Disinfection by-products in desalinated and blend water: formation and control strategy

Shakhawat Chowdhury

ABSTRACT

Desalinated seawater is the major source of drinking water in many countries. During desalination, several activities including pretreatment, desalination, stabilization, mixing, storage and distribution are performed. Few disinfectants are used during these activities to control the biofouling agents and microbiological regrowth. The reactions between the disinfectants and natural organic matter (NOM), bromide and iodide form disinfection by-products (DBPs) in product water. The product water is stabilized and mixed with treated freshwater (e.g., groundwater) to meet the domestic water demands. The DBPs in desalinated and blend water are an issue due to their possible cancer and non-cancer risks to humans. In this paper, formation and distribution of DBPs in different steps of desalination and water distribution systems prior to reaching the consumer tap were reviewed. The variability of DBPs among different sources and desalination processes was explained. The toxicities of DBPs were compared and the strategies to control DBPs in desalinated water were proposed. Several research directions were identified to achieve comprehensive control on DBPs in desalinated water, which are likely to protect humans from the adverse consequences of DBPs.

Key words | control of DBPs, desalinated and blend water, desalination, disinfection by-products, human exposure and risk, toxicity of DBPs

INTRODUCTION

Coastal regions are home to approximately two billion people. At least 14 mega cities with populations of more than ten million each and two-fifths of the major cities with populations between one and ten million are located in coastal areas (Tibbetts 2002). Seawater desalination has become the most common method to satisfy domestic water demands in coastal regions and in regions with a water crisis. Desalination of seawater is practised in many countries in the Middle East, the Mediterranean Basin, as well as in Australia and the USA (Reuther 2000; Dawoud 2005; De Munari et al. 2009; Greenlee et al. 2009) with the Middle East countries producing the most (Lattemann & Höpner 2008). For desalination, two main processes – thermal (MSF: multi-stage flash; MED: multi-effect distillation) and membrane (RO: reverse osmosis) – are used. In the Arabian Gulf and Red Sea, the dominant processes are MSF and MED while in the Mediterranean Sea, the dominant process is RO (Lattemann & Höpner 2008). The MSF processes produce approximately 65.3% of desalinated water in the Arabian Gulf while RO and MED contribute 23.4% and 13.3%, respectively (Lattemann & Höpner 2008). Higher levels of seawater pollution and low energy costs are probably the main causes for the abundance of MSF processes.

During desalination, feed water is collected through different intakes while open collection systems are widely used. Chlorine (Cl₂) in the form of HOCl or OCl⁻ is typically applied during pretreatment to prevent bacterial growth and biofouling, and to enhance the performance of
filters. Pretreatment is performed using continuous or intermittent chlorination with initial doses of 0.5–2.0 mg/L to achieve the target residuals of 0.25–0.5 mg/L (Kim et al. 2015). Chlorine is also applied in different stages of desalination and in final disinfection to inactivate microorganisms (MWH 2005). Some other disinfectants, such as chloramines (e.g., NH₂Cl), ozone (O₃) and chlorine dioxide (ClO₂) are also used (MWH 2005). The disinfectants react with natural organic matter (NOM) and inorganic compounds (e.g., ammonia, chloramine, Fe²⁺, Mn²⁺, S²⁻, bromide, iodide, etc.) to form disinfection by-products (DBPs), many of which have cancer and non-cancer risks to humans (USEPA 2016). Past studies reported that seawater could contain bromide and iodide in the ranges of 50,000–80,000 and 21–60 μg/L, respectively (Ali-Mohamed & Jamali 1989; Kristiansen et al. 1996; Agus et al. 2009; Duranceau 2010). The thermal desalination processes remove bromide and iodide to non-detectable levels. Although RO processes remove >99% bromide, RO permeate contains considerable amounts of bromide (250–600 μg/L) and iodide (<4–16 μg/L), which can increase brominated (Br-DBPs) and iodinated (I-DBPs) DBPs in desalinated and blend water (Kutty et al. 1995; Magara et al. 1996; Kim et al. 2015; Le Roux et al. 2015; Postigo et al. 2017). The Br-DBPs and I-DBPs are more cytotoxic and/or genotoxic than chlorinated DBPs (Cl-DBPs) (Richardson et al. 2007; Agus & Sedlak 2010; Wahab et al. 2010; Shi et al. 2013; Kim et al. 2015).

In the Middle East, desalinated water is often mixed with treated brackish groundwater, pH adjusted and chlorinated prior to distribution (Duranceau 2010). The chlorinated blend water remains in water distribution systems (WDS) or storage tanks for a few hours to several days during transportation from the coasts to inland cities, which can increase concentrations of DBPs (Tawabini et al. 2011; Kim et al. 2015). The RO permeate, which is rich in bromide, is mixed with treated brackish groundwater, rich in NOM, leading to the increased formation of Br-DBPs and I-DBPs. Past studies reported higher fractions of Br-DBPs in desalinated and blend water (Kutty et al. 1995). To date, over 100 DBPs have been reported in drinking water while approximately 600 DBPs are likely to be present (Richardson et al. 2007). The most investigated DBPs in desalinated and blend water are trihalomethanes (THMs) and haloacetic acids (HAAs) (Kim et al. 2015). Several emerging DBPs, including iodo-THMs (I-THMs), halonitromethanes (HNMs), haloacetonitriles (HANs), bromate, haloamides, nitrosamines, 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone (MX) and MX homologues, aromatic halogenated DBPs, halo- and nitro phenols can also be present (Richardson 2003; Richardson et al. 2008, 2010; Agus et al. 2009; Agus & Sedlak 2010; Richardson & Postigo 2012; Kim et al. 2015; Le Roux et al. 2015; Postigo et al. 2017). Many DBPs are of concern due to their possible cancer and non-cancer risks (King & Marrett 1996; Cantor et al. 1998, 1999; Hildesheim et al. 1998; Savitz et al. 2006). Some of the effects associated with DBP exposure include increased rates of bladder and colorectal cancers, pre-term deliveries, neural tube defects, miscarriages, cardiac irregularities and low birth weights (King & Marrett 1996; Cantor et al. 1998, 1999; Hildesheim et al. 1998; Savitz et al. 2006). Regulatory agencies, such as the United States Environmental Protection Agency (USEPA), Health Canada, World Health Organization (WHO) and the European Union (EU) have set the guideline limits for DBPs. USEPA has limits of 80 and 60 μg/L for THMs and HAA5, respectively (USEPA 2016). Health Canada has limits of 100 and 80 μg/L for THMs and HAA5, respectively (Health Canada 2017). The limits for bromate and chlorite in Canada are 10 and 1,000 μg/L, respectively (Health Canada 2017). The WHO guidelines for chloroform (TCM), bromodichloromethane (BDCM), dibromochloromethane (DBCM) and bromoform (TBM) are 300, 60, 100 and 100 μg/L, respectively (WHO 2011). The WHO limits bromate and chlorite to 10 and 700 μg/L, respectively (WHO 2011).

To date, many studies have focused on DBPs in freshwater sourced supply water. Despite the public health relevance, not much is known about DBPs in desalinated and blend water, and the consequent exposure and risk. Formation of DBPs in desalinated water can vary depending on sources and type of desalination processes. Further, DBPs in different stages of desalination require better understanding to control DBPs in desalinated and blend water. In this study, research on DBPs in desalinated and blend water was reviewed. Formation of DBPs in different stages of desalination was investigated. Variability of DBPs depending on desalination and sources was characterized. The effects of
bromide on the formation and distribution of DBPs in desalinated water was investigated. The cytotoxicity and genotoxicity of DBPs on mammalian cells were compared. Strategies were identified to better control DBPs in tap water. Finally, future research needs to control DBPs in desalinated and blend water were outlined.

**DESALINATION PROCESS**

Desalination processes are classified into two categories: thermal and membrane separation. Thermal process is the oldest method, in which steam is collected by boiling seawater. Thermal process is divided into three types: MSF, vapour compression (VC) and MED with MSF being dominant in the Middle East region. Among the membrane separation techniques, RO processes are mainly used (Kim et al. 2015). In MSF processes, seawater is heated while passing through multiple heating stages. Through different heating stages, the brine recirculation system contains heat recovery and heat denial units. Figure 1(a) illustrates a schematic of the MSF process where pressure decreases from the beginning to the end. The first chamber receives seawater, which is heated by a brine heater. The pressure around the first chamber is lower than the brine heater, leading to the formation of steam of a fraction of the seawater. The remaining water is passed through a series of supplementary stages with increased vacuum pressure. The vapour is condensed into fresh water and collected as potable water. The heat produced through condensation of vapour is generally recycled and reused to pre-heat the seawater.

RO processes are also used in Saudi Arabia, Bahrain, Jordan, Australia, UAE, Egypt and the USA (Patel & "Figure 1" Schematic of the main desalination processes in Saudi Arabia: (a) multistage flash (MSF) process and (b) reverse osmosis (RO) process.)
Oakland 1976; Al Arrayedh et al. 1987; Ahmed et al. 2001; Djebedjian et al. 2007; Greenlee et al. 2009). RO processes work with one, two or four RO passes depending on source water quality, product water standards, and regulation and design constraints. Figure 1(b) shows a schematic of the RO process. In RO processes, water is separated from a pressurized saline solution using the water-permeable membrane. The seawater is pretreated to remove large particles using screening, and disinfectant (typically chlorine) is used to inactivate the bio-fouling agents before passing through the RO process. A dechlorinating reagent, such as sodium bisulfate, is often used to control the damage of membrane materials. In this stage, anti-foaming and anti-scaling chemicals are used to increase membrane efficiency. Concentrations of DBPs in RO permeate depend on the rejection efficiency of membranes. Past studies reported higher DBPs in RO effluent than the thermal processes (Al-Ôtoum et al. 2016; Kim et al. 2015; Le Roux et al. 2015).

DBP FORMATION

Pretreatment of feed water

Brackish water or seawater is used as feed water for desalination. The estuaries and aquifers in coastal areas generally contain brackish water with lower salinity than seawater. Feed water is collected from open or sub-surface intakes, beach wells and infiltration galleries (Jones & Campbell 2005; WRA 2011). The intake water is screened, followed by pretreatment using continuous or intermittent chlorination with initial doses in the range of 0.5–2.0 mg/L. The chlorination assists in coagulation, controls algae in sedimentation basins and reduces mud-ball formation (Kim et al. 2015). The unintended reactions between NOM and chlorine form DBPs, many of which are mutagenic and can pose risk to humans (Richardson et al. 2007). Formation of DBPs depends on several factors including the type and dose of disinfectants, concentration and distribution of NOM, pH, temperature, contact time, and bromide and iodide concentrations (Kutty et al. 1995; Yang et al. 2015; Kim et al. 2015; Gong et al. 2016; Ioannou et al. 2016; Jiang et al. 2017, 2018). Bromide and iodide ions in feed water can increase Br-DBPs and I-DBPs during pretreatment (Gong et al. 2016; Ioannou et al. 2016; Jiang et al. 2017, 2018).

Table 1 summarizes DBPs in pretreated seawater for desalination, seawater under controlled laboratory studies and saline waste effluents treated with different disinfectants. In chlorinated seawater (pretreated seawater) collected from desalination plants, THMs and HAAs were in the ranges of 0–680 and 0–175 μg/L, respectively (Ali & Riley 1989; El Din et al. 1991; Kojima et al. 1995; Kutty et al. 1995; Magara et al. 1996; Allonier et al. 1999; Dalvi et al. 2000; El-Hassan & Al-Sulami 2005; Agus & Sedlak 2010; Le Roux et al. 2015). Several emerging DBPs including HANs, I-THMs and brominated phenols (Br-phenols) were also reported in pretreated seawater (Table 1). The DBPs in different sources showed wide ranges, possibly due to feed water quality, pretreatment, and type and doses of disinfectants (Table 1). In Saudi Arabia, concentrations of THMs, HAAs, HANs and I-THMs in chlorinated seawater were in the ranges of 3.1–27.9, ND–7.0, 0.4–0.8 and 1.9–2.6 μg/L, respectively (Table 1). In UAE, THMs and HAAs were <25–95 and ND–< 14.5 μg/L, respectively (Table 1) while in Qatar, THMs were in the range of 21.7–61.4 μg/L. The highest concentrations of THMs (490–680 μg/L) and HAAs (69–175 μg/L) were reported for a pilot plant in Tampa Bay, Florida, USA (Table 1). The total organic carbon (TOC) and chlorine doses were in the ranges of 4.3–10.9 and 2.5–5.0 mg/L, respectively (Agus et al. 2009). Sudden pollution near the desalination plants (e.g., oil spill) could also increase DBPs (El Din et al. 1991). In UAE, THMs and HAAs were below 100 μg/L in most cases (Table 1); however, THMs rose to 200 μg/L following an oil spill near the intake (El Din et al. 1991).

Laboratory studies on seawater showed different DBPs when Cl2, NH2Cl, ClO2 and O3 were used (Table 1). In chlorinated seawater in the laboratory, THMs, HAAs, HANs and haloacetamides (HAcAms) were in the ranges of ND–206, 0–122, 4.0–155 and 110–240 μg/L, respectively. In NH2Cl and ClO2 treated samples, total DBPs were much lower (Table 1) while O3 treated samples showed higher Br-THMs, Br-HAAs, bromate and HNMs. Overall, THMs in laboratory studies from Saudi Arabia, Qatar, Spain, the USA and Canada were in the ranges of 35–180, 60–165, 0.34–154, 43–206 and 22–33 μg/L, respectively (Table 1). In a laboratory study from Halifax, Canada, bromate was
<table>
<thead>
<tr>
<th>Location</th>
<th>Disinfectant</th>
<th>THMs</th>
<th>HAAs</th>
<th>HANs</th>
<th>Other DBPs</th>
<th>Dose; contact time</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Feed water of desalination plants</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red Sea coast, Saudi Arabia</td>
<td>Chlorine</td>
<td>6.2–18.4</td>
<td>5.4–6.9</td>
<td>0.4–0.8 DBAN</td>
<td>1.9–2.6 (I-THMs)</td>
<td>0.7–1.0 (continuous); 0.25–0.5 (residual)</td>
<td>Le Roux et al. (2015)</td>
</tr>
<tr>
<td>Al-Jubail, Saudi Arabia</td>
<td>ND</td>
<td>7.0</td>
<td></td>
<td></td>
<td></td>
<td>1.0 (residual); 24 h</td>
<td>Dalvi et al. (2000)</td>
</tr>
<tr>
<td>Jeddah, Saudi Arabia</td>
<td>3.3–24.0</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>0.2–0.3 (residual)</td>
<td>Kojima et al. (1995)</td>
</tr>
<tr>
<td>East coast, Saudi Arabia</td>
<td>3.1–27.9</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>2.0 (residual)</td>
<td>Kutty et al. (1995)</td>
</tr>
<tr>
<td>Umm Al-Nur, UAE</td>
<td>78–95</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>0.5–2.0 (residual)</td>
<td>El Din et al. (1991)</td>
</tr>
<tr>
<td>Ruwais, UAE</td>
<td>&lt;25</td>
<td>&lt;14.5</td>
<td></td>
<td></td>
<td></td>
<td>0.2–0.25; 10–15 min</td>
<td>Elshorbagy &amp; Abdulkarim (2006)</td>
</tr>
<tr>
<td>Okinawa, Japan</td>
<td>35</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td>Magara et al. (1996)</td>
</tr>
<tr>
<td>Ebara Corp., Japan</td>
<td>15–25</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>0.2–0.3 (residual)</td>
<td>Kutty et al. (1995)</td>
</tr>
<tr>
<td>Carlsbad, USA</td>
<td>3.0–52</td>
<td>9.5–19</td>
<td>0.5–1.9</td>
<td>0.3–0.6 (Br-phenols)</td>
<td>0.5–2.0 (initial); 2 h</td>
<td>2.5–5.0</td>
<td>Agus &amp; Sedlak (2010)</td>
</tr>
<tr>
<td>Tampa Bay, USA</td>
<td>490–680</td>
<td>69–175</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Agus et al. (2009)</td>
</tr>
<tr>
<td><strong>Laboratory studies with seawater</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Jubail, Saudi Arabia</td>
<td>Chlorine</td>
<td>80</td>
<td>ND</td>
<td></td>
<td></td>
<td>10.0; 72 h</td>
<td>Kutty et al. (1995)</td>
</tr>
<tr>
<td>Thuwail, Saudi Arabia</td>
<td></td>
<td></td>
<td>18–155</td>
<td>110–240; Halo-acetamides</td>
<td>5; 72 h</td>
<td></td>
<td>Nihemaiti et al. (2015)</td>
</tr>
<tr>
<td>Doha, Qatar</td>
<td>60–165</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>1.0–4.0; 168 h</td>
<td>Wahab et al. (2010)</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>154</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>1.0–3.0; 30 min</td>
<td>Simon et al. (2014)</td>
</tr>
<tr>
<td>Aquaria, undisclosed</td>
<td>ND</td>
<td>&lt;122</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shi et al. (2015)</td>
</tr>
<tr>
<td>North Sea coast, Norway</td>
<td>ND</td>
<td>3.2–6.3</td>
<td></td>
<td></td>
<td></td>
<td>0.7–3.5 (Cl2/DOC); 24 h</td>
<td>Kristiansen et al. (1996)</td>
</tr>
<tr>
<td>Seattle, USA</td>
<td>107</td>
<td>99</td>
<td>4.0 B/DCAN</td>
<td></td>
<td></td>
<td>1.0; 8 h</td>
<td>Fabbricino &amp; Korshin (2005)</td>
</tr>
<tr>
<td>Florida, USA</td>
<td>43–206</td>
<td>39–75</td>
<td></td>
<td></td>
<td></td>
<td>2.0 (Cl2/DOC); 24 h</td>
<td>Ged &amp; Boyer (2014)</td>
</tr>
<tr>
<td>Al-Jubail, Saudi Arabia</td>
<td>Chloramine</td>
<td>35</td>
<td>ND</td>
<td></td>
<td></td>
<td>10.0; 72 h</td>
<td>Dalvi et al. (2000)</td>
</tr>
<tr>
<td>Busan, Korea</td>
<td>Chlorine</td>
<td>ND</td>
<td>0.4–2.5</td>
<td></td>
<td></td>
<td>0.2–10.0; 72 h</td>
<td>Yu et al. (2014)</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>ND</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>0.2–0.4</td>
<td>Simon et al. (2014)</td>
</tr>
<tr>
<td>Al-Jubail, Saudi Arabia</td>
<td>Ozone</td>
<td>180 (TBM)</td>
<td>ND</td>
<td>ND</td>
<td></td>
<td>5.0; 72 h</td>
<td>Dalvi et al. (2000)</td>
</tr>
<tr>
<td>Halifax, Canada</td>
<td>22–33</td>
<td>ND</td>
<td></td>
<td></td>
<td></td>
<td>500–4,500; bromate</td>
<td>Brookman et al. (2011)</td>
</tr>
</tbody>
</table>

(continued)
in the range of 500–4,500 μg/L (Table 1) while the guideline limit was 10 μg/L (USEPA 2006; WHO 2011). In other ozone treated samples, TBM, TBAA and HNMs were 180, 61 and 16.5–34.8 μg/L, respectively (Table 1). Higher concentrations of Br-THMs, bromate and total DBPs in O3 treated water could be a health concern (USEPA 2018). However, O3 is not commonly used in desalination due to higher levels of bromide. In addition, the power plant cooling effluents reported higher levels of TBM while HAAs, HANs and Br-phenols were also detected (Table 1).

In recent years, several laboratory studies on simulated water demonstrated the formation of emerging DBPs, many of which are yet to be identified, quantified and assessed for human risks. In simulated drinking water containing bromide and disinfected with NH2Cl, as many as 29 aliphatic, aromatic or nitrogenous polar Br-DBPs were detected, and five of them were tentatively identified (Zhai et al. 2014). Application of NH2Cl favoured the formation of aromatic and nitrogenous polar Br-DBPs. In another study, Postigo et al. (2017) compared the formation of emerging DBPs in simulated drinking water containing bromide and iodide. This study reported preferential formation of I-DBPs (I-THMs, I-HAAs) and haloacetaldehydes (HALs) in chloraminated water rather than chlorinated water. In this study, Cl2 rapidly oxidized hypoiodous acid (HOI) to iodate, which served as a sink for iodide. In the presence of NH2Cl, HOI reacted with NOM to form I-DBPs, which acted as a sink for iodide (Bichsel & Von Gunten 2000). The total concentrations of I-THMs in NH2Cl treated water were 1.5–18 times higher than chlorinated water (Postigo et al. 2017). Gong et al. (2016) investigated the effects of linear alkylbenzene sulfonates (LAS), an important group of organic pollutants in urban wastewater effluents, on the formation of DBPs in the presence of bromide ions. This study reported the formation of Cl-DBPs during chlorination of LAS without bromide while Br-DBPs were formed during chlorination of LAS with bromide. The major polar Cl-DBPs and Br-DBPs from LAS were proposed to be 2,6-dichloro-3,5-dihydroxy-4-dodecylbenzenesulfonic acid and 2,6-dibromo-3,5-dihydroxy-4-dodecylbenzenesulfonic acid, respectively. In another study, Gong & Zhang (2015) reported formation of polar I-DBPs in chlorinated saline wastewater effluents containing iodide. As an example, a new group of polar I-DBPs, iodo-trihydroxybenzenesulfonic

<table>
<thead>
<tr>
<th>Location</th>
<th>Disinfectant</th>
<th>THMs</th>
<th>HAAs</th>
<th>HANs</th>
<th>Other DBPs</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquaria, undisclosed</td>
<td>Chlorine</td>
<td>61 (TBAA)</td>
<td>7.7–26.8 (TBAA)</td>
<td>ND</td>
<td>3.5–53.5</td>
<td>Shi et al. (2017); Jenner et al. (1999); Allonier et al. (1999)</td>
</tr>
<tr>
<td>Cooling effluent of power plants, France</td>
<td>Chlorine</td>
<td>0.1–3.0; 15 min</td>
<td>0.1–0.4 (TBAA)</td>
<td>1–6.74 (DBAN)</td>
<td>16.5–34.8 (HNMs)</td>
<td>Shi et al. (2017); Jenner et al. (1999); Allonier et al. (1999)</td>
</tr>
<tr>
<td>Power stations, UK</td>
<td>Chlorine</td>
<td>0.1–3.0; 15 min</td>
<td>0.1–0.4 (TBAA)</td>
<td>1–6.74 (DBAN)</td>
<td>16.5–34.8 (HNMs)</td>
<td>Shi et al. (2017); Jenner et al. (1999); Allonier et al. (1999)</td>
</tr>
</tbody>
</table>

S. Chowdhury | Formation and control of DBPs in desalinated water
Journal of Water and Health | 17.1 | 2019
Downloaded from https://iwaponline.com/jwh/article-pdf/17/1/1/564748/jwh0170001.pdf by guest on 23 October 2019
acids, was identified and quantified. Concentrations of bromide and iodide in seawater are high, and may form several emerging Br-DBPs and I-DBPs upon chlorination and/or chloramination.

Overall, THMs were higher than HAAs in feed water and laboratory studies using real seawater samples (Table 1). In chlorinated seawater, TCM was not detected while BDCM, BDCM and TBM were 0.9%, 4.3% and 94.7%, respectively (Br-THMs = 99.9%). In this study, MCAA, DCAA, TCAA, MBAA, DBAA, TBAA and CDBAA were 9.3%, 4.5%, 2.4%, 3.4%, 38.3%, 22.4% and 19.6%, respectively (Br-HAAs = 83.7%) while BCAA and BDCAA were not detected (Le Roux et al. 2015). The DBAA and TBAA contributed approximately 60.7% of total HAAs. In contrast, for chlorinated surface water, the major THMs were TCM (71.4%) and BDCM (28.6%) while DBCM and TBM were not detected. The major HAAs were MCAA (23.7%), DCAA (36.7%) and TCAA (13.0%), respectively (Cl-HAAs = 73.4%) (Kim et al. 2002; Sorlini & Collivignarelli 2005).

Seawater contains high levels of bromide ions, which are more reactive to hydrophilic NOM containing a larger proportion of aliphatic structure, and favours the formation of THMs over HAAs (Singer et al. 2002). In addition, higher pH (≥8.0) in feed water could form more THMs than HAAs while the reverse is true at lower pH (≤6.0). In general, HOCl reacts with bromide ions to form HOBr, which is almost 15 times as reactive as HOCl, resulting in faster replacement of lighter Cl⁻ atoms by heavier Br⁻ atoms, leading to the formation of chloro-bromo and other Br-DBPs (Liang & Singer 2003).

**Desalination plants prior to distribution**

The pretreated feed water is passed through thermal or membrane processes. In thermal plants, the heating chambers produce vapour, which is collected following condensation (Figure 1(a)), and thus many non-volatile DBPs (e.g., HAAs) are removed to trace levels in the product water. However, volatile DBPs (e.g., THMs) are partitioned into vapour phase (USEPA 1995; Chowdhury 2014) and can be present in desalinated water at relatively low concentrations (Table 2). For an example, THMs in MSF processes were reduced by 94% during distillation (Ali & Riley 1989; El Din et al. 1991; Dalvi et al. 2000; Le Roux et al. 2015). On the east coast of Saudi Arabia, concentrations of THMs in feed water were in the range of 3.1–27.9 μg/L, which were reduced to 0.1–3.5 μg/L in thermal distillate (Kutty et al. 1989). In thermal distillate, BDCM, BDCM and TBM were 39.5%, 31.6% and 28.9%, respectively (Table 2). However, TBM was 94.7% in the feed water, indicating a higher fraction of TBM removal during this process (Kutty et al. 1989). Concentrations of THMs in product water were affected by THMs in pretreated water, heat generation, partition of THMs into vapour phase and condensation during cooling. HAAs are not volatile and the product water had negligible concentrations of HAAs (Table 2). In the feed water from the Red Sea (Saudi Arabia), HAAs were in the range of 5.4–6.9 μg/L, which were not detected in thermal distillate (Le Roux et al. 2015). The DBPs with low initial concentrations and/or low partition coefficients are likely to be negligible in thermal distillate.

In RO processes, desalinated water is collected after passing through RO membranes. Depending on the rejection performance of the membranes, concentrations of DBPs vary in RO permeate (Kristiansen et al. 1996). RO plants often function with one, two or four RO passes based on the initial and final water quality and design parameters (Leenheer 1981; Peuravuori & Pihlaja 1998; Peuravuori et al. 2001; Kim et al. 2015). In the pretreated feed water of Tampa Bay RO plant, THMs and HAAs were in the ranges of 490–680 μg/L and 69–175 μg/L, respectively (Agus et al. 2009). In the RO permeate, these were in the ranges of 2.3–6.4 μg/L and 1.0–2.5 μg/L, respectively, indicating more than 99% removal of THMs and HAAs from feed water. The plant used hydranautics seawater composite membranes (Agus et al. 2009).

Higher levels of THMs and HAAs were reported in RO permeate in Saudi Arabia (Table 2). Le Roux et al. (2015) reported THMs in an RO plant with cellulose triacetate membranes in the range of 39–67 μg/L while in feed water, THMs were in the range of 14.5–18.4 μg/L (Table 2). THMs in RO permeate were higher due to the reaction of residual chlorine with the adsorbed and accumulated reactive organic matter in the fouling layer (Le Roux et al. 2015). In some RO plants, chloramines are used to limit biofouling and to reduce membrane damage (Kim et al. 2015). However, chloraminated RO permeate had...
<table>
<thead>
<tr>
<th>Location</th>
<th>Pretreated feed water</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THMs</td>
<td>HAAs</td>
</tr>
<tr>
<td>Thermal plant on Red Sea coast, Saudi Arabia</td>
<td>0.4</td>
<td>ND</td>
</tr>
<tr>
<td>Al-Jubail, Saudi Arabia</td>
<td>ND</td>
<td>1.6</td>
</tr>
<tr>
<td>Jeddah, Saudi Arabia</td>
<td>0.2–0.6</td>
<td>3.3–24.0</td>
</tr>
<tr>
<td>East Coast, Saudi Arabia</td>
<td>0.1–3.5</td>
<td>3.1–27.9</td>
</tr>
<tr>
<td>Jazan, Saudi Arabia</td>
<td>2.3–2.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Pretreated feed water</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THMs</td>
<td>HAAs</td>
</tr>
<tr>
<td>RO plant on Red Sea coast, Saudi Arabia</td>
<td>39–66.7</td>
<td>ND–0.71</td>
</tr>
<tr>
<td>Jeddah, Saudi Arabia</td>
<td>12.2–39.0</td>
<td>4.0–73.0</td>
</tr>
<tr>
<td>Qatar</td>
<td>8.5</td>
<td>2.0–3.0</td>
</tr>
<tr>
<td>Jazan, Saudi Arabia</td>
<td>2.3–6.4</td>
<td>1.0–2.5</td>
</tr>
<tr>
<td>Makah, Saudi Arabia</td>
<td>2.7</td>
<td>35.0</td>
</tr>
<tr>
<td>Carlsbad, USA</td>
<td>ND–6.7</td>
<td>2.1–6.1</td>
</tr>
<tr>
<td>Tampa Bay, USA</td>
<td>2.3–6.4</td>
<td>1.0–2.5</td>
</tr>
<tr>
<td>Okinawa, Japan</td>
<td>2.7</td>
<td>35.0</td>
</tr>
<tr>
<td>Ebara Corp., Japan</td>
<td>2.0–3.0</td>
<td>15.0–25.0</td>
</tr>
</tbody>
</table>
I-THMs in the range of 1.7–2.6 μg/L (Table 2). In addition to regulated DBPs, several emerging DBPs were reported in desalinated water. Le Roux et al. (2015) reported I-THMs in desalinated water from two plants in Jeddah, Saudi Arabia. The averages of DCIM, BCIM, DBIM, CDIM, BDIM and IF were ND, ND, 1.75, ND, 0.6 and ND, respectively. It is to be noted that I-THMs have also been reported in surface and groundwater sourced supply water (Ioannou et al. 2016). Overall, DBPs in thermal distillate were much lower than the RO permeate (Table 2). Thermal distillation needs higher energy, which primarily uses fossil fuels leading to higher costs of desalinated water. In addition, thermal plants release higher levels of CO2 into the environment (Darwish 2017; ESCWA 2009).

**Distribution systems within desalination plants**

The dissolved organic carbon (DOC) in RO permeates were in the range of <0.1–0.6 mg/L (Agus et al. 2009; Agus & Sedlak 2010), which were lower than the typical freshwater (Chowdhury et al. 2008). However, bromide and iodide were in the ranges of 250–600 μg/L and <4–16 μg/L, respectively, which were much higher than freshwater sources. Higher levels of bromide and iodide increased the Br-DBPs and I-DBPs (Magara et al. 1996; Agus et al. 2009; Agus & Sedlak 2010; Duranceau 2010; Ioannou et al. 2016). Recent studies have demonstrated the formation of emerging polar Br-DBPs and I-DBPs in the presence of bromide and iodide in source water (Zhai et al. 2014; Gong & Zhang 2015; Gong et al. 2016). Further, NH2Cl treatment showed preferential formation of I-DBPs (Postigo et al. 2017). In chlorine treatment, iodide reacts with HOCI and HOBr to form hypoiodous (HOI) acid, which can form I-THMs in the distribution systems of desalination plants. In addition, bromide can form Br-DBPs and bromo-iodo-DBPs (Br-I-DBPs). The Br-DBPs, I-DBPs and Br-I-DBPs are more cytotoxic and genotoxic to mammalian cells than the Cl-DBPs. The toxicity follows the order of Cl-THMs < Br-THMs < I-THMs (Richardson et al. 2007).

In an RO plant in Jeddah, Saudi Arabia, THMs in the distribution systems were in the range of 13.5–25.7 μg/L (Table 3). In this plant, averages of TCM, BDCM, DBCM and TBM were 0.5%, 1.0%, 2.6% and 93.4%, respectively (Table 3). In a MSF plant on the east coast of Saudi Arabia, averages of TCM, BDCM, DBCM and TBM were 47.8%, 29.9%, 7.5% and 7.5%, respectively, while in a MSF plant in Doha, these were 3.8%, 15.4%, 7.7% and 69.2%, respectively (Latif et al. 2019; Chowdhury 2013, 2016). In Al-Khobar (east coast), THMs in the distribution system of an MSF plant were in the range of 2.4–12.1 μg/L (Chowdhury 2013, 2016). Several other MSF plants showed low concentrations of THMs (Chowdhury et al. 2018) in distribution systems. In all plants, Br-THMs were dominant (Latif 1991; Chowdhury 2013, 2016). Higher concentrations of THMs in distribution systems of RO plants might be due to higher initial concentrations and higher levels of bromide in RO effluents than the thermal effluents.

**Blend water**

Desalinated water generally has lower pH than the neutral range, which is adjusted through stabilization by blending with treated brackish/groundwater or untreated seawater prior to supplying to the WDS. The RO permeates with low DOC are mixed with treated groundwater with high DOC resulting in higher DOC in the blend water. High concentrations of DOC, and bromide and iodide in blend water, are likely to increase Br-DBPs, I-DBPs and total DBPs upon chlorination.
In a Jeddah plant, THMs in blend water were in the range of 9.3–30.1 μg/L, of which TBM contributed 42–96% (Table 4). In Al-Khobar, THMs were in the range of 2.1–52.4 μg/L, of which Br-THMs were 60–86% (Chowdhury et al. 2018). In Doha (Qatar), THMs in blend water were in the range of 10.5–36.3 μg/L (Table 4). On the east coast, Saudi Arabia, THMs in blend water were in the range of 3.1–12.8 μg/L (Table 4) while TBM contributed 61–86% (Chowdhury et al. 2018). In a laboratory study, averages of THMs were 29.0, 40.5 and 42.6 μg/L for desalinated and treated groundwater blending ratios of 1:10, 1:5 and 1:2, respectively (Tawabini et al. 2014). Overall, THMs in blend water were higher than the THMs in desalinated water (Chowdhury et al. 2018).

### Water distribution system

Blend water with residual chlorine is pumped into the WDS to supply to cities. The water is transported to inland cities through inter-city pipe networks. In Saudi Arabia, desalinated water is transported from Jubail plant to Riyadh, which is a distance of almost 450 km. The water is transported further to Buraidah (Qassim), which is 350 km from Riyadh. The cities generally mix treated groundwater with desalinated water to augment water supplies. Depending on the distance and service areas, water can stay in the WDS for a few hours to several days, which can lead to the formation of additional DBPs. In particular, the summer temperature is very high, exceeding 40 °C on...
many summer days (Tarawneh & Chowdhury 2018), which can accelerate the formation of Br-DBPs and I-DBPs in bromide- and iodide-rich water (Zhai et al. 2014; Kim et al. 2015; Postigo et al. 2017). The province-wide survey of 162 water supply systems in Ontario, Canada showed the ranges of THMs in water treatment plants (WTP) and WDS of 0.5–273 and 0.5–289 μg/L, respectively, with averages of 31.6 and 40.2 μg/L, respectively, indicating an increase of average THMs by 27.2% in the WDS (Chowdhury et al. 2008). The data from the Drinking Water Surveillance Program (DWSP) in Ontario, Canada showed a significant increase of THMs in WDS than the WTP (MOE 2018). Further, due to the prolonged stay in WDS during intercity transportation and storage in the inland reservoirs, residual disinfectant may be exhausted, resulting in microbiological regrowth in WDS (Chowdhury 2012).

In Saudi Arabia, Fayad (1995) reported THMs in WDS from eight major cities (Dammam, Riyadh, Makkah, Madinah, Jeddah, Abha, Hail, Buraidah) in the range of 0.03–41.7 μg/L with averages of 0.8–18.2 μg/L (Table 5). In a few smaller areas including Dhahran, Jubail, Qatif, Rahima and Khafji, the average of THMs was in the range of 4.1–12.3 μg/L. In these areas, TCM, BDCM, DBCM and TBM were in the ranges of ND–9.3, ND–3.4, ND–1.5 and 1.6–12.0 μg/L, respectively, and the THMs were 0.1–5.5, 0.3–2.0, 0.2–1.8 and 0.5–10.7 μg/L, respectively (Table 5). In all locations, Br-THMs were in the range of 70–95% of THMs (Table 5). In addition, Alsohaimi et al. (2012) reported bromate concentrations in a few locations in Saudi Arabia in the range of 3.4–75.0 μg/L (Table 5).

In Kuwait, THMs were reported to be in the ranges of 8.4–92.4 μg/L (Latif 1999). In four locations, averages of TCM, BDCM, DBCM and TBM were in the ranges of ND–5.9, 1.3–7.9, 2.8–13.7 and 3.4–77.4 μg/L, respectively, with averages of 0.8–1.0, 2.2–2.9, 5.6–9.2 and 24.3–47.3 μg/L, respectively (Table 5). In Qafar, THMs were in the range of 1.5–89.3 μg/L (Al-Otoum et al. 2016). Concentrations of TCM, BDCM, DBCM and TBM were in the ranges of ND–4.6, 0.1–26.2, 0.1–7.2 and 1.4–56.0 μg/L, respectively, with averages of 0.5–0.8, 2.0–2.6, 1.0–4.6 and 9.6–14.6 μg/L, respectively (Table 5). In Egypt, THMs were in the range of 7.5–87.4 μg/L (Basiouny et al. 2008). In Bahrain, averages of TCM, BDCM, DBCM and TBM were in the ranges of 0.5–1.2, 0.3–0.7, 0.3–2.9 and 1.3–6.4 μg/L, respectively (Al-Saleh & Al-Haddad 1994). In most locations, Br-DBPs were higher than the Cl-DBPs while many Br-DBPs are considered probable or possible human carcinogens (USEPA 2018).

**Plumbing premise within the house**

Past studies have reported an increase of DBPs in plumbing pipes (PP) and hot water tanks (HWT) (Weisel & Chen 1994; Wu et al. 2001; Baribeau et al. 2004; Weinberg et al. 2006; Dion-Fortier et al. 2009; Chowdhury 2016). In three locations in Quebec, Canada, THMs in PP were 136–181% times the THMs in WDS. In HWT, THMs were 191–269% times the THMs in WDS and 132–159% of THMs in PP. HAAs in PP and HWT were 23–224% and 53–261% of HAAs in WDS, respectively. The reduction of HAAs from WDS to PP and HWT might be due to increased microbiological activities in PP because of the consumption of free chlorine residuals and destruction of HAAs within the PP by microorganisms (Wu et al. 2001; Baribeau et al. 2004; Weinberg et al. 2006). In blend water in Dhahran, THMs in PP and HWT were 1.1–2.4 and 1.6–3.0 times the THMs in WDS, respectively. Concentrations of HAAs were 0.9–1.8 and 1.2–1.9 times the HAAs in WDS, respectively (Chowdhury 2016).

The populations are exposed to water from taps in houses, while the regulatory and monitoring agencies recommend measuring DBPs at various points within the WDS. Depending on the size of PP, water may stay in PP and HWT for a considerable time before it reaches taps (Wu et al. 2001; Baribeau et al. 2004; Weinberg et al. 2006; Dion-Fortier et al. 2009). This stagnation may be even longer during off-peak hours (e.g., midnight to morning; late morning to early evening), which allows extended reactions between the residual organics and free residual chlorine and increases DBPs in the PP and HWT.

**HUMAN HEALTH RISK AND TOXICITY**

Several DBPs can pose cancer and non-cancer risks to humans (Table 6). The effects include higher rates of colorectal and bladder cancers, neural tube defects, miscarriages, cardiac irregularities and low birth weight babies...
Table 5 | DBPs in water distribution system prior to entering the consumer’s home (μg/L)

<table>
<thead>
<tr>
<th>Location</th>
<th>Desalination plant</th>
<th>DBPs</th>
<th>Range</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dhahran, Saudi Arabia</td>
<td>TCM</td>
<td>1.2-6.1</td>
<td>3.2</td>
<td>1.3</td>
<td></td>
<td></td>
<td>Chowdhury (2013)</td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.5-3.4</td>
<td>2</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>0.0-1.2</td>
<td>0.5</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>0.0-0.7</td>
<td>0.5</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dhahran, Saudi Arabia</td>
<td>TCM</td>
<td>1.3-9.3</td>
<td>5.5</td>
<td>2.2</td>
<td></td>
<td></td>
<td>Chowdhury (2016)</td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.5-1.3</td>
<td>0.8</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>0.1-0.4</td>
<td>0.2</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>0.1-0.2</td>
<td>0.1</td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red Sea community, Saudi</td>
<td>Yanbu MSF/RO</td>
<td>TCM</td>
<td>0.2-0.5</td>
<td>0.3</td>
<td></td>
<td></td>
<td>Ahmad &amp; Bajahlan (2009)</td>
</tr>
<tr>
<td>Arabia</td>
<td></td>
<td>BDCM</td>
<td>0.7-1.4</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>1.2-2.3</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>4.3-6.7</td>
<td>5.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jubail</td>
<td>Al-Jubail SWRO plant</td>
<td>TCM</td>
<td>0.0-0.7</td>
<td>0.2</td>
<td></td>
<td></td>
<td>El-Hassan &amp; Al-Sulami (2005)</td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.0-0.5</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>0.0-1.0</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>0.0-5.9</td>
<td>4.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khobar</td>
<td>Al-Khobar MS Plant</td>
<td>TCM</td>
<td>0.0-0.05</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.2-0.3</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>0.9-1.1</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>5.6-8.5</td>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dammam</td>
<td>TCM</td>
<td>0.0-0.04</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.3-0.5</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>1.0-1.9</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>7.8-9.7</td>
<td>9.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qatif</td>
<td>TCM</td>
<td>0.0-0.3</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.2-0.3</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>0.7-1.2</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>7.7-9.7</td>
<td>8.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rahima</td>
<td>TCM</td>
<td>0.25-0.3</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>1.1-1.5</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>9.0-12.0</td>
<td>10.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khafji</td>
<td>Al-Khafji SWRO Plant</td>
<td>TCM</td>
<td>0.0-0.9</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.7-0.9</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>0.7-0.9</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>1.6-2.0</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riyadh</td>
<td>TCM</td>
<td>0.0-0.1</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BDCM</td>
<td>0.3-0.5</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DBCM</td>
<td>1.2-1.4</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>2.3-2.7</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dammam (Summer)</td>
<td>TTHMs</td>
<td>0.2-26.9</td>
<td>9.1</td>
<td></td>
<td></td>
<td></td>
<td>Fayad (1993)</td>
</tr>
<tr>
<td>Dammam (Winter)</td>
<td></td>
<td>0.1-28.9</td>
<td>18.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riyadh (Summer)</td>
<td>TTHMs</td>
<td>1.0-8.4</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riyadh (Winter)</td>
<td></td>
<td>1.3-8.1</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buraidah (Summer)</td>
<td>TTHMs</td>
<td>0.5-5.0</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buraidah (Winter)</td>
<td></td>
<td>0.8-3.9</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
<table>
<thead>
<tr>
<th>Location</th>
<th>Desalination plant</th>
<th>DBPs</th>
<th>Range</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hail (Summer)</td>
<td>Hail</td>
<td>TTHMs</td>
<td>1.1–2.5</td>
<td>1.4</td>
<td></td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Hail (Winter)</td>
<td></td>
<td></td>
<td>1.1–6.3</td>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Madinah (Summer)</td>
<td>Madinah</td>
<td>TTHMs</td>
<td>5.4–11.0</td>
<td>4.6</td>
<td></td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Madinah (Winter)</td>
<td></td>
<td></td>
<td>2.6–13.1</td>
<td>6.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jeddah (Summer)</td>
<td>Jeddah</td>
<td>TTHMs</td>
<td>4.0–41.7</td>
<td>7.1</td>
<td></td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Jeddah (Winter)</td>
<td></td>
<td></td>
<td>0.03–17.8</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Makkah (Summer)</td>
<td>Makkah</td>
<td>TTHMs</td>
<td>5.9–17.6</td>
<td>6.9</td>
<td></td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Makkah (Winter)</td>
<td></td>
<td></td>
<td>1.4–19.3</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abha (Summer)</td>
<td>Abha</td>
<td>TTHMs</td>
<td>1.4–1.0</td>
<td>1.5</td>
<td></td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Abha (Winter)</td>
<td></td>
<td></td>
<td>1.1–1.3</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Andalus</td>
<td>Doha Water Blending Complex</td>
<td>TCM</td>
<td>0.0–2.0</td>
<td>0.5</td>
<td>0.7</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>1.0–2.8</td>
<td>2.0</td>
<td>0.4</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>2.7–7.2</td>
<td>4.6</td>
<td>1.1</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>5.8–16.8</td>
<td>9.6</td>
<td>2.8</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Al-Jubail</td>
<td></td>
<td>TCM</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td>Kutty et al. (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al-Jabiya, Kuwait</td>
<td>Doha Water Blending Complex</td>
<td>TCM</td>
<td>0.0–2.9</td>
<td>0.9</td>
<td>1.0</td>
<td></td>
<td>Kim et al. (2015)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>2.0–3.8</td>
<td>2.8</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>7.0–13.7</td>
<td>9.2</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>17.6–36.8</td>
<td>24.7</td>
<td>5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hawaiili, Kuwait</td>
<td>Doha Water Blending Complex</td>
<td>TCM</td>
<td>0.0–4.0</td>
<td>0.8</td>
<td>1.2</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>1.3–3.8</td>
<td>2.2</td>
<td>0.6</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>3.2–9.1</td>
<td>7.0</td>
<td>1.6</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>12.9–33.3</td>
<td>24.3</td>
<td>5.0</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Keifan, Kuwait</td>
<td>Shuwaikh Water Blending Complex</td>
<td>TCM</td>
<td>0.0–3.1</td>
<td>0.9</td>
<td>1.1</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>1.6–7.9</td>
<td>2.9</td>
<td>1.4</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>2.8–9.1</td>
<td>5.6</td>
<td>1.4</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>3.4–71.5</td>
<td>47.4</td>
<td>20.9</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Al-Sharq, Kuwait</td>
<td>Shuwaikh Water Blending Complex</td>
<td>TCM</td>
<td>0.0–5.9</td>
<td>1.0</td>
<td>1.5</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>1.6–3.3</td>
<td>2.4</td>
<td>0.5</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>3.0–10.3</td>
<td>6.7</td>
<td>1.5</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>7.4–77.4</td>
<td>44.5</td>
<td>20.3</td>
<td></td>
<td>Latif (1999)</td>
</tr>
<tr>
<td>Qatar</td>
<td>Ras Laffan, Ras Abu-Fontas, Ras-Girtas</td>
<td>TCM</td>
<td>0.0–4.6</td>
<td>0.82</td>
<td></td>
<td></td>
<td>Al-Otoum et al. (2016)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>0.01–26.2</td>
<td>2.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>0.01–2.4</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>1.4–56.0</td>
<td>14.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoora, Bahrain</td>
<td></td>
<td>TCM</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>0.5</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>0.3</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>1.3</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salmania, Bahrain</td>
<td></td>
<td>TCM</td>
<td>0.6</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BDCM</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBCM</td>
<td>2.3</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TBM</td>
<td>3.6</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
Exposure to DBPs can occur throughout a lifetime via multiple pathways, such as ingestion with drinking water, and inhalation and dermal absorption during showering, bathing, cooking, house cleaning and swimming (Cantor et al. 1998; Savitz et al. 2006). Past studies have reported increased cancer and non-cancer risks to humans from exposure to DBPs (Weisel & Chen 1997; Lee et al. 2007; Nuckols et al. 2008; Xu & Weisel 2010; Savitz et al. 2006; Semerjian & Dennis 2007; Chowdhury et al. 2018).

Among DBPs, Br-DBPs, N-DBPs and I-DBPs are more toxic than Cl-DBPs (Plewa et al. 2002, 2008; Muellner et al. 2007; Zhang et al. 2012; Wagner & Plewa 2017). A summary of some DBPs, their cytotoxicity, genotoxicity and risk factors are presented in Table 6. Most of the DBPs were cytotoxic and/or genotoxic (Table 6). Among THMs, TIM induced cytotoxicity to the Chinese hamster ovary (CHO) cell at the lowest concentration of 3,937 μg/L while BDCM induced genotoxicity to human-derived hepatoma line (HepG2) cell at the lowest concentration of 164 μg/L (Table 6). For IAA, the lowest values for cytotoxicity and genotoxicity were 93 and 930 μg/L, respectively (Table 6). In HANs, IAN induced cytotoxicity to the CHO cell at the lowest concentration of 17 μg/L while BAN induced genotoxicity at the lowest concentration of 4,798 μg/L (Table 6). Among the cyanogen halides, CNBr induced cytotoxicity at the lowest concentration of 106 μg/L (Table 6). The I-DBPs, Br-DBPs and N-DBPs were more cytotoxic and genotoxic than Cl-DBPs (Table 6). In drinking water,
<table>
<thead>
<tr>
<th>DBPs</th>
<th>Name</th>
<th>Symbol</th>
<th>Formula</th>
<th>CAS No.</th>
<th>MW</th>
<th>LCC (μM)</th>
<th>LGC (μM)</th>
<th>LCC [μg/L]</th>
<th>LGC [μg/L]</th>
<th>SF (mg/kg-day)</th>
<th>RFD (mg/kg-day)</th>
<th>DUR (per μg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THMs</td>
<td>Chloroform</td>
<td>TCM</td>
<td>CHCl₃</td>
<td>67-66-3</td>
<td>119.4 NA</td>
<td>10,000 NA</td>
<td>1,193,690 RA</td>
<td>RA</td>
<td>0.01</td>
<td>1.8 × 10⁻⁶</td>
<td>2.4 × 10⁻⁶</td>
<td></td>
</tr>
<tr>
<td>Bromodichloromethane</td>
<td>BDCM</td>
<td>CHBrCl₂</td>
<td>75-27-4</td>
<td>163.8</td>
<td>1</td>
<td>164</td>
<td>0.062</td>
<td>0.02</td>
<td>2.3 × 10⁻⁷</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibromochloromethane</td>
<td>DBCM</td>
<td>CHBr₂Cl</td>
<td>124-48-1</td>
<td>208.3</td>
<td>10</td>
<td>2,083</td>
<td>0.084</td>
<td>0.02</td>
<td>2.3 × 10⁻⁷</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromoform</td>
<td>TBM</td>
<td>CHBr₃</td>
<td>75-25-2</td>
<td>252.7</td>
<td>1,000 NA</td>
<td>2,527,731 NA</td>
<td>0.0079</td>
<td>0.02</td>
<td>2.3 × 10⁻⁷</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromodiodimethane</td>
<td>BDIM</td>
<td>CHBr₂</td>
<td>557-95-9</td>
<td>346.7</td>
<td>1,500 NS</td>
<td>520,098 NS</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorodiodimethane</td>
<td>CDIM</td>
<td>CHCl₂</td>
<td>638-73-3</td>
<td>302.3</td>
<td>100</td>
<td>3,022</td>
<td>604,556</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromochlorodioxidomethane</td>
<td>BCM</td>
<td>CHBrCl</td>
<td>34970-00-8</td>
<td>255.3</td>
<td>2,200 NS</td>
<td>561,609 NS</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichlorodioxidomethane</td>
<td>DCIM</td>
<td>CHClI</td>
<td>594-04-7</td>
<td>210.8</td>
<td>2,000 NS</td>
<td>421,658 NS</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodoform</td>
<td>TIM</td>
<td>CHI₃</td>
<td>75-47-8</td>
<td>393.7</td>
<td>10</td>
<td>3,937</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAAs</td>
<td>Bromochloroacetic acid</td>
<td>BCAA</td>
<td>C₂H₂BrClO₂</td>
<td>5589-96-3</td>
<td>173.4</td>
<td>300</td>
<td>3,000</td>
<td>520,170</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromodichloroacetic acid</td>
<td>BDCAA</td>
<td>C₂H₂BrClO₂</td>
<td>7113-314-7</td>
<td>207.8</td>
<td>500</td>
<td>103,920 NS</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorodibromochloroacetic</td>
<td>CDBAA</td>
<td>C₂H₂Br₂ClO₂</td>
<td>5278-95-5</td>
<td>252.3</td>
<td>10</td>
<td>1,250,250</td>
<td>3,279,900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichloroacetic acid</td>
<td>DCAA</td>
<td>C₂H₂Cl₂ClO₂</td>
<td>79-43-6</td>
<td>128.9</td>
<td>2,000 NS</td>
<td>257,880 NS</td>
<td>0.05</td>
<td>0.004</td>
<td>1.4 × 10⁻⁶</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromoacetic acid</td>
<td>DBAA</td>
<td>C₂H₂Br₂O₂</td>
<td>631-64-1</td>
<td>217.9</td>
<td>200</td>
<td>43,572</td>
<td>163,395</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroacetic acid</td>
<td>BAA</td>
<td>C₂H₃BrO₂</td>
<td>79-08-3</td>
<td>139.0</td>
<td>0.5</td>
<td>257</td>
<td>1,806</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroacetic acid</td>
<td>CAA</td>
<td>C₂H₃ClO₂</td>
<td>79-11-8</td>
<td>94.5</td>
<td>2,000 NS</td>
<td>25,230</td>
<td>3,279,900</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tribromoacetic acid</td>
<td>TBA</td>
<td>C₂H₃Br₂O₂</td>
<td>75-96-7</td>
<td>296.8</td>
<td>5</td>
<td>3,000</td>
<td>1,848</td>
<td>890,280</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trichloroacetic acid</td>
<td>TCAA</td>
<td>C₂H₃ClO₂</td>
<td>76-03-9</td>
<td>163.4</td>
<td>400</td>
<td>65,356</td>
<td>NS</td>
<td>0.07</td>
<td>2.0 × 10⁻６</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodoacetic acid</td>
<td>IAA</td>
<td>C₂H₃I₂O₂</td>
<td>64-69-7</td>
<td>186.0</td>
<td>0.5</td>
<td>93.0</td>
<td>930</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilodoacetic acids</td>
<td>DIAA</td>
<td>C₂H₃I₂O₂</td>
<td>598-89-0</td>
<td>311.8</td>
<td>100</td>
<td>31,184</td>
<td>311,840</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromoiodoacetic acids</td>
<td>BIAA</td>
<td>C₂H₃BrI₂O₂</td>
<td>71815-43-5</td>
<td>264.8</td>
<td>250</td>
<td>66,210</td>
<td>662,100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroiodoacetic acid</td>
<td>CIAA</td>
<td>C₂H₃ClI₂O₂</td>
<td>53715-09-6</td>
<td>220.4</td>
<td>170</td>
<td>37,466.3</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HANs</td>
<td>Bromochloroacetonitrile</td>
<td>BCAN</td>
<td>C₂H₃BrCN</td>
<td>83463-62-1</td>
<td>154.4</td>
<td>7</td>
<td>250</td>
<td>38,598</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dibromoacetonitrile</td>
<td>DBAN</td>
<td>C₂H₅BrN</td>
<td>3252-43-5</td>
<td>198.9</td>
<td>1</td>
<td>30</td>
<td>5,986</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichloroacetonitrile</td>
<td>DCAN</td>
<td>C₂H₅ClN</td>
<td>3018-12-0</td>
<td>109.9</td>
<td>10</td>
<td>2,400</td>
<td>263,849</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trichloroacetonitrile</td>
<td>TCAN</td>
<td>C₂H₅Cl₂N</td>
<td>545-06-2</td>
<td>144.4</td>
<td>25</td>
<td>1,000</td>
<td>144,379</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromoacetonitrile</td>
<td>BAN</td>
<td>C₂H₅BrN</td>
<td>590-17-0</td>
<td>120.0</td>
<td>1</td>
<td>120</td>
<td>4,798</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroacetonitrile</td>
<td>CAN</td>
<td>C₂H₅ClN</td>
<td>107-14-2</td>
<td>75.5</td>
<td>5</td>
<td>250</td>
<td>18,874</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodoacetonitrile</td>
<td>IAN</td>
<td>C₂H₅IN</td>
<td>624-75-9</td>
<td>167.0</td>
<td>0.1</td>
<td>17</td>
<td>5,008.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanogen</td>
<td>Cyanogen bromide</td>
<td>CNBr</td>
<td>506-68-1</td>
<td>105.9</td>
<td>1</td>
<td>500</td>
<td>52,961</td>
<td>0.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanogen chlorides</td>
<td>CNCl</td>
<td>506-77-4</td>
<td>61.5</td>
<td>3,000 NS</td>
<td>184,404 NS</td>
<td>NS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanogen iodide</td>
<td>CNI</td>
<td>506-78-5</td>
<td>152.9</td>
<td>1</td>
<td>200</td>
<td>30,584</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrosamines</td>
<td>N-nitrosodimethylamine</td>
<td>NDMA</td>
<td>C₆H₄N₂O</td>
<td>62-75-9</td>
<td>74.1 NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>51</td>
<td>1.4 × 10⁻³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haloacetamides</td>
<td>Bromoacetamide</td>
<td>BAcAm</td>
<td>C₆H₅BrNO</td>
<td>683-57-8</td>
<td>138.0</td>
<td>0.5</td>
<td>25</td>
<td>3,449</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroacetamide</td>
<td>CAcAm</td>
<td>C₆H₅CINO</td>
<td>79-07-2</td>
<td>93.5</td>
<td>75</td>
<td>7,013</td>
<td>70,133</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodoacetamide</td>
<td>IAcAm</td>
<td>C₆H₅INO</td>
<td>144-48-9</td>
<td>185.0</td>
<td>0.5</td>
<td>92</td>
<td>5,549</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haloaldehydes</td>
<td>Bromoacetaldehyde</td>
<td>C₂H₅BrO</td>
<td>17157-48-1</td>
<td>123.0</td>
<td>8</td>
<td>200</td>
<td>24,590</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroacetaldehyde</td>
<td>C₂H₅ClO</td>
<td>107-20-0</td>
<td>78.5</td>
<td>0.5</td>
<td>100</td>
<td>7,850</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iodoacetaldehyde</td>
<td>C₂H₅IO</td>
<td>55782-51-9</td>
<td>170.0</td>
<td>5</td>
<td>900</td>
<td>152,954</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(continued)
concentrations of DBPs, to date, were much lower (e.g., USEPA 2012; NLDOE 2016; MOE 2018) than the lowest concentrations needed to induce cytotoxicity and genotoxicity to the CHO and/or HepG2 cells (Zhang et al. 2012, 2017; Wagner & Plewa 2007). However, the slope factor (SF) and drinking water unit risk (DUR) demonstrated the possibility of cancer risks from several DBPs through the oral pathway (USEPA 2018). Although the concentrations of individual DBPs in supply water were much lower than the lowest concentrations needed to induce cytotoxicity and genotoxicity to the CHO cells, the effects of the mixture of DBPs need better understanding. In general, DBPs in drinking water are present in the form of a mixture. Consequently, the synergistic effects might play an important role in inducing cytotoxic and genotoxic effects. Future research is needed to explain the effects of a mixture of DBPs.

CONTROLLING DBPS

The DBPs are formed in many stages from source to the consumer’s tap (Figure 2). In producing and supplying the desalinated and blend water, desalination plants rarely adopt any approach to reduce DBPs throughout the stages of desalination and supply. In thermal plants, steam is mostly free from non-volatile DBPs (Stage II in Figure 2). However, volatile DBPs can be present at low concentrations. In product water from thermal plants, precursor concentrations for DBPs (e.g., NOM, bromide and iodide) are very low. In contrast, effluents from RO plants have higher DBPs and higher concentrations of precursors (Kutty et al. 1998; Magara et al. 1996; Kim et al. 2015; Le Roux et al. 2013), which are carried over through the next stages (Figure 2). Thermal plants are likely to reduce many DBPs in the distillate. However, these plants are energy intensive, leading to higher costs and greenhouse gas emissions. The cost of 1.0 m³ of desalinated water was reported to be in the range of US$1.31–2.37, which could be increased further depending on the cost of energy (e.g., fossil fuel) and partial/full withdrawal of subsidized oil supplies for desalination. In producing 1.0 m³ of desalinated water, MSF plants typically emit 13.9–25.0 kg of CO₂ into the environment (Darwish 2007; ESCWA 2009). There is a need to perform a risk–cost trade-off analysis in selecting the desalination process.
In Stages III–V, many plants in Saudi Arabia apply HOCl or Cl₂ (Kim et al. 2018). In these stages, desalinated seawater is mixed with treated groundwater containing higher levels of NOM, bromide and iodide. The higher levels of bromide and iodide can increase the formation of Br-DBPs, I-DBPs and Br-I-DBPs (Gong & Zhang 2018; Gong et al. 2019; Ioannou et al. 2019). Past studies reported increased formation of Br-DBPs and I-DBPs while a small fraction of volatile DBPs can be present in water. In desalinated and blend water, concentrations of Br-DBPs were much higher than the Cl-DBPs while I-DBPs were occasionally reported (Ioannou et al. 2016; Postigo et al. 2017). Removal of bromide and iodide prior to Stage V may be the second step (Figure 2). The third and final step prior to water consumption (post-Stage VI) may include filtration of water through granular activated carbon (GAC) filters. Past studies reported the decrease of THMs and HAAs using GAC filters in the ranges of 84–89% and 58–71%, respectively (Chowdhury et al. 2020). Weinberg et al. (2006) reported removal of 93–99% of THMs and 68–95% of HAAs using different types of activated carbon filters. Very recently, Jiang et al. (2018, 2019) have applied GAC adsorption to remove intermediate aromatic halogenated DBPs, which formed during chlorination and acted as intermediate DBPs to form the commonly known DBPs (e.g., THMs, HAAs, etc.). Through increasing the initial bromide level from 0.0 to 2.0 mg/L, removal of total organic halides (TOX) was increased from 52% to 74% (Jiang et al. 2019). In addition, an increase of chlorine contact time from 0.5 to 3.0 h increased TOX removal from 61% to 75%. Levesque et al. (2006) reported reductions of THMs by 30%, 87% and 92%, respectively, through storage in a refrigerator and boiling and filtering followed by storage in a refrigerator. However, boiling was found to increase DCAA by 35% and decrease TCAA by 42% while no change to the total HAAs was observed (Levesque et al. 2006). Filtration through the GAC point-of-use (PoU) filters can be an option while the cost of filters and handling of contaminated GAC laden waste can be other issues which need better attention.

Application of alternative disinfectants might reduce formation of DBPs. ClO₂ and NH₂Cl have been reported to produce low amounts of DBPs (Dalvi et al. 2006), which can be an option for Stage I (Figure 2). Laboratory studies on seawater with ClO₂ have reported very low concentrations of THMs and HAAs in Korea and Spain (Simon 2010; Chowdhury 2016). Although DBPs in product water from thermal plants are low (Stage II), concentrations at consumers’ taps can be significantly high due to the implications of the subsequent stages (Stages III–VI).

The efficient control of DBPs can be achieved through multiple steps. In Stage II, solar or low-energy distillation may be the first step, which can exclude the non-volatile DBPs while a small fraction of volatile DBPs can be present in water. In desalinated and blend water, concentrations of Br-DBPs were much higher than the Cl-DBPs while I-DBPs were occasionally reported (Ioannou et al. 2016; Postigo et al. 2017). Removal of bromide and iodide prior to Stage V may be the second step (Figure 2). The third and final step prior to water consumption (post-Stage VI) may include filtration of water through granular activated carbon (GAC) filters. Past studies reported the decrease of THMs and HAAs using GAC filters in the ranges of 84–89% and 58–71%, respectively (Chowdhury et al. 2020). Weinberg et al. (2006) reported removal of 93–99% of THMs and 68–95% of HAAs using different types of activated carbon filters. Very recently, Jiang et al. (2017, 2018) have applied GAC adsorption to remove intermediate aromatic halogenated DBPs, which formed during chlorination and acted as intermediate DBPs to form the commonly known DBPs (e.g., THMs, HAAs, etc.). Through increasing the initial bromide level from 0.0 to 2.0 mg/L, removal of total organic halides (TOX) was increased from 52% to 74% (Jiang et al. 2018). In addition, an increase of chlorine contact time from 0.5 to 3.0 h increased TOX removal from 61% to 75%. Levesque et al. (2006) reported reductions of THMs by 30%, 87% and 92%, respectively, through storage in a refrigerator and boiling and filtering followed by storage in a refrigerator. However, boiling was found to increase DCAA by 35% and decrease TCAA by 42% while no change to the total HAAs was observed (Levesque et al. 2006). Filtration through the GAC point-of-use (PoU) filters can be an option while the cost of filters and handling of contaminated GAC laden waste can be other issues which need better attention.

Application of alternative disinfectants might reduce formation of DBPs. ClO₂ and NH₂Cl have been reported to produce low amounts of DBPs (Dalvi et al. 2006), which can be an option for Stage I (Figure 2). Laboratory studies on seawater with ClO₂ have reported very low concentrations of THMs and HAAs in Korea and Spain (Simon 2010; Chowdhury 2016). Although DBPs in product water from thermal plants are low (Stage II), concentrations at consumers’ taps can be significantly high due to the implications of the subsequent stages (Stages III–VI).

The efficient control of DBPs can be achieved through multiple steps. In Stage II, solar or low-energy distillation may be the first step, which can exclude the non-volatile DBPs while a small fraction of volatile DBPs can be present in water. In desalinated and blend water, concentrations of Br-DBPs were much higher than the Cl-DBPs while I-DBPs were occasionally reported (Ioannou et al. 2016; Postigo et al. 2017). Removal of bromide and iodide prior to Stage V may be the second step (Figure 2). The third and final step prior to water consumption (post-Stage VI) may include filtration of water through granular activated carbon (GAC) filters. Past studies reported the decrease of THMs and HAAs using GAC filters in the ranges of 84–89% and 58–71%, respectively (Chowdhury et al. 2020). Weinberg et al. (2006) reported removal of 93–99% of THMs and 68–95% of HAAs using different types of activated carbon filters. Very recently, Jiang et al. (2017, 2018) have applied GAC adsorption to remove intermediate aromatic halogenated DBPs, which formed during chlorination and acted as intermediate DBPs to form the commonly known DBPs (e.g., THMs, HAAs, etc.). Through increasing the initial bromide level from 0.0 to 2.0 mg/L, removal of total organic halides (TOX) was increased from 52% to 74% (Jiang et al. 2018). In addition, an increase of chlorine contact time from 0.5 to 3.0 h increased TOX removal from 61% to 75%. Levesque et al. (2006) reported reductions of THMs by 30%, 87% and 92%, respectively, through storage in a refrigerator and boiling and filtering followed by storage in a refrigerator. However, boiling was found to increase DCAA by 35% and decrease TCAA by 42% while no change to the total HAAs was observed (Levesque et al. 2006). Filtration through the GAC point-of-use (PoU) filters can be an option while the cost of filters and handling of contaminated GAC laden waste can be other issues which need better attention.

Application of alternative disinfectants might reduce formation of DBPs. ClO₂ and NH₂Cl have been reported to produce low amounts of DBPs (Dalvi et al. 2006), which can be an option for Stage I (Figure 2). Laboratory studies on seawater with ClO₂ have reported very low concentrations of THMs and HAAs in Korea and Spain (Simon 2010; Chowdhury 2016). Although DBPs in product water from thermal plants are low (Stage II), concentrations at consumers’ taps can be significantly high due to the implications of the subsequent stages (Stages III–VI).
et al. 2014; Yu et al. 2014). However, ClO₂ is to be generated on-site, requiring transportation and storage of chemicals, which can increase the operational costs. In addition, ClO₂ forms chlorite, which is critical and limited to 0.7 mg/L (WHO 2011). Following production of desalinated water, application of NH₂Cl in Stages III–V is likely to produce lower amounts of DBPs. However, the weak performance of NH₂Cl may need additional contact times and higher costs (Figure 2). In addition, past studies reported relatively higher levels of NDMA and I-THMs in NH₂Cl treated supply water (USEPA 2012; Chowdhury 2014; Ioannou et al. 2016; Postigo et al. 2017) while these DBPs were more toxic than the regulated DBPs (USEPA 2018). In desalinated water, the product water is unlikely to have precursors for NDMA (e.g., liquid rocket fuel, dimethylamine (DMA), cationic polymers, ion-exchange resins with amine functional groups, etc.). The excellent disinfection capacity and low DBP formation potential of ClO₂ is attractive for the pretreatment of feed water at the intakes. The combined disinfection of ClO₂ (Stage I) and NH₂Cl (Stages III–V) can be evaluated in the context of performance, cost, types and amounts of different DBPs in desalinated and blend water, and human exposure and risk. Future study is warranted in this direction.

**FUTURE RESEARCH NEEDS**

Since 1974, studies have made significant progress on the occurrences and distributions of DBPs in supply water. In the past two decades, DBPs in desalinated and blend water have attracted the attention of many researchers. The advanced analytical capacities of the recent instruments have assisted in detecting many emerging DBPs in desalinated and blend water while their comprehensive effects upon humans are yet to be investigated. In addition, many DBPs are yet to be discovered, thus their effects upon humans are also unknown. Several issues need further attention to improve desalinated and blend water quality. The following research directions can assist in achieving better control on DBPs and their risks to humans:

- **During pretreatment (Stage I), use of Cl₂ is likely to form higher levels of Br-DBPs and I-DBPs in feed water.**

Thermal distillation removes most of the non-volatile DBPs and precursors to trace levels while volatile DBPs are likely to be present in the product water at relatively low concentrations. The RO process (Stage II) removes more than 99% of bromide and iodide from feed water while RO effluents contain considerable amounts of bromide (250–600 μg/L) and iodide (<4–16 μg/L), which are higher than most freshwater systems (Kutty et al. 1995; Magara et al. 1996; Kim et al. 2015; Le Roux et al. 2015). Concentrations of DBPs in RO effluents were higher (Table 2). Application of ClO₂ during pretreatment (Stage I) is likely to reduce DBPs while disinfection in the other stages (Stages II–VI) can be ensured using NH₂Cl. However, past studies reported relatively higher levels of NDMA and I-THMs in NH₂Cl treated supply water while these DBPs are more cytotoxic and genotoxic than the regulated DBPs (Table 6). Further, such a combined disinfection is likely to increase the cost and induce other health effects, thus needs better understanding. Future study is needed to investigate the feasibility of using the combined disinfection (ClO₂ and NH₂Cl) in different stages of desalination.

- **Dechlorination of pretreated water prior to feeding RO processes is likely to reduce DBPs formation.** Chloramines (NH₂Cl, NHCl₂) are often used to control biofouling agents in desalination intake structures and RO membranes, which also minimizes the damage of the membranes. However, it may form bromamine (BrH₂N) due to the high concentrations of bromide in feed water, leading to the loss of disinfectant residual. In addition, BrH₂N can also increase brominated DBPs (Zhai et al. 2014; Zhu & Zhang 2016). Recent studies have reported the formation of several emerging DBPs following chloramination of bromide and iodide containing water (Zhai et al. 2014; Gong & Zhang 2015; Gong et al. 2016; Postigo et al. 2017). Formation of DBPs in chloraminated seawater needs better understanding. Future study is warranted on dechlorination of pretreated water prior to feeding RO processes.

- **In Stages III–V (Figure 2), desalinated water is stabilized, mixed, stored and transported through the WDS. During these stages, NOM, bromide, iodide and DBPs are increased, which leads to increased demand for disinfectants.** There is a need for the removal of residual bromide...
and iodide, which can be performed in Stages III and IV. However, removal of bromide and iodide is a challenge. Advanced technologies can be applied for the removal of bromide and iodide. Future study is warranted for the cost-effective removal of bromide and iodide from the supply water.

- Filtration through PoU filters equipped with an activated carbon filtration unit has been reported to reduce the exposure concentrations of THMs and HAAs significantly (Levesque et al. 2006; Weinberg et al. 2006; Chowdhury et al. 2010; Jiang et al. 2017, 2018). The performance of these filters can be evaluated in the context of emerging DBPs. In addition, the cost of activated carbon filters is typically higher, which can be an additional financial burden (Chowdhury et al. 2010). Future research is needed to produce low-cost activated carbon PoU GAC filters.

- Thermal plants remove non-volatile DBPs, bromide and iodide to trace levels. In the context of DBPs, these plants are attractive. In contrast, these plants consume more energy and they emit higher levels of CO2 into the environment. The overall cost is likely to be higher. Development of hybrid or solar technology for seawater distillation is likely to produce better quality water at low cost. Future research is needed to develop low-cost distillation technology for seawater desalination.

- There are almost 600 types of DBPs (Richardson et al. 2007) in supply water whereas approximately 100 have been characterized with respect to cytotoxicity and genotoxicity (Wagner & Plewa 2017). Most of the DBPs reported, to date, are cytotoxic and/or genotoxic to the CHO cell while few studies have reported their genotoxicity on the human HepG2 cells (Zhang et al. 2012; Wagner & Plewa 2017). Although the lowest concentrations for such effects from DBPs were much higher than the environmentally available concentrations in supply water, the synergistic effects of various DBPs need better understanding. Future study is needed to explain the effects of a mixture of DBPs to humans.

- The seasonal and geographic variability of seawater quality affects the formation of DBPs. Temporal events (e.g., storms, algal blooms, oil spills) can increase DBPs formation. As an example, algal blooms are higher during summer, which increases the demand for Cl2 doses, leading to the formation of higher DBPs. Further research is needed to characterize the effects of seasonal, geographic variability and temporal events on the formation and speciation of DBPs.

- The contributions of THMs and HAAs to the total organic halide (TOX) are around 50% (Le Roux et al. 2015) and many DBPs are yet to be identified. The relation between TOX and DBPs should be assessed. Further study is needed to understand the characteristics of emerging DBPs. The feasibility of using TOX as the indicator of toxicity may be investigated in future.

- To date, no model has been reported to predict DBPs in different stages of desalination (Figure 2). Availability of models is likely to assist in predicting and controlling DBPs in different stages of desalination. Future study is needed to identify the factors affecting formation of DBPs, and develop and validate models using these factors.

- Use of ozone (O3) as a disinfectant during pretreatment and post-treatment of desalination processes may result in the formation of bromate and bromate is one of the highly undesirable DBPs in water. The methods of removing bromide prior to disinfection and bromate following disinfection need to be investigated prior to application of O3 for seawater desalination.

CONCLUSIONS

This study presented a review on the formation of DBPs in different stages of desalinated and blend water production and supplies from source to tap, and their toxic effects to mammalian cells. The high concentrations of bromide in seawater result in higher fractions of Br-DBPs while the presence of iodide and I-DBPs have been reported in recent years. Br-DBPs and I-DBPs are more cytotoxic and genotoxic than the regulated DBPs. In addition, new-generation DBPs are being identified in supply water. There is a need to better characterize DBPs, their formation kinetics, effects upon humans and control strategies. Coastal regions are the homes of around 2 billion people and groundwater aquifers in these regions might be polluted due to seawater intrusion. These populations, as well as
the populations supplied with desalinated and blend water, are likely to be affected by the high concentrations of bromide and iodide in seawater. There is no single approach to providing the solution for the entire spectrum of problems. A multi-barrier approach for different stages of desalinated and blend water supplies might assist in controlling DBPs at the exposure points, and thus better protect humans.

ACKNOWLEDGEMENT

The author acknowledges the support of research group at the exposure points, and thus better protect humans.

REFERENCES


Chowdhury, S. 2014 N-Nitrosodimethylamine (NDMA) in food and beverages: a comparison in context to drinking water. Human and Ecological Risk Assessment 20, 1291–1312.


USEPA (United States Environmental Protection Agency) 2006 *National Primary Drinking Water Regulations: Stage 2 Disinfectants and Disinfection Byproducts Rule: Final Rule*. Federal Register, USEPA, Washington, DC, USA.


First received 3 August 2018; accepted in revised form 25 November 2018. Available online 24 December 2018