Occurrence and Distribution of Disinfection Byproducts in Domestic Wastewater Effluent, Tap Water, and Surface Water during the SARS-CoV-2 Pandemic in China

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ABSTRACT: Intensified efforts to curb transmission of the Severe Acute Respiratory Syndrome Coronavirus-2 might lead to an elevated concentration of disinfectants in domestic wastewater and drinking water in China, possibly resulting in the generation of numerous toxic disinfection byproducts (DBPs). In this study, the occurrence and distribution of five categories of DBPs, including six trihalomethanes (THMs), nine haloacetic acids (HAAs), two haloketones, nine nitrosamines, and nine aromatic halogenated DBPs, in domestic wastewater effluent, tap water, and surface water were investigated. The results showed that the total concentration level of measured DBPs in wastewater effluents (78.3 μg/L) was higher than that in tap water (56.0 μg/L, p = 0.05), followed by surface water (8.0 μg/L, p < 0.01). Moreover, HAAs and THMs were the two most dominant categories of DBPs in wastewater effluents, tap water, and surface water, accounting for >90%, respectively. Out of the regulated DBPs, none of the wastewater effluents and tap water samples exceeded the corresponding maximum guideline values of chloroform (300 μg/L), THM4 (80 μg/L), NDMA (100 ng/L), and only 2 of 35 tap water samples (67.6 and 63.3 μg/L) exceeded the HAA5 (60 μg/L) safe limit. HAAs in wastewater effluents showed higher values of risk quotient for green algae. This study illustrates that the elevated use of disinfectants within the guidance ranges during water disinfection did not result in a significant increase in the concentration of DBPs.

INTRODUCTION

The Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) has rapidly spread to over 200 countries worldwide within months of its outbreak, causing unprecedented damage to human health and the economy.1−3 Over 93.6 million confirmed cases and 2022405 deaths have been recorded globally as of January 18, 2021 and the confirmed SARS-CoV-2 cases continue to rise at an alarming rate.1−3 Epidemiological studies have demonstrated that the SARS-CoV-2 virus undergoes human to human transmission through respiratory droplets.4,5 A few studies have detected the presence of infectious SARS-CoV-2 virus in human feces, highlighting the possibility of stool transmission.6,7 In addition, high concentrations of viral RNA have also been detected in the stool samples.6,7 Zang et al. suggested that the infectious viruses could be inactivated by the fluids present in the gastrointestinal tract, resulting in loss of infectivity.8 Currently, there is no scientific evidence whether or not domestic wastewater and drinking water played an important role in the transmission of SARS-CoV-2.6,8,10 Nonetheless, effective disinfection of environmental matrices is crucial to minimize virus transmission through air, wastewater, and other possible routes.11−14 Disinfection was considered the most effective step to eliminate or deactivate the viruses, including SARS-CoV-2, and prevent transmission. As a result, the dose of disinfectants in domestic wastewater and drinking water was elevated appropriately to curb the spread of SARS-CoV-2.10,11,14,15 During the SARS-CoV-2 pandemic in China, the disinfectant doses used for disinfection of drinking water and domestic wastewater were elevated within the guidance ranges according to the standards of Chinese GB-5749-2006 and GB-18918-2002, respectively. In the regulation of GB-5749-2006, it required that the disinfection time of drinking water must be above 30 min, the free chlorine in finished water must be controlled in the range of 0.3−4.0 mg/L, and the residual chlorine in tap water must be above 0.05 mg/L. In the regulation of GB-18918-2002, it required that the disinfection time of drinking water must be above 30 min, the free chlorine in finished water must be controlled in the range of 0.3−4.0 mg/L, and the residual chlorine in tap water must be above 0.05 mg/L. In the regulation of GB-18918-2002, disinfections were used to

special issue: Environmental Transmission and Control of COVID-19

received: October 12, 2020
revised: January 18, 2021
accepted: January 26, 2021
in-depth investigation of the prevalence of DBPs in wastewater, drinking water, and surface water is essential for ensuring human health and environmental safety during the SARS-CoV-2 pandemic in China.

The objective of this study was to investigate the occurrence and distribution of traditional DBPs (e.g., THMs and HAAs) as well as emerging DBPs (e.g., NAs and nine aromatic DBPs) in domestic wastewater effluents, drinking water, and surface water during the SARS-CoV-2 pandemic in Beijing and Wuhan. This study focused on the generation of multiple categories of DBPs, including four categories of halogenated and nonhalogenated aliphatic DBPs (THMs, HAAs, HKs, and NAs) and nine aromatic halogenated DBPs. Moreover, the DBPs in different aqueous environments and locations, an ecological risk assessment, and the potential sources of DBPs in surface water during the SARS-CoV-2 pandemic were analyzed, providing significant guidance for the use of disinfectants in emergency disinfection of wastewater and drinking water in the future.

### MATERIALS AND METHODS

**Chemicals and Materials.** Details of the chemicals, including the 35 measured DBPs (6 THMs, 9 HAAs, 2 HKs, 9 NAs, and 9 aromatic halogenated DBPs) and the internal and surrogate standards used in this study have been described in Section 1 of the Supporting Information. All organic solvents used in this study, including methyl tert-butyl ether, dichloromethane, acetonitrile, and methanol, were liquid chromatography grade and were purchased from Merck (Germany) and Tedia (USA). All other chemicals used in this study were purchased from the China National Pharmaceutical Group Corp. (Beijing, China) at the highest purities available. Ultrapure water was produced by a Millipore Milli-Q system (USA). High-purity nitrogen (99.99%) was purchased from Haisaw Group Corp. (Beijing, China).

**Sample Collection and Characterization.** Three domestic wastewater influent and effluent samples (W3–W5), 43 surface water samples (WS1–WS43), and 24 tap water samples (WT1–WT24) were collected from 6 different districts of Wuhan in May 2020 during the SARS-CoV-2 pandemic in the Huanan Seafood Wholesale Market, Wuhan. Two domestic wastewater effluent samples (W1 and W2), 8 surface water samples (BS1–BS8), and 11 tap water samples (BT1–BT11) were collected from five different districts of Beijing in June 2020 during the SARS-CoV-2 pandemic in the Xinfadi Seafood Wholesale Market, Beijing. Due to the strict controls by the government, we could not collect more domestic wastewater effluent samples. Sodium thiosulfate is an effective chlorine quenching agent and is commonly used in the analysis of NAs, THMs, and HAAs, but sodium thiosulfate can degrade some other DBPs, including HANs, NNMs, halocetaldehydes, HKs, and halo-aromatic DBPs. The results of the additional quenching experiments demonstrated that the 2 HKs and 9 halo-aromatic DBPs measured in this study showed no significant degradation over the holding time before the extraction (Section 4 of the Supporting Information). In this study, 105% of the requisite stoichiometric amount of sodium thiosulfate was placed in the amber glass sampling bottles to quench the maximum residual chlorine in tap water and surface water (0.6 mg/L Cl2) as well as in wastewater samples (1.4 mg/L Cl2). All collected samples were transferred to the laboratory in ice packs within 5 h.

Most scientific studies since the outbreak of SARS-CoV-2 have focused on the efficiency of virus elimination or deactivation. In contrast, only a few studies have evaluated the changes in the occurrence, distribution, and the potential risks of DBPs due to the elevated use of disinfectants. With the intensified disinfection efforts in the pandemic, concerns of toxic DBPs arise from the following three places. (1) In most domestic wastewater treatment plants, the disinfected wastewater effluents containing carcinogenic and mutagenic DBPs is discharged into the natural water system or reused for agricultural irrigation. Doing so poses potential ecological risks, especially when the dose of disinfectants increased during the virus pandemic. (2) The smell of chlorine disinfectant in tap water was also mentioned by residents, giving rise to concerns of the generation of toxic DBPs which are harmful to human health due to the elevated dose of disinfectants. (3) Wastewater from the widespread public disinfection steps with excessive disinfectants and generated DBPs could be discharged into the surface water through the drainage pipe network, potentially increasing the ecological risk. Therefore, an in-depth investigation of the prevalence of DBPs in wastewater, drinking water, and surface water is essential for ensuring human health and environmental safety during the SARS-CoV-2 pandemic in China.
The water samples were filtered with 0.45 μm membranes, and water quality parameters were measured. The pH was measured with a pH meter (Orion STAR A211, Thermo, USA). UV254 of the collected samples was measured using an ultraviolet spectrophotometer (UV7595, Shanghai Analytical Instrument Factory, China). The concentrations of total nitrogen (TN) and dissolved organic carbon (DOC) were measured with a portable spectrophotometer (DR2800, HACH, USA) and a TOC analyzer (TOC-L CPH, Shimadzu, Japan), respectively. The total organic chlorine, bromine, and iodine (TOCl, TOBr, and TOI) were measured by an ion chromatograph (ICS5000, Dionex, USA) after transformation into hydrogen halides by combustion (950 °C, AQF-2100H, Mitsubishi Chemical Analytech, Japan). The measured values of the TOCl, TOBr, and TOI might be affected because of the use of a thiosulfate quench causes dehalogenation of some halogenated DBPs (including HANs, HNMs, halocetaldehydes, HKs, and halo-aromatic DBPs).\[22,42-45\] Prior to pretreatment, all samples were collected in amber glass bottles and stored at 4 °C in darkness.

**Sample Pretreatment and Instrumental Analysis.** Sample pretreatment for the quantification of 9 HAAs, including monochloroacetic acid (MCAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), monobromoacetic acid (MBAA), dibromoacetic acid (DBAA), tribromoacetic acid (TBAA), bromochloroacetic acid (BCAA) bromochloroiodoacetic acid (BDCAA), and chlorodibromoacetic acid (CDBAA), were conducted following the US EPA Method 552.3. Sample pretreatments for the analysis of 35 halogenated aliphatic DBPs, including 6 THMs (chloroform (TCM), bromoform (TBM), iodoform (TIM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), dichlorodiiodomethane (DCIM), 2 HKs (1,1-dichloropropanone (1,1-DCP), 1,1,1-trichloro-2-propanone (1,1,1-TCP)), and 9 NAs (nitrosodimethylamine (NDMA), nitrosomethylamine (NMEA), nitrosodiethylamine (NDEA), nitrosopyrrolidine (NPYR), nitrosodiethylamine (DEA), nitrosodipropylamine (NMP), nitrosopropylamine (NMP)), and 9 aromatic DBPs were conducted following the US EPA Method 552.3. Sample pretreatments for the analysis of 35 halogenated aliphatic DBPs, including 6 THMs (chloroform (TCM), bromoform (TBM), iodoform (TIM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), dichlorodiiodomethane (DCIM), 2 HKs (1,1-dichloropropanone (1,1-DCP), 1,1,1-trichloro-2-propanone (1,1,1-TCP)), and 9 NAs (nitrosodimethylamine (NDMA), nitrosomethylamine (NMEA), nitrosodiethylamine (NDEA), nitrosopyrrolidine (NPYR), nitrosodiethylamine (DEA), nitrosodipropylamine (NMP), nitrosopropylamine (NMP), and nitrosodiethylamine (NDMA), nitrosomethylamine (NMEA), nitrosodiethylamine (NDEA), nitrosopyrrolidine (NPYR), nitrosodiethylamine (DEA), nitrosodipropylamine (NMP), and nitrosopropylamine (NMP).
(NDPA), nitrosopiperidine (NPIP), nitrosodibutylamine (NDBA), nitro-sodphenylenamine (NDPHA)) were conducted following the US EPA Method 551.1 and US EPA Method 521, respectively. These 26 DBPs (HAAs, THMs, HKs, and NAs) were analyzed by a gas chromatograph–triple-quadrupole mass spectrometer (GC/MS-TQ8060, Shimadzu, Japan).

Sample pretreatment for the analysis of 9 aromatic halogenated DBPs, including 2,4,6-trichlorophenol (2,4,6-TCIP), 2,4,6-tribromophenol (2,4,6-TBrP), 2,4,6-triodophenol (2,4,6-TIP), 3,5-dichloro-4-hydroxybenzaldehyde (3,5-DCl-4-HB), 3,5-dibromo-4-hydroxybenzaldehyde (3,5-DBr-4-HB), 3,5-diodo-4-hydroxybenzaldehyde (3,5-DI-4-HB), 3,5-dichlorosalicilic acid (3,5-DCl-2-HBA), 3,5-dibromosalicylic acid (3,5-DBr-2-HBA), 3,5-diodosalicylic acid (3,5-DI-2-HBA), were conducted following a modified method according to a previous study, and further details are described in Section 2 of the Supporting Information. The 9 aromatic halogenated DBPs were analyzed using a high-performance liquid chromatograph–triple quadrapole mass spectrometer (HPLC/MS-TQ8060, Shimadzu, Japan). Further instrumental analysis parameters of the GC-MS and HPLC-MS are described in Section 3 of the Supporting Information.

Ecological Risk Assessment. Domestic wastewater effluents are generally chlorinated before being discharged into natural water. Although the wastewater effluents containing amounts of toxic halogenated and nonhalogenated DBPs might cause potential ecological risks, their levels are not regulated. Therefore, it becomes necessary to assess the ecological risk of DBPs in domestic wastewater effluents, especially after an enhanced scale of disinfection witnessed in this pandemic. In this study, risk quotients (RQs) for three taxonomic groups (fish, daphnid, green algae) were used to assess the ecological risk of DBPs. The RQ values were obtained using the eqs 1 and 2 according to previous studies.

\[
\text{RQ} = \frac{\text{MEC}}{\text{PNEC}} \tag{1}
\]

\[
\text{PNEC} = \frac{\text{LC}_{50} \text{ or } \text{EC}_{50}}{\text{SF}} \tag{2}
\]

Here, MEC is the monitored environmental concentration of the individual DBP in the samples, PNEC is the predicted maximum no-effect concentration, the value of LC_{50} or EC_{50} was obtained from ECOSAR v1.11, which was developed by the US EPA Office of Chemical Safety and Pollution Prevention and intended for use in applications such as rapid screening of chemicals for ecotoxicity hazards and prioritization of chemicals, and SF is the safety factor (1000) of DBPs for the acute toxicity.

Quality Assurance/Quality Control. The DBPs were analyzed using GC-MS and HPLC-MS and quantified using internal standard methods. The calibration curves were obtained with good linear relationships (R^2 > 0.99). The limit of detection (LOD) and the limit of quantitation (LOQ) were calculated on the basis of the concentration of each analyte that produced a response 3 and 10 times the signal to noise ratio, respectively. Recoveries of the DBPs were evaluated by the analysis of water samples spiked with three different concentrations of DP standards. The values of LOD, LOQ, and recoveries of the 35 measured DBPs are given in Tables S1–S3 in the Supporting Information. A blank control sample was inserted after the analysis of every five samples to evaluate the background response of the instrument. If the response of the blank sample exceeded 5% of the test sample value, the blank value was deducted. Each sample was prepared in duplicate.

Data Analysis. All data analyses and principal component analyses (PCA) were performed by SPSS version 20.0 and Origin 9.5 software. The differences were considered statistically significant at p < 0.01.

RESULTS AND DISCUSSION

The disinfection of wastewater, drinking water, public roads, air, and vehicles was intensified during the SARS-CoV-2 pandemic in China. Unprecedented amounts of chlorine disinfectants were used to sanitize public roads and vehicles; the 84-disinfectant (available chlorine 5.5–6.5%) was used widely as an effective chlorine-based disinfectant, and it was diluted approximately 150–250 times to sanitize the public environment. As shown in Figure 1a, the total concentration of 35 DBPs in different water samples followed the order (average concentration in Beijing and Wuhan) wastewater (77.7, 78.7 μg/L) > tap water (43.4, 60.8 μg/L) > surface water (3.9, 8.8 μg/L). The levels of DBPs in water samples collected from Wuhan were higher than those in Beijing, especially in drinking water and surface water.

Occurrence of DBPs in Domestic Wastewater Effluents. Five categories of halogenated and nonhalogenated DBPs were measured in the domestic wastewater influent and effluent samples. The wastewater influent samples could not be obtained in Beijing due to stringent control measures during the SARS-CoV-2 outbreak. Figure 1b,c shows the total concentration of the 35 measured DBPs in the domestic wastewater influent and effluent samples collected from Beijing and Wuhan. The total concentrations of the 35 measured DBPs in wastewater effluent were 59.9–95.4 μg/L (average 77.7 μg/L) in Beijing and 59.7–99.0 μg/L (average 78.7 μg/L) in Wuhan. The results indicated that the total concentration of the 35 measured DBPs in the wastewater effluents of Wuhan was almost equal to that of Beijing. The total concentrations of the DBPs in wastewater influent (W3–W5) ranged from 7.7 to 12.8 μg/L (average 9.3 μg/L), which was significantly lower than that of disinfected wastewater effluent (average 78.7 μg/L, p < 0.01). Most DBPs in wastewater influent could be ascribed to the chlorinated drinking water (in large part) and flushing water in toilets.

Figure 1d–f shows the individual concentration weights of the five categories of DBPs in domestic wastewater influents and effluents in Beijing and Wuhan. The ranking order of the average concentrations and corresponding concentration weights of the DBPs in wastewater effluents in Beijing was HAAs (47.9 μg/L, 62%) > THMs (23.4 μg/L, 30%) > HKs (6.3 μg/L, 8%) > NAs (104.4 ng/L, 0.1%) > nine aromatic DBPs (23.0 ng/L, < 0.1%). The concentrations of the different DBPs in the wastewater effluents in Wuhan were in the order HAAs (39.4 μg/L, 50%) > THMs (36.7 μg/L, 47%) > HKs (2.5 μg/L, 3%) > NAs (163.4 ng/L, 0.2%) > 9 aromatic DBPs (59.9 ng/L, 0.1%). The ranking order in wastewater influents in Wuhan was HAAs (5.2 μg/L, 55%) > THMs (4.2 μg/L, 45%) > NAs (8.3 ng/L, 0.1%) > nine aromatic DBPs (7.2 ng/L, 0.1%) > HKs (ND). HAAs and THMs were the two most dominant categories of DBPs in all domestic wastewater influents and effluents among the five measured categories.
This is consistent with previous studies on DBPs in chlorinated domestic wastewater effluents.\textsuperscript{17,27}

The concentration weights of five different categories of DBPs in the collected wastewater influents and effluents are shown in Figure 2. The results reveal that TCM (15.7 μg/L, 49%), TCAA (18.5 μg/L, 43%), and 1,1,1-TCP (2.3 μg/L, 60%) were the dominant species among the three carbonaceous DBPs (THMs, HAAs, and HKs), respectively. Moreover, none of the domestic wastewater effluents exceeded the chloroform maximum guideline level (300 μg/L) by China. The two Cl-aromatic DBPs, 3,5-DCl-4-HB (20.6 ng/L) and 2,4,6-TClP (12.5 ng/L), were the dominant species among the nine aromatic halogenated DBPs, accounting for over 50%. NDEA (51.2 ng/L) and NDMA (37.5 ng/L) were the two most dominant species and accounted for 51% of the nine NAs. The highest detected concentration of NDEA instead of NDMA (detection frequency 58%), has attracted more attention in drinking water in recent years.\textsuperscript{28,49,50}

Occurrence of DBPs in Drinking Water. Total concentrations of the 35 measured DBPs in drinking water samples collected from Beijing and Wuhan are shown in Figure 3a. The total concentration of DBPs was higher in the samples collected from Wuhan (33.9−113.5 μg/L, average 57.2 μg/L) in comparison to Beijing (36.0−57.5 μg/L, average 43.4 μg/L) across all categories. As shown in Figure 3c,d, the average concentrations and the corresponding concentration weights of the five categories of DBPs in tap water samples collected from Wuhan were in the order THMs (36.8 μg/L, 64%) > HAAs (19.5 μg/L, 34%) > HKs (0.9 μg/L, 2%) > aromatic DBPs (61.3 ng/L, 0.1%) > NAs (38.2 ng/L, <0.1%). Although the average concentrations of the DBPs in tap water in Beijing were lower than those in Wuhan, the order of the DBP concentration was consistent. The higher concentrations of DBPs in Wuhan might be due to the relatively high chlorine doses during disinfection. Further, the results show that the concentration of TOCl (Table S9) in the drinking water was higher in Wuhan (average 490.9 μg/L) than in Beijing (average 255.3 μg/L) and accounted for >90% of TOX (total organic halogenated compounds), which was consistent with a high chlorine dose during disinfection. THMs and HAAs were the two most dominant categories of DBPs, with their mass concentration accounting for >95% among the five categories of DBPs. The concentration weights showed no significant difference except for minor changes, indicating that the composition of NOM in drinking water in Beijing might be similar to that in Wuhan according to their corresponding drinking water quality parameters (TOC, TN, UV\textsubscript{254}, etc.).

Individual data on the 35 measured DBPs in tap water samples are provided in the Table S7. The relative abundance of individual DBPs in the five different categories of DBPs in

### Table 1. Average Concentrations of the Five Categories of DBPs in Wastewater Effluents, Tap Water, and Surface Water

| sample          | location | THMs (μg/L) | HAAs (μg/L) | HKs (μg/L) | NAs (ng/L) | 9 aromatic DBPs (ng/L) |
|-----------------|----------|-------------|-------------|------------|------------|------------------------|
| wastewater      | Beijing  | 23.4        | 47.9        | 2.5        | 104.4      | 23.0                   |
|                 | Wuhan    | 36.7        | 39.4        | 6.3        | 163.4      | 59.9                   |
| tap water       | Beijing  | 27.9        | 13.8        | 1.6        | 34.1       | 58.6                   |
|                 | Wuhan    | 36.8        | 19.5        | 0.9        | 38.2       | 61.3                   |
| surface water   | Beijing  | 1.5         | 2.4         | 0.2        | 9.1        | 8.6                    |
|                 | Wuhan    | 1.2         | 7.6         | 0.1        | 8.4        | 18.1                   |
| wastewater      | previous study\textsuperscript{27} | 28          | 47          | 0.8        | 688        | /                      |

https://dx.doi.org/10.1021/acs.est.0c06856
Environ. Sci. Technol. XXXX, XXX, XXX−XXX
tap water samples collected in Beijing and Wuhan are shown in Figure S1. The average concentrations and concentration weights of individual DBPs in all tap water samples were in the following order. TCM (24.7 μg/L, 69%) was the dominant species among THMs, followed by DCBM (18.9 μg/L, 21%). In addition, the average concentration of TCM in Wuhan tap water was 26.7 μg/L, which showed no significant increase in comparison with the detection results from the Wuhan Municipal Health Commission before this pandemic (October 2019, 30.9 μg/L; December 2019, 20.9 μg/L; January 2020, 28.4 μg/L).53 DCAA (9.4 μg/L, 30%) and TCAA (8.6 μg/L, 28%) were the most two dominant species among HAAs. The average concentration of 1,1,1-TCP (0.6 μg/L) was slightly higher than that of 1,1-DCP (0.5 μg/L). The three Cl-aromatic DBPs, including 3,5-DCl-2-HBA (19.7 ng/L), 3,5-DCl-4-HB (17.7 ng/L), and 2,4,6-TClP (15.1 ng/L), were the dominant species among the nine aromatic halogenated DBPs and accounted for 70%, which was much higher than those of the measured Br-aromatic (27%) and I-aromatic DBPs (3%). Increasing the chlorine dose for emergency disinfection can accelerate the formation and decomposition of aromatic (non)halogenated DBPs and thus increase the formation of aliphatic DBPs, including THMs, HAAs, and other DBPs, in disinfected waters.54−57 This might account for the low detection frequencies and concentrations of the nine aromatic DBPs measured in Wuhan and Beijing. For all tap water samples, NDMA (22.9 ng/L), NMEA (13.8 ng/L), and NDEA (8.9 ng/L) were the three most dominant species and accounted for 69% among nine NAs. The average concentration of the regulated NDMA was significantly higher in the tap waters of Wuhan (27.9 ng/L) than in Beijing (10.3 ng/L, p < 0.01), which might be due to more precursors for NAs in the source water or different disinfection methods used in Wuhan drinking water treatment plants.28 Out of the most dominant categories of DBPs (THMs and HAAs) in drinking waters, four THMs (THM4, TCM, DCBM, DBCM, and TBM) and five HAAs (HAAS, MCAA, DCAA, TCAA, MBAA, and DBAA), are currently regulated by the US EPA. Maximum contaminant levels of THM4 and HAAS in μg/L and NDMA in ng/L in tap water collected from Beijing and Wuhan.

Figure 3. Column charts and pie charts of the concentrations of the measured DBPs in tap water samples collected from Beijing and Wuhan: (a) total concentration of the 35 DBPs; (b) individual concentrations of different categories of DBPs (the left Y axis presents concentrations of six THMs, nine HAAs, and two HKs at the μg/L level, and the right Y axis in red presents concentrations of the nine NAs and nine aromatic DBPs at the ng/L level); (c) concentration weights of the five categories of DBPs in Beijing tap water samples; (d) concentration weights of the five categories of DBPs in Wuhan tap water samples; (e) concentrations of the regulated THM4 and HAAS in μg/L and NDMA in ng/L in tap water collected from Beijing and Wuhan.
respectively. The maximum guideline levels of DBP in drinking water in China are TCM (60 μg/L), TBM (100 μg/L), DCBM (60 μg/L), DBCM (100 μg/L), DCAA (50 μg/L), and TCAA (100 μg/L), respectively. Out of the nine NAs, the levels of NDMA have been regulated by WHO and several countries due to its high detection frequency, teratogenicity, and carcinogenicity. The guideline levels of NDMA mandated by WHO and the state of California are 100 and 10 ng/L, respectively. In China, NDMA was first regulated in drinking water in Shanghai city at 100 ng/L in 2018. Up to now, HKs, HANs, HNMs, and other DBPs were unregulated due to their lower detection frequencies and lower concentrations, despite the fact that some of them present high toxicity. As shown in Figure 3e, the occurrence of THM4, HAAs, and NDMA was compared to the corresponding guideline values. The results indicate that THM4 and HAAs were in the ranges of 24.6–40.8 μg/L (average 33.2 μg/L) and 3.4–67.6 μg/L (average 14.1 μg/L), respectively. Moreover, none of the tap water samples exceeded the guideline level for THM4 (80 μg/L), and 6% of the samples (2 out of 35) exceeded the guideline level (60 μg/L) of HAAs. In addition, the concentrations of NDMA were in the range of 4.8–56.1 ng/L (average 22.9 ng/L) at a high detection frequency of 80% (28 out of 35). In comparison to the California notification guidance level of 10 ng/L, 46% (16 out of 35) of the tap water samples exceeded this value. None of the tap water samples exceeded the WHO guidance level of 100 ng/L. In comparison to a previous study, the average concentration (22.9 ng/L) and detection frequency (80%) of NDMA were higher in drinking water in comparison to those of NDMA detected during the absence of the SARS-CoV-2 pandemic in China (average 13 ng/L, 41%). This might be caused by an increase in the concentration of disinfectants in drinking water during the pandemic.

Occurrence of the DBPs in Surface Water. As shown in Figures 1a and 4a, in comparison to domestic wastewater and tap water, the concentrations and detection frequencies of DBPs in surface water were much lower than those in wastewater domestic and tap water (Table S8). Further, the total concentration of the 35 DBPs was higher in the surface water of Wuhan (average 8.8 μg/L) in comparison to Beijing (average 4.0 μg/L). In general, DBPs might not be detected in surface water, except some surface water was the receiving water of domestic wastewater or industrial wastewater.
In this study, most of the HAAs, THMs, NAs, and nine aromatic DBPs occurred in surface water and the concentrations of TOCl ranged from 32.3 to 304.8 μg/L (average 122.6 μg/L, Table S10). It could be inferred that the occurrence of DBPs in surface water might have been affected by disinfections during the pandemic, although the evidence is limited. DBPs in the surface water in Beijing (Wuhan) might come from the following sources. (1) Disinfected domestic wastewater effluents containing DBPs might be discharged into the surface water through the intricate water systems. (2) DBPs or residual chlorine produced by the disinfection of public roads and air might be transported into surface water through urban drainage systems or atmospheric transport. A previous study also implied that urban centers might be important sources of HAAs.59 Figure 4 b−d shows the concentration weights of individual DBPs among the measured DBPs. The results indicate that THMs and HAAs were the two most dominant categories of DBPs among the measured DBPs. The order of DBPs observed in surface water was consistent with that of disinfected domestic wastewater. TCM, DCBM, and DBCM were the dominant species among THMs. At the same time, MCAA and TCAA were the dominant species among HAAs (Figure 5e,f). In addition, the concentration weights of HAAs in surface water were higher than those in domestic wastewater and in tap water, which might be due to the following reasons. (1) In comparison with domestic wastewater and tap water, surface water is exposed to air for a long time. Most of the THMs are semivolatile compounds, especially TCM. As the most dominant DBP among THMs with a low Henry constant, it was easier for them, but not HAAs, to escape from surface water into the air. (2) Some HAAs are the degradation products of halogenated organic compounds of both natural and anthropogenic organic matters.59

Possible Relationships of DBPs among Different Aqueous Environments. The characteristics and possible relationships of DBPs in domestic wastewater effluents, tap water, and surface water samples were further investigated with principal component analysis (PCA). As shown in Figure 5a, three different types of water samples showed distinct clusters with the two principal components accounting for 79.2% variances. The disinfected water, including wastewater effluents and tap water, were completely separate from the non-disinfected surface water, suggesting that no excessive amounts of disinfectant and DBPs entered the surface water. The total DBP concentration (8.0 μg/L) in surface water was significantly different from those in wastewater (78.3 μg/L, p < 0.01) and tap water (56.0 μg/L, p < 0.01). Wastewater and tap water also were clustered in different quadrants due to their different distributions of DBPs. In addition, the PCA results of water quality parameters (Figure 5b) indicated that the surface water samples were distinctly separated from wastewater and tap water samples due to the different compositions of organic matters, especially TOC, and UV254. The wastewater and tap water samples were separated in different clusters due to the different composition
of organic matters, especially TN, TOC, and TOBr (Figure 5b). The tap water samples collected from Beijing and Wuhan were clustered in different quadrants (Figure 5c,d). This suggests that the preferred disinfection method and the dosage varied between Beijing and Wuhan. Further, the significantly different TOCl concentrations in the tap water samples of Beijing (255.3 μg/L) and Wuhan (490.9 μg/L, p < 0.01) also explain their presence in different clusters. Air disinfection was possibly responsible for the occurrence of DBPs in surface water. As shown in Figure 5d, water samples collected from different suburban and urban regions showed distinct clusters with respect to DBPs but this was not the case for water quality parameters. The total concentration of DBPs in urban surface water samples (10.4 μg/L) showed a significant difference from suburban surface water samples (5.5 μg/L, p < 0.01). This variation might be due to the following reasons. First, a higher intensity of air disinfection in urban regions resulted in a signifi-

cant increase in domestic wastewater and toxif DBPs were not available, and the values of experimentally measured LC50 (EC50) values could not be obtained, the current approach could be adopted for the estimation of ecological risk in this study. Our study highlights several DBPs with potential high ecological risks, which should be paid more attention. This study’s limited results provide a reference for a prioritized control of some potentially high risk DBPs in domestic wastewater disinfection.

Environmental Implications and Limitations

During the SARS-CoV-2 pandemic, disinfection as an effective strategy to inactivate the virus was actively performed in various settings, including households, workplaces, and public facilities. In comparison to the times before the pandemic struck, the use of the disinfectants in drinking water and domestic wastewater was also reasonably elevated to limit the spread of the infection, resulting in the possible generation of toxic DBPs. The results demonstrated that the generated DBPs showed no significant increase in domestic wastewater and drinking water disinfection during this pandemic comparison to previous studies. The detection frequency and concentrations of 35 DBPs were very low in surface water. For the regulated DBPs, none of the tap water samples exceeded the US EPA and WHO recommended maximum guideline for

There were some limitations in the ecological risk assessment of the measured DBPs in this study because the RQ was calculated by LC50 (EC50), which was an estimated value obtained from ECOSAR v1.11 and the ecological risk of each DBP was assessed independently. Since assays fully substantiating the synergistic and antagonistic effects among DBPs were not available, and the values of experimentally measured LC50 (EC50) values could not be obtained, the current approach could be adopted for the estimation of ecological risk in this study. Our study highlights several DBPs with potential high ecological risks, which should be paid more attention. This study’s limited results provide a reference for a prioritized control of some potentially high risk DBPs in domestic wastewater disinfection.

![Figure 6](https://doi.org/10.1021/acs.est.0c06856)

**Figure 6.** RQ values of the five categories of DBPs including (a) THMs and HKs, (b) HAAs, (c) NAs, and (d) nine aromatic DBPs for the three taxonomic groups in domestic wastewater effluents in Beijing and Wuhan.
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We distribute limited DBPs that were not identified. Additional information on the environment,
disinfectants and DBPs released in air, soils, and sediments were not clear, and the unknown DBPs were not volatile disinfectants and DBPs released in air, soils, and sediments were not clear, and the unknown DBPs were not identified. Additionally, the intensity and frequency of disinfection of outdoor common spaces and public transit systems increased to minimize the virus transmission, which also require consideration of the effects on the health of human skin, respiratory, and other physiological systems when humans are exposed to the volatile disinfectants and DBPs in the air.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/10.1021/acs.est.0c06856.

Additional details of chemicals and materials, instrumental parameters, and data of detected concentrations of DBPs (PDF)

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Notes

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ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (21625702), Postdoctoral Science Foundation of China (2020M680703), and Postdoctoral Science Foundation of Hangzhou, China (E0BH2B040).

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