting the prevailing DBP species to brominated DBPs (Table 2) [12,17,56,71,72,76,79–82], because bromine species ($HOBr/OBr^-$) are more active substitution agents than their chlorine counterparts [72,79]. In addition to producing halogenated DBPs, bromide exhibits different effects on the formation of *N*-nitrosodimethylamine (NDMA) in different water matrixes (e.g., model compound water, surface water, and wastewater) [83]. Similarly, the disinfection or chemical oxidation of iodide-containing waters can result in the formation of iodinated DBPs, with the formation characteristics relying on the water types and disinfectant types [73]. The formation of iodinated DBPs during the chemical oxidation of natural water generally follows this order: chloramines > chlorine > ozone [84].

2.2.2. NOM

NOM in drinking water sources either originates externally from the water body (i.e., allochthonous NOM) or is generated *in situ* (i.e., autochthonous NOM). Allochthonous NOM is com-

monly produced from the breakdown of terrestrial plants and thus contains a high aromatic content, while autochthonous NOM, which is mainly derived from phytoplankton, macrophyte, and bacterial sources, tends to have a low aromatic but high organic nitrogen content [72,75,85].

As can be seen in Fig. 1, during the 1980–1990, studies related to DBP precursors in source water principally focused on terrestrial-derived NOM (e.g., humic acid and fulvic acids) and microbial-derived NOM (e.g., amino acids and protein). Later, as water demand dramatically increased due to population growth and urbanization, alternative water sources were sought, and water bodies impaired by unwelcome factors, such as municipal wastewater discharge and algal blooms, were embraced [81]. Consequently, increased attention was paid to wastewater EfOM and algal organic matter (AOM)—both of which principally have microbial origins with abundant dissolved organic nitrogen (DON)—as significant DBP precursors [71,82].

Humic substances are the primary precursors of THMs and HAAs; they are also important in HNMs formation [72]. Moreover, amino acids are the principal precursors of N-DBPs, such as HANs, HAMs, and HNMs [80,81], and the chlorination of amino acids can generate aldehydes, which are further transformed into chloral hydrate (CH) with subsequent or concomitant chlorine substitution [44]. Moreover, produced by exudation or cell lysis during algal eutrophication, AOM is rich in nitrogen with little aromatic structure and thus has substantial potential to produce N-DBPs [49]. Both extracellular and intracellular AOM yield more HAAs than THMs, in which trichloronitromethane (TCNM) and dichloroacetonitrile (DCAN) are two commonly found N-DBPs formed from AOM [71]. In particular, AOM can serve as a significant precursor of NAs and iodinated THMs during chloramination [86,87].

2.2.3. Anthropogenic contaminants

Various anthropogenic contaminants, such as pharmaceuticals and personal care products (PPCPs), industrial chemicals and their byproducts, fungicides, and pesticides, can enter into drinking water sources through wastewater effluent discharge or

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Table 1
Major DBPs detected in disinfected wastewater and their occurrence levels.

Wastewater types	Disinfectants	Dominant DBP species and their occurrence level ($\mu g \cdot L^{-1}$)	References
WWTP effluents	Chlorine	THMs: 11–92 HAAs: 13–136 DHALs: 2.1–12 THALs: 3.8–49 HANs: 0.9–30 NAs: N/A–12.7	[66]
WWTP effluents	Chloramines	THMs: 0.6–15 HAAs: 0–22 DHALs: N/A–6.4 THALs: N/A–2.0 HANs: N/A–12 NAs: N/A–3.165	[66]
WWTP effluents	Chlorine	THMs: 2.3–60.7 HAAs: 7.3–120.1 HANs: 2.9–48.6 HNMs: 1.0–7.4 NAs: 0.35–1.19	[60]
Cooling water	Chlorine	TBM: 3.1–100 DBAA: 7.4–10.3 DBAN: < 0.1–3.6 2,4,6-TBP: 0.02–0.37	[65]
Desalination brine	Chlorine	TBM: 0.2–104 DBAA: 0.6–11.6 DBAN: 0–1.2 2,4,6-TBP: 0.53–0.96	[65]
Ballast water	Chlorine	TBM: 6–920 DBAA: 0.1–230 DBAN: 0.3–133 2,4,6-TBP: 0.1–0.45	[65]
Seawater toilet effluents (first treatment)	Chlorine	TBM: 27 DBAA: 6 DBAN: N/A 2,4,6-TBP: N/A	[67,68]
Seawater toilet effluents (second treatment)	Chlorine	TBM: 32 DBAA: 9 DBAN: N/A 2,4,6-TBP: 0.97	[67,68]

DBP levels in seawater toilet effluents refer to average concentrations. DHALs: dihalogenated acetaldehydes; THALs: trihalogenated acetaldehydes; TBM: tribromomethane; DBAA: dibromoacetic acid; DBAN: dibromoacetonitrile; 2,4,6-TBP: 2,4,6-tribromophenol; N/A: not available.

agricultural runoff, before being transformed into DBPs during subsequent disinfection treatment in DWTPs [12,17,53]. For example, the excretion of individuals using medical drugs and uncontrolled drug disposal (e.g., discarding drugs into toilets) increase the concentrations of pharmaceuticals in municipal wastewater, which may be poorly removed at WWTPs before being discharged into nearby natural water bodies. In a *de facto* water reuse route, these residual pharmaceuticals can return to the raw water downstream of the DWTPs [88]. Furthermore, poor management of veterinary drugs or feed additives in livestock manure at animal feeding operations can lead to the introduction of these substances to source water through agricultural runoff [88].

Most investigations on DBP formation from anthropogenic contaminants focus on NAs and iodinated DBPs, both of which are highly carcinogenic or toxic [12,76]. Levels of NAs and their precursors are negligible in pristine water sources with little pollution from conventional wastewater effluent, which is a dominant source of NAs and their chloramine-reactive and ozone-reactive precursors [86]. The identified chloramine-reactive NA precursors mainly include the herbicide diuron [48], the drug ranitidine [52], and the drug methadone [89]. Moreover, among the identified ozone-reactive NA precursors, dimethylsulfamide is a decomposition product of the fungicide tolylfluanid [90], while 1,1,5,5-tetra methylcarbohydrazide is typically derived from municipal

wastewater containing industrial effluents [91]. As for iodinated DBPs, iodinated X-ray contrast media, which are widely used at medical centers and cannot be completely removed by WWTPs, are more reactive with chlorine than chloramine to form iodinated DBPs, providing a different pathway for the formation of iodinated DBPs from iodide and NOM [51,76].

3. Factors affecting DBPs and DBP precursors in drinking water sources

Water quality—particularly NOM characteristics—in drinking water sources can be greatly influenced by both natural events and anthropogenic activities. Fig. 3 presents a series of examples of factors affecting DBPs and DBP precursors in drinking water sources. Special attention should be paid to climate change, which has profound impacts on source water quality, including basic physical and chemical parameters (e.g., temperature, pH, turbidity, and dissolved oxygen), DOM, nutrients, metals, micropollutants, and biological contaminants (e.g., pathogens and cyanobacteria) [4,6]. Besides the constant increase in the global averaged annual surface temperature, a changing climate is strongly associated with the increasing frequency and intensity of climate- and weather-related natural disasters (e.g., droughts, floods, tropical storms, and wildfires) and unwelcome events (e.g., seawater intrusion and harmful algal blooms), which lead to changes in source water availability and quality [92–95]. However, it should be noted that climate change is not the only cause of the aforementioned natural disasters or extreme events.

Anthropogenic activities can pollute water sources via both point and non-point routes. Wastewater discharges (e.g., domestic wastewater, industrial wastewater, farm wastewater, and hydraulic fracturing wastewater) receive considerable attention as point sources contributing to source water pollution. In contrast, atmospheric deposition and agriculture/urban runoff are perceived to be non-point sources [96,97]. In general, non-point pollution sources contribute more contaminants to water sources than point pollution sources.

3.1. Natural factors

3.1.1. Droughts

Droughts can have multiple impacts on drinking water sources. First, the loss of water due to enhanced evaporation in a drought can concentrate the NOM, halides, and anthropogenic contaminants originally present in raw water, thereby increasing the formation of DBPs during drinking water production [12,92]. Second, when droughts are compounded with a *de facto* reuse scenario, the fraction of treated wastewater effluent in the receiving water bodies grows accordingly, raising the contributions of halides, as well as EfOM containing soluble microbial products (SMPs) and anthropogenic contaminants, to DBP formation [50,98]. Third, the resultant increase in the nutrient contents in source water during a drought can trigger algal blooms, altering the composition of organic matter and increasing AOM-related DBP precursors [93,99]. Therefore, autochthonous NOM most likely serves as the dominant origin of DBP precursors in eutrophic lakes or in source water experiencing low or intermittent rainfall events [85].

3.1.2. Storms and floods

Extreme storms and floods can rapidly increase sediment, organic matter, turbidity, and pathogens in source water through urban drainage (e.g., combined sewer overflow), subsurface flow, surface runoff, and the re-suspension of bottom sediments [100–102]. It is also noteworthy that the adverse effects derived from
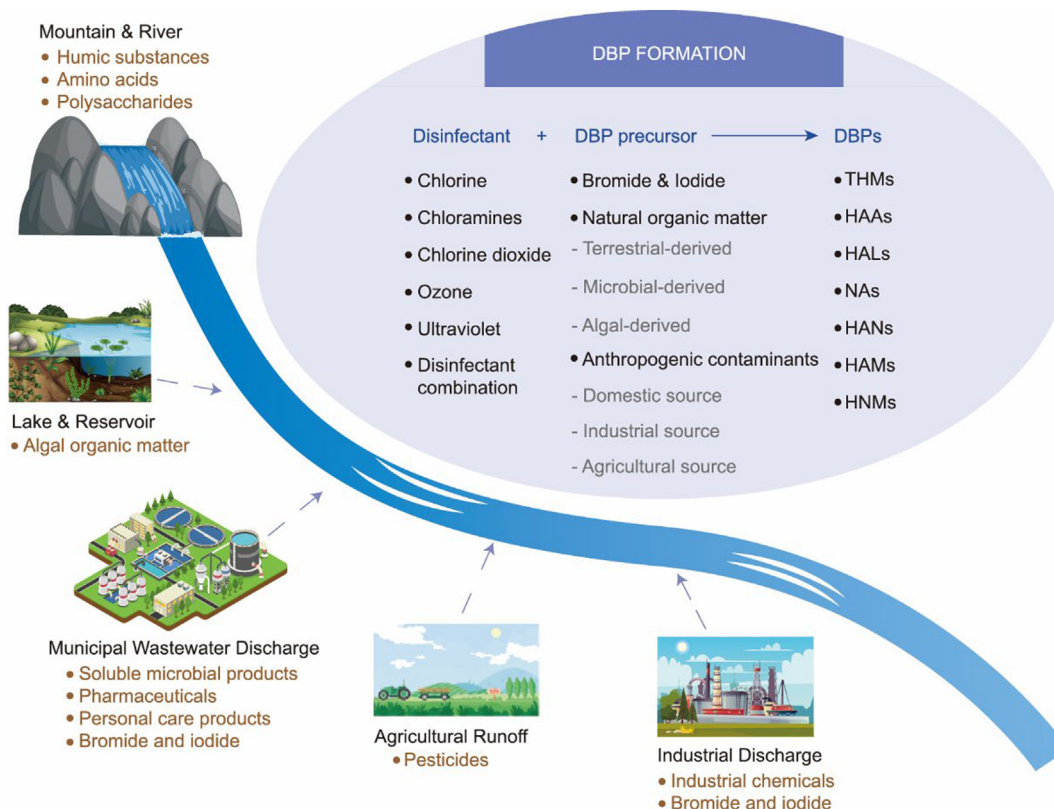
Fig. 2. Schematic of different origins of DBP precursors in drinking water sources and the reaction pathways of organic and inorganic DBP precursors with disinfectants to form DBPs.

short-term extreme flooding can last for several weeks, even after water levels have returned to base flow conditions.

The effects of storms and floods on DOM and DBP precursors depend on the characteristics of the catchments and the precipitation patterns of the storm events [103,104]. More specifically, terrestrial-derived DOM with high levels of DBP FP was reported to enter a large watershed during storm events, with a higher DBP precursor content resulting from a more intense storm event [105]. Rainfall events can alter the reactivity of organic matter in drinking water sources with an increase in THM FP, whereas the impact on HAA FP has been shown to be less noticeable [106]. Decreases in the proportions of brominated THM FP and brominated HAA FP during and after rainfall were also observed, compared with pre-rainfall periods [106]. In addition, storm drainage was found to contribute to NA precursors, with the FPs of total NAs approaching approximately 100 ng·L^{-1} [80]. Notably, intensive short-term events such as tropical storms, which mainly occur in coastal regions and are connected to extensive rainfall and flooding, have been reported to export DBP precursors into source water and thus significantly impact drinking water quality [23,107].

3.1.3. Seawater intrusion

The occurrence of seawater intrusion is related to local sea level rise and/or prolonged dropdown in coastal groundwater levels as a result of climate change, groundwater over-extraction, land-use change, or sea-level fluctuations [94]. Apart from elevated levels of total dissolved solids and chloride ions, the formation and speciation of DBPs (e.g., THMs, HAAs, and bromate) as a function of increased bromide and iodide resulting from seawater intrusion are of particular concern when estuary surface water or coastal groundwater is adopted as source water, especially in dry seasons [108–110].

Bromide in the Pearl River Basin, which is the second largest river area in China, can reach 1975.64 μg·L^{-1} in dry seasons as a result of seawater intrusion [110]. Moreover, an increasing bromide level (up to 0.8 mg·L^{-1}) in source water exported from the Sacramento–San Joaquin River Delta in the United States was reported, which was related to saltwater intrusion from San Francisco Bay, leading to an increase in the levels of total THMs, a shift toward the formation of more brominated species during chlorination, and the increased production of bromate during ozonation [111]. It should be noted that even small changes in saltwater intrusion can significantly impact the levels of total THMs and the extent of bromine incorporation in THMs [108,109]. Higher frequencies of regulatory violations of halogenated organic DBPs, especially brominated THMs, and HAAs, in groundwater systems on coastal islands in Washington DC, USA, have been reported. Plausible reasons include elevated bromide levels originating from seawater intrusion and the different composition and amount of DOM present in groundwater compared with surface water [112].

3.1.4. Wildfires

In recent years, the amount, scale, and severity of wildfires have gradually increased across the world as a consequence of climate change, fuel load accumulation, extensive droughts, or increased human activities in forests [95]. Post-fire rainstorms increase surface runoff and erode ash and soil from burned landscapes, thereby posing a great threat to forest watersheds. In addition, elevated nutrient levels accompanied by resultant post-fire algal blooms, which increase suspended sediment and metals, as well as changes in the quantity and composition of DOM in water sources, are reported to be associated with wildfires [5,95]. Wildfires can destroy forest ecosystems within a short time, and changes in

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Table 2
General information on DBP precursors in drinking water sources.

Representative substances	Main sources	Characteristics or composition	DBP formation patterns	Representative references
Bromide	A series of natural and anthropogenic activities	Present in water sources at levels ranging from a few micrograms per liter to several milligrams per liter	• Increase total DBP formation • Shift prevailing DBP species to brominated DBPs	[56,79]
Iodide	A series of natural and anthropogenic activities	Present in water sources at levels between 0.5 and 200 $\mu g \cdot L^{-1}$	• Promote the formation of iodinated DBPs	[76,79]
Humic substances	Breakdown of terrestrial plants	High aromatic content	• Serve as primary precursors of THMs and HAAs	[72]
Amino acids	Microbial activity	High organic nitrogen content	• Serve as principal precursors of N-DBPs and HALs	[80,81]
Algal organic matter	Exudation or cell lysis during algal eutrophication	Low aromatic portions and high organic nitrogen contents	• Show substantial potential to produce N-DBPs	[71,75]
Effluent organic matter	Biological WWTP effluent	High organic nitrogen content	• Show substantial potential to produce N-DBPs	[75,82]
Anthropogenic contaminants	Domestic and industrial discharge, farm wastewater, or agriculture runoff	Pharmaceuticals, personal care products, fungicides, pesticides, industrial chemicals	• Contribute to the formation of highly toxic DBPs such as NAs and iodinated DBPs	[12,17,76]

source water quality and treatability persist for several years or even decades [113,114].

Changes in the quantity and composition of DOM in drinking water sources resulting from wildfire heating and subsequent rainfall events may influence DBP formation and speciation during water disinfection treatment. Post-fire rainstorm samples show elevated DOM reactivity in the formation of HAN and TCNM, whereas their DOM reactivity in forming THM and HAA is similarly to non-storm samples [115]. Wildfires also lead to more abundant NDMA precursors [114]. Fire-altered terrestrial DOM is generally found to be more reactive in producing N-DBPs compared with humic acids and even algal and bacterial materials [115–117]. Notably, increased HAN precursors in post-fire watersheds may also be associated with algal blooms due to increased nitrogen exported from burned catchments [113]. In addition, the growth of bromide concentrations in raw water and an increase in the bromine incorporation factor in THMs and HAAs after wildfire have been reported [114,116].

3.1.5. Algae blooms

Eutrophication and climate change can promote the proliferation and expansion of harmful algal blooms, which can influence source water quality, water treatment performance, and drinking water safety [93]. The characterization of algae-derived NOM and the formation and speciation of DBPs have been extensively studied [71,85]. Both AOM and its associated toxins can serve as DBP precursors during disinfection [118,119]. As mentioned above, AOM exhibits a lower specific C-DBP FP (μg of C-DBP/mg of dissolved organic carbon (DOC)) than allochthonous NOM, whereas algal-impacted water is considered to have a higher potential for the formation of N-DBPs [120,121]. Interestingly, although the overall DOC in water changes during the algal growth phase, the specific C-DBP FP is not a function of this phase [121,122]. A full-scale study further confirmed that harmful algal bloom events in drinking water sources contribute to the enrichment of DBP precursors [123]. Algal blooms can also arise from wildfires due to elevated nutrient (e.g., inorganic nitrogen and phosphorus) inputs into water sources [124]. Moreover, post-fire algal blooms have been found to increase the chlorine reactivity of wildfire-affected terrestrial DOM for DBP formation through biogeochemical processes [125].

3.1.6. Sunlight

Heightened solar UV radiation, likely due to climate change and ozone depletion, can alter organic matter characteristics in fresh water systems via temperature variation and photolysis. The effect may vary depending on the origin, composition, and form of organic matter present in the source water [126,127]. Although the overall DOC in natural water samples does not change significantly after irradiation, solar irradiation causes a shift in the DOC from a humic-like to a hydrophilic character and thus decreases the aromaticity of DOM [128]. Consequently, the reactivity of DOC with respect to HAA formation tends to decline after irradiation, whereas the relative degree of bromine incorporation into THMs and HAAs shows an increasing trend [128]. Furthermore, significant increases in specific HAN FP (μg of HAN/mg of DOC) and specific CH FP (μg of CH/mg of DOC) are reported when leachates from fresh litter are exposed to sunlight [129]. Unlike NOM, the SMPs in EfOM are relatively amenable to solar photolysis, and the reactive intermediate species formed by the solar irradiation of SMPs favor the formation of THMs, CH, and TCNM [130]. The effects of sunlight on the HAN FP and TCNM FP of wastewater effluent have also been investigated [131,132]. In addition, solar irradiation can promote the release of DOM from particulate organic matter. The photo-released DOM from soil mainly contains humic-like components exhibiting a high THM FP, whereas the
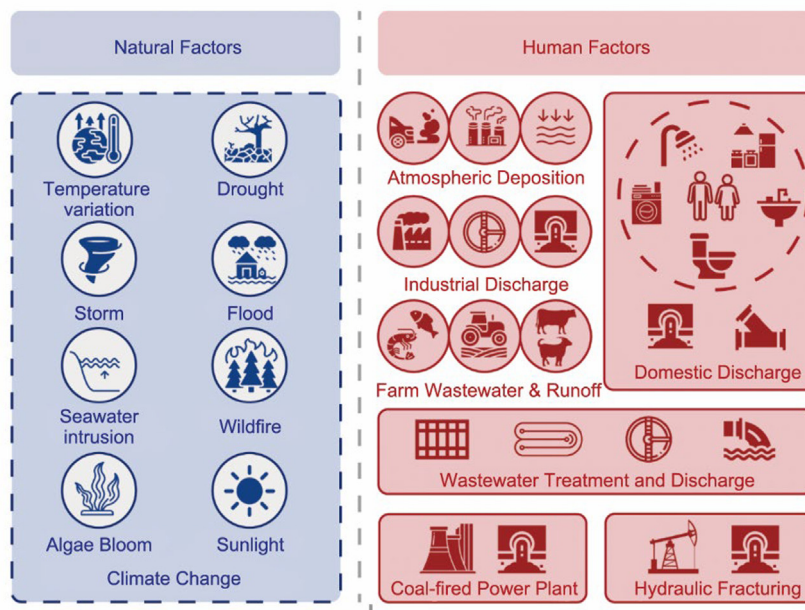
Fig. 3. Natural and human factors affecting DBPs and DBP precursors in drinking water sources. Note that, although climate change is known to be anthropogenic, it acts to intensify many otherwise natural factors, so it is shown at the bottom of that category.

photo-released DOM from litter leaves principally comprises protein-like substances with a high HAA FP [133,134]. Notably, sunlight photolysis is reported to mitigate NDMA formation when methadone serves as the NDMA precursor during chloramination [135].

3.2. Human factors

3.2.1. Atmospheric deposition

Pollutant emissions to the atmosphere can be generally categorized into anthropogenic emissions (e.g., industrial stacks, municipal waste incinerators, agricultural activities, and vehicle exhaust), natural emissions (e.g., volcanic eruptions, windblown gases and particles from forest fires, windblown dust, soil particles, and sea spray), and re-emitted emissions [136]. Primary carbonaceous particulate matter (PM) in the atmosphere predominantly originates from the intentional combustion of biomass and fossil fuel [137]. Thus, atmospheric deposition is generally classified as an anthropogenic factor.

Atmospheric deposition results in significant impacts on surface water quality [136,138]. Both dry (i.e., particulate and gaseous deposition) and wet depositions (i.e., precipitation such as rain and snow) can contribute to an increase in DBP precursors in surface water [18,139,140]. Hou et al. [18] demonstrated that the contribution of PM-derived DOM to the formation of some CX_3R-type DBPs (e.g., trichloroacetic acid (TCAA), DCAN, TCNM, and dichloroacetamide) during the chlorination of rainwater could not be ignored. Moreover, He et al. [139] reported that atmospheric dry deposition contributed DOM and DBP precursors to surface water and that these were particularly related to the formation of trichloromethane (TCM), dichloroacetic acid, and TCAA. However, information from the literature on PM-derived DBP precursors remains limited, and further research is required.

3.2.2. Domestic effluent discharge

Municipal wastewater, which comprises greywaters (i.e., wastewater from showers, kitchen sinks, bathroom washbasins, and laundry) and blackwaters (i.e., urine and feces), is recognized as an important source of NAs and their precursors [57,86,141].

Given that domestic wastewater is generally collected in sewer systems, treated in WWTPs, and discharged into adjacent natural water bodies [142], and that EfOM can affect the quality of raw water in the context of its *de facto* reuse [50,82], this section mainly focuses on the impact of WWTP effluent on DBP precursors and DBP levels in receiving water bodies.

DBPs are formed during disinfection treatment, which is typically the last barrier in water treatment plants. Therefore, the effluents of WWTPs contain both DBP precursors and formed DBPs generated during wastewater disinfection [14,143]. In a US survey, the median concentrations of THMs, HAAs, HANs, dihalogenated HALs, and trihalogenated HALs in chlorinated WWTP effluents were reported to be 57.0, 70.0, 16.0, 7.2, and 16.0 $\mu g \cdot L^{-1}$, respectively [66]. With regard to surface water, Heng et al. [26] investigated the occurrence of volatile halogenated DBPs in an urban river supplied by reclaimed wastewater in Beijing, China. Their results indicated that TCM and CH were detected in all river water samples, with the highest levels reaching 485.1 and 30.8 $\mu g \cdot L^{-1}$, respectively.

Wastewater-derived DBP precursors are also of concern [50,144]. In general, EfOM is a combination of NOM, SMPs, and trace harmful chemicals such as anthropogenic micropollutants [82]; it is characterized by a higher DON content, lower DOC/DON ratio, and higher N-DBP FP than NOM [145]. Notably, certain PPCPs and NDMA FP in drinking water sources are suggested to serve as potential indicators of the impact of treated wastewater on watersheds [8].

3.2.3. Farm wastewater or agriculture runoff

Chemicals used in crop production (e.g., fertilizers, herbicides, and pesticides), animal husbandry (e.g., veterinary drugs, feeds, and additives), and aquaculture (e.g., fertilizers, feeds, and additives), as well as constituents of the excretion of livestock and aquatic products, are likely to be present in farm wastewater effluent or agriculture runoff and may enter water sources [2,25,146]. In addition to determining the yields of DBPs from specific DBP precursors, such as herbicides (e.g., diuron and bromacil) and veterinary antibiotics (e.g., minocycline) [48,147,148], several studies have quantified the levels of different DBPs and DBP FPs in farm

effluent or agriculture runoff. The contribution of farm wastewater or runoff to DBPs and DBP precursors generally depends on the feeds, pesticides, and pharmaceuticals used in the farms, as well as the treatment procedures applied to treat farm wastewater, which mainly include biological treatment, chemical oxidation, and disinfection.

Eckard et al. [149] reported that the THM FP of irrigation runoff from agriculture systems was higher than that of runoff from a natural forested area and that of shrubland/grassland watersheds. However, compared with other domestic and industrial wastewaters, runoff related to crop production is a less significant contributor to NAs and their precursors [25,86]. To be specific, runoff from animal husbandry can serve as a source of NDMA, N-nitrosopyrrolidine (NPYR), and their chloramine- and ozone-reactive precursors [86]. In fact, the concentrations of NDMA, N-nitrosodiethylamine (NDEA), NPYR, N-nitrosomorpholine (NMOR), and N-nitrosodibutylamine (NDBA) in swine wastewater can reach hundreds to thousands of nanograms per liter [25]. Notably, the contribution of livestock-breeding wastewater to NAs and NA precursors is largely dependent on the treatment process. For example, almost all NA precursors can be transformed into NAs when livestock-breeding wastewater is subject to complete anaerobic digestion, whereas residual NA precursors can exist in the case of incomplete anaerobic digestion [150].

Aside from agricultural activities, wastewater generated from aquaculture can also contribute DBPs and their precursors. For example, DOC and bromide levels in shrimp farm effluents have been reported to be relatively high, and the THM FP of analyzed shrimp farm effluent can range from 810 to 3100 $\mu g \cdot L^{-1}$ [146]. Chen et al. [25] reported that NDMA, NDEA, and NDBA were detected in an aquaculture pond, with NDBA being the most abundant NA species. The NA level and NA FP in fishery ponds were found to be lower than those in other wastewaters (e.g., WWTP effluent, industrial wastewater, and livestock-breeding wastewater); however, N-nitrosomethylethylamine (NMEA) has rarely been detected in wastewaters other than fishery ponds [150].

3.2.4. Industrial effluent discharge

The compositions of industrial effluents are quite complex. DBPs and their precursors may be present in different treated industrial wastewater effluents, and their levels and constituents largely depend on the nature of the industrial processes. Some examples can shed light on the role of industrial effluent discharge. First, the treated wastewater from shale drilling operations, waste from coal-fired power utilities, brine from oil and gas wells, and discharge from some specific industrial facilities are reported to contain elevated bromide levels, and their discharge can increase the bromide levels in receiving natural water bodies [151,152]. The following two sections will further introduce bromide-related processes and their impacts on DBP formation in detail.

Second, industrial wastewater, including textile printing and dyeing wastewater, electroplating wastewater, metal finishing wastewater, food processing wastewater, pulping wastewater, fine chemicals wastewater, mechanical industrial wastewater, cosmetics and personal care product manufacturing wastewater, and pharmaceutical manufacturing wastewater, have been found to contain NAs and their precursors. Notably, discharge from metal finishing and electronics-related facilities, as well as the effluent of textile printing and dyeing processes, contain high NDMA levels [25,57,150]. Textile printing and dyeing wastewater also possess a high NDMA FP, while electroplating industrial wastewater has significantly high levels of NDEA and NDEA FP [150].

Third, in addition to the aforementioned industrial wastewaters that contribute bromide or NAs and their precursors, effluent discharge from other industrial facilities can act as a source of DBPs and DBP precursors [65,153]. Interestingly, dairy processing facilities, in which iodine and iodine sanitizers (e.g., iodophors) are commonly used, can be a potential and significant source of iodinated DBPs in receiving water bodies [154]. The combined use of iodine, other iodine compounds, and disinfectants (i.e., chlorine) within dairy processing facilities or downstream WWTPs contributes to the formation of iodinated DBPs, especially iodinated THMs. In addition, coking wastewater generated from the manufacturing and processing of iron in steel industries has been found to possess a relatively high DBP FP [155].

3.2.5. Coal-fired power plants

The addition of bromide-containing salts (e.g., calcium bromide) to a coal combustion unit is an effective method to enhance mercury removal in coal-fired power plants operating wet flue gas desulfurization [152]. In general, the dosed bromide cannot be removed and will ultimately be discharged, leading to the enrichment of bromide in source water and downstream DWTP intakes [156,157]. Although bromide in surface water typically does not pose a threat to ecosystems, a dramatic increase in total DBP formation and a shift to more brominated DBP species at downstream DWTPs can be expected when bromide loadings are elevated in source water [158,159]. It was reported that a wet scrubber installation at a power plant increased bromide levels in raw water and the concentration of brominated DBPs in finished water at four downstream DWTPs [152].

3.2.6. Gas extraction

Hydraulic fracturing has gradually emerged on a global scale, expanding the extraction of natural gas from geologic deposits. During this process, part of the injected water eventually returns to the surface as flowback water or produced water (fluids that are extracted together with the natural gas during production), both of which typically contain elevated levels of total dissolved solids, salinity, and toxic metals and metalloids [160,161]. Hydraulic fracturing wastewater (HFW) may be reused onsite for gas extraction, injected into underground, or discharged to surface water after treatment [151]. However, surface water can be adversely impacted by HFW due to surface leaks and spills occurring near drilling locations, the direct disposal of untreated wastewater, and the discharge of inadequately treated wastewater [78].

The impact of HFW on the DBP formation at downstream DWTPs is mainly associated with bromide enrichment in drinking water sources [151,162]. For example, the discharge of treated HFW was found to contribute to a sharp increase in the bromide level in a US river, ranging from 88 to 1220 $\mu g \cdot L^{-1}$ [152]. With the use of blended solutions prepared by diluting HFW with fresh water, Parker et al. [24] found that the impact of HFW on DBP formation and speciation was largely dependent on the dilution factor and the type of disinfectant. More specifically, when the dilution factors were as low as 0.01%–0.1%, HFW promoted the formation of THMs and HANs during chlorination, the production of NDMA and iodinated THMs during chloramination, and the generation of bromate during ozonation [24]. Moreover, a shift toward increased bromine substitution for the formation of THMs, dihalogenated HAAs, trihalogenated HAAs, and dihalogenated HANs during chlorination has been reported when the water to is disinfected is influenced by shale gas produced water [163].

Elevated ammonia levels in treated oil and gas wastewater have been found to enhance the formation of N-DBPs during chlorination [164]. Other non-bromide ions, including metal ions (e.g., magnesium, calcium, and barium) and sulfate, also affect DBP formation due to catalytic effects [165]. Notably, in addition to DBP precursors (e.g., bromide and phenols), treated produced water from oil and gas extraction, in which the concentration of total THMs and dibromochloronitromethane could reach micrograms per liter level, can be a source of formed brominated DBPs [56].

4. Discussion

In this section, we will discuss the technical feasibility of adopting DBPs and DBP precursors as promising indicators for assessing pollution in drinking water sources (Fig. 4). In general, DBP precursors in drinking water sources can be determined using DBP FP tests, in which source water samples are dosed with a stoichiometric excess of specific disinfection agents (e.g., chlorine or chloramines) for a reaction time that is designed to maximize DBP formation under certain reaction conditions [166,167]. The formed DBPs in Fig. 4 are mainly DBPs derived from disinfected wastewater (e.g., WWTP effluent, farm effluent, and industrial effluent), which is discharged into adjacent natural water bodies and leads to the presence of DBPs in drinking water sources.

DBPs that are originally present in drinking water sources and DBP precursors determined using DBP FP tests can potentially be used to trace the origins of DOM in drinking water sources and evaluate the impacts of natural or anthropogenic events on source water quality. Moreover, DBPs and DBP precursors combined with other general parameters (e.g., DOC, DON, UV absorbance at 254 nm (UV_{254}), and fluorescence excitation–emission matrix spectroscopy) and certain contamination indicators (e.g., primidone, carbamazepine, caffeine, and sucralose) can provide further insightful information. A detailed discussion is presented below.

4.1. Concentration and speciation of existing DBPs derived from disinfected wastewater and DBPs generated during DBP FP tests

Since DBPs are unique secondary contaminants produced during water disinfection, it is expected that the presence of relatively high levels of DBPs in drinking water sources indicates the effect of treated wastewater discharge on water sources [14]. Reports have frequently identified a suite of DBPs (i.e., THMs, HAAs, and HALs) at high concentrations in source water impacted by WWTP effluents [26,66,168]. Furthermore, the detection of iodinated DBPs in drinking water sources might result from the discharge of wastewater with a high iodinated DBP level, such as WWTP effluents that receive dairy waste and wastewater produced during dairy processing [154]. Remarkably, high NA levels in source water can be associated with the discharge of WWTP effluent, treated farm wastewater, or industrial wastewater, and he special treatment of farm or industrial wastewater may generate specific NA species [25,150]. More specifically, treated wastewater from metal finishing and electronics-related facilities, textile printing, and dyeing typically contain high levels of NDMA, whereas NMEA is barely detected in wastewater except for those from fishery ponds [25,150].

With respect to DBP precursors, EfOM in WWTP effluent and AOM derived from algae blooms are important sources of DON in drinking water sources, which makes a significant contribution to the formation of N-DBPs (e.g., HANs, HAMs, HNMs, and NAs) during disinfection (Fig. 4) [71,145]. Notably, in addition to eutrophication and climate change, droughts and wildfires can trigger algal blooms. An increase in the overall DBP formation and a greater extent of bromine incorporation in DBPs during DBP FP tests can likely be ascribed to an elevated bromide level in drinking water sources. Similarly, increased iodide levels promote the formation of iodinated DBPs, especially in the case of chloramine disinfection. As mentioned above, increasing bromide and iodide levels in water sources may be caused by seawater intrusion, aquaculture wastewater discharge, coal-fired power plant discharge, and hydraulic fracturing. A series of micropollutants derived from var-
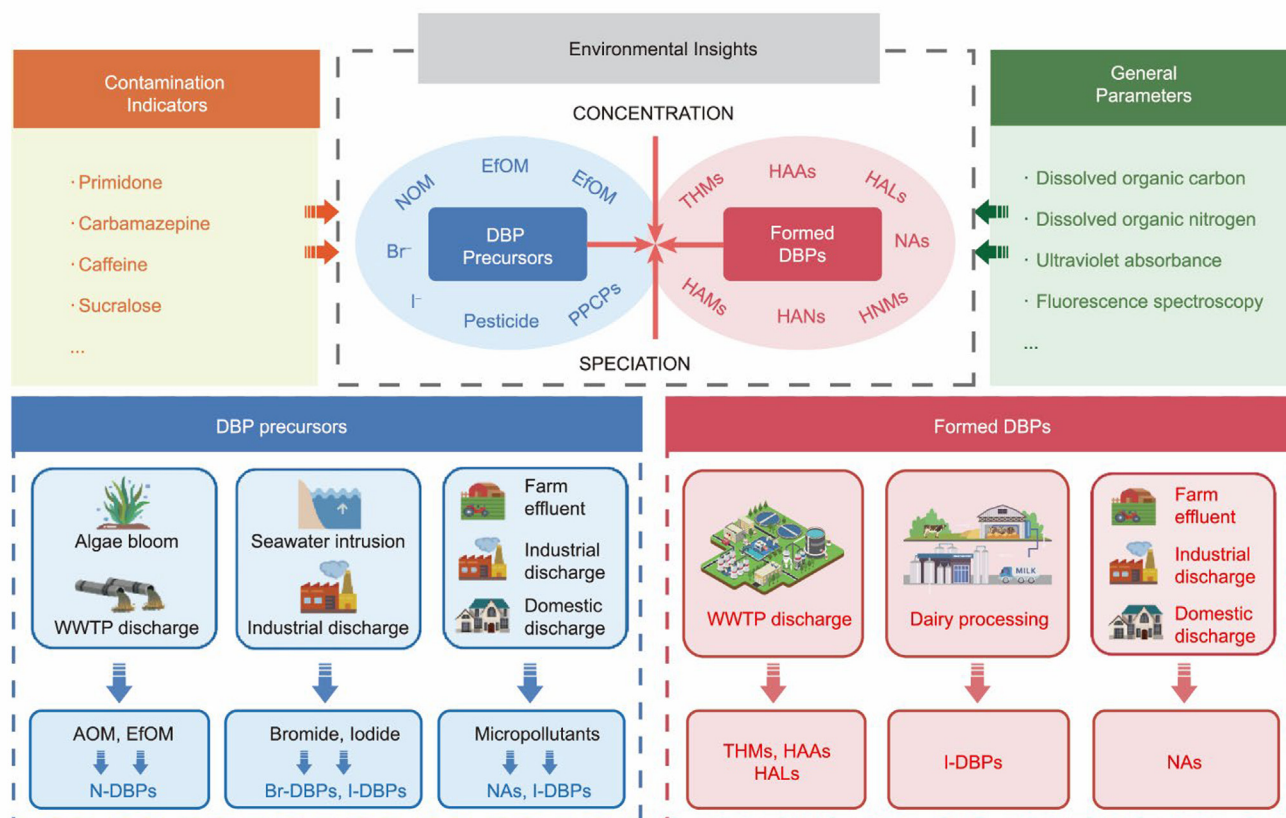

Fig. 4. A schematic illustration of insights into the use of DBPs and DBP precursors as potential contamination indicators in drinking water sources. Br-DBPs: brominated DBPs; I-DBPs: iodinated DBPs.

ious wastewater discharges (e.g., farm effluent, industrial discharge, and domestic discharge), including PPCPs, industrial chemicals, fungicides, and pesticides, can serve as the precursors of NAs [17]. Moreover, the increased formation of iodinated DBP during a DBP FP test using free chlorine may be associated with contamination from wastewater containing high levels of iodinated X-ray contrast media [51,169]. Interestingly, the ratio of HAN FP to THM FP has been adopted to assess the impact of wildfires on source water [115], implying that different DBP FP ratios can be applied as pollution indicators.

4.2. DBPs and DBP precursors combined with other general parameters or certain contamination indicators

Several analytical methods have been used to characterize the organic matter present in source water and evaluate the effectiveness of water treatment processes, including bulk parameter (e.g., DOC and DON) determination, spectroscopic methods (e.g., UV and visible absorption spectroscopy, and fluorescence), chromatographic methods (e.g., high-performance size exclusion chromatography) and mass spectrometric methods (e.g., liquid chromatography–mass spectrometry and gas chromatography–mass spectrometry) [170,171]. This subsection discusses studies that have combined DBPs and DBP precursors with other general parameters or certain contamination indicators to determine the origins of pollution in drinking water sources and to evaluate changes in source water quality arising from natural or human events.

Specific DBP FP (µg of DBP/mg of DOC), which is obtained by normalizing the DBP FP via DOC concentration, is considered to indicate the relative abundance of disinfectant-reactive components in organic matter; thus, it can provide insights into the sources of DBP precursors [20,21]. For example, post-fire rainfall samples were found to have increased reactivity in forming HAN and TCNM, whereas the impact of wildfire on DOM reactivity toward the formation of THMs and HAAs was reported to be insignificant [5,116]. However, efforts are needed to quantitatively relate DOM origins with the ranges of specific DBP FP values, because this is expected to provide a benchmark for tracing the source of DOM. Wastewater discharge with higher DON content and a lower DOC/DON ratio can result in a higher N-DBP FP of wastewater-impacted water bodies [145]. Recently, a companion study systematically investigated the spatial variation in DOM characteristics on a basin scale using size-exclusion chromatography and fluorescence spectroscopy and identified 36 DBPs that had formed in chlorinated surface water [172]. Based on the results of DOM characterization and DBP formation, Fang et al. [172] reported a high diversity in DOM characteristics along the Yangtze River; the varied DOM characteristics corresponded with different formation patterns of DBPs upon chlorination. In addition, inspired by the perspective that DBP monitoring can provide insights into hydro-biogeochemical dynamics within a watershed, Leonard et al. [173] combined historical drinking water quality archives, including the speciation and levels of DBPs, synoptic watershed sampling, and targeted spectroscopic characterization methods, to identify an export control point for DOM in a subalpine headwater stream.

In addition to the aforementioned general parameters, certain contamination indicators in source water can be jointly used with DBPs and DBP precursors to provide more in-depth information regarding pollution in drinking water sources. Primidone, carbamazepine, and NDMA FP have been shown to be possible indicators of wastewater discharge [8]. Based on this finding, Aydin et al. [19] made efforts to explore the source of contaminants in a watershed in Turkey by determining caffeine levels and measuring THM FP

and NDMA FP. The presence of caffeine and THM FP suggests that the pollution is due to the discharge of municipal wastewater, whereas NDMA FP is mostly associated with domestic discharge, industrial discharge, and/or agriculture runoff. With the combined use of these indicators, Aydin et al. [19] were able to identify specific contamination sources of the watershed.

5. Summary and environmental insights

DBP precursors in drinking water sources have a range of origins, including natural, domestic, industrial, and agricultural sources. These precursors are generally classified into inorganic halide ions, NOM, and anthropogenic contaminants. The presence of bromide and iodide can promote total DBP formation, especially brominated DBPs and iodinated DBPs. With respect to NOM, allochthonous NOM with a high aromatic content can act as the primary precursors of C-DBPs, whereas autochthonous NOM with low aromatic and high organic nitrogen contents contributes significantly to the formation of N-DBPs. Research related to DBP formation from anthropogenic contaminants mostly focuses on NAs and iodinated DBPs. There are two primary disinfectant types—that is, chloramines and ozone—that have a higher potential to react with the precursors to form NAs. Moreover, it has been found that conventional wastewater effluent can be a dominant source of chloramine-reactive NA precursors and ozone-reactive NA precursors. It is notable that iodinated DBPs are generally formed from the reactions of iodide, NOM, and chloramine, while iodinated X-ray contrast media significantly contribute to the formation of iodinated DBP upon chlorination.

Table 3 summarizes the impacts of different natural events and anthropogenic activities on DOM characteristics, DBP precursors, and DBPs in drinking water sources, as well as the corresponding relevant processes. Clearly, the changes in source water quality arising from different processes are quite different, but different events may share some similarities. For example, droughts generally lead to a higher concentration of halide, NOM, and anthropogenic contaminants in source water, whereas storms and floods can transport terrestrial-derived DOM through storm water runoff and introduce wastewater-related contaminants through urban point-pollution sources. In comparison, elevated bromide levels can have either a natural or an anthropogenic origin.

DBP precursors originating from various sources (e.g., natural, domestic, industrial, and agricultural sources) exhibit different DBP formation behaviors. Moreover, based on the theoretical absence of DBPs in non-polluted natural waters, the detection of relatively high levels of DBPs in drinking water sources implies contamination by treated wastewater discharge (e.g., WWTP effluent, farm effluent, and industrial effluent). Thus, we argue that DBPs and DBP precursors in raw water can serve as alternative indicators to assess the pollution of drinking water sources. Here, environmental insights and future research needs are highlighted in three aspects.

(1) The concentration and speciation of DBPs originally present in source water and DBP precursors determined using DBP FP tests can provide insightful information on the pollution significance of drinking water sources and can be used to trace pollution origins. When used jointly with other common water quality parameters (e.g., DOC, DON, UV_{254}, fluorescence, and molecular weight distribution) or certain individual contaminants (e.g., primidone, carbamazepine, caffeine, and sucralose), DBPs and DBP precursors can offer a more comprehensive picture of the impacts of various natural incidents and human-induced activities on environmental quality in watersheds that serve as drinking water sources.

Table 3
Summary of the impacts of natural events and anthropogenic activities on DBPs and DBP precursors in source water.

Influencing factors	Main related processes	Key messages	Representative references
Droughts	• Higher concentration of contaminants • Larger contribution of reclaimed wastewater to source water • Algal blooms and AOM release	• Elevated EfOM, AOM, and halide content • Increased DBP formation	[12]
Storms and floods	• Introduction of terrestrial-derived DOM through runoff • Introduction of contaminants through urban drainage	• Increased THM FP and NDMA FP • Reduced proportion of brominated THM FP and brominated HAA FP • Impacts vary with catchment characteristics and storm hydrograph	[100,103,106]
Seawater intrusion	• Enrichment of halides	• Increased total DBP formation • Elevated bromine incorporation extent in DBPs	[108]
Wildfires	• Post-fire rainstorm • Post-fire algal blooms	• DOM quantity and compositions are altered • Increased DOM reactivity in forming N-DBPs (e.g., HANs, HNMs, and NAs) • Unobvious variation of DOM reactivity in forming C-DBPs (e.g., THMs and HAAs)	[5,115,116]
Algae blooms	• Release of AOM and toxins	• AOM possesses lower specific C-DBP FP and higher N-DBP FP compared with allochthonous NOM	[120,121]
Sunlight irradiation	• Photolysis of DOM • Promotion of the release of DOM from particulate organic matter	• Insignificant variation in overall DOC level • A decrease in the aromaticity of DOM and thus a decrease in HAA FP • Photo-released DOM from soil exhibits a different DBP FP compared with that from litter leaves	[128,133,134]
Atmospheric deposition	• Introduction of particulate matter through both dry and wet deposition	• Increased DBP precursor content	[18,139]
Domestic discharge	• Discharge of disinfected treated wastewater	• Increased concentrations of existing DBPs • Elevated EfOM (e.g., SMPs and anthropogenic contaminants) content • Higher DON content, lower DOC/DON ratio, and higher N-DBP FP	[26,141,145]
Farm effluent or runoff	• Release of chemicals used or produced in crop production, animal husbandry, and aquaculture	• Crop production runoff is a less important source of NAs and NA precursors • Animal husbandry runoff is a vital source of NDMA, NPYR, and their precursors • NMEA is rarely detected in farm wastewaters other than fishery ponds	[25,86,150]
Industrial discharge	• Release of chemicals used or produced in industries	• Facilities that produce or use brominated flame retardants act as bromide sources • Dairy processing facilities are a potential source of iodinated DBPs • Discharges from metal finishing and electronics-related facilities and wastewater from textile printing and dyeing contain a high NDMA level	[25,152,154]
Coal-fired power plants	• Enrichment of bromide	• Increased total DBP formation • Elevated bromine incorporation extent in DBPs	[158,159]
Gas extraction	• Enrichment of halides, ammonia, and metal ions	• Increased total DBP formation • Elevated bromine incorporation extent in DBPs	[164,165]

(2) Effective and feasible risk management for drinking water sources requires the identification of harmful substances, pollution origins, and hazardous events posing potential risks to water quantity and quality. This study suggests that DBPs and DBP precursors can be used as potential contamination indicators to improve the understanding of policy-makers, stakeholders, and researchers regarding the origins of major pollutants in drinking water sources. Desired management strategies can then be tailored accordingly to minimize pollution impacts.

(3) Academic studies are urged to offer more quantitative information and to establish a database regarding the use of DBP/DBP precursors as indicators and corresponding pollution information. For example, a quantitative correlation of different DOM sources with specific DBP FP (μg of DBP/mg of DOC) ranges or DBP FP ratios (e.g., the ratio of HAN FP to THM FP) may provide a benchmark for tracing the origins of DOM in drinking water sources. Moreover, the challenge of how to better integrate alternative indicators with traditional water quality parameters must be surmounted in future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Compliance with ethics guidelines

Rong Xiao, Yang Deng, Zuxin Xu, and Wenhai Chu declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2023.08.017.

References

[1] United Nations Children's Fund (UNICEF), World Health Organization (WHO). Progress on household drinking water, sanitation and hygiene 2000–2017: special focus on inequalities. Report. New York: UNICEF, WHO; 2019 Jun.

[2] World Health Organization (WHO). Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Report. Geneva: WHO; 2017.

[3] Palansooriya KN, Yang Y, Tsang YF, Sarkar B, Hou D, Cao X, et al. Occurrence of contaminants in drinking water sources and the potential of biochar for water quality improvement: a review. Crit Rev Environ Sci Technol 2020;50(6):549–611.

[4] Delpla I, Jung AV, Baures E, Clement M, Thomas O. Impacts of climate change on surface water quality in relation to drinking water production. Environ Int 2009;35(8):1225–33.

[5] Hohner AK, Rhoades CC, Wilkerson P, Rosario-Ortiz FL. Wildfires alter forest watersheds and threaten drinking water quality. Acc Chem Res 2019;52(5):1234–44.

[6] Ritson JP, Graham NJD, Templeton MR, Clark JM, Gough R, Freeman C. The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: a UK perspective. Sci Total Environ 2014;473–4:714–30.

[7] Zhang H, Li H, Gao D, Yu H. Source identification of surface water pollution using multivariate statistics combined with physicochemical and socioeconomic parameters. Sci Total Environ 2022;806(Pt 3):151274.

[8] Guo YC, Krasner SW. Occurrence of primidone, carbamazepine, caffeine, and precursors for N-nitrosodimethylamine in drinking water sources impacted by wastewater. J Am Water Resour Assoc 2009;45(1):58–67.

[9] Daneshvar A, Aboulfadl K, Viglino L, Broséus R, Sauvé S, Madoux-Humery AS, et al. Evaluating pharmaceuticals and caffeine as indicators of fecal contamination in drinking water sources of the Greater Montreal region. Chemosphere 2012;88(1):131–9.

[10] Hillebrand O, Nödler K, Licha T, Sauter M, Geyer T. Caffeine as an indicator for the quantification of untreated wastewater in karst systems. Water Res 2012;46(2):395–402.

[11] Wu M, Qian Y, Boyd JM, Hrudey SE, Le XC, Li XF. Direct large volume injection ultra-high performance liquid chromatography–tandem mass spectrometry determination of artificial sweeteners sucralose and acesulfame in well water. J Chromatogr A 2014;1359:156–61.

[12] Richardson SD, Kimura SY. Emerging environmental contaminants: challenges facing our next generation and potential engineering solutions. Environ Technol Innovation 2017;8:40–56.

[13] Richardson SD, Plewa MJ, Wagner ED, Schoeny R, Demarini DM. Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: a review and roadmap for research. Mutat Res 2007;636(1–3):178–242.

[14] Xiao R, Ou T, Ding S, Fang C, Xu Z, Chu W. Disinfection by-products as environmental contaminants of emerging concern: a review on their occurrence, fate and removal in the urban water cycle. Crit Rev Environ Sci Technol 2023;53(1):19–46.

[15] Li XF, Mitch WA. Drinking water disinfection byproducts (DBPs) and human health effects: multidisciplinary challenges and opportunities. Environ Sci Technol 2018;52(4):1681–9.

[16] Bond T, Templeton MR, Graham N. Precursors of nitrogenous disinfection by-products in drinking water—a critical review and analysis. J Hazard Mater 2012;235–236:1–16.

[17] Sgroi M, Vagliasindi FGA, Snyder SA, Roccaro P. N-nitrosodimethylamine (NDMA) and its precursors in water and wastewater: a review on formation and removal. Chemosphere 2018;191:685–703.

[18] Hou M, Chu W, Wang F, Deng Y, Gao N, Zhang D. The contribution of atmospheric particulate matter to the formation of CX3R-type disinfection by-products in rainwater during chlorination. Water Res 2018;145:531–40.

[19] Aydin E, Yaman FB, Ates Genceli E, Topuz E, Erdim E, Gurel M, et al. Occurrence of THM and NDMA precursors in a watershed: effect of seasons and anthropogenic pollution. J Hazard Mater 2012;221–222:86–91.

[20] Kraus TEC, Bergamaschi BA, Hernes PJ, Doctor D, Kendall C, Downing BD, et al. How reservoirs alter drinking water quality: organic matter sources, sinks, and transformations. Lake Reserv Manage 2011;27(3):205–19.

[21] Kraus TEC, Anderson CA, Morgenstern K, Downing BD, Pellerin BA, Bergamaschi BA. Determining sources of dissolved organic carbon and disinfection byproduct precursors to the McKenzie River. Oregon J Environ Qual 2010;39(6):2100–12.

[22] Wei J, Ye B, Wang W, Yang L, Tao J, Hang Z. Spatial and temporal evaluations of disinfection by-products in drinking water distribution systems in Beijing. China Sci Total Environ 2010;408(20):4600–6.

[23] Majidzadeh H, Uzun H, Chen H, Bao S, Tsui MTK, Karanfil T, et al. Hurricane resulted in releasing more nitrogenous than carbonaceous disinfection byproduct precursors in coastal watersheds. Sci Total Environ 2020;705:135785.

[24] Parker KM, Zeng T, Harkness J, Vengosh A, Mitch WA. Enhanced formation of disinfection byproducts in shale gas wastewater-impacted drinking water supplies. Environ Sci Technol 2014;48(19):11161–9.

[25] Chen W, Chen Y, Huang H, Lu Y, Khorram MS, Zhao W, et al. Occurrence of N-nitrosamines in the Pearl River Delta of China: characterization and evaluation of different sources. Water Res 2019;164:114896.

[26] Heng B, Zhang R, Wang Z, Zhang Y, Wang Y, Song Z, et al. Occurrence and risk assessment of volatile halogenated disinfection by-products in an urban river supplied by reclaimed wastewater. Ecotoxicol Environ Saf 2021;211:111912.

[27] Rook JJ. Formation of haloforms during chlorination of natural waters. Water Treat Exam 1974;23:234–43.

[28] Bellar TA, Lichtenberg JJ, Kroner RC. The occurrence of organohalides in chlorinated drinking waters. J Am Water Work Assoc 1974;66(12):703–6.

[29] Coleman WE, Lingg RD, Melton RG, Kopfler FC. The occurrence of volatile organics in five drinking water supplies using GC/MS. In: Keith LH, editor. Identification of Analysis of Organic Pollutants in Water. Michigan: Ann Arbor Science Publishers; 1976. p. 305–27.

[30] Suffet IH, Brenner L, Silver B. Identification of 1,1,1-trichloroacetone (1,1,1-trichloropropanone) in two drinking waters: a known precursor in haloform reaction. Environ Sci Technol 1976;10(13):1273–5.

[31] Norwood DL, Johnson JD, Christman RF, Hass JR, Bobenrieth MJ. Reactions of chlorine with selected aromatic models of aquatic humic material. Environ Sci Technol 1980;14(2):187–90.

[32] TTrehy ML, Bieber TI. Detection, identification, and quantitative analysis of dihaloacetonitriles in chlorinated natural waters. In: Keith LH, editor. Advances in the Identification and Analysis of Organic Pollutants in Water. Michigan: Ann Arbor Science Publishers; 1981. p. 941–75.

[33] Miller JW, Uden PC. Characterization of non-volatile aqueous chlorination products of humic substances. Environ Sci Technol 1983;17(3):150–7.

[34] Bond T, Huang J, Templeton MR, Graham N. Occurrence and control of nitrogenous disinfection by-products in drinking water—a review. Water Res 2011;45(15):4341–54.

[35] Werdehoff KS, Singer PC. Chlorine dioxide effects on THMFP, TOXFP, and the formation of inorganic by-products. J Am Water Work Assoc 1987;79(9):107–13.

[36] Bolyard M, Fair PS, Hautman DP. Occurrence of chlorate in hypochlorite solutions used for drinking water disinfection. Environ Sci Technol 1992;26(8):1663–5.

[37] Krasner SW, Weinberg HS, Richardson SD, Pastor SJ, Chinn R, Sclimenti MJ, et al. Occurrence of a new generation of disinfection byproducts. Environ Sci Technol 2006;40(23):7175–85.

[38] Zhao Y, Qin F, Boyd JM, Anichina J, Li XF. Characterization and determination of chloro- and bromo-benzoquinones as new chlorination disinfection byproducts in drinking water. Anal Chem 2010;82(11):4599–605.

[39] Chu W, Gao N, Yin D, Krasner SW, Templeton MR. Trace determination of 13 haloacetamides in drinking water using liquid chromatography triple quadrupole mass spectrometry with atmospheric pressure chemical ionization. J Chromatogr A 2012;1235:178–81.

[40] Pan Y, Zhang X. Four groups of new aromatic halogenated disinfection byproducts: effect of bromide concentration on their formation and speciation in chlorinated drinking water. Environ Sci Technol 2013;47(3):1265–73.

[41] Zhang D, Chu W, Yu Y, Krasner SW, Pan Y, Shi J, et al. Occurrence and stability of chlorophenylacetonitriles: a new class of nitrogenous aromatic dbps in chlorinated and chloraminated drinking waters. Environ Sci Technol Lett 2018;5(6):394–9.

[42] Oliver BG. Dihaloacetonitriles in drinking water: algae and fulvic acid as precursors. Environ Sci Technol 1983;17(2):80–3.

[43] Oliver BG, Shindler DB. Trihalomethanes from the chlorination of aquatic algae. Environ Sci Technol 1980;14(12):1502–5.

[44] Trehy ML, Yost RA, Miles CJ. Chlorination byproducts of amino acids in natural waters. Environ Sci Technol 1986;20(11):1117–22.

[45] Ding S, Deng Y, Bond T, Fang C, Cao Z, Chu W. Disinfection byproduct formation during drinking water treatment and distribution: a review of unintended effects of engineering agents and materials. Water Res 2019;160:313–29.

[46] Rule KL, Ebbett VR, Vikesland PJ. Formation of chloroform and chlorinated organics by free-chlorine-mediated oxidation of triclosan. Environ Sci Technol 2005;39(9):3176–85.

[47] Canosa P, Rodriguez I, Rubi E, Negreira N, Cela R. Formation of halogenated by-products of parabens in chlorinated water. Anal Chim Acta 2006;575(1):106–13.

[48] Chen WH, Young TM. NDMA formation during chlorination and chloramination of aqueous diuron solutions. Environ Sci Technol 2008;42(4):1072–7.

[49] Oya M, Kosaka K, Asami M, Kunikane S. Formation of N-nitrosodimethylamine (NDMA) by ozonation of dyes and related compounds. Chemosphere 2008;73(11):1724–30.

[50] Chen B, Nam SN, Westerhoff PK, Krasner SW, Amy G. Fate of effluent organic matter and DBP precursors in an effluent-dominated river: a case study of wastewater impact on downstream water quality. Water Res 2009;43(6):1755–65.

[51] Duirk SE, Lindell C, Cornelison CC, Kormos J, Ternes TA, Attene-Ramos M, et al. Formation of toxic iodinated disinfection by-products from compounds used in medical imaging. Environ Sci Technol 2011;45(16):6845–54.

[52] Shen R, Andrews SA. Demonstration of 20 pharmaceuticals and personal care products (PPCPs) as nitrosamine precursors during chloramine disinfection. Water Res 2011;45(2):944–52.

[53] Chu WH, Krasner SW, Gao NY, Templeton MR, Yin DQ. Contribution of the antibiotic chloramphenicol and its analogues as precursors of dichloroacetamide and other disinfection byproducts in drinking water. Environ Sci Technol 2016;50(1):388–96.

[54] Watson K, Shaw G, Leusch FDL, Knight NL. Chlorine disinfection by-products in wastewater effluent: bioassay-based assessment of toxicological impact. Water Res 2012;46(18):6069–83.

[55] Luo Y, Feng L, Liu Y, Zhang L. Disinfection by-products formation and acute toxicity variation of hospital wastewater under different disinfection processes. Separ Purif Technol 2020;238:116405.

[56] Hladik ML, Focazio MJ, Engle M. Discharges of produced waters from oil and gas extraction via wastewater treatment plants are sources of disinfection by-products to receiving streams. Sci Total Environ 2014;466–467:1085–93.

[57] Chuang YH, Shabani F, Munoz J, Aflaki R, Hammond SD, Mitch WA. Comparing industrial and domestic discharges as sources of N-nitrosamines and their chloramine or ozone-reactive precursors. Environ Sci Water Res Technol 2019;5(4):726–36.

[58] Kim D, Amy GL, Karanfil T. Disinfection by-product formation during seawater desalination: a review. Water Res 2015;81:343–55.

[59] Ding S, Chu W, Bond T, Wang Q, Gao N, Xu B, et al. Formation and estimated toxicity of trihalomethanes, haloacetonitriles, and haloacetamides from the chlor(am)ination of acetaminophen. J Hazard Mater 2018;341:112–9.

[60] Li Z, Liu X, Huang Z, Hu S, Wang J, Qian Z, et al. Occurrence and ecological risk assessment of disinfection byproducts from chlorination of wastewater effluents in East China. Water Res 2019;157:247–57.

[61] David M, Linders J, Gollasch S, David J. Is the aquatic environment sufficiently protected from chemicals discharged with treated ballast water from vessels worldwide?—A decadal environmental perspective and risk assessment. Chemosphere 2018;207:590–600.

[62] Cui H, Chen B, Jiang Y, Tao Y, Zhu X, Cai Z. Toxicity of 17 disinfection by-products to different trophic levels of aquatic organisms: ecological risks and mechanisms. Environ Sci Technol 2021;55(15):10534–41.

[63] Luan X, Liu X, Fang C, Chu W, Xu Z. Ecotoxicological effects of disinfected wastewater effluents: a short review of in vivo toxicity bioassays on aquatic organisms. Environ Sci Water Res Technol 2020;6(9):2275–86.

[64] Liu J, Zhang X. Comparative toxicity of new halophenolic DBPs in chlorinated saline wastewater effluents against a marine alga: halophenolic DBPs are generally more toxic than haloaliphatic ones. Water Res 2014;65:64–72.

[65] Grote M, Boudenne JL, Croué JP, Escher BI, von Gunten U, Hahn J, et al. Inputs of disinfection by-products to the marine environment from various industrial activities: comparison to natural production. Water Res 2022;217:118383.

[66] Krasner SW, Westerhoff P, Chen B, Rittmann BE, Amy G. Occurrence of disinfection byproducts in United States wastewater treatment plant effluents. Environ Sci Technol 2009;43(21):8320–5.

[67] Ding G, Zhang X, Yang M, Pan Y. Formation of new brominated disinfection byproducts during chlorination of saline sewage effluents. Water Res 2013;47(8):2710–8.

[68] Yang X, Shang C, Huang JC. DPB formation in breakpoint chlorination of wastewater. Water Res 2005;39(19):4755–67.

[69] Gilca AF, Teodosiu C, Fiore S, Musteret CP. Emerging disinfection byproducts: a review on their occurrence and control in drinking water treatment processes. Chemosphere 2020;259:127476.

[70] Hua G, Reckhow DA. Comparison of disinfection byproduct formation from chlorine and alternative disinfectants. Water Res 2007;41(8):1667–78.

[71] Hua LC, Lai CH, Wang GS, Lin TF, Huang C. Algogenic organic matter derived DBPs: precursor characterization, formation, and future perspectives—a review. Crit Rev Environ Sci Technol 2019;49(19):1803–34.

[72] Bond T, Goslan EH, Parsons SA, Jefferson B. A critical review of trihalomethane and haloacetic acid formation from natural organic matter surrogates. Environ Technol Rev 2012;1(1):93–113.

[73] MacKeown H, von Gunten U, Criquet J. Iodide sources in the aquatic environment and its fate during oxidative water treatment—a critical review. Water Res 2022;217:118417.

[74] Heeb MB, Criquet J, Zimmermann-Steffens SG, von Gunten U. Oxidative treatment of bromide-containing waters: formation of bromine and its reactions with inorganic and organic compounds—a critical review. Water Res 2014;48:15–42.

[75] Krasner SW. The formation and control of emerging disinfection by-products of health concern. Philos Trans R Soc A Math Phys Eng 1904;2009(367):4077–95.

[76] Dong H, Qiang Z, Richardson SD. Formation of iodinated disinfection byproducts (I-DBPs) in drinking water: emerging concerns and current issues. Acc Chem Res 2019;52(4):896–905.

[77] Watson K, Farré MJ, Knight N. Strategies for the removal of halides from drinking water sources, and their applicability in disinfection by-product minimisation: a critical review. J Environ Manage 2012;110:276–98.

[78] Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environ Sci Technol 2014;48(15):8334–48.

[79] Hua G, Reckhow DA, Kim J. Effect of bromide and iodide ions on the formation and speciation of disinfection byproducts during chlorination. Environ Sci Technol 2006;40(9):3050–6.

[80] Chu WH, Gao NY, Deng Y, Krasner SW. Precursors of dichloroacetamide, an emerging nitrogenous DBP formed during chlorination or chloramination. Environ Sci Technol 2010;44(10):3908–12.

[81] Shah AD, Mitch WA. Halonitroalkanes, halonitriles, haloamides, and N-nitrosamines: a critical review of nitrogenous disinfection byproduct formation pathways. Environ Sci Technol 2012;46(1):119–31.

[82] Shon HK, Vigneswaran S, Snyder SA. Effluent organic matter (EfOM) in wastewater: constituents, effects, and treatment. Crit Rev Environ Sci Technol 2006;36(4):327–74.

[83] Beita-Sandí W, Erdem CU, Karanfil T. Effect of bromide on NDMA formation during chloramination of model precursor compounds and natural waters. Water Res 2020;170:115323.

[84] Bichsel Y, von Gunten U. Formation of iodo-trihalomethanes during disinfection and oxidation of iodide-containing waters. Environ Sci Technol 2000;34(13):2784–91.

[85] Tomlinson A, Drikas M, Brookes JD. The role of phytoplankton as pre-cursors for disinfection by-product formation upon chlorination. Water Res 2016;102:229–40.

[86] Zeng T, Glover CM, Marti EJ, Woods-Chabane GC, Karanfil T, Mitch WA, et al. Relative importance of different water categories as sources of N-nitrosamine precursors. Environ Sci Technol 2016;50(24):13239–48.

[87] Liu C, Ersan MS, Plewa MJ, Amy G, Karanfil T. Formation of iodinated trihalomethanes and noniodinated disinfection byproducts during chloramination of algal organic matter extracted from Microcystis aeruginosa. Water Res 2019;162:115–26.

[88] World Health Organization (WHO). Pharmaceuticals in drinking-water. Report. Geneva: WHO; 2012.

[89] Hanigan D, Thurman EM, Ferrer I, Zhao Y, Andrews S, Zhang J, et al. Methadone contributes to N-nitrosodimethylamine formation in surface waters and wastewaters during chloramination. Environ Sci Technol Lett 2015;2(6):151–7.

[90] Schmidt CK, Brauch HJN. N, N-dimethylsulfamide as precursor for N-nitrosodimethylamine (NDMA) formation upon ozonation and its fate during drinking water treatment. Environ Sci Technol 2008;42(17):6340–6.

[91] Kosaka K, Asami M, Ohkubo K, Iwamoto T, Tanaka Y, Koshino H, et al. Identification of a new N-nitrosodimethylamine precursor in sewage containing industrial effluents. Environ Sci Technol 2014;48(19):11243–50.

[92] Bell JE, Brown CL, Conlon K, Herring S, Kunkel KE, Lawrimore J, et al. Changes in extreme events and the potential impacts on human health. J Air Waste Manag Assoc 2018;68(4):265–87.

[93] O'Neil JM, Davis TW, Burford MA, Gobler CJ. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. Harmful Algae 2012;14:313–34.

[94] Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, et al. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv Water Resour 2013;51:3–26.

[95] Bladon KD, Emelko MB, Silins U, Stone M. Wildfire and the future of water supply. Environ Sci Technol 2014;48(16):8936–43.

[96] Federal–Provincial–Territorial Committee on Drinking Water (CDW), Canadian Council of Ministers of the Environment (CCME). From source to tap: guidance on the multi-barrier approach to safe drinking water. Report. Manitoba: CDW, CCME; 2004.

[97] Wee SY, Aris AZ. Endocrine disrupting compounds in drinking water supply system and human health risk implication. Environ Int 2017;106:207–33.

[98] Andersen CB, Lewis GP, Sargent KA. Influence of wastewater-treatment effluent on concentrations and fluxes of solutes in the Bush River, South Carolina, during extreme drought conditions. Environ Geosci 2004;11 (1):28–41.

[99] Cheung MY, Liang S, Lee J. Toxin-producing cyanobacteria in freshwater: a review of the problems, impact on drinking water safety, and efforts for protecting public health. J Microbiol 2013;51(1):1–10.

[100] Bei E, Liao X, Meng X, Li S, Wang J, Sheng D, et al. Identification of nitrosamine precursors from urban drainage during storm events: a case study in southern China. Chemosphere 2016;160:323–31.

[101] Majidzadeh H, Uzun H, Ruecker A, Miller D, Vernon J, Zhang H, et al. Extreme flooding mobilized dissolved organic matter from coastal forested wetlands. Biogeochemistry 2017;136(3):293–309.

[102] Zhao B, Wong Y, Ihara M, Nakada N, Yu Z, Sugie Y, et al. Characterization of nitrosamines and nitrosamine precursors as non-point source pollutants during heavy rainfall events in an urban water environment. J Hazard Mater 2022;424(Pt C):127552.

[103] Delpla I, Jones TG, Monteith DT, Hughes DD, Baurès E, Jung AV, et al. Heavy rainfall impacts on trihalomethane formation in contrasting northwestern European potable waters. J Environ Qual 2015;44(4):1241–51.

[104] Ruecker A, Uzun H, Karanfil T, Tsui MTK, Chow AT. Disinfection byproduct precursor dynamics and water treatability during an extreme flooding event in a coastal blackwater river in southeastern United States. Chemosphere 2017;188:90–8.

[105] Nguyen HVM, Lee MH, Hur J, Schlautman MA. Variations in spectroscopic characteristics and disinfection byproduct formation potentials of dissolved organic matter for two contrasting storm events. J Hydrol 2013;481:132–42.

[106] Delpla I, Rodriguez MJ. Experimental disinfection by-product formation potential following rainfall events. Water Res 2016;104:340–8.

[107] Chang CJ, Huang CP, Chen CY, Wang GS. Assessing the potential effect of extreme weather on water quality and disinfection by-product formation using laboratory simulation. Water Res 2020;170:115296.

[108] Ged EC, Boyer TH. Effect of seawater intrusion on formation of bromine-containing trihalomethanes and haloacetic acids during chlorination. Desalination 2014;345:85–93.

[109] Kolb C, Pozzi M, Samaras C, VanBriesen JM. Climate change impacts on bromide, trihalomethane formation, and health risks at coastal groundwater utilities. ASCE ASME J Risk U A 2017;3(3):04017006.

[110] Wu CD, Hu CX, Zhang JY, Hu B, Wang L, Liang JL. Survey of seawater intrusion in the Pearl River Basin and modeling bromate formation during ozonation of the raw water. Ozone Sci Eng 2013;35(6):465–71.

[111] Krasner SW, Sclimenti MJ, Means EG. Quality degradation: implications for DBP formation. J Am Water Works Assoc 1994;86(6):34–47.

[112] Young TR, Deem S, Leslie JC, Salo-Zieman V, He H, Dodd MC. Drivers of disinfection byproduct formation and speciation in small, chlorinated coastal groundwater systems: relative roles of bromide and organic matter, and the need for improved source water characterization and monitoring. Environ Sci Water Res Technol 2020;6(12):3361–79.

[113] Chow AT, Tsai KP, Fegel TS, Pierson DN, Rhoades CC. Lasting effects of wildfire on disinfection by-product formation in forest catchments. J Environ Qual 2019;48(6):1826–34.

[114] Uzun H, Dahlgren RA, Olivares C, Erdem CU, Karanfil T, Chow AT. Two years of post-wildfire impacts on dissolved organic matter, nitrogen, and precursors of disinfection by-products in California stream waters. Water Res 2020;181:115891.

[115] Hohner AK, Cawley K, Oropeza J, Summers RS, Rosario-Ortiz FL. Drinking water treatment response following a Colorado wildfire. Water Res 2016;105:187–98.

[116] Wang JJ, Dahlgren RA, Erşan MS, Karanfil T, Chow AT. Wildfire altering terrestrial precursors of disinfection byproducts in forest detritus. Environ Sci Technol 2015;49(10):5921–9.

[117] Hohner AK, Terry LG, Townsend EB, Summers RS, Rosario-Ortiz FL. Water treatment process evaluation of wildfire-affected sediment leachates. Environ Sci Water Res Technol 2017;3(2):352–65.

[118] Chu W, Yao D, Deng Y, Sui M, Gao N. Production of trihalomethanes, haloacetaldehydes and haloacetonitriles during chlorination of microcystin-LR and impacts of pre-oxidation on their formation. J Hazard Mater 2017;327:153–60.

[119] Li L, Gao N, Deng Y, Yao J, Zhang K. Characterization of intracellular and extracellular algae organic matters (AOM) of Microcystic aeruginosa and formation of AOM-associated disinfection byproducts and odor and taste compounds. Water Res 2012;46(4):1233–40.

[120] Fang J, Yang X, Ma J, Shang C, Zhao Q. Characterization of algal organic matter and formation of DBPs from chlor(am)ination. Water Res 2010;44 (20):5897–906.

[121] Pivokonsky M, Naceradska J, Kopecka I, Baresova M, Jefferson B, Li X, et al. The impact of algogenic organic matter on water treatment plant operation and water quality: a review. Crit Rev Environ Sci Technol 2016;46(4):291–335.

[122] Nguyen ML, Westerhoff P, Baker L, Hu Q, Esparza-Soto M, Sommerfeld M. Characteristics of algae-produced dissolved organic carbon. J Environ Eng 2005;131(11):1574–82.

[123] Foreman K, Vacs Renwick D, McCabe M, Cadwallader A, Holsinger H, Kormondy C, et al. Effects of harmful algal blooms on regulated disinfection byproducts: findings from five utility case studies. AWWA Water Sci 2021;3(3):e1223.

[124] Tsai KP, Uzun H, Chen H, Karanfil T, Chow AT. Control wildfire-induced Microcystis aeruginosa blooms by copper sulfate: trade-offs between reducing algal organic matter and promoting disinfection byproduct formation. Water Res 2019;158:227–36.

[125] Tsai KP, Chow AT. Growing algae alter spectroscopic characteristics and chlorine reactivity of dissolved organic matter from thermally-altered forest litters. Environ Sci Technol 2016;50(15):7991–8000.

[126] Soh YC, Roddick F, van Leeuwen J. The future of water in Australia: the potential effects of climate change and ozone depletion on Australian water quality, quantity and treatability. Environmentalist 2008;28(2):158–65.

[127] Lee MH, Hur J. Photodegradation-induced changes in the characteristics of dissolved organic matter with different sources and their effects on disinfection by-product formation potential. Clean (Weinh) 2014;42 (5):552–60.

[128] Chow AT, Leech DM, Boyer TH, Singer PC. Impact of simulated solar irradiation on disinfection byproduct precursors. Environ Sci Technol 2008;42(15):5586–93.

[129] Chow AT, Díaz FJ, Wong KH, O'Geen AT, Dahlgren RA, Wong PK. Photochemical and bacterial transformations of disinfection by-product precursors in water. J Environ Qual 2013;42(5):1589–95.

[130] Wu J, Ye J, Peng H, Wu M, Shi W, Liang Y, et al. Solar photolysis of soluble microbial products as precursors of disinfection by-products in surface water. Chemosphere 2018;201:66–76.

[131] Xu J, Kralles ZT, Hart CH, Dai N. Effects of sunlight on the formation potential of dichloroacetonitrile and bromochloroacetonitrile from wastewater effluents. Environ Sci Technol 2020;54(6):3245–55.

[132] Xu J, Kralles ZT, Dai N. Effects of sunlight on the trichloronitromethane formation potential of wastewater effluents: dependence on nitrite concentration. Environ Sci Technol 2019;53(8):4285–94.

[133] Lee HS, Hur J, Shin HS. Dynamic exchange between particulate and dissolved matter following sequential resuspension of particles from an urban watershed under photo-irradiation. Environ Pollut 2021;283:117395.

[134] Lee HS, Hur J, Lee MH, Brogi SR, Kim TW, Shin HS. Photochemical release of dissolved organic matter from particulate organic matter: spectroscopic characteristics and disinfection by-product formation potential. Chemosphere 2019;235:586–95.

[135] Hsieh MC, Lai WWP, Lin AYC. Sunlight photolysis mitigates the formation of N-nitrosodimethylamine (NDMA) during the chloramination of methadone. Chem Eng J 2020;384:123307.

[136] Ritter L, Solomon K, Sibley P, Hall K, Keen P, Mattu G, et al. Sources, pathways, and relative risks of contaminants in surface water and groundwater: a perspective prepared for the Walkerton inquiry. J Toxicol Environ Health A 2002;65(1):1–142.

[137] Seinfeld JH, Pankow JF. Organic atmospheric particulate material. Annu Rev Phys Chem 2003;54(1):121–40.

[138] Shi M, Geng B, Zhao T, Wang F. Influence of atmospheric deposition on surface water quality and DBP formation potential as well as control

technology of rainwater DBPs: a review. Environ Sci Water Res Technol 2021;7(12):2156–65.

[139] He J, Wang F, Zhao T, Liu S, Chu W. Characterization of dissolved organic matter derived from atmospheric dry deposition and its DBP formation. Water Res 2020;171:115368.

[140] He J, Shi M, Wang F, Duan Y, Zhao T, Shu S, et al. Removal of CX3R-type disinfection by-product precursors from drinking water with conventional drinking water treatment processes. Water Res 2020;185:116099.

[141] Zeng T, Mitch WA. Contribution of N-nitrosamines and their precursors to domestic sewage by greywaters and blackwaters. Environ Sci Technol 2015;49(22):13158–67.

[142] Xu Z, Xu J, Yin H, Jin W, Li H, He Z. Urban river pollution control in developing countries. Nat Sustain 2019;2(3):158–60.

[143] Peng L, Wang F, Zhang D, Fang C, van der Hoek JP, Chu W. Effect of oxidation ditch and anaerobic–anoxic–oxic processes on CX3R-type disinfection by-product formation during wastewater treatment. Sci Total Environ 2021;770:145344.

[144] Krasner SW, Westerhoff P, Chen B, Rittmann BE, Nam SN, Amy G. Impact of wastewater treatment processes on organic carbon, organic nitrogen, and DBP precursors in effluent organic matter. Environ Sci Technol 2009;43(8):2911–8.

[145] Dotson A, Westerhoff P, Krasner SW. Nitrogen enriched dissolved organic matter (DOM) isolates and their affinity to form emerging disinfection by-products. Water Sci Technol 2009;60(1):135–43.

[146] Marhaba TF, Mangmeechai A, Chaiwatpongsakorn C, Pavasant P. Trihalomethanes formation potential of shrimp farm effluents. J Hazard Mater 2006;136(2):151–63.

[147] Leavey-Roback SL, Krasner SW, Suffet IM. Veterinary antibiotics used in animal agriculture as NDMA precursors. Chemosphere 2016;164:330–8.

[148] Hu CY, Deng YG, Lin YL, Hou YZ. Chlorination of bromacil: kinetics and disinfection by-products. Separ Purif Technol 2019;212:913–9.

[149] Eckard RS, Bergamaschi BA, Pellerin BA, Kraus T, Hernes PJ. Trihalomethane precursors: land use hot spots, persistence during transport, and management options. Sci Total Environ 2020;742:140571.

[150] Qiu Y, Bei E, Li X, Xie S, Xiao H, Luo Y, et al. Quantitative analysis of source and fate of N-nitrosamines and their precursors in an urban water system in East China. J Hazard Mater 2021;415:125700.

[151] States S, Cyprych G, Stoner M, Wydra F, Kuchta J, Monnell J, et al. Marcellus shale drilling and brominated THMs in Pittsburgh, Pa., drinking water. J Am Water Works Assoc 2013;105(8):E432–48.

[152] McTigue NE, Cornwell DA, Graf K, Brown R. Occurrence and consequences of increased bromide in drinking water sources. J Am Water Works Assoc 2014;106(11):E492–508.

[153] Simpson AMA, Mitch WA. Chlorine and ozone disinfection and disinfection byproducts in postharvest food processing facilities: a review. Crit Rev Environ Sci Technol 2022;52(11):1825–67.

[154] Hladik ML, Hubbard LE, Kolpin DW, Focazio MJ. Dairy-impacted wastewater is a source of iodinated disinfection byproducts in the environment. Environ Sci Technol Lett 2016;3(5):190–3.

[155] Lin C, Zhuo X, Yu X, Yuan M, Wei C. Identification of disinfection by-product precursors from the discharge of a coking wastewater treatment plant. RSC Adv 2015;5(54):43786–97.

[156] Good KD, VanBriesen JM. Current and potential future bromide loads from coal-fired power plants in the Allegheny River Basin and their effects on downstream concentrations. Environ Sci Technol 2016;50(17):9078–88.

[157] Good KD, VanBriesen JM. Power plant bromide discharges and downstream drinking water systems in Pennsylvania. Environ Sci Technol 2017;51(20):11829–38.

[158] Kolb C, Good KD, VanBriesen JM. Modeling trihalomethane increases associated with source water bromide contributed by coal-fired power plants in the Monongahela River Basin. Environ Sci Technol 2020;54(2):726–34.

[159] VanBriesen JM, Carpenter AT, Good KD, Kolb C, Wilson JM. Power plant bromide discharges and potential effects on DBP formation. J Am Water Works Assoc 2021;113(6):48–55.

[160] Warner NR, Christie CA, Jackson RB, Vengosh A. Impacts of shale gas wastewater disposal on water quality in western Pennsylvania. Environ Sci Technol 2013;47(20):11849–57.

[161] Ferrar KJ, Michanowicz DR, Christen CL, Mulcahy N, Malone SL, Sharma RK. Assessment of effluent contaminants from three facilities discharging Marcellus Shale wastewater to surface waters in Pennsylvania. Environ Sci Technol 2013;47(7):3472–81.

[162] Landis MS, Kamal AS, Kovalcik KD, Croghan C, Norris GA, Bergdale A. The impact of commercially treated oil and gas produced water discharges on bromide concentrations and modeled brominated trihalomethane disinfection byproducts at two downstream municipal drinking water plants in the upper Allegheny River, Pennsylvania, USA. Sci Total Environ 2016;542(Pt A):505–20.

[163] Huang KZ, Xie YF, Tang HL. Formation of disinfection by-products under influence of shale gas produced water. Sci Total Environ 2019;647:744–51.

[164] Harkness JS, Dwyer GS, Warner NR, Parker KM, Mitch WA, Vengosh A. Iodide, bromide, and ammonium in hydraulic fracturing and oil and gas wastewaters: environmental implications. Environ Sci Technol 2015;49(3):1955–63.

[165] Huang KZ, Tang HL, Xie YF. Impacts of shale gas production wastewater on disinfection byproduct formation: an investigation from a non-bromide perspective. Water Res 2018;144:656–64.

[166] Krasner SW, Mitch WA, Westerhoff P, Dotson A. Formation and control of emerging C- and N-DBPs in drinking water. J Am Water Works Assoc 2012;104(11):E582–95.

[167] Krasner SW, Mitch WA, McCurry DL, Hanigan D, Westerhoff P. Formation, precursors, control, and occurrence of nitrosamines in drinking water: a review. Water Res 2013;47(13):4433–50.

[168] Li Z, Song G, Bi Y, Gao W, He A, Lu Y, et al. Occurrence and distribution of disinfection byproducts in domestic wastewater effluent, tap water, and surface water during the SARS-CoV-2 pandemic in China. Environ Sci Technol 2021;55(7):4103–14.

[169] Emmanuel E, Perrodin Y, Keck G, Blanchard JM, Vermande P. Ecotoxicological risk assessment of hospital wastewater: a proposed framework for raw effluents discharging into urban sewer network. J Hazard Mater 2005;117(1):1–11.

[170] Matilainen A, Gjessing ET, Lahtinen T, Hed L, Bhatnagar A, Sillanpää M. An overview of the methods used in the characterisation of natural organic matter (NOM) in relation to drinking water treatment. Chemosphere 2011;83(11):1431–42.

[171] Pan Y, Li H, Zhang X, Li A. Characterization of natural organic matter in drinking water: sample preparation and analytical approaches. Trends Environ Anal Chem 2016;12:23–30.

[172] Fang C, Yang X, Ding S, Luan X, Xiao R, Du Z, et al. Characterization of dissolved organic matter and its derived disinfection byproduct formation along the Yangtze River. Environ Sci Technol 2021;55(18):12326–36.

[173] Leonard LT, Vanzin GF, Garayburu-Caruso VA, Lau SS, Beutler CA, Newman AW, et al. Disinfection byproducts formed during drinking water treatment reveal an export control point for dissolved organic matter in a subalpine headwater stream. Water Res X 2022;15:100144.