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Comparative analysis of chlorination byproduct formation in galvanized iron and high-density polyethylene pipes using low-cost filtration techniques

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Abstract

Two prominent chlorination disinfection byproducts (DBPs)—trihalomethanes and trihaloacetic acids—are formed in drinking water when chlorine reacts with other constituents. The production of these DBPs has emerged as a significant public health concern. At the same time, disinfection of potable water remains essential as a safety measure to effectively combat waterborne diseases by eliminating pathogenic microorganisms. To regulate the formation of these two major DBPs in the water distribution network, one of the key factors is the nature of the pipe material used, along with the implementation of cost-effective abatement techniques. This study compared two types of potable water supply pipe materials—galvanized iron and high-density polythene pipes—for their role in the production of chlorine DBPs. Both materials showed different weightage ratios of DBP formation when chlorinated water came into contact with the inner surface of distribution pipes. Two filtration setups, i.e., granular activated carbon (GAC) and sand filtration media, were evaluated as abatement techniques for removing DBPs, depending on the water source and pipe material used. The findings contribute to understanding the differences in the generation of major DBP species under known supply media, as well as the removal efficiency of DBP precursors by GAC and sand filtration. Overall, the results reveal that GAC and sand filtration media can serve as low-cost and sustainable alternatives to costly, complex filtration membranes for DBP removal.

Keywords: Controlled chlorination; Chromatograms; Mass spectrometry; Granular activated carbon; Silica medium; Dissolved organic matter

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1. Introduction

In recent years, drinking water disinfection has emerged as an important public health measure, effectively preventing waterborne diseases by removing pathogenic microorganisms. With the advancement of technology, concerns over water pollution have increased significantly.[1] Chlorination is one of the most effective and low-cost methods to eliminate microorganisms and is a viable approach for suppressing microbial

activity in the water supply network.[2] A free chlorine residual of up to 0.2 mg/L is typically maintained in the distribution system, as it helps minimize the risk of further contamination. However, chlorine concentration tends to decline over time due to its dissolution behavior. These findings by Al-Jasser[3] are fully supported by the findings of Clark and Wymer;[4] however, Jahin *et al.*[5] noted that higher chlorine dosages are commonly applied worldwide to ensure effective disinfection.[3-5]

Dissolved organic matter is a complex natural component found in water, often introduced through anthropogenic activities, and is recognized as a primary contributor to the formation of chlorination disinfection byproducts (DBPs).[6] Substances such as organic impurities, ammonia compounds, and residual metallic ions (e.g., ferrous ions, magnesium) are prominent components that interact with chlorine and are consumed during the reaction.[3]

Kali *et al.*[7] found that the most prevalent DBP groups are trihalomethanes (THMs) and trihaloacetic acids (THAAs), which are formed when chloramine and chlorine react with organic and inorganic matter. In addition, Maul *et al.*[8] and Rossman *et al.*[9] observed a rapid decrease in both free and total chlorine residuals in the water distribution system (WDS) as hydraulic residence time increased. Due to limitations in chlorine persistence within the WDS, secondary chlorination is often required to maintain effective sterilization and disinfection of drinking water. However, this secondary chlorination can further react with natural organic matter (NOM) and microbial contaminants, leading to the formation of additional DBPs during water delivery.[10]

WDSs play a crucial role in the secondary formation of DBPs, potentially increasing the risk of excessive DBP accumulation during water transport.[11] The complex environment within WDS, including residual chlorine and organic matter, influences further DBP formation. A study by Charisiadis *et al.*[12] found a significant positive correlation between hydraulic residence time and THM levels in the WDS.

Different regions use varying pipe materials based on supply conditions and regulatory standards. Cast iron, the most widely used material, is prone to corrosion, releasing iron ions that accelerate DBP formation.[13] In comparison, galvanized steel pipes exhibit a higher rate of chlorine decay.[13] Hydraulic shocks in plastic pipes can lead to microplastic release, which may contribute to DBP formation, further deteriorating water quality.[14]

He *et al.*[13] reported that the rate of haloacetic acid formation among four plastic pipe materials followed the order: high-density polyethylene (HDPE) > polypropylene (PP) > polyvinyl chloride. In another study, Chen *et al.*[15] found that biofilm accumulation in pipes used for 2 years increased THM and THAA concentrations to 59.5–123 μg/L and 35.1–51.6 μg/L, respectively—significantly higher than levels in new pipes.

Volatile chlorinated hydrocarbons, which are known carcinogens, have been regulated by the United States (US) Environmental Protection Agency (EPA) at a maximum contaminant level of 0.005 mg/L.[16] Even though chlorination is the most widely used technique for disinfecting water, it has some disadvantages. Long-term exposure can lead to cancer due to the formation of DPBs, which can also negatively affect the kidney, liver, and contribute to other health issues.[17] Moreover, the factors influencing DBPs formation in WDS (e.g., pipe materials, deposits, and biofilms) are not isolated but act synergistically to promote DBP formation.[11]

Different countries report varying average concentrations of THMs, ranging from 0 to 1000 mg/L. For instance, the average THM concentrations in treated water samples in Nigeria range from 0 to 95 mg/L.[18] Similarly, up to 18 mg/L of DBPs were detected in finished water and up to 22 mg/L of DBPs in distribution systems in the US.[19] In China, the average concentrations of THMs and HAAs throughout the treatment process were 19.9 mg/L and 3.4 mg/L, respectively.[20] These data indicate that DBP concentrations in WDS are spatially variable.[21]

In the Chinese WDS, the concentration of THMs ranged from 3.67 μg/L to 30.30 μg/L, while tribromomethane concentrations were below 3.15 μg/L.[22] The average total THM concentration in China was approximately 16.6 μg/L, which is lower than that reported in the US and Saudi Arabia (33.6 μg/L).[23] HAAs in China ranged from 0.83 to 18.8 μg/L in WDS water, with dichloroacetic acid and trichloroacetic acid showing similar concentration ranges in WDS samples.[24]

In addition, Amjad *et al.*[25] found that higher levels of total THMs were reported in Islamabad compared to Rawalpindi, possibly due to Islamabad's reliance on surface water, whereas Rawalpindi residents primarily access groundwater through tube wells, open wells, or pressure pumps. This suggests that groundwater, which contains lower concentrations of NOM, may lead to reduced DBP formation. In densely populated Pakistan, with an average life expectancy of 70 years, cancer cases related to THM exposure are reportedly increasing. Karachi, the largest metropolitan city with approximately 18 million residents, is projected to have a high burden of cancer cases linked to DBP exposure.[26] However, according to Pejman *et al.*,[27] both Rawalpindi and Islamabad have still reported fewer cases than Tehran.

According to Clark *et al.*,[28] there are four main strategies for controlling DBPs and microbial contaminants in drinking water: biological filtration, conventional filtration, membrane technology, and coagulation. Chaukura *et al.*[29] further identified effective methods for DBP removal, including adsorption, air stripping, ozonation, chlorination, enhanced coagulation, membrane filtration, and advanced oxidation processes. In general, Jiang *et al.*[10] categorized DBP control into three major strategies: source control, the use of alternative disinfectants, and precursor removal. Source control includes implementing environmental management policies or replacing chlorine with alternative disinfectants such as chloramines or chlorine dioxide, although these alternatives can still pose health risks. Due to its low cost, simplicity, and minimal energy requirements, sand filtration is widely used in drinking water treatment. Similarly, ultrafiltration has been recognized as a promising technique. However, the removal efficiency of ultrafiltration depends on the membrane pore size and the characteristics of NOM.[30]

For the quantification of THMs and HAAs, Kennedy *et al.*[31] conducted a pipe setup experiment similar to that of Liao *et al.*,[32] in which a 56-day testing period was selected to investigate DBP formation under maintained booster chlorination dosages throughout the experiment. In addition, EPA[33] examined the effects of initial chlorine dosages across various pipe materials and analyzed the formation and transformation of DBPs in WDS following booster chlorination.

DBP concentrations in each sample were measured using gas chromatography-mass spectrometry equipped with an electron capture detector (GC-MS [ECD]). In this study, chlorine dosage levels were separately assessed—ranging from initial chlorination (0.43 mg/L) to booster chlorination (1.03 mg/L)—to evaluate their impact on DBP formation. GC-MS(ECD) is employed in DBP research due to its high halogen sensitivity and has been recommended by Chakraborty *et al.*[34] In comparison, Seyed Khademi *et al.*[35] utilized Raman spectroscopy to trace impurities in water, while González García *et al.*[37] used ion spectroscopy to identify dissolved ions and contaminants. Similarly, González García *et al.*[37] explored the variation of HAAs in a laboratory-scale distribution system consisting of four independent pipe loops made of HDPE, polyvinyl chloride, PP, and galvanized steel.

Although the generation of these prominent harmful chlorine DBPs in the water supply has been characterized and quantified based on the nature of the pipe material, there remains a need for cost-effective techniques suited to the specific pipe medium used. Some techniques discussed in Chaukura *et al.*[29] such as adsorption, air stripping, ozonation followed by enhanced coagulation, and membrane technology, are well-known but cannot be considered as cost-effective or sustainable when compared to sand filtration media, granular activated carbon (GAC), or even the adsorbing filter made from banana peels studied in Jahin *et al.*[5] Moreover, multiple studies have shown that sand filtration and GAC play a significant role in the removal of NOM, a known precursor of DBPs.[6] Specifically, carbon-based adsorbents have been shown to significantly reduce emerging contaminants in water.[38] To the best of our knowledge, no comparative study has examined the formation and removal of major DBPs in relation to the cost-effective treatment of water distributed through galvanized iron (GI) and HDPE pipes.

This study was conducted in District Mardan (geographic coordinates: 34°05'N–34°32'N and 71°48'E–72°25'E), one of the central districts of Khyber Pakhtunkhwa (KP) Province, Pakistan. The study area was divided into three zones based on groundwater hydrology: an urbanized/industrial zone (Shergarh and Takhtbhai) and a non-industrial (control) zone (Surkhabi), referred to as Zone 1, Zone 2, and Zone 3, respectively, as shown in Figure 1. The industrial zones are characterized by activities such as manufacturing, car washes, markets, and other commercial processes, while the non-industrial zone involves anthropogenic activities unrelated to industrial production.

A total of 10 water samples were collected across the three zones for the identification and quantification of DBPs. Of these, six samples (three for each pipe type under non-filtration conditions) and four samples (two for each pipe type under filtration conditions) were analyzed. Each sample was tested under controlled chlorine dosages.

A prototype laboratory-scale experimental setup was constructed to replicate a municipal WDS, simulating water flow through GI and HDPE pipes under controlled conditions. Water samples were analyzed both without filtration and with filtration, using abatement techniques such as sand filtration media and a combined sand-GAC

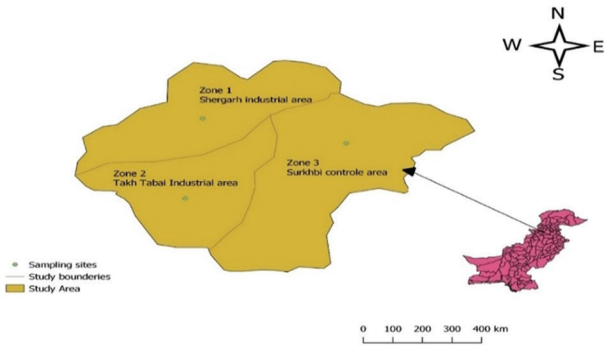

Figure 1. Study area division

filtration system in a rapid, small-scale column test. The two main chlorination DBPs—THMs and THAAs—were quantified using GC-MS (ECD), both with and without the application of filtration media.

2. Materials and methods

2.1. Chemicals and reagents

Granular chlorine powder (calcium hypochlorite) was obtained from the Water Quality Laboratory, Public Health Engineering Department, KP, Pakistan. Two DBP standard compounds—chloroform and THAAs—were purchased from certified chemical suppliers in Pakistan. The solvent for liquid-liquid extraction (LLE), ethyl acetate, was also obtained from the Public Health Engineering Department, KP, Pakistan, and was used to separate solutes from water samples. Distilled water used throughout the study was obtained from the Water Quality Laboratory, Public Health Engineering Department, KP, Pakistan. Fluorescence spectrometry was performed at the Central Resource Laboratory, University of Peshawar, KP, Pakistan.

2.2. Sampling site

In this study, multi-stage random sampling was employed to ensure systematic and representative sampling across all three zones of District Mardan. Primary sampling units were selected in each zone—two in industrial zones and one in the controlled (non-industrial) zone—to identify and quantify the formation of chlorination DBPs. In contrast, secondary sampling units consisted of two samples—one from the industrial zone and one from the controlled or non-industrial zone—which were used for the assessment of DBP abatement techniques through both quantitative and qualitative analysis.

In all three zones, groundwater was the selected source, and elevated head tanks or overhead reservoirs were utilized to provide head elevation and facilitate water distribution to consumers. Tubewells served as the intake source at each site. The groundwater potential for most sources was between 90 m and 120 m, with a static water level ranging from 18 to 30 m. The average yield per tubewell was 6–8 m, and the discharge rate varied between 0.00315 m^3/s and 0.00526 m^3/s. For consistency in sample analysis, only water from tubewells older than 10 years, connected to a minimum 5 km distribution network, was selected. All samples were collected at terminal (end-user) points of the distribution system.

Before analysis with GC-MS (ECD), key water quality parameters influencing DBP formation were measured. These included pH (using a pH meter), dissolved oxygen (DO) (using a DO meter), turbidity (using a nephelometer), taste (evaluated by taste test), dissolved organic matter (DOM) (using fluorescence spectrometry), temperature (measured with a thermometer), and water hardness (determined using the titration method), as shown in Table 1.

2.3. Setup

For all sampling procedures, appropriate glassware was used throughout the entire analysis. Sampling containers were thoroughly washed with detergent, rinsed with tap water, followed by ultrapure water, and then dried in an oven at 150°C for 1–2 h. Samples were collected in 100 mL amber glass bottles with PP screw caps and tetrafluoroethylene-lined septa. Bottles were carefully filled to avoid the presence of air bubbles.

In addition, a laboratory-scale pilot WDS was constructed to evaluate the effects of different chlorine dosages. It consisted of pipe loops made of GI and HDPE, as shown in Figure 2. Each loop measured approximately 1.5–3 m in length, with a pipe diameter of 25 mm. The loops were equipped with ball valves, elbows, unions, and sockets to monitor water flow behavior, as well as control pressure and velocity. They were also used to direct water flow in the desired direction. Flow velocity was maintained between 0.2 m/s and 1.8 m/s. A 0.3 HP centrifugal pump (Model QB60, Taifu, Pakistan) was installed to ensure continuous water circulation.

In the distribution network, a 0.189 m^3 (50-gallon) water reservoir was used to receive water samples directly from the field site. Special attention was given to collecting grab samples from different zones while monitoring temperature and sunlight exposure using the mobile water quality testing laboratory of the Public Health Engineering Department, KP. Before introducing water samples into the pilot-scale laboratory distribution system, the system was rinsed with ultrapure water for 30 min to remove any residual contaminants.

The methodology for operating the laboratory distribution system consisted of four main steps: flushing,

Table 1. Summary of water sample characteristics and their observed ranges

Parameters	Range
pH	7.2–7.8
Dissolved oxygen	5–5.7 mg/L
Turbidity	1–3 NTU
Taste	Fair
Temperature	30–38°C
Hardness	Soft water
Dissolved organic matter	1.8–2.2 mg/L

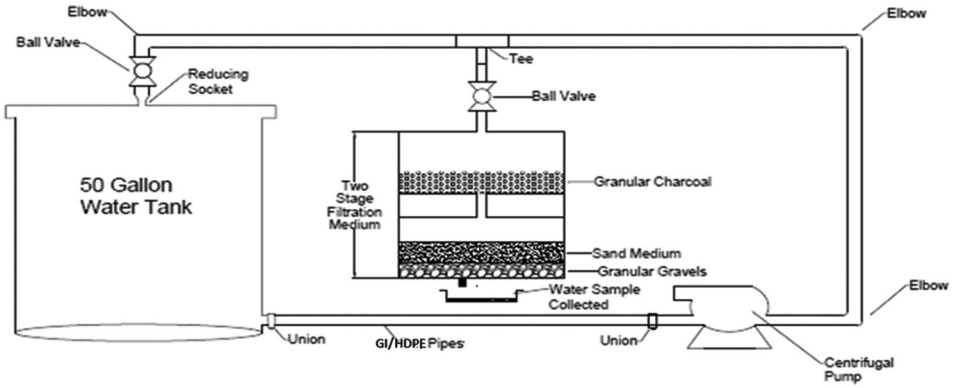

Figure 2. Schematic diagram of the laboratory-scale experimental water distribution setup
Abbreviations: GI: Galvanized iron; HDPE: High-density polyethylene.

parameter adjustment, chlorine dosage application, and sampling. After flushing with ultrapure water, samples were added to the 0.189 m^3 (50-gallon) reservoir and suctioned into the system using a centrifugal pump. The flow and velocity within each loop were maintained uniform and uninterrupted, ensuring homogenous mixing of particles upon chlorine addition. Chlorine dosages of 0.2 mg/L, 1.8 mg/L, and 2.4 mg/L were then introduced sequentially into the system—0.2 mg/L for Zone 1, 1.8 mg/L for Zone 2, and 2.4 mg/L for Zone 3. THMs and THAAs were subsequently identified and quantified at each dosage level.

2.4. Abatement techniques

For the abatement technique, two filtration media—GAC and sand filtration—were introduced as rapid, small-scale column tests, controlled by a ball valve installed between the distribution network sections under a fixed chlorine dosage of 2.4 mg/L. This ball valve diverted water flow toward the filtration media while isolating the reservoir line. The small-scale column test setup was designed to simulate pilot- or full-scale fixed-bed GAC and sand filters.

The rapid column test was conducted to evaluate the adsorption efficiency of GAC and the filtration capacity of sand media. The carbon fraction used had a particle size of 170–230 mesh (mean diameter: 76 μm), and it was washed with ultrapure water and dried overnight. The dried carbon was then stored in a desiccator before use. The GAC column was packed with the prepared GAC particles. The minimum velocity was calculated using the Reynolds number (Re_min), and according to the US EPA/ Chromium Manual, the recommended range to maintain laminar flow is Re = 0.5–1.0.[39]

The physical characteristics of GAC were determined according to the American Society for Testing and Materials (ASTM) standard test methods, including: moisture content (ASTM D2867), ash content (ASTM D2866), iodine number (ASTM D4607), bulk density (ASTM D2854), hardness number (ASTM D3802), and uniformity coefficient (ASTM D2862).

For the sand filtration media, a column-shaped setup was used, comprising a 1000 mm quartz sand layer, operated in downflow mode at a specified filtration rate. The bed depth of the sand filter column was 700 mm, filled with silica sand of 0.7 mm particle size and a uniformity coefficient of 1.4. The granular filter column operated at a filtration rate of 4.6 m/h under a rising head.

Before determining the formed DBPs, EPA Method 551.1[34] was slightly modified by replacing the original LLE solvent—methyl tert-butyl ether—with ethyl acetate, due to environmental concerns outlined in.[34] The negative environmental impact of methyl tert-butyl ether, particularly in drinking water contamination, has been well documented.[40] The LLE separation process was conducted after the samples had completed the distribution phase in the laboratory-scale water distribution model. A separatory funnel was used, and a 1:2 solute-to-solvent ratio was maintained. In this case, the solutes were THMs and THAAs, and the solvent was ethyl acetate. The extraction began by partially combining the solute and solvent, followed by vigorous shaking for 5 min. Then, an additional 10 mL of solvent was added, and the mixture was again shaken for 5 min. This process was repeated 5 times, resulting in the extraction of a 100 mL sample using 50 mL of solvent, with 5-min shaking intervals after each addition. After extraction, the separatory funnel formed two distinct layers. The water layer was removed using a funnel dropper, leaving behind the solvent layer containing the extracted compounds.

To determine THMs and THAAs, as recommended by EPA Method 555.1,[34] GC-MS (ECD) analysis was conducted using a GCMS-5977B system (Agilent

Technologies, United States of America). A fused silica capillary DB-1 column (30 m × 0.32 mm inner diameter × 0.25 μm film thickness) was used. Helium (99.99% purity) served as the carrier gas, and nitrogen (99.99%) was used as the makeup gas. The analytical operating conditions are summarized in Table S1.

Standard internal peak areas were used to prepare the calibration standards. A linear regression equation was applied to generate the calibration curve and calculate the concentration in the extract ($C_{extract}$), as shown in Equation II. After obtaining $C_{extract}$, the concentration in the water sample (C_{water}) was determined using Equation III, based on the sample and extract volumes. Finally, both values were inserted into Equation I to calculate the total concentration of chlorine DBPs, with full equation details provided in the Supplementary File.

$$\text{TTHMs} + \text{THAAs} = \text{Prominent chlorine DBPs} \quad \text{(I)}$$

$$C_{extract} = \frac{\text{Measured peak area}}{\text{Peak area of internal standard}} \times (m + b) \quad \text{(II)}$$

$$C_{water} = \frac{C_{extract} \times V_{extract}}{V_{water}} \quad \text{(III)}$$

3. Results and discussion

3.1. Fraction of DBPs in selected zones under controlled dosages

To assess the occurrence of chlorine DBPs, EPA[33] conducted a sequence-wise batch chlorination of the water distribution network model and observed the corresponding variations in DBP formation at different controlled chlorine dosages.

In this study, the fractions of DBPs detected in water samples from Zone 1, Zone 2, and Zone 3 varied. Key psychochemical characteristics contributing to DBP formation were identified for each sample. The analysis was carried out in phases, beginning with a dosage of 0.2 mg/L, followed by 1.8 mg/L, and finally 2.4 mg/L, applied to both pipe materials.

At the initial chlorine dosage of 0.2 mg/L, the results (Figure S1) show no detectable levels of THMs and THAAs in the chromatograms for both pipe types (Figure S2). Other chlorine-related compounds with chromatographic retention are identified and listed in Table S2. The absence of THMs and THAAs may be attributed to the very low residual chlorine concentration, which is likely insufficient to initiate significant DBP formation.

A chlorine dosage of 1.8 mg/L was applied to the Zone 2 water sample to evaluate the formation of THMs and THAAs in water samples passed through GI and HDPE pipes. Key water quality parameters—including pH, DO, turbidity, taste, temperature, hardness, and DOM—were measured before GC-MS (ECD) analysis, as shown in Figure S3. GC-MS analysis of the GI pipe water sample initially detected 11 compounds, as summarized in Table S3. Among the target DBPs, trichloromethane was identified at a retention time of 1.532 min, corresponding to peak number 4, with a molecular weight of 119 g/mol and a mass spectrometry signal area of 3,029,057, as shown in Figures 3 and S4.

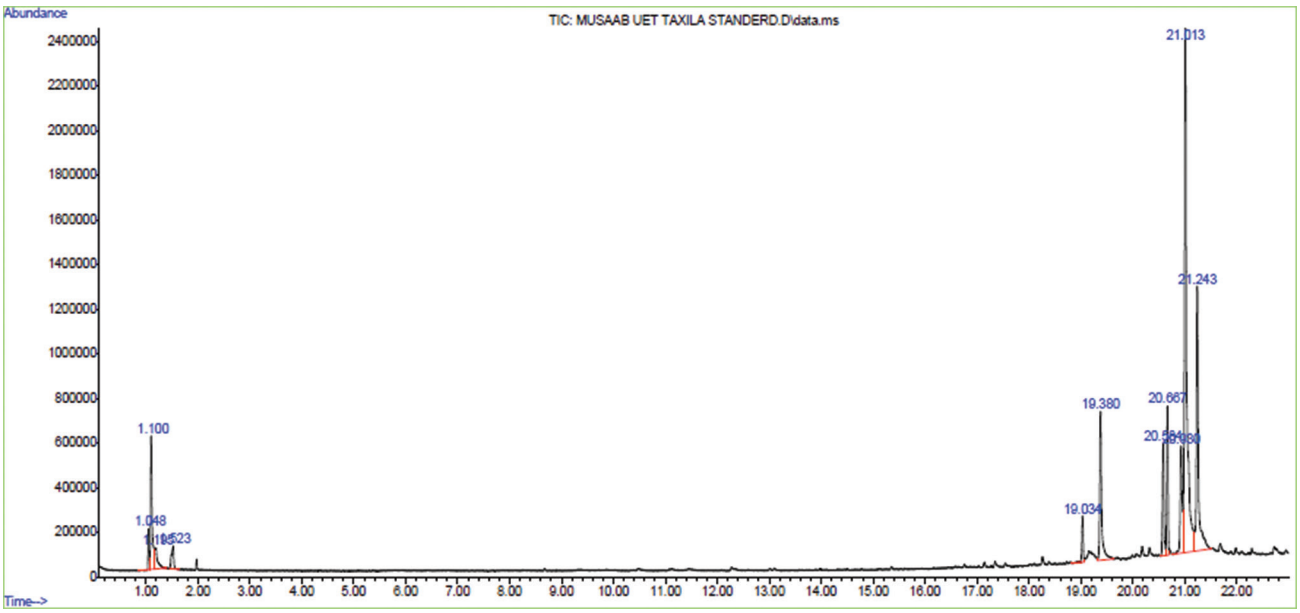

Figure 3. Chromatogram of the galvanized iron pipe water sample treated with a 1.8 mg/L chlorine dosage

Since gas chromatography separates compounds based on their volatility, trichloromethane—a small and volatile molecule—was eluted earlier than larger, less volatile compounds such as fatty acids (e.g., hexadecenoic acid and oleic acid), which exhibited longer retention times due to stronger interaction with the stationary phase. In addition, due to the use of an ECD, the system displayed higher sensitivity to halogenated compounds, while non-halogenated compounds generated weaker signals.

After analyzing the GI pipe water sample, the HDPE pipe water sample was examined using GC-MS (ECD) over an 8–9-h run time. However, no halogenated chlorine DBPs or related compounds were detected. The absence of THMs and THAAs in the HDPE water sample from Zone 2 suggests a lower production rate of chlorine DBPs, likely due to reduced interactions between the HDPE pipe surface and the water, even in the presence of organic matter. Furthermore, the non-identification of DBPs in HDPE water samples may be attributed to the shorter contact time and the inert, smooth surface of HDPE, which minimizes chlorine reactions with pipe material and precursors. This observation supports the hypothesis that HDPE pipe material results in lower DBP formation compared to GI pipes.

Secondary chlorination can further react with NOM and residual microorganisms to form additional DBPs during water distribution.[10] Therefore, for this phase of secondary chlorination, the chlorine dosage was increased to 2.4 mg/L. Water samples from both GI and HDPE pipes in Zone 3 were analyzed under this dosage, with the corresponding water quality parameters presented in Figure S5.

The GI pipe water sample was evaluated using GC-MS (ECD). Both targeted halogenated DBP families—THAAs and THMs—were detected, with peak number 2 appearing at a retention time of 4.452 min, as shown in Figure 4, and corresponding mass spectra provided in Figure S6. In addition to these target DBPs, other compounds with their respective retention times are listed in Table S4.

For the HDPE pipe water sample, both DBPs—THAAs and THMs—were detected at peak number 2, with a retention time of 4.340 min, as illustrated in Figure 5, and the corresponding mass spectrum is shown in Figure S7. The detection of these DBPs in the HPDE water sample underscores the material's potential role as a source or mediator in DBP formation within the WDS. Additional detected compounds and their retention times are summarized in Table S5.

However, for the GI pipe water sample, it was found that under a chlorine dosage of 2.4 mg/L, approximately 0.212 mg/L of THAAs and 0.199 mg/L of THMs were detected after running under controlled conditions. Moreover, under a chlorine dosage of 1.8 mg/L chlorine in the same GI pipe, approximately 0.193 mg/L of THMs were detected. Similarly, for the HDPE pipe under a chlorine dosage of 2.4 mg/L, approximately 0.2 mg/L of THAAs and 0.167 mg/L of THMs were detected, as shown in Figure 6.

According to a previous study by Chen *et al.*,[15] biofilms in 2-year-old pipes increased the concentration of THMs

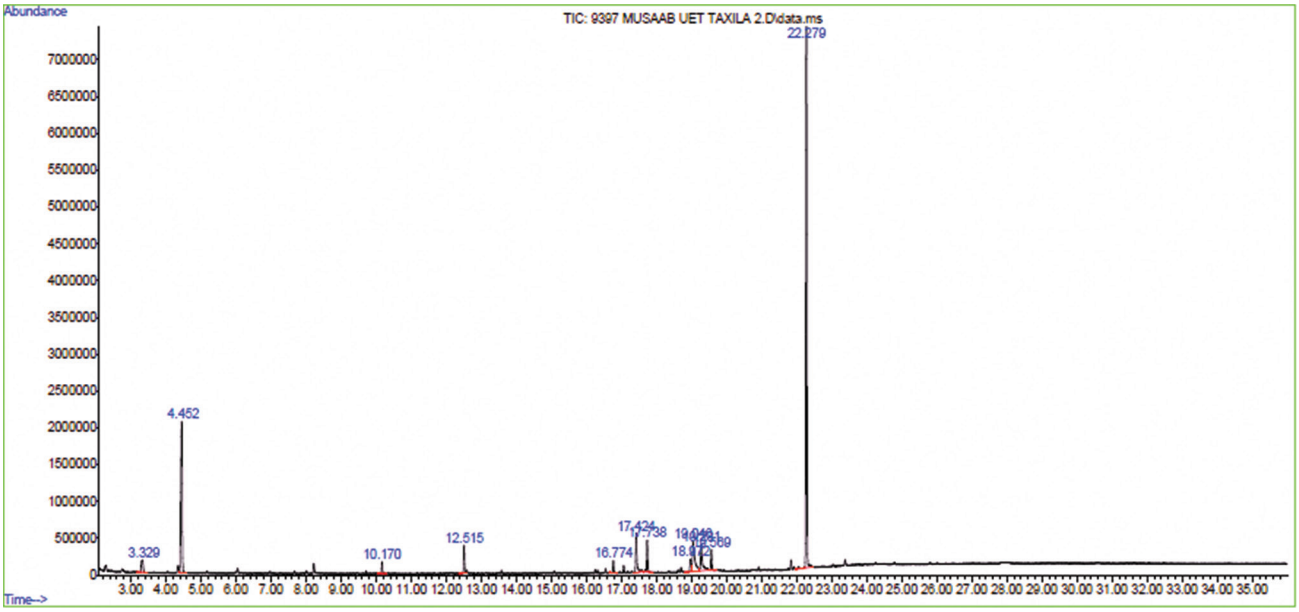

Figure 4. Chromatogram of the galvanized iron pipe water sample treated with a 2.4 mg/L chlorine dosage

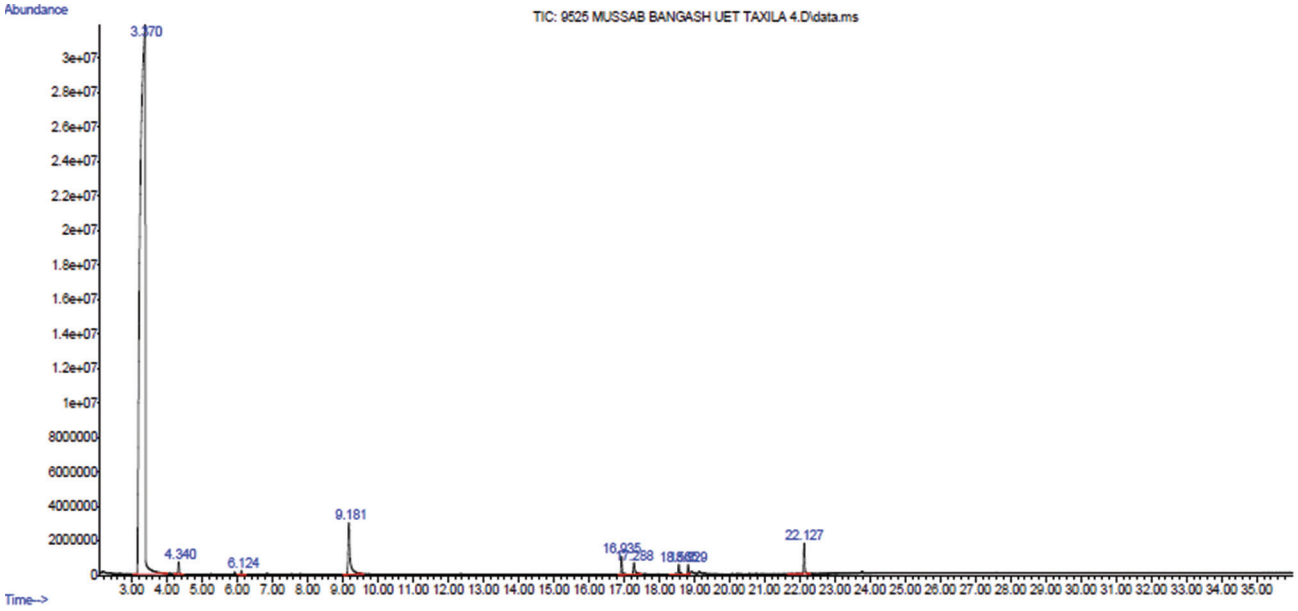

Figure 5. Chromatogram of the high-density polyethylene pipe water sample treated with a 2.4 mg/L chlorine dosage

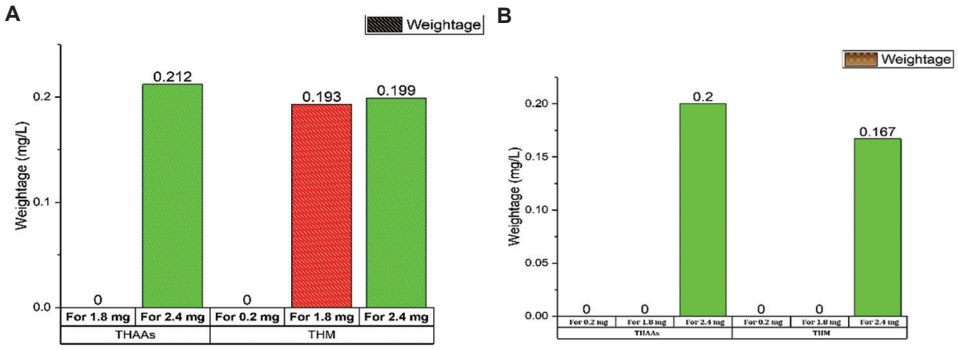

Figure 6. Concentration of chlorination byproducts in water samples passed through two pipe materials under varying chlorine dosages: (A) Galvanized iron; (B) High-density polyethylene
Abbreviations: THAA: Trihaloacetic acid; THM: Trihalomethane.

and THAAs to 59.5–123 µg/L and 35.1–51.6 µg/L, respectively. These values are significantly lower than the concentrations found in this study, where 0.212 mg/L of THAAs and 0.199 mg/L of THMs were detected in GI pipes and 0.2 mg/L of THAAs and 0.167 mg/L of THMs in HDPE pipes.

In addition, mean concentrations of THMs vary significantly across countries. For instance, in Nigeria, the mean concentrations of THMs range from 0 to 1000 mg/L, with treated water samples containing 0 to 95 mg/L.[18] In the US, up to 18 mg/L of DBPs have been detected in finished water and up to 22 mg/L of DBPs in distribution systems.[19] In China, the average concentrations of THMs and HAAs throughout the treatment period were 19.9 mg/L and 3.4 mg/L, respectively.[20]

3.2. Filtration media

In a study by Yu *et al.*,[40] prominent DBPs were partially removed through the use of cost-effective sand filtration media and a GAC filter. A composite filtration setup was developed, consisting of a top sand layer, a GAC layer beneath it, and a bottom layer of fine sand mixed with angular gravel. The gravel size ranged from 2 to 4 mm, designed to assess water quality as it passed through the medium.

To evaluate the effectiveness of the filtration media in removing chlorine DBPs, two separate filtration setups were investigated: the first setup consisting of sand media, and the second setup using GAC—recognized as one of the most versatile and widely used adsorbents for water purification.[41]

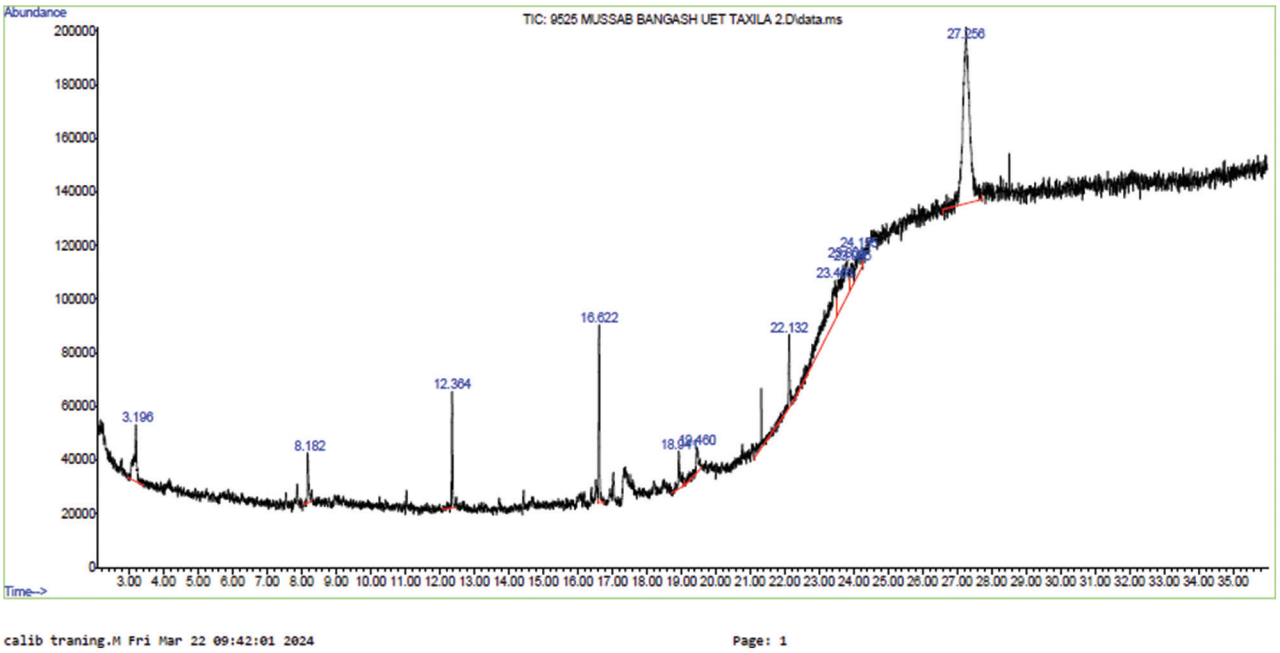

Figure 7. Chromatogram of the galvanized iron pipe water sample after treatment with the first filtration media setup

Sand filtration media have been shown to be effective in removing turbidity and suspended particles when properly applied. In this study, the GI pipe-passed water sample, treated with sand filtration and subsequently analyzed using GC-MS after the application of a 2.4 mg/L chlorine dosage, shows a notable reduction in THMs in the resulting chromatogram. However, THAAs are still detected at a retention time of 3.196 min, identified at peak number 1 with an area of 1,115,036. The corresponding mass spectrum indicates a molecular mass of 165 g/mol, as shown in Figure 7, with the three best-hit mass spectra illustrated in Figure S8. Other non-DBP elements and their retention times are summarized in Table S6.

The absence of THMs and the presence of THAAs demonstrate the partial effectiveness of the sand filtration media setup in removing chlorine DBPs, as shown in Figure 8. This indicates that THM removal can be achieved by controlling the sources of DBP formation—particularly by reducing suspended and dissolved particles and retaining organic matter in water, which is considered a key precursor to chlorine DBPs. However, the presence of THAAs in the mass spectra challenges the full effectiveness of the first filtration media setup.

The second filtration media setup (GAC) was analyzed using GC-MS (ECD) under controlled conditions. For the GI pipe water sample treated with the GAC setup and exposed to the controlled chlorine dosage, the performance was evaluated using chromatograms and

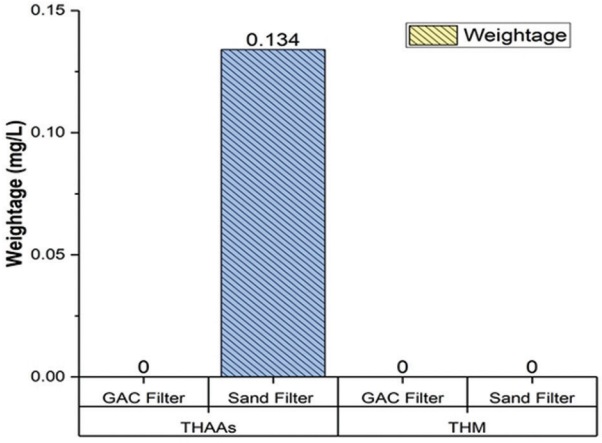

Figure 8. Concentration of chlorination disinfection byproducts in the galvanized iron pipe water samples after treatment with the first and second filtration media setups
Abbreviations: GAC: Granular activated carbon; THAA: Trihaloacetic acid; THM: Trihalomethane.

mass spectra. The resulting chromatograms did not show any detectable presence of the target DBPs (THMs or THAAs), nor any related halogenated compounds, as shown in Table S7. This demonstrates the strong removal capacity of the second filtration setup.

Based on the results, the first filtration setup (sand media) reduced THAAs in the GI pipe water sample from 0.212 mg/L to 0.134 mg/L, indicating a removal efficiency of 36.8%. It also reduced THMs from 0.193 mg/L and

0.199 mg/L to negligible levels, indicating an approximate removal efficiency of 99%. The second filtration setup (GAC media) achieved an estimated 99% removal of both THMs and THAAs, thereby demonstrating its superior performance.

In the HDPE pipe, water samples from Zone 3 were analyzed after passing through both the first (sand media) and second (GAC media) filtration setups. Based on the obtained chromatograms, no prominent chlorine DBPs—or related halogenated compounds—were detected. The absence of THMs and THAAs after filtration demonstrates the combined effectiveness of the pipe material and the filtration media in reducing precursors, including dissolved and suspended organic particles. This highlights adsorption-based filtration as a cost-effective abatement strategy. Both filtration setups successfully reduced the initially identified 0.2 mg/L of THAAs to negligible levels, indicating a high removal capacity for the HDPE pipe system. The reduction in dissolved organic carbon content following filtration is illustrated by the fluorescence spectra in Figure 9.

3.3. Comparison

From a comparative perspective on the formation of DBPs in water samples passed through GI and HDPE pipes, it was observed that in the GI pipe water samples, approximately 0.212 mg/L of THAAs and 0.199 mg/L of THMs were detected under a chlorine dosage of 2.4 mg/L, while approximately 0.193 mg/L of THMs were detected under a chlorine dosage of 1.8 mg/L in a controlled environment.

Similarly, in the HDPE pipe water sample, under a chlorine dosage of 2.4 mg/L, approximately 0.2 mg/L of THAAs and 0.167 mg/L of THMs were detected. These results indicate that lower chlorine dosages resulted in lower concentrations of chlorine DBPs. With a 33% increase in chlorine dosage, THAAs in the GI pipe water sample increased to 0.212 mg/L, and THMs increased by 3.11%, while a comparable trend was observed in the HDPE pipe water samples. This pattern supports the hypothesis that an increased chlorine dosage enhances reactions with NOM in the water and that longer contact time promotes the formation of DBPs.

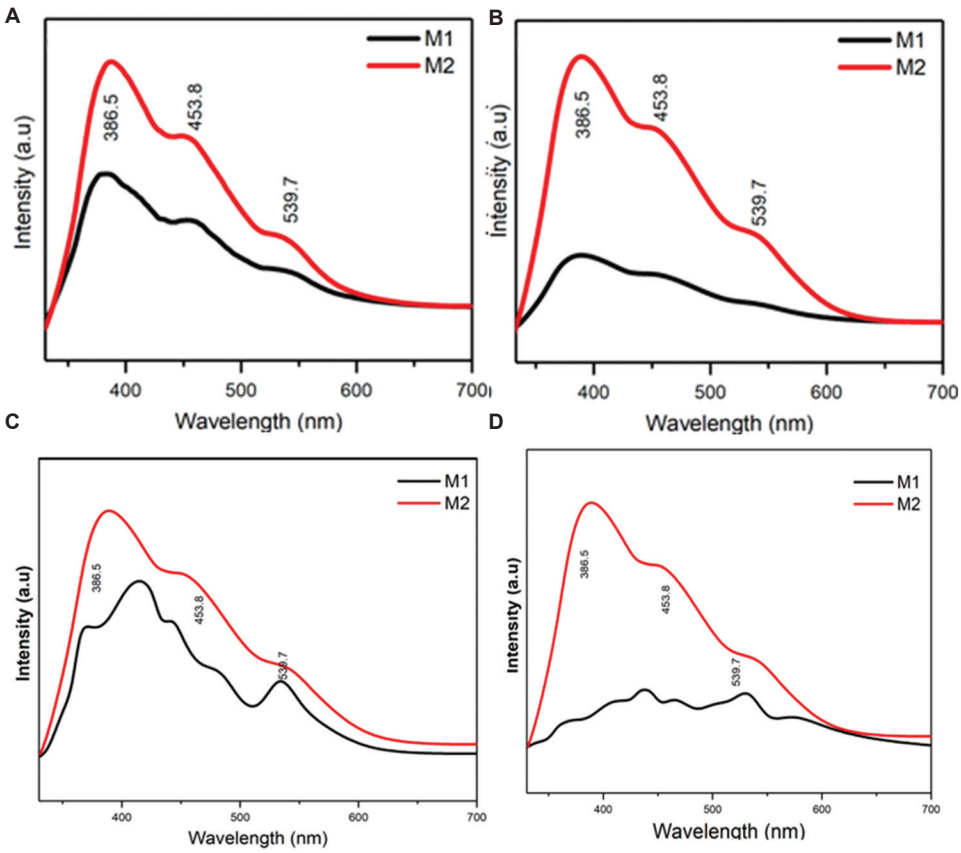

Figure 9. Fluorescence spectra of dissolved organic matter in water samples before (M2) and after (M1) filtration: (A) High-density polyethylene pipe—first filtration medium; (B) High-density polyethylene pipe—second filtration medium; (C) Galvanized iron pipe—first filtration medium; (D) Galvanized iron pipe—second filtration medium

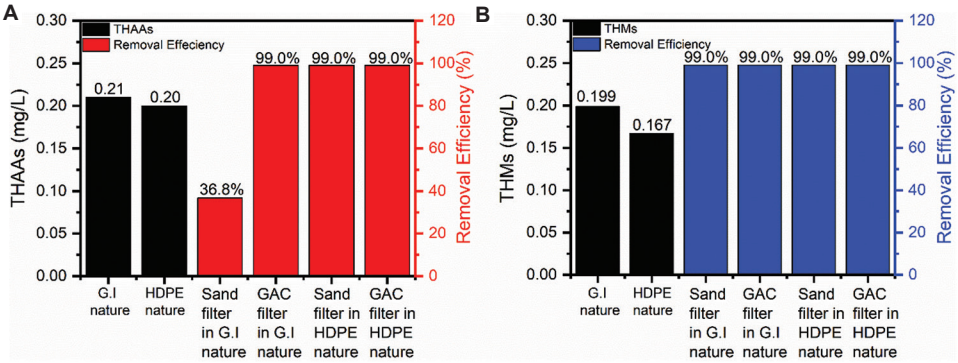

Figure 10. Comparison of detected chlorination disinfection byproducts in water samples and their removal efficiency by filtration setups
Abbreviations: GAC: Granular activated carbon; GI: Galvanized iron; HDPE: High-density polyethylene; THAA: Trihaloacetic acids; THM: Trihalomethane.

Moreover, it was observed that the second filtration media setup was more efficient than the first filtration media setup, particularly in the case of the GI pipe. In the GI pipe water sample, the first filtration media setup removed approximately 36.8% of THAAs and 99% of THMs. In contrast, for the HDPE pipe, both filtration setups were effective in removing approximately 99% of chlorine DBPs, due to the lower formation rate of chlorine DBPs. This shows that both filtration setups are effective in reducing DBPs, although their efficiency may vary depending on pipe material.

However, due to its non-absorptive nature, the second filtration media setup may not retain chemical contaminants through absorption, including DBPs. Instead, it is specifically designed for the adsorption of organic compounds, featuring a GAC layer positioned beneath a sand layer and above a gravel pack, and operates through a multi-stage process. Initially, suspended particles, particularly organic matter, are removed by the sand layer. The water then penetrates the fine GAC medium, where adsorption of DBPs occurs. Finally, the gravel layer provides additional filtration and helps stabilize the water's physical properties. This setup effectively removes THMs and THAAs under controlled conditions, as shown in Figure 10.

4. Conclusion

The following conclusions were drawn from the investigation of the water samples:

(i) The formation of chlorine DBPs—particularly THMs and THAAs—increased with higher chlorine dosages under controlled conditions for both pipe materials
(ii) The material properties of GI pipes—such as their tendency to corrode, release metal ions, and trap organic matter—contribute more significantly to the formation of chlorine DBPs compared to HDPE pipes
(iii) Sand filtration is a cost-effective method for reducing chlorine DBPs; however, it is insufficient on its own to achieve the desired DBP removal due to its limited effect on DOM. In contrast, the GAC filter—due to its high adsorptive capacity—can be considered a more effective and feasible option for removing chlorine DBPs under controlled chlorination. This highlights the superior performance of adsorption-based over absorption-based filtration techniques
(iv) Optimizing chlorine dosage in the water supply can help balance effective disinfection while minimizing DBP formation.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data supporting the study's findings are available from the corresponding author upon request.

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