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Review

Disinfection Methods for Swimming Pool Water: Byproduct Formation and Control

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Abstract: This paper presents a comprehensive and critical comparison of 10 disinfection methods of swimming pool water: chlorination, electrochemically generated mixed oxidants (EGMO), ultraviolet (UV) irradiation, UV/chlorine, UV/hydrogen peroxide (H₂O₂), UV/H₂O₂/chlorine, ozone (O₃)/chlorine, O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine for the formation, control and elimination of potentially toxic disinfection byproducts (DBPs): trihalomethanes (THMs), haloacetic acids (HAAs), haloacetonitriles (HANs), trihaloacetaldehydes (THAs) and chloramines (CAMs). The statistical comparison is carried out using data on 32 swimming pools accumulated from the reviewed studies. The results indicate that O₃/UV and O₃/UV/chlorine are the most promising methods, as the concentration of the studied DBPs (THMs and HANs) with these methods was reduced considerably compared with chlorination, EGMO, UV irradiation, UV/chlorine and O₃/chlorine. However, the concentration of the studied DBPs including HAAs and CAMs remained much higher with O₃/chlorine compared with the limits set by the WHO for drinking water quality. Moreover, the enhancement in the formation of THMs, HANs and CH with UV/chlorine compared with UV irradiation and the increase in the level of HANs with O₃/UV/chlorine compared with O₃/UV indicate the complexity of the combined processes, which should be optimized to control the toxicity and improve the quality of swimming pool water.

Keywords: chlorination; disinfection byproducts; electrochemically generated mixed oxidants; hydrogen peroxide; ozone; swimming pool water; ultraviolet irradiation

1. Introduction

Chlorination methods for the disinfection of swimming pool water lead to the formation of potentially toxic disinfection byproducts (DBPs) such as trihalomethanes (THMs), haloacetic acids (HAAs), haloacetonitriles (HANs), trihaloacetaldehyde (THAs) and chloramines (CAMs) (Tables A1 and A2: given as Appendix A) [1–4]. With this awareness, the demand for alternatives to chlorine disinfection has increased. The alternative methods aimed at improving the quality of swimming pool water are: electrochemically generated mixed oxidants (EGMO) [3,5–8], ultraviolet (UV) irradiation [9–12], UV-based advanced oxidation processes (UV-based AOPs) such as UV/H₂O₂ [13], ozone (O₃) [14–16], and ozone-based AOPs such as O₃/H₂O₂ and O₃/UV [17–19]. The use of O₃ and UV irradiation for the disinfection of swimming pool water has been adopted in some cases, though together with chlorine for the provision of a residual disinfectant [20]. However, chlorination methods for disinfection are widely used in practice [21,22]. AOPs are still in the research and development phase for the disinfection of swimming pool water [22].

The efficiency of the ozonation process can be increased by combining O_3 with H_2O_2 and UV such as O_3/H_2O_2 and O_3/UV . Although substantial research has been done on the application of O_3/H_2O_2 and O_3/UV processes for the disinfection of drinking water [23–28], a limited number of studies is available on the disinfection of swimming pool water. The use of O_3/H_2O_2 and O_3/UV is reported by Glauner et al. [17], and O_3/UV by Kristensen et al. [18] and Cheema et al. [19]. Similarly, significant research has been done on the use of UV-based AOPs (UV/H_2O_2) for the disinfection of drinking water [23,25–30], but in swimming pool water only by Spiliotopoulou et al. [13]. Moreover, the studies conducted on the use of O_3/H_2O_2 , O_3/UV and UV/H_2O_2 for the treatment of swimming pool water only investigated few DBPs such as THMs and HANs.

It is recognized that the conditions for the treatment of drinking water are completely different from the treatment of swimming pool water. Compared with drinking water, swimming pool water DBPs have their own distinct characteristics due to the different nature of organic precursors [20,31,32] and continuous loading of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON), which are released by swimmers. All these factors add an additional complication to the disinfection and toxicological safety of swimming pool water [1]. For instance, the reported level of total organic carbon (TOC) in tap water (used as source water) and swimming pool water was in the range of 0.3–1.4 and 0.5–7.0 $mg \cdot L^{-1}$, respectively. Similarly, the level of nitrate–nitrogen ($NO_3^- - N$) was higher in swimming pool water (6.6–23.8 $mg \cdot L^{-1}$) compared with tap water (1.1–1.9 $mg \cdot L^{-1}$) [3]. Consistently, the reported level of total nitrogen (TN) in drinking water was lower (0.1–0.3 $mg \cdot L^{-1}$) compared with swimming pool water (3.6–12.3 $mg \cdot L^{-1}$) [7,33]. The temperature of swimming pool water is generally higher (25–35 °C) compared with drinking water used as source water (1.0–23 °C) [34], which is an important parameter to restrain the continuous anthropogenic pollutant release [32] and increases the demand for higher doses of disinfectants due to their higher rates of decay, for instance, in the case of chlorination [35,36]. The reported level of free residual chlorine (FRC) in tap water and swimming pool water was in the range of 0.03–0.57 and 0.24–1.4 $mg \cdot L^{-1}$, respectively. Analogous to that the pH of tap water (6.8–7.8) was lower than swimming pool water (7.6–8.2) [3]. Thus, the studies of drinking water disinfection cannot be replicated to optimize the treatment conditions of swimming pool water.

In the last few years research has been increasing on alternative methods for the disinfection of swimming pool water, as is evident from several published studies. Although the comparative analysis of different disinfection methods within studies is available, it has not been done between the studies. For instance, a comparison between chlorination, EGMO and O_3 /chlorine [3,6]; between chlorination and EGMO [5,7,8]; between chlorination, UV irradiation and UV/chlorine [10,37]; between chlorination and UV/chlorine [9,11,12]; between chlorination, UV irradiation, UV/chlorine, UV/ H_2O_2 and UV/ H_2O_2 /chlorine [13]; between chlorination and O_3 /chlorine [14–16,38]; between UV irradiation and O_3/UV [18]; between chlorination, O_3 /chlorine, O_3/H_2O_2 /chlorine and O_3/UV /chlorine [17]; and between chlorination, UV/chlorine, O_3 /chlorine, O_3/UV and O_3/UV /chlorine [19]. A comprehensive and critical review of performance and a comparison of all the disinfection methods is lacking. Moreover, all of the studies reported in this review considered different DBPs (see Appendix A: Tables A3–A7). A thorough analysis is lacking for making sound inferences about the effects of disinfection methods on certain types of DBPs. Therefore, more studies are needed to conduct a synthesis of the recent developments of disinfection methods used for disinfection of swimming pool water and draw informed conclusions about the performance potential of different disinfection methods for the formation and control of DBPs.

The main objective of this paper is to study the effects of different disinfection methods on the formation, control and elimination of DBPs, and to evaluate the differences between distinct methods.

The treatment performance of 10 disinfection methods is analysed in this paper for the formation and/or elimination of DBPs such as THMs, HAAs, HANs, THAs and CAMs. The examined disinfection methods are: chlorination, EGMO, UV irradiation, UV/chlorine, UV/ H_2O_2 , UV/ H_2O_2 /chlorine, O_3 /chlorine, O_3/H_2O_2 /chlorine, O_3/UV and O_3/UV /chlorine.

The research focused on the following specific questions:

- What are the concentrations of DBPs with different methods of disinfection?
- How do the tested disinfection methods affect the formation and/or elimination of DBPs?
- Is the performance of different disinfection methods statistically different for the formation of DBPs?
- Which disinfection method is best to improve the quality of swimming pool water?

The presented results contribute to the scientific knowledge on the use of various disinfection methods to combat the toxicity and improve the quality of swimming pool water. In addition, future research needs are also outlined in this paper.

2. Methods of Disinfection

Different methods used for the disinfection of swimming pool water are summarized in Table 1.

Table 1. Methods used for the disinfection of swimming pool water.

Disinfection Method	Chemicals Used for Disinfection
Chlorination	Chlorine gas, calcium/sodium hypochlorite, Dichloroisocyanorates
Electrochemically generated mixed oxidants	Electrolysis of salt brine solution → Chlorine in the form of hypochlorous acid is the primary oxidant
Ultraviolet (UV) irradiation	UV irradiation without post-chlorination
UV irradiation/chlorine	UV irradiation with post-chlorination (chlorine gas, calcium/sodium hypochlorite)
UV irradiation/hydrogen peroxide	UV irradiation with hydrogen peroxide
UV irradiation/hydrogen peroxide/chlorine	UV irradiation with hydrogen peroxide and post-chlorination (chlorine gas)
Ozone/chlorine	Ozone with post-chlorination (chlorine gas, sodium hypochlorite)
Ozone/hydrogen peroxide/chlorine	Ozone with hydrogen peroxide and post-chlorination (chlorine gas)
Ozone/UV irradiation	Ozone with UV irradiation
Ozone/UV irradiation/chlorine	Ozone with UV irradiation and post-chlorination (chlorine gas)

Note: The methods and chemicals indicated are used in the studies reviewed in this paper.

2.1. Chlorination

Chlorination is the most commonly used method of disinfection for the prevention of waterborne diseases and inactivation of pathogenic microorganisms in swimming pools [20]. The chemicals used for chlorination are given in Table 1. However, the use of chlorination in pools has many drawbacks, such as the presence of chlorine-resistant microorganisms such as *Cryptosporidium parvum* and *Giardia lamblia* [39] and the formation of potentially toxic DBPs [1,40]. Past research identified more than 100 DBPs in pool water samples [16,36]. Among the known carbonaceous DBPs (C-DBPs), the most common are THMs, HAAs, THAs; among the nitrogenous DBPs (N-DBPs), the most common are HANs and CAMs [1–4]. The formation and distribution of DBPs depends on several factors such as water source, bromide ion (Br^-) concentration, chlorine dose and FRC, TOC, TN, temperature and pH [4,15,22,34,41]. The level of FRC is of major concern [15,35,36], as it plays a vital role in the formation of DBPs. It is recommended to maintain the FRC in the range of 0.8–2.0 and 0.8–3.0 $\text{mg}\cdot\text{L}^{-1}$ in the case of indoor and outdoor pools, respectively [34].

2.2. EGMO

In the EGMO technique an electric current (240–400 V) is passed through a salt brine solution (3000–6000 $\text{mg}\cdot\text{L}^{-1}$) to produce oxidants. The primary oxidant produced is chlorine in the form of hypochlorous acid (HOCl) [42]. It has been suggested that oxidants other than chlorine, such as O_3 , chlorine dioxide, H_2O_2 and hydroxyl radical (OH^\bullet), are also produced [42]. However, several studies have demonstrated the drawbacks that chlorine in the form of HOCl is the primary oxidant produced and other oxidants have not been detected at measureable levels [3,43–45]. Dowd [46] found that EGMO produced the same levels of THMs in model and real waters as free chlorine. Considering that, with EGMO disinfection the toxicity concerns are similar to those of typical chlorine disinfection. The overall disinfectant dosage of EGMO technique is also quantified in terms of FRC [42,47,48].

2.3. UV Irradiation

UV irradiation is commonly applied as a secondary disinfection process in chlorinated pools, and has been found to be very effective for the control of *Cryptosporidium parvum* and *Giardia lamblia* [49,50]. The UV-based processes are cost-competitive with chlorine to improve the quality of swimming pool water and air [9,51]. The use of UV irradiation in the form of low-pressure UV (LPUV) and medium-pressure UV (MPUV) with and without post-chlorination has been explored by some recent studies [10–12,18]. Furthermore, the effect of different doses of UV irradiation was also investigated to control the formation of DBPs [10,12,19]. The available research reported the formation of N-DBPs (HANs) with UV irradiation and UV/chlorine [10–13,19].

2.4. UV-Based AOPs

The oxidizing ability of the UV/H₂O₂ process may be attributed to the formation of OH• produced by UV irradiation of H₂O₂ as shown in Equation (1):



This process requires a relatively high dose of H₂O₂ and much longer UV irradiation time compared with the O₃/UV process [52]. However, the dosage of H₂O₂ in the UV/H₂O₂ process needs to be optimized. An excess of H₂O₂ showed a strongly negative effect as a radical scavenger because of its ability to react with the OH• produced during the decomposition process and form a less reactive HO₂•, as shown in Equations (2) and (3). On the other hand, a low concentration of H₂O₂ results in insufficient formation of OH• and leads to a slower oxidation rate [52].



The effectiveness of the UV/H₂O₂ process with and without post-chlorination for the formation and/or control of DBPs (THMs and HANs) in swimming pool water has been investigated by Spiliotopoulou et al. [13].

2.5. Ozonation

The use of O₃ has increased for disinfection due to its high oxidation potential (E₀ = 2.07 V) compared to chlorine (E₀ = 1.36 V) (Table 2). However, O₃ as a residual disinfectant is unsuitable in swimming pool water, as it readily vaporizes and decomposes. In addition, it is toxic and heavier than air, which leads to adverse health effects [20]. Due to a lack of residuals and the relatively high dose requirement, O₃ disinfection is usually followed by deozonation before water enters the pool, and the addition of chlorine (O₃/chlorine) [14–17].

Table 2. The oxidation potential of some reactive species.

Substance	Oxidation Potential (V)
Hydroxyl radical (OH•)	2.86
Ozone molecule (O ₃)	2.07
Hydrogen peroxide (H ₂ O ₂)	1.78
Chlorine (Cl ₂)	1.36
Chlorine dioxide (ClO ₂)	1.27

Adopted from Muruganandham et al. [52].

O₃ reacts with a variety of organic and inorganic compounds in an aqueous solution as molecular O₃ or through the formation of OH• induced by O₃ decomposition. Despite its effectiveness in treating several organic compounds, the accumulation of refractory compounds is of major concern as it

impedes the mineralization of the organic matter present in water. Some compounds are found to be refractory to the ozonation process [53–55]. Therefore, O₃ is combined with other oxidants to improve the efficiency.

2.6. Ozone-Based AOPs

The efficiency of the ozonation process was increased by combining O₃ with UV irradiation and H₂O₂ such as O₃/UV and O₃/H₂O₂ [17–19]. By O₃/UV and O₃/H₂O₂ processes, OH[•] was generated and accelerated to give it a higher oxidation potential (E₀ = 2.86 V) than O₃ (E₀ = 2.07 V) (Table 2). OH[•] attacks most organic compounds promptly and non-selectively. Thus, the degradation of organic compounds is facilitated by both O₃ and OH[•]. Consequently, the elimination of a variety of very persistent substances can be achieved [52].

Photolysis of O₃ in the presence of water generates OH[•] as shown in Equation (4):



The decomposition of organic matter may proceed in three different ways: by O₃, by direct UV photolysis, and by photolysis of O₃, which generates OH[•].

The practicality of the O₃/UV process with and without post-chlorination for the formation and/or control of THMs and HANs in swimming pool water has been investigated by Kristensen et al. [18] and Cheema et al. [19].

The interaction between O₃ and H₂O₂ leads to the generation of OH[•], as shown in Equation (5):



The feasibility of the O₃/H₂O₂ process with and without post-chlorination for the formation and/or control of THMs in swimming pool water has been investigated by Glauner et al. [17].

3. Methodology

The comparative performance and impact analysis is mainly based on the information compiled from the available studies so far, which used different methods for disinfection of swimming pool water. These were 18 studies published in peer-reviewed journals with different methods of disinfection from nine countries. Some studies only reported descriptive statistics (means, standard deviations and ranges), and these values carry the accumulated effect of many pools. Therefore, the studies only reporting descriptive statistics could not be used to conduct statistical analysis to draw informed comparison. Consequently, individual pools were selected from all the available studies where such records were provided. In total, 32 pools were selected from the 14 published research studies with different methods for disinfection. The novel database compiled to conduct this analysis is given as Tables A3–A7. The treatment performance of 10 disinfection methods was analysed in this study. These were chlorination, EGMO, UV irradiation, UV/chlorine, UV/H₂O₂, UV/H₂O₂/chlorine, O₃/chlorine, O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine. Different parameters such as pool location (indoor and outdoor), disinfectant dose, method of detection, temperature, pH, TOC, TN, THMs, HAAs, HANs, THAs and CAMs were also presented for the comparison of different disinfection methods. These parameters were gathered from the reviewed studies or estimated using the information available in those studies.

Firstly, the effects of disinfection methods on the formation and/or elimination of DBPs are discussed based on all the available studies. Then, statistical analyses are carried out and descriptive statistics are computed for some parameters where adequate data were available based on 32 individual pools. Finally, the comparison among different methods is done with one-way ANOVA for the significance and z-Test for the comparison of means.

4. Results and Discussion

4.1. Effect of Disinfection Methods on DBPs Formation

The effects of different methods are discussed on the most documented species of different DBPs.

4.1.1. Effect on THMs

According to the study by Lee et al. [6], the concentration of TCM with chlorination, EGMO and O₃/chlorine was 41, 27 and 29 µg·L⁻¹, respectively. However, the levels of brominated THMs, such as BDCM, DBCM and TBM, were higher with EGMO (9.8, 9.1 and 19 µg·L⁻¹, respectively) compared with chlorination (3.0, 0.5 and <0.2 µg·L⁻¹, respectively) and O₃/chlorine (2.4, 0.2 and <0.2 µg·L⁻¹, respectively). The high levels of brominated THMs are attributed to the presence of Br⁻ from NaCl salt used in the EGMO process, which is mostly from seawater and contains Br⁻. However, Kanan [7] observed the high level of TCM (207 µg·L⁻¹) with EGMO compared with chlorination (119 µg·L⁻¹) (Table A3).

In another comparative study of chlorination, EGMO and O₃/chlorine the concentration of TCM was 21, 15 and 7.0 µg·L⁻¹, respectively, indicating the decrease in the formation of TCM with O₃/chlorine [3]. In some other studies, it is reported that the concentration of different categories of DBPs in swimming pool water disinfected with O₃/chlorine was lower than the pool disinfected with chlorine. This indicates the efficacy of O₃/chlorine due to its high oxidation potential compared with chlorination (Table 2); thus the degradation of persistent organic substances is possible [14,15]. For instance, Hang et al. [15] reported a higher concentration of TCM, BDCM and DBCM (220, 202 and 3.8 µg·L⁻¹, respectively) with chlorination compared with 141, 106 and 2.0 µg·L⁻¹, respectively in the case of O₃/chlorine (Table A3).

In the study of different doses of O₃ in clean pool water (TOC 1.5 mg·L⁻¹), the formation of TCM increased from 25 to 60 µg·L⁻¹ with the first three subsequent doses (2 mg·L⁻¹ of O₃ each) and then with further addition decreased to 45 µg·L⁻¹, but still remained higher compared with chlorination (25 µg·L⁻¹) [14] (Table A3). Daiber et al. [16] also reported almost twice the level of TCM with O₃/chlorine (31 µg·L⁻¹) compared with chlorination (17 µg·L⁻¹). Chlorination of polluted pool water (TOC 2.4 mg·L⁻¹) resulted in elevated levels of TCM (35 µg·L⁻¹) compared with initial concentrations (5 µg·L⁻¹) before chlorination. With the addition of O₃ (0.7–3.4 mg·L⁻¹), the concentration of TCM decreased from 35 to 18 µg·L⁻¹ and with increasing O₃ dosage (100 mg·L⁻¹) it decreased to 7.0 µg·L⁻¹. The increase in the formation of TCM with initial dose of O₃ in the clean pool water is likely due to decomposition of O₃ to OH[•] and radical oxidation of fraction of DOC present in the pool water, which has low reactivity towards chlorine. The radical oxidation of that fraction of DOC enhances its reactivity to chlorine, and consequently the formation of TCM. The decrease in the concentration of TCM with a fourth and fifth dose is due to mineralization of that fraction of DOC with increasing oxidation [14]. Cheema et al. [19] observed a similar trend in the formation of THMs with different doses of O₃, as reported by Hansen et al. [14] (Table A3).

The previous research gives limited and conflicting information regarding the effects of UV-based treatment on water chemistry in the presence of residual chlorine and the occurrence of THMs in swimming pool water. For example, Beyer et al. [9] reported the lower concentration of THMs with the use of UV/chlorine. On the other hand, Cassan et al. [37] observed a higher concentration of THMs with UV irradiation compared with chlorination and UV/chlorine. In further contrast, Kristensen et al. [18] observed no effect on THM concentrations in a swimming pool treated with chlorination and UV irradiation (Table A3). Some recent studies reported that THMs were not formed directly by exposure to UV irradiation but in the post-chlorination (UV/chlorine) [10,12,13,19]. This might be due to the fact that the reactivity of organic precursors present in the pool water towards chlorine increases with UV treatment. Consequently, the activated organic matter reacts with chlorine and THMs are formed. For instance, the concentration of TCM decreased from 16 µg·L⁻¹ with chlorination to 13 µg·L⁻¹ with UV irradiation, but increased with UV/chlorine to 65 µg·L⁻¹ [13] (Table A3).

Furthermore, the comparison between LPUV and MPUV irradiation without post-chlorination demonstrates the efficiency of MPUV irradiation for decreasing the concentration of TCM [18] and with post-chlorination suggests the effectiveness of LPUV irradiation [10,11]. For instance, the concentration of TCM was $75 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination and 60 and $52 \mu\text{g}\cdot\text{L}^{-1}$ with MPUV/chlorine and LPUV/chlorine, respectively [11] (Table A3). The increase in the levels of TCM was attributed to the production of chlorine radical (Cl^\bullet) through the photolysis of FRC, which further reacted with organic matter to form TCM. On the other hand, the concentration of DBCM and TBM was less with MPUV irradiation [37]. This lower concentration of brominated species of THMs was due to their broad absorption band with a maximum at 220 nm; MPUV lamps are more efficient for their photo-degradation compared with LPUV lamps [56] (cited in [10]). The progressive transformation of TBM into TCM and BDCM by substitution of bromine atom to chlorine atom might increase the concentration of TCM with MPUV irradiation [37].

Moreover, the effect of different doses of UV irradiation followed by chlorine indicated that the level of THMs increased with increasing the dose of UV irradiation [10,12,19]. For instance, the reported concentration of TCM was $43 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination and 78 and $100 \mu\text{g}\cdot\text{L}^{-1}$ with the UV dose of 2.35 and $4.7 \text{J}\cdot\text{cm}^{-2}$, respectively [10]. Similar to the prior study, the concentration of TCM shows the increase from $12 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination to $32 \mu\text{g}\cdot\text{L}^{-1}$ with UV/chlorine ($2.1 \text{J}\cdot\text{cm}^{-2}$), which remained higher with the UV dose up to $19 \text{J}\cdot\text{cm}^{-2}$ but decreased ($10 \mu\text{g}\cdot\text{L}^{-1}$) with the UV dose of $47.5 \text{J}\cdot\text{cm}^{-2}$ [19] (Table A3). This decrease in the level of TCM with increasing UV dose might be due to the decrease in the DOC level by oxidation at a very high UV dose and resulted in a lower amount of organic precursors available for reaction [19].

The efficacy of UV-based AOPs, such as UV/ H_2O_2 with and without post-chlorination, was studied by Spiliotopoulou et al. [13]. The study results show that the concentration of THM was lower with UV/ H_2O_2 compared with UV/chlorine. For example, the concentration of TCM was 65 and $9.1 \mu\text{g}\cdot\text{L}^{-1}$ with UV/chlorine and UV/ H_2O_2 , respectively. However, the concentration of TCM increased with post-chlorination (UV/ H_2O_2 /chlorine) to $36 \mu\text{g}\cdot\text{L}^{-1}$ (Table A3).

The effectiveness of ozone-based AOPs was first studied by Glauner et al. [17]. They reported the effective removal of TOC with O_3 /UV and O_3 / H_2O_2 compared with ozonation. The contact time of 3 min between oxidant and pool water in AOPs was sufficient for the increased elimination efficiency of TOC compared with 20 min contact time in case of ozonation. However, ozonation showed a decreased THMs formation potential due to selective oxidation compared with OH^\bullet reactions in AOPs, which are non-specific and produce activated compounds suitable for THMs formation in the post-chlorination step. As a result, the formation potential of THMs increased with O_3 /UV/chlorine and O_3 / H_2O_2 /chlorine processes compared with O_3 /chlorine. Nevertheless, the concentration of THMs is not reported with different methods of disinfection. On the other hand, Kristensen et al. [18] observed the decrease in concentration of TCM from $53 \mu\text{g}\cdot\text{L}^{-1}$ with UV irradiation to $35 \mu\text{g}\cdot\text{L}^{-1}$ with O_3 /UV. Analogous to the previous research, Cheema et al. [19] observed the positive effect of O_3 /UV on the decrease of THMs compared with separate UV irradiation and ozonation processes. The concentration of TCM was 35, 25, $5.0 \mu\text{g}\cdot\text{L}^{-1}$ with UV irradiation, O_3 /chlorine and O_3 /UV, respectively. Still, the formation of TCM was increased ($13 \mu\text{g}\cdot\text{L}^{-1}$) in the post-chlorination step (O_3 /UV/chlorine) [19] (Table A3).

4.1.2. Effect on HAAs

In the comparative studies of chlorination, EGMO and O_3 /chlorine, the concentration of TCAA was 156, 97 and $17 \mu\text{g}\cdot\text{L}^{-1}$, respectively [3]. Conversely, Kanan [7] and Yeh et al. [8] observed that the concentration of DCAA and TCAA was higher in EGMO disinfected pools compared with the chlorinated pools. For instance, the concentration of DCAA in chlorinated and EGMO disinfected indoor pools was $1233 \mu\text{g}\cdot\text{L}^{-1}$ and $2400 \mu\text{g}\cdot\text{L}^{-1}$, respectively, and the concentration of TCAA in chlorinated and EGMO disinfected indoor pools was $1153 \mu\text{g}\cdot\text{L}^{-1}$ and $2600 \mu\text{g}\cdot\text{L}^{-1}$, respectively [8] (Table A4).

In another study, the concentration of BCAA in chlorinated pools and O₃/chlorine disinfected pools was 874 and 424 µg·L⁻¹, respectively. The concentration of all species of HAAs in chlorinated pools was much higher compared with O₃/chlorine disinfected pools [15]. This indicates that with O₃/chlorine the decomposition of persistent organic substances is achievable. Contrarily, Daiber et al. [16] reported a very high level of DCAA and TCAA with O₃/chlorine (343 and 1865 µg·L⁻¹, respectively) compared with chlorination (89 and 65 µg·L⁻¹, respectively) (Table A4).

UV exposure followed by post-chlorination did not significantly affect the formation of HAAs. The formation of DCAA and TCAA remained almost stable with chlorination and different doses of UV irradiation [10]. The concentration of DCAA was 196 µg·L⁻¹ with chlorination and 201 and 197 µg·L⁻¹ with the UV dose of 2.35 and 4.7 J·cm⁻², respectively. The concentration of TCAA was 118 µg·L⁻¹ with chlorination and 119 and 106 µg·L⁻¹ with the UV dose of 2.35 and 4.7 J·cm⁻², respectively (Table A4). UV irradiation followed by post-chlorination significantly reduced the level of DBAA and TBAA compared with chlorination, though not with different doses of UV irradiation [12], which indicated that brominated HAAs are photolysed by UV treatment [57]. The level of DBAA was 80 µg·L⁻¹ with chlorination and 15 and 20 µg·L⁻¹ with the UV dose of 2.35 and 4.7 J·cm⁻², respectively. The level of TBAA was 45 µg·L⁻¹ with chlorination and 2.5 and 5.0 µg·L⁻¹ with the UV dose of 2.35 and 4.7 J·cm⁻², respectively [12] (Table A4).

Unfortunately, the concentration of HAAs was not reported in the available studies with the use of UV-based AOPs (UV/H₂O₂ and UV/H₂O₂/chlorine) and ozone-based AOPs (O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine).

4.1.3. Effect on HANs

Lee et al. [3] reported that the concentration of DCAN with chlorination, EGMO and O₃/chlorine, was 3.9, 3.8 and 1.3 µg·L⁻¹, respectively. The concentrations of brominated HANs were much higher in EGMO disinfected pools compared with chlorinated pools. For instance, the concentration of BCAN and DBAN was 3.5 and 2.6 µg·L⁻¹, respectively with EGMO, and 0.8 and 0.5 µg·L⁻¹, respectively with chlorination, which might be due to the presence of Br⁻ from NaCl salt used in the EGMO process as salt used is mostly from seawater and contains Br⁻. As reported by Lee et al. [3], Kanan [7] observed a similar trend in the formation of DCAN and BCAN with EGMO and chlorination. Analogous to the prior research, Hang et al. [15] also reported a higher concentration of DCAN (9.2 µg·L⁻¹) with chlorination compared with (5.3 µg·L⁻¹) O₃/chlorine (Table A5).

In a study of different doses of O₃ in the clean pool water (TOC 1.5 mg·L⁻¹), the formation of DCAN increased from 2.2 to 4.2 µg·L⁻¹ with the five subsequent doses (2 mg·L⁻¹ of O₃ each) [14] (Table A5). Daiber et al. [16] also reported a higher level of DCAN with O₃/chlorine (14 µg·L⁻¹) compared with chlorination (9.4 µg·L⁻¹). Chlorination of polluted pool water (TOC 2.4 mg·L⁻¹) resulted in elevated levels of DCAN (7.0 µg·L⁻¹) compared with initial concentrations (2.5 µg·L⁻¹) before chlorination. With the addition of O₃ (0.7–3.4 mg·L⁻¹), the concentration of DCAN decreased from 7.0 to 4.0 µg·L⁻¹; with increasing O₃ dosage (100 mg·L⁻¹), it decreased to 2.5 µg·L⁻¹, which was equal to the initial concentration [14]. Cheema et al. [19] observed a similar trend in the formation of DCAN with different doses of O₃ as reported by Hansen et al. [14] for clean pool water. The concentration of DCAN and BCAN increased from 1.8 and 0.2 µg·L⁻¹ to 2.5 and 0.4 µg·L⁻¹, respectively (Table A5).

The available research reported the formation of HANs with UV irradiation and UV/chlorine [10–13,19]. For instance, Spiliotopoulou et al. [13] observed that the concentration of DCAN increased from 1.9 µg·L⁻¹ with chlorination to 4.9 µg·L⁻¹ with UV irradiation, which further increased to 5.4 µg·L⁻¹ with UV/chlorine (Table A5). The use of LPUV and MPVU irradiation followed by chlorination showed that the concentrations of DCAN (8.0 µg·L⁻¹) with chlorination and LPUV/chlorine (7.7 µg·L⁻¹) were not significantly different. However, the concentration of DCAN with MPVU/chlorine increased to 10 µg·L⁻¹ [11]. Contrarily, a significant increase in the level of DCAN from 8.0 µg·L⁻¹ with chlorination to 15 µg·L⁻¹ with LPUV/chlorine was observed by Cimetiere and De Laat [10] (Table A5).

The concentration of DCAN and DBAN was higher with UV irradiation but remained almost stable when increasing the UV dose [10,12,19]. A significant increase in the level of DCAN was observed from $8.0 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination to 15 and $17 \mu\text{g}\cdot\text{L}^{-1}$ with the UV dose of 2.35 and $4.7 \text{J}\cdot\text{cm}^{-2}$, respectively, showing that the level remained almost similar with different doses of UV irradiation [10]. Similarly, the concentration of DCAN increased from $1.8 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination to $4.0 \mu\text{g}\cdot\text{L}^{-1}$ with UV/chlorine ($2.1 \text{J}\cdot\text{cm}^{-2}$), which remained stable at $4.0 \mu\text{g}\cdot\text{L}^{-1}$ with the UV dose of $47.5 \text{J}\cdot\text{cm}^{-2}$ [19]. The level of DBAN significantly increased from $12 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination to 28 and $35 \mu\text{g}\cdot\text{L}^{-1}$ with the UV dose of 2.35 and $4.7 \text{J}\cdot\text{cm}^{-2}$, respectively [12] (Table A5).

The use of the UV/H₂O₂ process with and without post-chlorination contributed to a negligible decrease in the concentration of HANs compared with UV/chlorine [13]. The study results showed that the concentration of DCAN was 5.4, 3.6 and $3.1 \mu\text{g}\cdot\text{L}^{-1}$ with UV/chlorine, UV/H₂O₂, and UV/H₂O₂/chlorine, respectively (Table A5).

The level of DCAN was lower with O₃/UV ($3.0 \mu\text{g}\cdot\text{L}^{-1}$) compared with UV irradiation ($4.5 \mu\text{g}\cdot\text{L}^{-1}$) but higher compared with O₃/chlorine ($2.5 \mu\text{g}\cdot\text{L}^{-1}$). This might be due to the fact that UV irradiation increased chlorine demand, which favours the formation of DCAN. The chlorine demand is subsequently removed with the ozonation of the UV treated pool water. This leads to a decrease in the level of DCAN. However, the level of DCAN increased in the post-chlorination step (O₃/UV/chlorine) to $3.2 \mu\text{g}\cdot\text{L}^{-1}$ compared with O₃/UV ($3.0 \mu\text{g}\cdot\text{L}^{-1}$) [19] (Table A5).

4.1.4. Effect on THAs

The concentration of CH with chlorination, EGMO and O₃/chlorine was 17, 10 and $3.6 \mu\text{g}\cdot\text{L}^{-1}$, respectively [3]. The lower level of CH with O₃/chlorine ($101 \mu\text{g}\cdot\text{L}^{-1}$) compared with chlorination ($165 \mu\text{g}\cdot\text{L}^{-1}$) was also observed by Daiber et al. [16] (Table A6). However, the formation of CH increased with UV/chlorine compared with chlorination that increased further with increasing the dose of UV irradiation [10]. For instance, the concentration of CH increased from $237 \mu\text{g}\cdot\text{L}^{-1}$ with chlorination to 261 and $275 \mu\text{g}\cdot\text{L}^{-1}$ with UV dose of 2.35 and $4.7 \text{J}\cdot\text{cm}^{-2}$, respectively (Table A6). This indicates that the use of O₃/chlorine for disinfection of swimming pool water is effective to overcome this possibly carcinogenic DBP compared with chlorination, EGMO and UV/chlorine.

The studies conducted to control the formation of toxic DBPs in swimming pool water with the use of UV-based AOPs (UV/H₂O₂ and UV/H₂O₂/chlorine) and ozone-based AOPs (O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine) did not explore the concentration of CH.

4.1.5. Effect on CAMs

The concentration of TCAM remained unchanged with chlorination ($370 \mu\text{g}\cdot\text{L}^{-1}$) and MPUV/chlorine ($350 \mu\text{g}\cdot\text{L}^{-1}$). After the installation of LPUV/chlorine, the concentration of TCAM increased ($450 \mu\text{g}\cdot\text{L}^{-1}$) compared with chlorination [11] (Table A7). This might be due to fast re-formation of TCAM from the reaction of photolysis products of TCAM with chlorine, and also a higher concentration of FRC with the application of LPUV/chlorine (free chlorine promotes TCAM formation). On the other hand, while comparing LPUV and MPUV irradiation, the concentration of TCAM was lower after the inclusion of MPUV irradiation than after inclusion of LPUV irradiation. This indicates the photodecay efficiency of CAMs using MPUV irradiation compared with LPUV irradiation at the same dose [11,51].

The concentration of CAMs is not significantly reduced with the use of O₃/chlorine compared with chlorination in swimming pools [38], although O₃ is a strong oxidizing agent and should oxidize CAMs to reduce the concentration. The concentration of tCAMs was 1470 and $1310 \mu\text{g}\cdot\text{L}^{-1}$ in chlorinated and O₃/chlorine disinfected pools, respectively [38] (Table A7).

The concentration of CAMs was not examined by the studies that used UV-based AOPs (UV/H₂O₂ and UV/H₂O₂/chlorine) and ozone-based AOPs (O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine).

4.2. Comparison of Different Disinfection Methods for DBPs Formation

The results of ANOVA and z-Test for comparison of means are shown in Table 3, indicating the statistical significance or non-significance of observed difference among different methods of disinfection. The quantitative differences among different methods for the studied water quality parameters are discussed below and are substantiated by the corresponding figures.

Table 3. The results (*p*-values) of one-way ANOVA and z-test for comparison of means.

Parameter	TCM	DCAA	TCAA	DCAN	CH
ANOVA results					
	0.10	0.20	0.11	0.004	0.53
z-test results					
Chlorination VS EGMO	0.09	0.22	0.26	0.08	NA
Chlorination VS UV irradiation	0.71	NA	NA	NA	NA
Chlorination VS UV/chlorine	0.89	0.06	0.06	0.47	0.51
Chlorination VS O ₃ /chlorine	0.72	NA	NA	0.06	NA
Chlorination VS O ₃ /UV/chlorine	0.03	NA	NA	0.03	NA
EGMO VS UV irradiation	0.04	NA	NA	NA	NA
EGMO VS UV/chlorine	0.07	0.04	0.004	0.17	NA
EGMO VS O ₃ /chlorine	0.03	NA	NA	0.01	NA
EGMO VS O ₃ /UV/chlorine	0.001	NA	NA	0.005	NA
UV irradiation VS UV/chlorine	0.51	NA	NA	NA	NA
UV irradiation VS O ₃ /chlorine	0.97	NA	NA	NA	NA
UV irradiation VS O ₃ /UV/chlorine	0.02	NA	NA	NA	NA
UV/chlorine VS O ₃ /chlorine	0.50	NA	NA	0.01	NA
UV/chlorine VS O ₃ /UV/chlorine	0.0001	NA	NA	0.002	NA
O ₃ /chlorine VS O ₃ /UV/chlorine	0.01	NA	NA	0.56	NA

Note: Bold values indicate significant difference at $\alpha = 0.05$ ($p < 0.05$) for ANOVA and z-test results; NA: Not Available.

As seen in Table 3, only a few DBP species could be examined (TCM, DCAA, TCAA, DCAN and CH), as sufficient data were not available in other cases. For similar reasons, the comparison of presented species was not possible with all the disinfection methods.

THMs: The formation of TCM with EGMO was much higher (mean and standard deviation: $85 \pm 56 \mu\text{g}\cdot\text{L}^{-1}$) compared with chlorination ($44 \pm 55 \mu\text{g}\cdot\text{L}^{-1}$) as well as UV irradiation ($38 \pm 23 \mu\text{g}\cdot\text{L}^{-1}$) and UV/chlorine ($47 \pm 37 \mu\text{g}\cdot\text{L}^{-1}$), although only significantly different from UV irradiation (Figure 1 and Table 3). Similarly, the formation of TCM with O₃/chlorine ($39 \pm 32 \mu\text{g}\cdot\text{L}^{-1}$) is less than with chlorination, UV/chlorine and EGMO, but only significantly different from EGMO (Figure 1 and Table 3). However, the level of TCM with O₃/UV/chlorine ($16 \pm 4.1 \mu\text{g}\cdot\text{L}^{-1}$) is significantly reduced compared with chlorination, EGMO, UV irradiation, UV/chlorine and O₃/chlorine (Figure 1 and Table 3). The level of TCM with UV/H₂O₂, UV/H₂O₂/chlorine and O₃/UV was 11 ± 2.8 , 31 ± 7.8 and $20 \pm 21 \mu\text{g}\cdot\text{L}^{-1}$, respectively (Figure 1).

HAAs: The concentration of DCAA and TCAA with EGMO is more than twice (1373 ± 1908 and $816 \pm 805 \mu\text{g}\cdot\text{L}^{-1}$, respectively) compared with chlorination (619 ± 633 and $470 \pm 553 \mu\text{g}\cdot\text{L}^{-1}$, respectively), though means are not significantly different (Figure 2 and Table 3). The concentration of DCAA and TCAA with UV/chlorine was 218 ± 109 and $124 \pm 42 \mu\text{g}\cdot\text{L}^{-1}$, respectively, which is significantly lower compared with EGMO (Figure 2 and Table 3). However, the concentration of DCAA and TCAA with O₃/chlorine was 272 ± 101 and $943 \pm 1305 \mu\text{g}\cdot\text{L}^{-1}$, respectively, which is comparable with UV/chlorine in case of DCAA (Figure 2). The level of HAAs with UV/H₂O₂, UV/H₂O₂/chlorine, O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine methods is not reported in the literature. Furthermore, the level of TCAA reduced with UV/chlorine and met the guidelines set by WHO for drinking water quality [58], but the level of DCAA remained much higher (Table A2). Therefore, to control the formation of DCAA, which is possibly a human carcinogen [59] (Table A2),

the application of UV-based AOPs (UV/H₂O₂ and UV/H₂O₂/chlorine) and ozone-based AOPs (O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine) needs to be investigated.

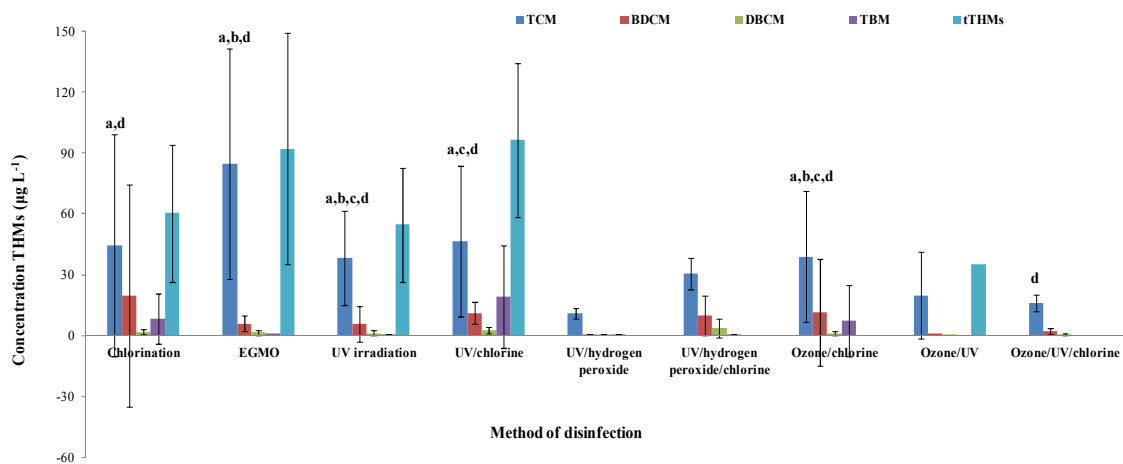


Figure 1. Mean and standard deviation of THMs with different methods of disinfection. Note: “a” shows that chlorination, EGMO, UV irradiation, UV/chlorine and ozone/chlorine are not significantly different from each other; “b” shows that EGMO is significantly different from UV irradiation and ozone/chlorine; “c” shows that UV irradiation, UV/chlorine and ozone/chlorine are not significantly different from each other; “d” shows that ozone/UV/chlorine is significantly different from chlorination, EGMO, UV irradiation, UV/chlorine and ozone/chlorine at $\alpha = 0.05$ ($p < 0.05$); Statistical analysis to compare the means in case of UV/hydrogen peroxide, UV/hydrogen peroxide/chlorine and ozone/UV was not carried out because of fewer data points.

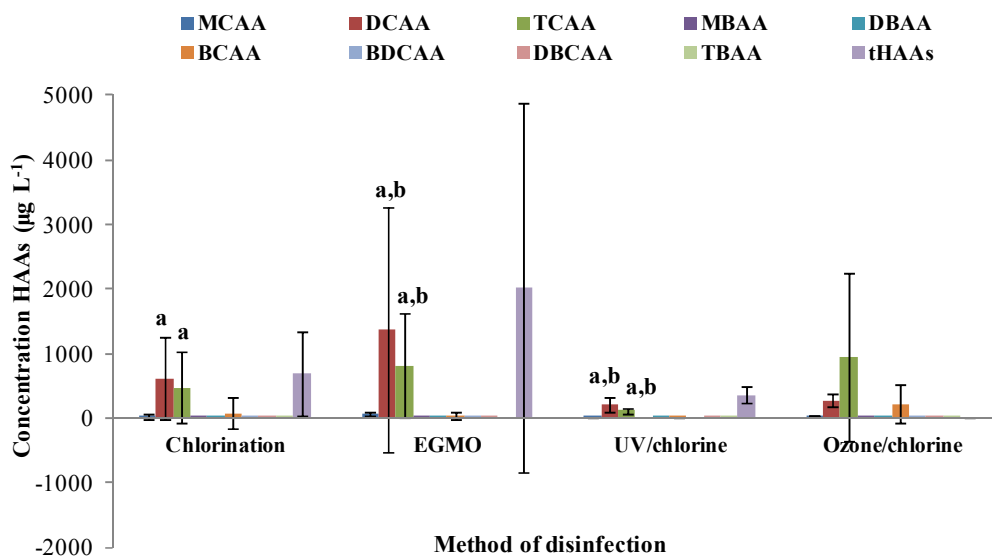


Figure 2. Mean and standard deviation of HAAs with different methods of disinfection. Note: “a” shows that chlorination, EGMO and UV/chlorine are not significantly different from each other; “b” shows that UV/chlorine is significantly different from EGMO at $\alpha = 0.05$ ($p < 0.05$). Statistical analysis to compare the means in the case of ozone/chlorine was not carried out because of fewer data points.

HANs: The average level of DCAN with EGMO is much higher ($17 \pm 13 \mu\text{g}\cdot\text{L}^{-1}$) compared with chlorination ($7.9 \pm 6.9 \mu\text{g}\cdot\text{L}^{-1}$) as well as UV/chlorine ($9.9 \pm 8.3 \mu\text{g}\cdot\text{L}^{-1}$) though did not exhibit a significant difference (Figure 3 and Table 3). Similarly, the mean value of DCAN is almost halved with O_3 /chlorine ($4.0 \pm 2.9 \mu\text{g}\cdot\text{L}^{-1}$) compared with chlorination but not significantly different (Figure 3 and Table 3). Furthermore, the level of DCAN with O_3 /UV ($3.0 \mu\text{g}\cdot\text{L}^{-1}$) and O_3 /UV/chlorine ($3.6 \pm 0.5 \mu\text{g}\cdot\text{L}^{-1}$) is considerably reduced, although increased in the post-chlorination step but is significantly lower compared with chlorination (Figure 3 and Table 3). Moreover, the level of DCAN with EGMO and UV/chlorine is significantly different compared with O_3 /chlorine and O_3 /UV/chlorine; however, O_3 /chlorine and O_3 /UV/chlorine do not demonstrate a significant difference (Figure 3 and Table 3). Based on the limited evidence, the level of DCAN was 3.8 ± 1.6 , 2.9 ± 1.0 and $2.6 \pm 0.7 \mu\text{g}\cdot\text{L}^{-1}$ with UV irradiation, UV/ H_2O_2 and UV/ H_2O_2 /chlorine, respectively (Figure 3).

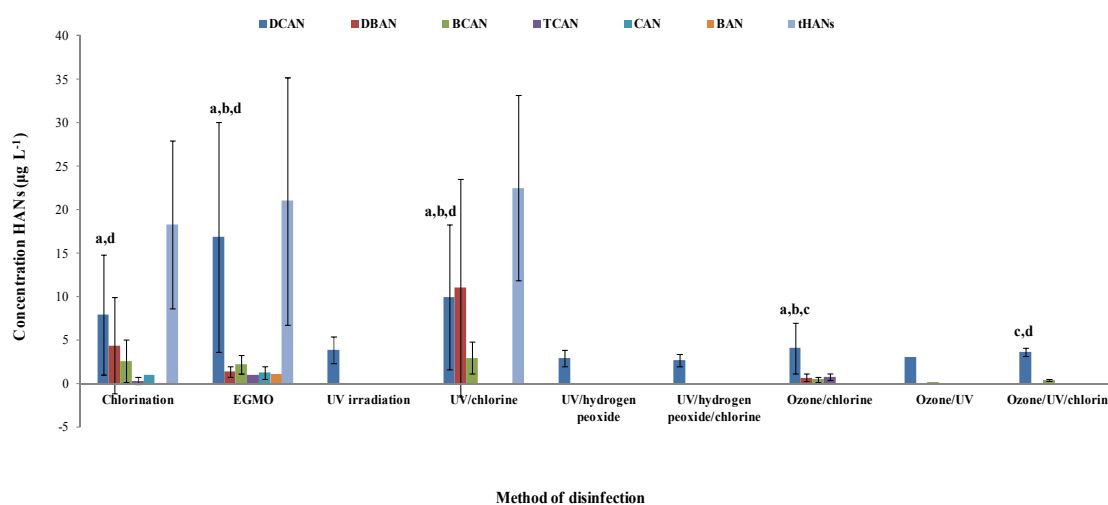


Figure 3. Mean and standard deviation of HANs with different methods of disinfection. Note: “a” shows that chlorination is not significantly different from EGMO, UV/chlorine and ozone/chlorine; “b” shows that EGMO and UV/chlorine are significantly different from ozone/chlorine; “c” shows that ozone/chlorine and ozone/UV/chlorine are not significantly different from each other; “d” shows that ozone/UV/chlorine is significantly different from chlorination, EGMO and UV/chlorine at $\alpha = 0.05$ ($p < 0.05$). Statistical analysis to compare the means in case of UV irradiation, UV/hydrogen peroxide, UV/hydrogen peroxide/chlorine and ozone/UV was not carried out because of fewer data points.

THAs: The mean concentration of CH with UV/chlorine ($309 \pm 130 \mu\text{g}\cdot\text{L}^{-1}$) is higher compared with chlorination ($253 \pm 139 \mu\text{g}\cdot\text{L}^{-1}$), though not significantly different (Figure 4 and Table 3). Based on the limited evidence, the average level of CH with O_3 /chlorine is $101 \mu\text{g}\cdot\text{L}^{-1}$. The level of CH with UV/ H_2O_2 , UV/ H_2O_2 /chlorine, O_3 / H_2O_2 /chlorine, O_3 /UV and O_3 /UV/chlorine methods is not reported in the literature. The level of CH is much higher compared with the guidelines set by WHO for drinking water quality [58] (Table A2). To control the formation of CH, which is possibly a human carcinogen [59] (Table A2), the application of UV-based AOPs (UV/ H_2O_2 and UV/ H_2O_2 /chlorine) and ozone-based AOPs (O_3 / H_2O_2 /chlorine, O_3 /UV and O_3 /UV/chlorine) needs to be investigated.

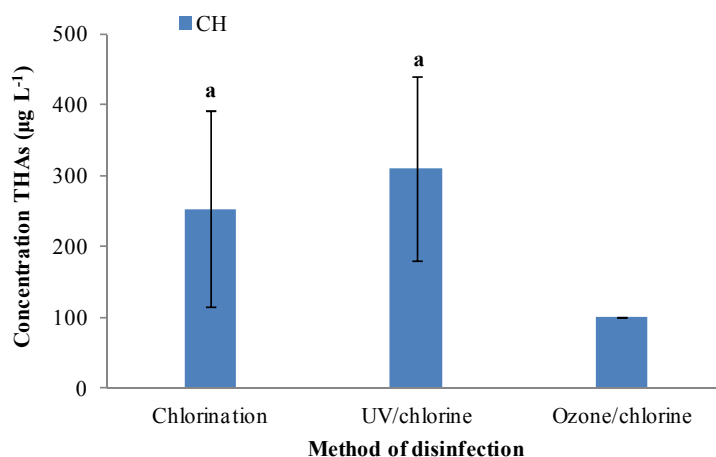


Figure 4. Mean and standard deviation of THAs with different methods of disinfection. Note: “a” shows that chlorination and UV/chlorine are not significantly different at $\alpha = 0.05$ ($p < 0.05$). Statistical analysis to compare the means in the case of ozone/chlorine was not carried out because of fewer data points.

CAMs: The concentration of TCAM with UV/chlorine ($400 \pm 71 \mu\text{g}\cdot\text{L}^{-1}$) is almost equivalent with chlorination ($370 \mu\text{g}\cdot\text{L}^{-1}$) (Figure 5). However, the concentration of TCAM with UV/H₂O₂, UV/H₂O₂/chlorine, O₃/chlorine, O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine methods is not reported in the literature. The level of tCAMs with chlorination and O₃/chlorine is also comparable with the values of 1745 ± 389 and $1600 \pm 410 \mu\text{g}\cdot\text{L}^{-1}$, respectively. Furthermore, the level of tCAMs remained much higher than the guidelines set by WHO for swimming pool water [20] (Table A2). Therefore, to control the formation of tCAMs, which is a very toxic DBP, the application of UV-based AOPs (UV/H₂O₂ and UV/H₂O₂/chlorine) and ozone-based AOPs (O₃/H₂O₂/chlorine, O₃/UV and O₃/UV/chlorine) need to be investigated.

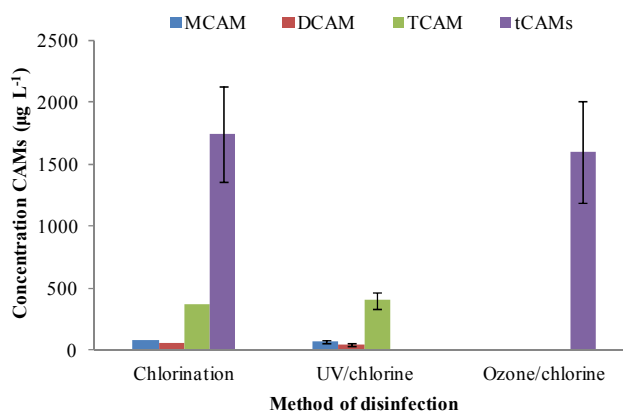


Figure 5. Mean and standard deviation of CAMs with different methods of disinfection. Note: a statistical analysis to compare the means was not carried out because of fewer data points.

Based on our review, the developments in disinfection methods and corresponding concentrations of DBPs in swimming pool water are summarized in Figure 6. This could serve as a quick guide for a scientific reference and the application of emerging disinfection methods to control the formation of toxic DBPs.

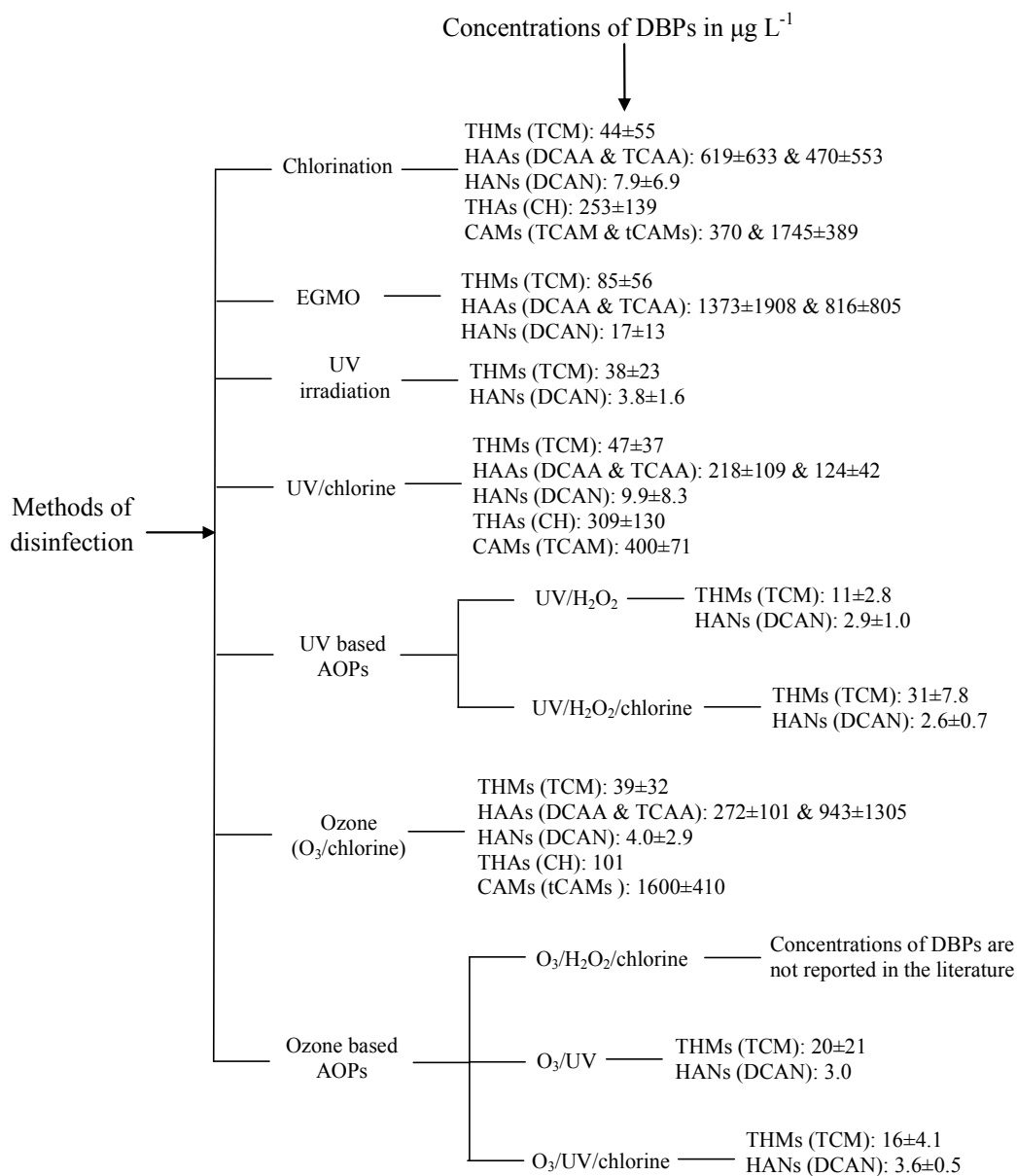


Figure 6. A graphical summary of concentrations of DBPs with different disinfection methods examined in this study.

4.3. Major Governing Factors for DBPs Formation

Many studies on chlorinated pools have shown that the formation and distribution of DBPs depends on several factors such as source water, Br^- concentration, chlorine dose and FRC, TOC, TN, temperature and pH [4,7,12,15,22,34,41,60].

The higher temperature leads to more sweat production, which is an organic precursor from anthropogenic inputs [22]. The organic precursors can be natural organic matter (NOM) from the source water used to fill the pool and many other anthropogenic inputs such as sweat, urine, lotions, cosmetics, sunscreens and soap residuals [2,3,20,22,61] as well as skin lipids [32]. Since the higher temperature accelerates the consumption of FRC, higher doses of chlorine are required to ensure FRC in swimming pool water [35,36]. The formation of DBPs is correlated with FRC, therefore, the higher temperature promoted the formation of DBPs [7,33,34,62].

TOC and TN are other dominant factors influencing the formation of DBPs [3,63]. In swimming pool water the continuous loading of DOC and DON is obtained from swimmers. Chu and

Nieuwenhuijsen [64] observed that DOC was significantly increased with the number of swimmers, ranging from 3.3 to 13 mg·L⁻¹. In a study of two outdoor swimming pools, it was estimated that on average 1.09 g DOC per person is brought into swimming pool water [65] (cited in [61]). Manasfi et al. [4] attributed that the higher level of DBPs in freshwater pools was due to more bathers compared with seawater pools. However, Peng et al. [61] concluded that the introduction of anthropogenic pollutants and consequent DBPs formation in swimming pool water cannot be predicted simply from the number of visitors. The actual DBPs formation can be estimated with the content of organic matter in the pool water. Thus, DOC is proved to be a suitable parameter to predict THMs production [61]. DON leads to the formation of N-DBPs (HANs and CAMs) [21,36,66]. Some amino acids (nitrogen-containing compounds) such as histidine present in sweat and urine favour the formation of HAAs (C-DBPs) during chlorination [7,67]. The highest level of HAAs could be due to their less volatile nature compared with other DBPs (e.g., THMs) [3]. Therefore, HAAs are more likely to remain in the pool water after their formation [21,22]. On the other hand, turbulence caused by the movement of swimmers could influence the release of volatile DBPs (e.g., THMs) into the air [68,69]. In addition, the very high concentrations of HAAs are likely due to bather organic loads in swimming pool water, which tend to preferentially form HAAs rather than THMs. Furthermore, HAAs are highly soluble in water and do not degrade in the presence of high FRC [33].

Unlike temperature and TOC, which have positive correlations with most of the studied DBPs, pH has both positive and negative relationships with DBPs. This mixed impact makes pH management a more complicated task. However, most of the research indicated that at pH < 7.0 the formation of THMs decreases; the formation of HAAs remains constant but the level of HANs increases, and the level of TCAM is drastically increased [62].

The type of source water also plays a major role for the formation of DBPs [21]. For instance, seawater contains higher levels of Br⁻ compared with freshwater (tap, surface or ground) and leads to the formation of brominated species of DBPs [4,12], which are more toxic compared with their chlorinated analogues [16,70].

This review highlighted the formation of DBPs with different methods of disinfection, thus indicating the occurrence of DBPs in swimming pool water. Different parameters such as pool location (indoor and outdoor), type of source water, disinfectant dose, method of detection, temperature, pH, TOC and TN were also presented for the comparison of different disinfection methods. The values of these parameters, given in Tables A3–A7, were comparable in most cases when different technologies were compared while using same or similar swimming pools. For instance, the study conducted by Hang et al. [15] reported values of temperature and pH for chlorinated pool and O₃/chlorine pool were 28 °C and 7.1–7.4, respectively; both pools were indoor, and used the tap water as source water. Similarly, the values of temperature, pH and TOC in chlorinated, UV irradiation and UV/chlorine disinfected pools were 27–28 °C, 7.2 and 1.8–1.9 mg·L⁻¹, respectively in case of study by Cassan et al. [37]. Analogous to that, Cimetiere and De Laat [10] reported the similar level of temperature, pH and TOC in indoor chlorinated pools as well as with different dosage of UV irradiation for disinfection of indoor swimming pools (Table A1). Furthermore, for chlorination, UV irradiation, UV/chlorine, UV/H₂O₂ and UV/H₂O₂/chlorine the reported values of temperature, pH and TOC, and type of source water were same [13]. Therefore, a comparative evaluation of 10 disinfection methods carried out in this review could provide reliable assessment of their performance, as many other governing factors were not much different in individual case studies.

4.4. Advantages and Disadvantages of Disinfection Methods for Swimming Pool Water

The critical examination of the reviewed literature revealed that each methods has advantages as well as drawbacks. Thus, a thorough understanding should be established to advance research and make informed decisions on application of these methods. Based on the reviewed studies, some advantages and disadvantages of the studied methods are synthesized in Table 4.

Table 4. Summary of advantages and disadvantages of the disinfection methods for swimming pool water.

Disinfection Method	Advantages [Reference]	Disadvantages [Reference]
Chlorination	Provides rapid and long-lasting disinfection effects [22].	Presence of chlorine-resistant microorganisms such as <i>Cryptosporidium parvum</i> and <i>Giardia lamblia</i> [39]. Formation of potentially toxic carbonaceous and nitrogenous-based DBPs [1–4,40].
Electrochemically generated mixed oxidants		Chlorine in the form of HOCl is the primary oxidant [43,44]. Toxicity concerns are similar, as in the case of typical chlorine disinfection [46].
Ultraviolet (UV) irradiation	Effective for the control of microorganisms such as <i>Cryptosporidium parvum</i> and <i>Giardia lamblia</i> [49,50]. Cost-competitive with chlorine to improve the quality of swimming pool water and air [9,51].	The formation of nitrogenous-based DBPs (HANs) [10–13].
UV irradiation/chlorine		The formation of nitrogenous-based DBPs (HANs) [10–13,19]. The post-chlorination leads to the formation of carbonaceous DBPs (THMs) [10,12,13,19].
UV irradiation/hydrogen peroxide	Decrease in the formation of carbonaceous DBPs (THMs) [13].	The formation of nitrogenous-based DBPs (HANs) [13].
UV irradiation/hydrogen peroxide/chlorine		With this process post-chlorination is required, which leads to the formation of carbonaceous DBPs (THMs) [13].
Ozone/chlorine		Ozone as a residual disinfectant is unsuitable in swimming pool water, because it readily vaporizes and decomposes. In addition, it is toxic and heavier than air, which leads to adverse health effects [20]. Lack of residuals and the relatively high doses required, ozone disinfection is usually followed by deozonation before water enters the pool and sequential disinfection by chlorine is required [3,6,14–17,19].
Ozone/hydrogen peroxide/chlorine	The effective removal of TOC with ozonation. The contact time of 3 min between oxidant and pool water was sufficient for the increased elimination efficiency of TOC compared with 20 min contact time in case of ozonation [17].	Residual disinfection with chlorine is needed [17,19]. OH• reactions in AOPs are non-specific and produce activated compounds suitable for THMs formation in the post-chlorination step. Therefore, the formation potential of THMs increased [17].
Ozone/UV irradiation	Decrease in THMs and HANs formation [19]	
Ozone/UV irradiation/chlorine	The effective removal of TOC with ozonation. The contact time of 3 min between oxidant and pool water was sufficient for the increased elimination efficiency of TOC compared with 20 min contact time in case of ozonation [17]	Residual disinfection with chlorine is needed [17,19]. The increase in the level of THMs and HANs with ozone/UV/chlorine compared with ozone/UV was observed, indicating the complication of post-chlorination [19]. OH• reactions in AOPs are non-specific and produce activated compounds suitable for THMs formation in the post-chlorination step. Therefore, the formation potential of THMs increased [17].

Note: Disinfection byproducts (DBPs); Hypochlorous acid (HOCl); Trihalomethanes (THMs); Haloacetonitriles (HANs); Hydroxyl radical (OH•); Advanced oxidation processes (AOPs); Total organic carbon (TOC). The advantages and disadvantages of the disinfection methods indicated in the studies reviewed in this paper.

5. Future Research Needs

1. In case of EGMO disinfection, the toxicity concerns are similar as in case of chlorination because both often results in harmful DBPs, which in many cases could be much higher than the guidelines set by WHO for drinking water quality. Since these methods are considered cost-effective, further research is needed to improve these methods.
2. The level of HAAs, THAs and CAMs with UV/H₂O₂, UV/H₂O₂/chlorine, O₃/H₂O₂/chlorine O₃/UV and O₃/UV/chlorine is not reported in the literature. Furthermore, the level of TCAA reduced with UV/chlorine and met the guidelines set by WHO for drinking water quality, but

the level of DCAA and CH remained much higher. Therefore, to control the formation of DCAA and CH, which are possible human carcinogens, and CAMs, which are very toxic, the application of UV-based AOPs (UV/H₂O₂ and UV/H₂O₂/chlorine), O₃/chlorine and ozone-based AOPs (O₃/UV and O₃/UV/chlorine) need exploration.

3. The enhancement in the formation of THMs, HANs and CH in the post-chlorination step (UV/chlorine) compared with UV irradiation, the increase in THMs with UV/H₂O₂/chlorine compared with UV/H₂O₂ and the increase in the level of HANs with O₃/UV/chlorine compared with O₃/UV, indicate the complexity of the combined process, which needs to be optimized.
4. The application of O₃/H₂O₂ is only tested for THMs and even the levels of THMs are not presented in the literature. Therefore, the future applications of this method should investigate the formation and/or elimination of toxic DBPs.
5. The optimization in the post-chlorination step and the application of UV-based AOPs (UV/H₂O₂), O₃/chlorine and ozone-based AOPs (O₃/H₂O₂ and O₃/UV) for the disinfection of swimming pool water need further attention to control the toxicity and enhance the quality of swimming pool water.

6. Conclusions

Chlorination of swimming pool water leads to the formation of potentially toxic DBPs including THMs, HAAs, HANs, THAs and CAMs. With this knowledge, the demand for alternatives to chlorine disinfection has increased. Alternative methods tested for their potential to improve the quality of swimming pool water are: EGMO, UV irradiation, UV-based AOPs (UV/H₂O₂), O₃ and ozone-based AOPs (O₃/H₂O₂ and O₃/UV). However, these methods are still in the research and development phase. The specific conclusions drawn from this research are:

1. In the case of THMs and HANs, the level of TCM and DCAN is almost twice with EGMO compared with chlorination. Similarly, the level of TCM and DCAN is higher with UV/chlorine compared with chlorination, UV irradiation, O₃/chlorine, O₃/UV and O₃/UV/chlorine. Although the level of TCM is significantly reduced with O₃/UV/chlorine compared with chlorination, UV irradiation, UV/chlorine, O₃/chlorine and O₃/UV, the level of DCAN increased in the post-chlorination step (O₃/UV/chlorine) compared with O₃/UV process.
2. The concentration of DCAA and TCAA (representatives of HAAs) with EGMO is more than twice compared with chlorination. However, the level of DCAA and TCAA reduced more than half with UV/chlorine compared with chlorination. Furthermore, the concentration of DCAA with O₃/chlorine was much less than with chlorination. On the other hand, the level of CH (THAs) with UV/chlorine and chlorination is not significantly different.
3. The comparative studies for the formation of CAMs with different methods of disinfection are very limited in number. Thus, based on limited evidence, the formation of TCAM with UV/chlorine is comparable with chlorination. Similarly, the level of tCAMs with chlorination and O₃/chlorine is not much different.
4. The comparative studies of LPUV and MPUV irradiation without post-chlorination indicated the effectiveness of MPUV to reduce the formation of THMs but with post-chlorination the efficacy of LPUV/chlorine was emphasized. On the other hand, to reduce the level of HANs the efficiency of LPUV/chlorine and MPUV/chlorine is not clear because of contradictory information.
5. The ozone-based AOPs, O₃/UV and O₃/UV/chlorine, significantly reduced THMs and HANs, and, thus, stand out as the most promising disinfection methods, though more research is needed to validate this hypothesis, especially related to effects on other DBPs that have not yet been studied by these methods.

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comments on the written manuscript. J.P.v.d.H. further improved the concept, structure, contents and writing of the manuscript.

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Appendix A

Table A1. Types and species of DBPs studied in this review.

DBPs Type	DBPs Species	Abbreviation	Chemical Formula
Trihalomethanes (THMs)	Trichloromethane (chloroform)	TCM	CHCl ₃
	Bromodichloromethane	BDCM	CHBrCl ₂
	Dibromochloromethane	DBCM	CHBr ₂ Cl
	Tribromomethane (bromoform)	TBM	CHBr ₃
Haloacetic acids (HAAs)	Monochloroacetic acid	MCAA	CH ₂ ClCOOH
	Dichloroacetic acid	DCAA	CHCl ₂ COOH
	Trichloroacetic acid	TCAA	CCl ₃ COOH
	Monobromoacetic acid	MBAA	CH ₂ BrCOOH
	Dibromoacetic acid	DBAA	CHBr ₂ COOH
	Bromochloroacetic acid	BCAA	CHBrClCOOH
	Bromodichloroacetic acid	BDCAA	CBrCl ₂ COOH
	Dibromochloroacetic acid	DBCAA	CBr ₂ ClCOOH
Tribromoacetic acid	TBAA	CBr ₃ COOH	
Haloacetonitriles (HANs)	Dichloroacetonitrile	DCAN	CHCl ₂ CN
	Trichloroacetonitrile	TCAN	CCl ₃ CN
	Bromochloroacetonitrile	BCAN	CHBrClCN
	Dibromoacetonitrile	DBAN	CHBr ₂ CN
	Chloroacetonitrile	CAN	CH ₂ ClCN
	Bromoacetonitrile	BAN	CH ₂ BrCN
Trihaloacetaldehydes (THAs)	Chloral hydrate	CH	CCl ₃ CH(OH) ₂ or C ₂ H ₃ Cl ₃ O ₂
Chloramines (CAMs)	Monochloramine	MCAM	NH ₂ Cl
	Dichloramine	DCAM	NHCl ₂
	Trichloramine	TCAM	NCl ₃

Table A2. Carcinogenic group classification and WHO guidelines for DBPs.

Compound	Carcinogenic Group US EPA, IRIS [59]	WHO Guidelines-Upper Limits (µg·L ⁻¹) WHO [20,58] *
Chloroform	B2	300
Bromodichloromethane	B2	60
Dibromochloromethane	C	100
Bromoform	B2	100
Total trihalomethanes	–	100
Monochloroacetic acid	–	20
Dichloroacetic acid	B2	50
Trichloroacetic acid	B2	200
Dichloroacetonitrile	D	20
Dibromoacetonitrile	D	70
Chloral hydrate	C	10
Total chloramines	–	<200

Note: Group B2: Probable human carcinogen (sufficient data from animal studies), Group C: Possible human carcinogen; Group D: Not classifiable as to human carcinogenicity; * The guideline value of tCAM is for swimming pool water, other parameters have only drinking water reference.

Table A3. Concentration of THMs with different disinfection methods.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of THMs (µg·L ⁻¹)					Method of Detection	Author
						TCM	BDCM	DBCM	TBM	∑THMs		
Chlorination												
NA	NA/NA	NA	NA	**	NA/NA					38	NA	Beyer et al. [9]
France	Indoor/Tap	27	7.2	1.7	1.8/NA	27	5.1	3.1	1.0	36	GC-MS	Cassan et al. [37]
U.S./S2W	Indoor/Tap	31	7.4	3.0	11/4.7	119	3.0	<1.0		122	GC-ECD	Kanan [7]
France/BLA	Indoor/NA	25	7.6	1.08	5.5/NA	55	6.8	1.6	0.7	64	HS-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	2.7	2.8/NA	28	3.4	0.9	0.7	33	HS-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	2.2	5.1/NA	61	5.4	1.2	0.7	69	HS-GC-MS	Cimetiere and De Laat [10]
Denmark/Lyngby	NA/Ground	26	7.1	0.4	1.6/NA	16	1.1	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	0.6	2.1/NA	13	0.8	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe hot	NA/Ground	34	7.2	1.4	2.1/NA	47	5.2	0.7	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
U.S./3-Public Pool	Indoor/Tap	NA	NA	NA	NA/NA	17	9.0	5.0	<1.0		GC-MS	Daiber et al. [16]
China/B	Indoor/Tap	28	7.1	3.4	30 a/NA	220	202	3.8	28		GC-ECD	Hang et al. [15]
Denmark/Clean	NA/Ground	27	7.3	1.7	1.5 a/NA	25	6.0	<0.6	<0.6		PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	1.0	2.4 a/NA	35	6.0	2.0			PAT-GC-MS	Hansen et al. [14]
U.S.	Indoor/Tap	28	7.5	2.5	NA/NA	75		1.5	1.3		MIMS	Afifi and Blatchley III [11]
France/Pool-1	Indoor/Sea	32	8.1	0.6	2.7/NA	2.5		2.5	25		LLE-GC-ECD	Cheema et al. [12]
France/Pool-2	Indoor/Sea	30	8.1	0.5	3.1/NA	2.5		3.0	30		LLE-GC-ECD	Cheema et al. [12]
France/Pool-3	Indoor/Sea	33	8.2	0.9	3.9/NA	<0.8		2.5	25		LLE-GC-ECD	Cheema et al. [12]
Denmark/Gladsaxe main	NA/Ground	26	7.2	1.0	1.7 a/NA	12	2.2	0.4			PAT-GC-MS	Cheema et al. [19]
EGMO												
U.S./S4C	Indoor/Tap	27	7.4	4.0	7.1/9.1	37	1.0	<1.0		38	GC-ECD	Kanan [7]
U.S./S4W	Indoor/Tap	30	7.4	3.0	6.5/3.2	49	3.0	<1.0		53	GC-ECD	Kanan [7]
U.S./S6L	Indoor/Tap	29	7.6	2.0	7.9/4.8	72	3.0	<1.0		76	GC-ECD	Kanan [7]
U.S./S6T	Indoor/Tap	34	7.4	3.0	7.7/2.5	72	12	4.0	1.0	90	GC-ECD	Kanan [7]
U.S./S15L	Indoor/Tap	27	7.7	2.8	3.8/0.8	38	6.0	1.0		45	GC-ECD	Kanan [7]
U.S./S15T	Indoor/Tap	32	7.8	1.2	7.5/1.2	121	5.0	1.0		127	GC-ECD	Kanan [7]
U.S./S17L	Indoor/Tap	28	7.6	3.5	7.3/4.1	82	11	2.0		95	GC-ECD	Kanan [7]
U.S./S17T	Indoor/Tap	33	7.4	3.5	24/4.4	207	6.0	<1.0		213	GC-ECD	Kanan [7]
UV irradiation												
France	Indoor/Tap	27	7.2	0.145	1.9/NA	76	16	2.7	0.5	95	GC-MS	Cassan et al. [37]
Denmark/Gladsaxe hot	NA/Ground	32	NA	1.8 *	NA/NA	34				34	MIMS	Kristensen et al. [18]
Denmark/Gladsaxe hot	NA/Ground	32	NA	1.8 **	NA/NA	37				37	MIMS	Kristensen et al. [18]
Denmark/Gladsaxe hot	NA/Ground	32	NA	3.6 ***	NA/NA	53				53	MIMS	Kristensen et al. [18]
Denmark/Lyngby	NA/Ground	26	7.1	4.2	1.6/NA	13	0.7	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.2	2.1/NA	17	0.9	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]

Table A3. Cont.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of THMs (µg·L ⁻¹)					Method of Detection	Author
						TCM	BDCM	DBCM	TBM	∑THMs		
UV/chlorine												
NA	NA/NA	NA	NA	NA	NA/NA					21	NA	Beyer et al. [9]
France	Indoor/Tap	28	7.2	0.145/2.1	1.8/NA	58	15	2.2	0.5	75	GC-MS	Cassan et al. [37]
France/BLA	Indoor/NA	25	7.6	2.35/2.5	5.5/NA	85	15	2.6	0.6	103	HS-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	2.35/1.6	2.8/NA	64	13	2.0	0.5	80	HS-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	2.35/2.3	5.1/NA	97	16	2.9		118	HS-GC-MS	Cimetiere and De Laat [10]
France/BLA	Indoor/NA	25	7.6	4.7/2.2	5.5/NA	101	18	3.3	0.4	122	HS-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	4.7/1.5	2.8/NA	89	17	1.9	0.4	108	HS-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	4.7/2.3	5.1/NA	120	21	3.2		144	HS-GC-MS	Cimetiere and De Laat [10]
Denmark/Lyngby	NA/Ground	26	7.1	4.2/2.0	1.6/NA	65	11	1.8	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.2/2.0	2.1/NA	35	2.6	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe hot	NA/Ground	34	7.2	4.2/2.0	2.1/NA	87	8.8	0.9	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
U.S.	Indoor/Tap	27	7.6	0.06 **/3.0	NA/NA	60		2.5	0.5		MIMS	Afifi and Blatchley III [11]
U.S.	Indoor/Tap	27	8.0	0.06 */3.1	NA/NA	52		2.5	1.5		MIMS	Afifi and Blatchley III [11]
France/Pool-1	Indoor/Sea	32	8.1	2.35/0.6	2.7/NA	2.5		4.0	45		LLE-GC-ECD	Cheema et al. [12]
France/Pool-2	Indoor/Sea	30	8.1	2.35/0.5	3.1/NA	3.5		4.0	40		LLE-GC-ECD	Cheema et al. [12]
France/Pool-3	Indoor/Sea	33	8.2	2.35/0.9	3.9/NA	2.0		4.0	45		LLE-GC-ECD	Cheema et al. [12]
France/Pool-1	Indoor/Sea	32	8.1	4.7/0.6	2.7/NA	5.0		5.5	58		LLE-GC-ECD	Cheema et al. [12]
France/Pool-2	Indoor/Sea	30	8.1	4.7/0.5	3.1/NA	1.0		4.5	55		LLE-GC-ECD	Cheema et al. [12]
France/Pool-3	Indoor/Sea	33	8.2	4.7/0.9	3.9/NA	4.5		5.5	60		LLE-GC-ECD	Cheema et al. [12]
Denmark/Gladsaxe main	NA/Ground	26	7.2	2.1/1.0	1.9 a/NA	32	5.5	1.0			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.2/1.0	1.8 a/NA	31	6.0	1.3			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	9.5/1.0	1.7 a/NA	35	6.2	1.5			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	19/1.0	1.7 a/NA	30	7.2	1.8			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	47.5/1.0	1.2 a/NA	10	5.8	1.6			PAT-GC-MS	Cheema et al. [19]
UV/H₂O₂												
Denmark/Lyngby	NA/Ground	26	7.1	14.3/1.0	1.6/NA	9.1	<0.6	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	16/1.0	2.1/NA	13	<0.6	<0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]
UV/H₂O₂/chlorine												
Denmark/Lyngby	NA/Ground	26	7.1	14.3/1.0/2.0	1.6/NA	36	17	7.1	0.8		PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	16/1.0/2.0	2.1/NA	25	3.1	0.6	<0.6		PAT-GC-MS	Spiliotopoulou et al. [13]

Table A3. Cont.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of THMs (µg·L ⁻¹)					Method of Detection	Author
						TCM	BDCM	DBCM	TBM	tTHMs		
O₃/chlorine												
U.S./6-Public Pool	Outdoor/Tap	NA	NA	NA/NA	NA/NA	31	<1.0	<1.0	<1.0		GC-MS	Daiber et al. [16]
China/A	Indoor/Tap	28	7.4	NA/2.1	13 a/NA	141	106	2.0	47		GC-ECD	Hang et al. [15]
Denmark/Clean	NA/Ground	27	7.3	2.0/1.7	1.5 a/NA	42	7.0	<0.6	<0.6		PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	4.0/1.7	1.5 a/NA	60	7.0	<0.6	<0.6		PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	6.0/1.7	1.5 a/NA	59	8.0	<0.6	<0.6		PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	8.0/1.7	1.5 a/NA	45	7.0	<0.6	<0.6		PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	10/1.7	1.5 a/NA	45	7.0	<0.6	<0.6		PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	0.7/1.0	2.4 a/NA	25	6.2	2.5			PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	1.2/1.0	2.4 a/NA	25	7.0	2.7			PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	1.8/1.0	2.4 a/NA	22	7.0	2.6			PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	3.4/1.0	2.4 a/NA	18	5.8	2.2			PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	100/1.0	2.4 a/NA	7.0	1.0	<0.6			PAT-GC-MS	Hansen et al. [14]
Denmark/Gladsaxe main	NA/Ground	26	7.2	1.0/1.0	1.8 a/NA	17	1.2	0.5			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	2.0/1.0	1.7 a/NA	21	1.7	0.5			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.0/1.0	1.7 a/NA	25	1.6	0.4			PAT-GC-MS	Cheema et al. [19]
O₃/UV												
Denmark/Gladsaxe hot	NA/Ground	32	NA	NA/3.6 ***	NA/NA	35				35	MIMS	Kristensen et al. [18]
Denmark/Gladsaxe main	NA/Ground	26	7.2	7.0/9.5	NA/NA	5.0	1.0	0.1			PAT-GC-MS	Cheema et al. [19]
O₃/UV/chlorine												
Denmark/Gladsaxe main	NA/Ground	26	7.2	1.0/9.5/1.0	1.5 a/NA	21	4.0	1.4			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	2.0/9.5/1.0	1.5 a/NA	20	3.0	1.3			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.0/9.5/1.0	1.4 a/NA	15	2.5	0.7			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	7.0/9.5/1.0	1.3 a/NA	13	1.0	0.3			PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	10/9.5/1.0	1.3 a/NA	12	0.1	0.1			PAT-GC-MS	Cheema et al. [19]

Note: Trihalomethanes (THMs); Chloroform (TCM); Bromodichloromethane (BDCM); Dibromochloromethane (DBCM), Bromoform (TBM); Total trihalomethanes (tTHMs); Temperature (T); Total organic carbon (TOC); Total nitrogen (TN); Electrochemically generated mixed oxidants (EGMO); Ultraviolet irradiation (UV); Ozone (O₃); Gas chromatography (GC); Mass spectrometry (MS); Headspace (HS); Purge and trap (PAT); Electron capture detection (ECD); Membrane introduction mass spectrometry (MIMS); Not available (NA); Bold values are above the guideline values set by WHO for drinking water quality [58]; THMs concentration with low, medium, and combined low and medium pressure UV, respectively (*, **, ***); Organic carbon is reported as dissolved organic carbon (a); Unit for disinfectant dose: Free residual chlorine (mg·L⁻¹); UV (J·cm⁻²); O₃ (mg·L⁻¹).

Table A4. Concentration of HAAs with different methods of disinfection.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of HAAs (µg·L ⁻¹)										Method of Detection	Author
						MCAA	DCAA	TCAA	MBAA	DBAA	BCAA	BDCAA	DBCAA	TBAA	tHAAs		
Chlorination																	
U.S./S2W	Indoor/Tap	31	7.4	3.0	11/4.7		896	718	1.0	<1.0	14	36	<1.0	1665	GC-ECD	Kanan [7]	
France/BLA	Indoor/NA	25	7.6	1.08	5.5/NA	7.8	168	183		<1.0	8.0			367	LLE-GC-MS	Cimetiere and De Laat [10]	
France/GAN	Indoor/NA	25	7.6	2.7	2.8/NA	6.0	128	77		<1.0	7.0			218	LLE-GC-MS	Cimetiere and De Laat [10]	
France/BEL	Indoor/NA	25	7.4	2.2	5.1/NA	19	361	136		<1.0	16			531	LLE-GC-MS	Cimetiere and De Laat [10]	
Australia/5	Covered outdoor/Tap	26	7.5	5.0	NA/NA	33	760	870	<0.5	<0.5	<0.5	8	<0.5		GC-ECD	Yeh et al. [8]	
Australia/6	Indoor/Tap	32	7.4	0.9	NA/NA	<0.5	770	460	<0.5	<0.5	<0.5	<0.5	<0.5		GC-ECD	Yeh et al. [8]	
Australia/7	Indoor/Tap	33	7.5	3.4	NA/NA	120	2100	1700	<0.5	<0.5	<0.5	11	<0.5		GC-ECD	Yeh et al. [8]	
U.S./3-Public Pool	Indoor/Tap	NA	NA	NA	NA/NA	9.4	89	65	9.6	19	37	14	6.1	<4.0	GC-ECD	Daiber et al. [16]	
China/B	Indoor/Tap	28	7.1	3.4	30 ^a /NA	10	296	21	2.3	<0.4	874	<0.4	<0.4		GC-ECD	Hang et al. [15]	
France/Pool-1	Indoor/Sea	32	8.1	0.6	2.7/NA					45	2.0		5.0	32	GC-ECD	Cheema et al. [12]	
France/Pool-2	Indoor/Sea	30	8.1	0.5	3.1/NA					45	3.5		4.0	25	GC-ECD	Cheema et al. [12]	
France/Pool-3	Indoor/Sea	33	8.2	0.9	3.9/NA					80	6.5		7.0	45	GC-ECD	Cheema et al. [12]	
EGMO																	
U.S./S4C	Indoor/Tap	27	7.4	4.0	7.1/9.1		688	789	<1.0	1.0	10	27	3.0	1518	GC-ECD	Kanan [7]	
U.S./S4W	Indoor/Tap	30	7.4	3.0	6.5/3.2		81	241	1.0	<1.0	4.0	60	5.0	392	GC-ECD	Kanan [7]	
U.S./S6L	Indoor/Tap	29	7.6	2.0	7.9/4.8		928	552	1.0	2.0	30	48	3.0	1563	GC-ECD	Kanan [7]	
U.S./S6T	Indoor/Tap	34	7.4	3.0	7.7/2.5		1033	351	1.0	4.0	36	36	7.0	1468	GC-ECD	Kanan [7]	
U.S./S15L	Indoor/Tap	27	7.7	2.8	3.8/0.8		115	102	2.0	5.0	21	47	14	306	GC-ECD	Kanan [7]	
U.S./S15T	Indoor/Tap	32	7.8	1.2	7.5/1.2		690	183	2.0	6.0	31	45	2.0	960	GC-ECD	Kanan [7]	
U.S./S17L	Indoor/Tap	28	7.6	3.5	7.3/4.1		504	288	5.0	25	106	110	32	1070	GC-ECD	Kanan [7]	
U.S./S17T	Indoor/Tap	33	7.4	3.5	24/4.4		6787	1925	4.0	16	176	93	4.0	9005	GC-ECD	Kanan [7]	
Australia/5	Indoor/Tap	32	7.5	1.0	NA/NA	110	2400	2600	<0.5	<0.5	<0.5	16	<0.5		GC-ECD	Yeh et al. [8]	
Australia/6	Outdoor/Tap	27	7.4	2.6	NA/NA	40	480	650	<0.5	<0.5	<0.5	8.0	<0.5		GC-ECD	Yeh et al. [8]	
Australia/7	Outdoor/Tap	28	7.5	5.3	NA/NA	64	1400	1300	<0.5	<0.5	<0.5	8.0	<0.5		GC-ECD	Yeh et al. [8]	
UV/chlorine																	
France/BLA	Indoor/NA	25	7.6	2.35/2.5	5.5/NA	10	158	187		<1.0	5.0			360	LLE-GC-MS	Cimetiere and De Laat [10]	
France/GAN	Indoor/NA	25	7.6	2.35/1.6	2.8/NA	8.0	136	75		<1.0	5.1			224	LLE-GC-MS	Cimetiere and De Laat [10]	
France/BEL	Indoor/NA	25	7.4	2.35/2.3	5.1/NA	21	372	139		<1.0				531	LLE-GC-MS	Cimetiere and De Laat [10]	
France/BLA	Indoor/NA	25	7.6	4.7/2.2	5.5/NA	8.7	147	144		<1.0	7.3			307	LLE-GC-MS	Cimetiere and De Laat [10]	
France/GAN	Indoor/NA	25	7.6	4.7/1.5	2.8/NA	9.0	149	79		<1.0	6.0			240	LLE-GC-MS	Cimetiere and De Laat [10]	
France/BEL	Indoor/NA	25	7.4	4.7/2.3	5.1/NA	22	344	122		<1.0	8.6			496	LLE-GC-MS	Cimetiere and De Laat [10]	
France/Pool-1	Indoor/Sea	32	8.1	2.35/0.6	2.7/NA					10	2.5		3.0	12	GC-ECD	Cheema et al. [12]	
France/Pool-2	Indoor/Sea	30	8.1	2.35/0.5	3.1/NA					15	3.5		1.5	3.0	GC-ECD	Cheema et al. [12]	
France/Pool-3	Indoor/Sea	33	8.2	2.35/0.9	3.9/NA					15	4.5		1.5	2.5	GC-ECD	Cheema et al. [12]	
France/Pool-1	Indoor/Sea	32	8.1	4.7/0.6	2.7/NA					10	3.5		1.5	3.0	GC-ECD	Cheema et al. [12]	
France/Pool-2	Indoor/Sea	30	8.1	4.7/0.5	3.1/NA					10	2.0		1.4	2.5	GC-ECD	Cheema et al. [12]	
France/Pool-3	Indoor/Sea	33	8.2	4.7/0.9	3.9/NA					20	6.5		1.8	5.0	GC-ECD	Cheema et al. [12]	
O₃/chlorine																	
U.S./6-Public Pool	Outdoor/Tap	NA	NA	NA	NA/NA	31	343	1865	<1.0	<1.0	2.6	12	<2.0	<4.0	GC-ECD	Daiber et al. [16]	
China/A	Indoor/Tap	28	7.4	2.1	13 ^a /NA	41	200	20	16	<0.4	425	<0.4	1.2	8.1	GC-ECD	Hang et al. [15]	

Note: Haloacetic acids (HAAs); Monochloroacetic acid (MCAA); Dichloroacetic acid (DCAA); Trichloroacetic acid (TCAA); Monobromoacetic acid (MBAA); Dibromoacetic acid (DBAA); Bromochloroacetic acid (BCAA); Bromodichloroacetic acid (BDCAA); Dibromochloroacetic acid (DBCAA); Tribromoacetic acid (TBAA); Total haloacetic acid (tHAAs); Temperature (T); Total organic carbon (TOC); Total nitrogen (TN); Electrochemically generated mixed oxidants (EGMO); Ultraviolet irradiation (UV); Ozone (O₃); Liquid-liquid extraction (LLE); Gas chromatography (GC); Mass spectrometry (MS); Electron capture detection (ECD); Not available (NA); Bold values are above the guideline values set by WHO for drinking water quality [58]; Organic carbon is reported as dissolved organic carbon (^a); Units for disinfectant dose: Free residual chlorine (mg·L⁻¹); UV (J·cm⁻²); O₃ (mg·L⁻¹).

Table A5. Concentration of HANs with different disinfection methods.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of HANs (µg·L ⁻¹)							Method of Detection	Author
						DCAN	DBAN	BCAN	TCAN	CAN	BAN	tHANs		
Chlorination														
U.S./S2W	Indoor/Tap	31	7.4	3.0	11/4.7	22		1.0		1.0		25	GC-ECD	Kanan [7]
France/BLA	Indoor/NA	25	7.6	1.08	5.5/NA	19	0.6	3.8	0.06			23	LLE-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	2.7	2.8/NA	3.0	0.0	0.9	0.0			4.0	LLE-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	2.2	5.1/NA	15	0.0	5.7	0.0			21	LLE-GC-MS	Cimetiere and De Laat [10]
Denmark/Lyngby	NA/Ground	26	7.1	0.4	1.6/NA	1.9							PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	0.6	2.1/NA	1.4							PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe hot	NA/Ground	34	7.2	1.4	2.1/NA	2.6							PAT-GC-MS	Spiliotopoulou et al. [13]
U.S./3-Public Pool	Indoor/Tap	NA	NA	NA	NA/NA	9.4	<1.0	7.4	<1.0				GC-MS	Daiber et al. [16]
China/B	Indoor/Tap	28	7.1	3.4	30 ^a /NA	9.2	<0.34	3.2	<0.46				GC-ECD	Hang et al. [15]
Denmark/Clean	NA/Ground	27	7.3	1.7	1.5 ^a /NA	2.2							PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	1.0	2.4 ^a /NA	7.0							PAT-GC-MS	Hansen et al. [14]
U.S.	Indoor/Tap	28	7.5	2.5	NA/NA	8.0							MIMS	Affii and Blatchley III [11]
France/Pool-1	Indoor/Sea	32	8.1	0.6	2.7/NA		12	1.0					LLE-GC-ECD	Cheema et al. [12]
France/Pool-2	Indoor/Sea	30	8.1	0.5	3.1/NA		9.0	1.5					LLE-GC-ECD	Cheema et al. [12]
France/Pool-3	Indoor/Sea	33	8.2	0.9	3.9/NA		12	1.0					LLE-GC-ECD	Cheema et al. [12]
Denmark/Gladsaxe main	NA/Ground	26	7.2	1.0	1.7 ^a /NA	1.8		0.2					PAT-GC-MS	Cheema et al. [16]
EGMO														
U.S./S4C	Indoor/Tap	27	7.4	4.0	7.1/9.1	15		1.0		1.0		16	GC-ECD	Kanan [7]
U.S./S4W	Indoor/Tap	30	7.4	3.0	6.5/3.2	21		2.0		1.0		24	GC-ECD	Kanan [7]
U.S./S6L	Indoor/Tap	29	7.6	2.0	7.9/4.8	12		1.0		1.0		15	GC-ECD	Kanan [7]
U.S./S6T	Indoor/Tap	34	7.4	3.0	7.7/2.5	13	2.0	4.0		1.0		21	GC-ECD	Kanan [7]
U.S./S15L	Indoor/Tap	27	7.7	2.8	3.8/0.8	7.0	1.0	2.0		1.0		11	GC-ECD	Kanan [7]
U.S./S15T	Indoor/Tap	32	7.8	1.2	7.5/1.2	4.0				1.0		6	GC-ECD	Kanan [7]
U.S./S17L	Indoor/Tap	28	7.6	3.5	7.3/4.1	16	1.0	3.0		1.0	1.0	22	GC-ECD	Kanan [7]
U.S./S17T	Indoor/Tap	33	7.4	3.5	24/4.4	47		2.0	1.0	3.0		53	GC-ECD	Kanan [7]
UV irradiation														
Denmark/Lyngby	NA/Ground	26	7.1	4.2	1.6/NA	4.9							PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.2	2.1/NA	2.7							PAT-GC-MS	Spiliotopoulou et al. [13]
UV/chlorine														
France/BLA	Indoor/NA	25	7.6	2.35/2.5	5.5/NA	29	0.4	5.6	0.06			35	LLE-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	2.35/1.6	2.8/NA	8.0	0.0	2.6	0.05			11	LLE-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	2.35/2.3	5.1/NA	14	0.0	4.7	0.0			18	LLE-GC-MS	Cimetiere and De Laat [10]
France/BLA	Indoor/NA	25	7.6	4.7/2.2	5.5/NA	29	0.2	6.4	0.08			36	LLE-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	4.7/1.5	2.8/NA	11	0.0	3.0	0.05			14	LLE-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	4.7/2.3	5.1/NA	15	0.0	5.7	0.0			21	LLE-GC-MS	Cimetiere and De Laat [10]
Denmark/Lyngby	NA/Ground	26	7.1	4.2/2.0	1.6/NA	5.4							PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.2/2.0	2.1/NA	2.3							PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe hot	NA/Ground	34	7.2	4.2/2.0	2.1/NA	5.6							PAT-GC-MS	Spiliotopoulou et al. [13]
U.S.	Indoor/Tap	27	7.6	0.06 ^{**} /3.0	NA/NA	10							MIMS	Affii and Blatchley III [11]
U.S.	Indoor/Tap	27	8.0	0.06 ^{**} /3.1	NA/NA	7.7							MIMS	Affii and Blatchley III [11]
France/Pool-1	Indoor/Sea	32	8.1	2.35/0.6	2.7/NA		17	3.5					LLE-GC-ECD	Cheema et al. [12]
France/Pool-2	Indoor/Sea	30	8.1	2.35/0.5	3.1/NA		17	2.6					LLE-GC-ECD	Cheema et al. [12]
France/Pool-3	Indoor/Sea	33	8.2	2.35/0.9	3.9/NA		28	3.4					LLE-GC-ECD	Cheema et al. [12]
France/Pool-1	Indoor/Sea	32	8.1	4.7/0.6	2.7/NA		19	2.8					LLE-GC-ECD	Cheema et al. [12]
France/Pool-2	Indoor/Sea	30	8.1	4.7/0.5	3.1/NA		15	3.0					LLE-GC-ECD	Cheema et al. [12]
France/Pool-3	Indoor/Sea	33	8.2	4.7/0.9	3.9/NA		35	3.5					LLE-GC-ECD	Cheema et al. [12]
Denmark/Gladsaxe main	NA/Ground	26	7.2	2.1/1.0	1.9 ^a /NA	4.0		0.7					PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.2/1.0	1.8 ^a /NA	4.5		0.7					PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	9.5/1.0	1.7 ^a /NA	4.5		0.7					PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	19/1.0	1.7 ^a /NA	4.6		0.6					PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	47.5/1.0	1.2 ^a /NA	4.0		0.5					PAT-GC-MS	Cheema et al. [19]

Table A5. Cont.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of HANs (µg·L ⁻¹)						Method of Detection	Author
						DCAN	DBAN	BCAN	TCAN	CAN	BAN		
UV/H₂O₂													
Denmark/Lyngby	NA/Ground	26	7.1	14.3/1.0	1.6/NA	3.6						PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	16/1.0	2.1/NA	2.2						PAT-GC-MS	Spiliotopoulou et al. [13]
UV/H₂O₂/chlorine													
Denmark/Lyngby	NA/Ground	26	7.1	14.3/1.0/2.0	1.6/NA	3.1						PAT-GC-MS	Spiliotopoulou et al. [13]
Denmark/Gladsaxe main	NA/Ground	26	7.2	16/1.0/2.0	2.1/NA	2.1						PAT-GC-MS	Spiliotopoulou et al. [13]
O₃/chlorine													
U.S./6-Public Pool	Outdoor/Tap	NA	NA	NA	NA/NA	14	<1.0	<1.0	<1.0			GC-MS	Daiber et al. [16]
China/A	Indoor/Tap	28	7.4	2.1	13 ^a /NA	5.3	<0.34	<0.28	<0.46			GC-ECD	Hang et al. [15]
Denmark/Clean	NA/Ground	27	7.3	2.0/1.7	1.5 ^a /NA	2.7						PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	4.0/1.7	1.5 ^a /NA	2.7						PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	6.0/1.7	1.5 ^a /NA	3.5						PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	8.0/1.7	1.5 ^a /NA	3.2						PAT-GC-MS	Hansen et al. [14]
Denmark/Clean	NA/Ground	27	7.3	10/1.7	1.5 ^a /NA	4.2						PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	0.7/1.0	2.4 ^a /NA	4.5						PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	1.2/1.0	2.4 ^a /NA	4.0						PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	1.8/1.0	2.4 ^a /NA	4.0						PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	3.4/1.0	2.4 ^a /NA	4.0						PAT-GC-MS	Hansen et al. [14]
Denmark/Polluted	NA/Synthetic	27	7.3	100/1.0	2.4 ^a /NA	2.5						PAT-GC-MS	Hansen et al. [14]
Denmark/Gladsaxe main	NA/Ground	26	7.2	1.0/1.0	1.8 ^a /NA	1.8		0.3				PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	2.0/1.0	1.7 ^a /NA	1.8		0.3				PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.0/1.0	1.7 ^a /NA	2.5		0.4				PAT-GC-MS	Cheema et al. [19]
O₃/UV													
Denmark/Gladsaxe main	NA/Ground	26	7.2	7.0/9.5	NA/NA	3.0		0.1				PAT-GC-MS	Cheema et al. [19]
O₃/UV/chlorine													
Denmark/Gladsaxe main	NA/Ground	26	7.2	1.0/9.5/1.0	1.5 ^a /NA	4.2		0.6				PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	2.0/9.5/1.0	1.5 ^a /NA	4.0		0.5				PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	4.0/9.5/1.0	1.4 ^a /NA	3.5		0.3				PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	7.0/9.5/1.0	1.3 ^a /NA	3.2		0.3				PAT-GC-MS	Cheema et al. [19]
Denmark/Gladsaxe main	NA/Ground	26	7.2	10/9.5/1.0	1.3 ^a /NA	3.0		0.2				PAT-GC-MS	Cheema et al. [19]

Note: Haloacetonitlies (HANs); Dichloroacetonitrile (DCAN); Dibromoacetonitrile (DBAN); Bromochloroacetonitrile (DBAN); Trichloroacetonitrile (TCAN); Chloroacetonitrile (CAN); Bromoacetonitrile (BAN); Total haloacetonitlies (tHANs); Temperature (T); Total organic carbon (TOC); Total nitrogen (TN); Electrochemically generated mixed oxidants (EGMO); Ultraviolet irradiation (UV); Ozone (O₃); Liquid–liquid extraction (LLE); Gas chromatography (GC); Mass spectrometry (MS); Purge and trap (PAT); Electron capture detection (ECD); Membrane introduction mass spectrometry (MIMS); Not available (NA); Bold values are above the guideline values set by WHO for drinking water quality [58]; HANs concentration with low and medium pressure UV, respectively (*, **); Organic carbon is reported as dissolved organic carbon (^a). Units for disinfectant dose: Free residual chlorine (mg·L⁻¹); UV (J·cm⁻²); O₃ (mg·L⁻¹).

Table A6. Concentration of THAs with different methods of disinfection.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	CH (µg·L ⁻¹)	Method of Detection	Author
Chlorination								
France/BLA	Indoor/NA	25	7.6	1.08	5.5/NA	363	LLE-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	2.7	2.8/NA	104	LLE-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	2.2	5.1/NA	378	LLE-GC-MS	Cimetiere and De Laat [10]
U.S./3-Public Pool	Indoor/Tap	NA	NA	NA	NA/NA	165	GC-MS	Daiber et al. [16]
UV/chlorine								
France/BLA	Indoor/NA	25	7.6	2.35/2.5	5.5/NA	367	LLE-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	2.35/1.6	2.8/NA	136	LLE-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	2.35/2.3	5.1/NA	404	LLE-GC-MS	Cimetiere and De Laat [10]
France/BLA	Indoor/NA	25	7.6	4.7/2.2	5.5/NA	399	LLE-GC-MS	Cimetiere and De Laat [10]
France/GAN	Indoor/NA	25	7.6	4.7/1.5	2.8/NA	150	LLE-GC-MS	Cimetiere and De Laat [10]
France/BEL	Indoor/NA	25	7.4	4.7/2.3	5.1/NA	400	LLE-GC-MS	Cimetiere and De Laat [10]
O₃/chlorine								
U.S./6-Public Pool	Outdoor/Tap	NA	NA	NA/NA	NA/NA	101	GC-MS	Daiber et al. [16]

Note: Trihaloacetaldehyde (THA); Chloral hydrate (CH); Temperature (T); Total organic carbon (TOC); Total nitrogen (TN); Ultraviolet irradiation (UV); ; Ozone (O₃); Liquid-liquid extraction (LLE); Gas chromatography (GC); Mass spectrometry (MS); Not available (NA); Bold values are above the guideline values set by WHO for drinking water quality [58]; Units for disinfectant dose: Free residual chlorine (mg·L⁻¹); UV (J·cm⁻²); O₃ (mg·L⁻¹).

Table A7. Concentration of CAMs with different methods of disinfection.

Country/Pool ID	Pool Type/Source Water	T (°C)	pH	Disinfectant Dose	TOC/TN (mg·L ⁻¹)	Concentration of CAMs (µg·L ⁻¹)				Method of Detection	Author		
						MCAM	DCAM	TCAM	tCAMs				
Chlorination													
Burnaby	Indoor/NA	NA	NA	NA	NA/NA						1470	DPD-KI	Mah and Heacock [38]
Burnaby	Whirlpool/NA	NA	NA	NA	NA/NA						2020	DPD-KI	Mah and Heacock [38]
U.S.	Indoor/Tap	28	7.5	2.5	NA/NA	82	61	370		MIMS			Afifi and Blatchley III [11]
UV/chlorine													
U.S.	Indoor/Tap	27	7.6	0.06 **/3.0	NA/NA	55	37	350		MIMS			Afifi and Blatchley III [11]
U.S.	Indoor/Tap	27	8.0	0.06 */3.1	NA/NA	75	53	450		MIMS			Afifi and Blatchley III [11]
O₃ /chlorine													
Burnaby	Indoor/NA	NA	NA	NA/NA	NA/NA						1310	DPD	Mah and Heacock [38]
Burnaby	Whirlpool/NA	NA	NA	NA/NA	NA/NA						1890	DPD	Mah and Heacock [38]

Note: Chloramines (CAMs); Monochloramine (MCAM); Dichloramine (DCAM); Trichloramine (TCAM); Total chloramines (tCAMs); Temperature (T); Total organic carbon (TOC); Total nitrogen (TN); Ultraviolet irradiation (UV); Ozone (O₃); Diethyl-p-phenylenediamine (DPD); Colorimetric method (KI); Membrane introduction mass spectrometry (MIMS); Not available (NA); Bold values are above the guideline values set by WHO for swimming pool water quality [20]; Concentration of CAMs with low and medium pressure UV, respectively (*, **); Units for disinfectant dose: Free residual chlorine (mg·L⁻¹); UV (J·cm⁻²); O₃ (mg·L⁻¹).

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