Water SA 51(1) 11–17 / Jan 2025
https://doi.org/10.17159/wsa/2025.v51.i1.4136

Research paper

Occurrence of volatile organic contaminants in tap water due to the use of plastic plumbing pipes

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In the present era, polymeric pipes have emerged as the replacement for metallic alternatives in constructing water distribution networks within cities or homes, due to their notable flexibility and durability. Nevertheless, there have been increased concerns over the safety of consuming water that has come into contact with polymeric materials. This issue arises from the possible leaching of organic contaminants, either due to plastic deterioration or from biofilms that typically develop within polymeric pipes. These biofilms may act as a source of disinfection byproducts during water and/or system disinfection. The objective of the study was to investigate the presence of volatile organic compounds (VOCs) that could migrate from plastic plumbing pipes into tap water. For this purpose, 50 tap water samples from different houses within the Al-Madinah Al-Munawwarah residential area (Saudi Arabia) were collected and analysed for the occurrence of VOCs; trichloromethane (1,1,1-TCA), dichloropropane (1,2-DCP), 1,2,3-trichloropropane (1,2,3-TCP) benzyl chloride (BC) 2-nitropropane (2-NP) 2,4-dichlorophenol (2,4-DCP), 4-ethylphenol (4-EP), benzene and 2-butanone using CG-MS. The most prevalent compounds were benzene, 2-butanone, 1,1,1-TCA, 1,2-DCP, BC, and 1,2,3-TCP. These were identified in 78%, 76%, 68%, 58%, 50%, and 42% of the samples assessed, respectively. The levels of 1,2,3-TCP, benzene, 2,4-DCP and BC exceeded the allowable limit in 43%, 10%, 8% and 6% of the samples, respectively. The remaining VOCs were within the WHO standards. The analysis of water source samples revealed the presence of BC, 1,2-DCP, and 4-EP in 40%, 40%, and 30% of samples, respectively, with no other VOCs detected. This suggests that these contaminants primarily originate from polymeric pipes used in household plumbing systems.

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DATES
Received: 23 March 2024
Accepted: 8 January 2025

KEYWORDS
volatile organic compounds
plastic pipes
drinking water
Al-Madinah Al-Munawwarah

INTRODUCTION

Plastic is considered the material of this century (Volova, 2004) and has had a significant influence on many aspects of modern civilization since its emergence in the late 1940s. After the Bronze and Iron Ages, it is conceivable to classify our current time as the Plastic Age (Kramm and Völker, 2023). Plastic materials have substituted numerous substances such as cotton, wool, and metals. The increased applications of plastic pipes in the construction of residential water networks and public water supply systems has led to their replacing their metal plumbing counterparts (Lewandowski, 2015; Pajaro-Castro et al., 2014). Nowadays, more than 54% of pipes installed worldwide are made of polymers. Polyvinyl chloride (PVC) is the most widespread brand of pipe, accounting for 62% of total use, while polyethylene (PE) in its various forms comprises 33.5% (Dietrich, 2020). Polymeric pipes are preferred in plumbing works due to their inherent characteristics, such as their lightweight nature, ability to withstand physical stress, resistance to friction and chemicals, high durability, ease of connection, and chemical specifications that make them less prone to erosion or sensitive to other environmental factors (Zhang and Liu, 2014). Aside from their cost-effectiveness, simple installation, and potential to withstand temperature fluctuations, plastic pipes are very useful in infrastructure projects in seismically vulnerable areas due to their inherent capacity for self-welding at contact points, which prevents leakage or disintegration (Chasis, 2014).

The extensive use of plastic pipes in plumbing applications has raised considerable health concerns (De Villiers et al., 2011). Early assessment studies had solely focused on the association between polymeric pipes and the perception of water odour and taste. Nevertheless, numerous recent studies have indicated that plastic pipes could be a possible source of many unfavourable organic pollutants, including chemicals (Skjevrak, 2003; Durand and Dietrich, 2007; Lund et al., 2011; Ryssel et al., 2015; Zhang and Liu, 2014; Chong et al., 2019) and microplastics (Tong et al., 2020; Swanepoel et al., 2023; Yang et al., 2024), which are susceptible to leaching/infiltration into tap water. Many monomers, antioxidants, catalysts, colourants, solvents, fillers, lubricants, and other additives used in pipe processing are suspected to leave behind organic compounds that are released into water. The contaminants can migrate from polymeric pipes into water indirectly. This occurs either through the breakdown of additives used in pipe production or as byproducts generated from reactions involving certain compounds or organisms present in the water. These contaminants diffuse directly into the water from the chemical components of the pipe materials (Zhang and Liu, 2014).

The leachable volatile organic compounds (VOCs) from high-density polyethylene (HDPE) pipes include 2,4-di-tert-butyl-phenol (2,4-DTBP); a known degradation product of antioxidant agents like Irgafos 168 (a hydrolytically stable phosphite compound commonly used to prevent polymer deterioration). Other leachable VOCs include aromatic hydrocarbons, a range of esters, aldehydes,

terpenoids, and ketones (Skjevrak et al., 2003), as well as fragments from vinyl chloride (Durand et al., 2005). It has been suggested that the leaching and migration of organic compounds from unplasticized polyvinyl chloride (uPVC) pipes are exacerbated by biofilm formation, which creates an optimal environment for microbial metabolic activities (Fadel, 2022). It is believed that common disinfectants like chlorine dioxide (ClO_2) and sodium hypochlorite (NaClO) could boost the concentration of organic pollutants in water. It has been proposed that polymeric pipes degrade by chain scission in the presence of water disinfectants that generate free radicals (e.g., ClO_2), releasing oxygen-containing functional groups, polymeric additives, and small organic molecules (Stefan, 2023; He et al., 2023). Recent investigations carried out following wildfires found a clear connection between the exposure of polymeric pipes, including PEX, HDPE, PP, PVC, and CPVC, to high temperatures and the release of VOCs such as benzene, toluene, butanone, 1,1,1-trichloroethane (1,1,1-TCA), and other pollutants in water samples collected from drinking water distribution networks (Proctor et al., 2020; Isaacson et al., 2021; Draper et al., 2022; Whelton et al., 2023) and private wells (Jankowski et al., 2023) within regions impacted by wildfires. Considering the widespread use of plastic plumbing pipes in the Saudi market (Merah et al., 2007) and the region's extreme temperatures, it is hypothesized that organic contaminants could leach into tap water (Al-Malack and Sheikheldin, 2001; Lubrizol Advanced Materials, Inc., 2017). Consequently, examining the presence of these pollutants in tap water is a significant research need.

Previous work conducted in the authors' laboratory has shown that frequently utilised polymeric plumbing pipes release significant levels of VOCs into water samples that remained stagnant within the pipes (Shaikh et al., 2018, 2019). Earlier studies employed a modified analytical technique that integrated solid-phase extraction for sample preparation, followed by gas chromatography with flame ionization detection (GC-FID) for the analysis of specific VOCs. Building on the previous findings, the current study will adopt an official EPA method to analyse specific VOCs in water samples, ensuring the accuracy, integrity and reliability of the results.

METHODOLOGY

Water samples

Fifty water samples from houses within Al-Madinah Al-Munawwarah (Saudi Arabia) residential areas were collected from different inhabited homes. Samples were collected by house occupiers in a 1 L amber glass bottle in the morning to allow the pipe to incubate with water samples for at least 6 h. To verify if the water sources (public network) contain any of the investigated VOCs, 10 water samples were also collected from the domestic distribution network source before the water enters the plastic pipes in the residences houses. Figure 1 shows the sample locations (50 homes and 10 domestic water network sites).

Sample separation and determination of volatile compounds

The preparation and analysis of samples were carried out following USEPA Method 8260C for the quantitation of purgeable organic compounds (POCs) in drinking water (USEPA, 2018a; Ladak et al., 2022). Sample preparation was conducted making use of the Teledyne Tekmar Atomx XYZ purge and trap (P&T) system. The analysis was performed on Thermo Scientific ISQ 7000 Single Quadrupole GC-MS System (Thermo Scientific, Waltham, MA, USA)

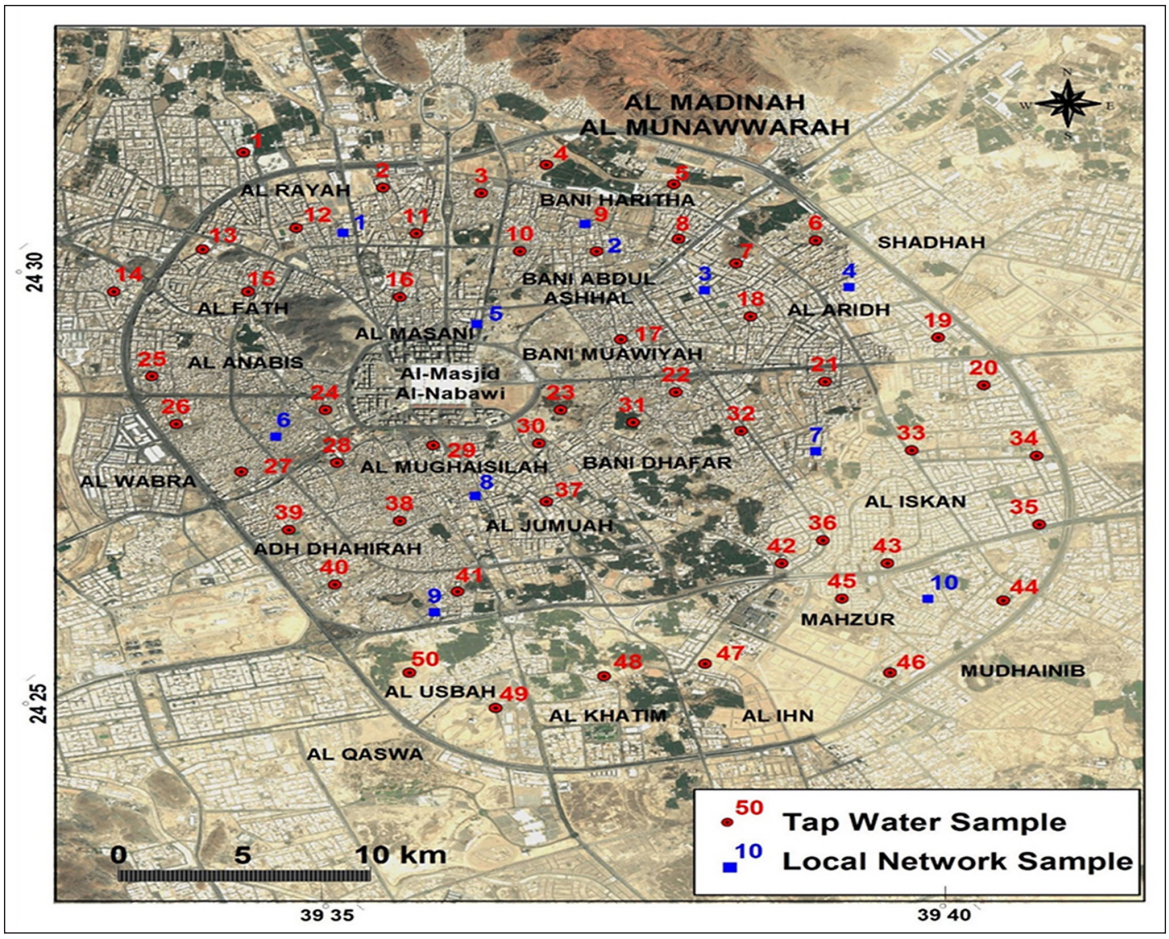

Figure 1. Location of tap and public network water samples

Table 1. Results of VOC analysis for tap and source water

Samples	Parameter	Pollutant concentration (µg/L)								
		2,4-DCP	2-NP	4-EP	BC	1,2,3-TCP	1,2-DCP	Benzene	2-Butanone	1,1,1-TCA
Tap water samples (n = 50)	Freq. (%)	12 (24%)	18 (36%)	40 (40%)	25 (50%)	21 (42%)	29 (58%)	39 (78%)	38 (76%)	34 (68%)
	Max. conc.	13.97	11.75	20.14	22.50	35.15	21.97	7.51	14.49	22.05
	Min. conc.	1.07	1.02	1.64	1.06	7.81	4.88	0.26	0.18	0.07
	Average	5.44	4.01	7.54	7.10	19.42	11.20	3.01	4.36	7.77
	SD	4.47	3.61	5.21	7.41	7.69	4.37	2.02	3.33	5.57
	#samples above limit	4 (8%)	0	0	3 (6%)	21 (42%)	0	5 (10%)	0	0
Domestic network samples (n = 10)	Freq. (%)	4 (40%)	nd	4 (40%)	3 (30%)	nd	nd	nd	nd	nd
	Max. conc.	4.84	…	15.6	19.43	…	…	…	…	…
	Min. conc.	0.53	…	5.68	14.21	…	…	…	…	…
	Average	2.37	…	9.64	16.41	…	…	…	…	…
	SD	1.09	…	2.67	3.65	…	…	…	…	…
	No. of samples above limit	0	0	0	0	0	0	0	0	0
WHO limit (µg/L)		9	210	--	20	0.03	40	5	50	200

1,1,1-TCA: 1,1,1-trichloroethane. 1,2-DCP: dichloropropane. 1, 2,3-TCP: 1,2,3-trichloropropane. BC: benzyl chloride. 2-NP: 2-nitropropane. 4-EP: 4-ethylphenol 2,4-DCP: 2,4-dichlorophenol. SD: standard deviation.

and calibration standards. Mix (11 components-31029) and Mega Mix (76 components-30633) from Restek (Bellefonte, PA, USA) were used for preparation of VOC standards by proper dilution with purge and trap grade methanol (Ar-Razi Saudi Methanol Co. Al-Jubail, KSA) to attain the required concentrations for the experiments.

Sample preparation and analysis

The protocol used in this work for the analysis of VOCs involved the application of purge and trap for sample preparation and quantification with GC/MS). Briefly, 10 mL of a sample was purged with N_2 gas at a flow rate of 40 mL/min for 11 min at 20°C, then desorbed at a flow 300 mL/min for 2.00 min at 250°C. The separation of the analytes was performed by Thermo Scientific TraceGOLD TG-VMS, 20 m × 0.18 mm, 1 µm film (Thermo Scientific, Waltham, MA, USA). The oven temperature was initially set at 40°C for 1 min, then gradually raised to 170°C at a rate of 10°C/min, ramped up to 250°C at a rate of 50°C/min, and kept for a period of 2 min. The carrier gas used in this experiment was high-purity helium with a concentration of 99.99%. It was maintained at a constant flow rate of 1 mL/min. The temperatures of the injection port, transfer line, and ion source were all adjusted to 250°C. A total energy of 70 eV was utilized for electron ionization (EI), while the scanning range for mass analysis was configured to span from 50 to 650 atomic mass units (amu) in full scan mode. The injection was conducted using a split mode configuration, employing a split ratio of 10:1. The solvent delay time of 3 min was uniformly established for all samples produced using various procedures. The Xcalibur 2.0 workstation was employed for data processing.

Statistical analysis

The data were recorded and analysed using Microsoft Excel software. Categorical variables were represented as frequencies and percentages and were presented in tables, whereas for continuous variables mean and standard deviation were calculated.

RESULTS AND DISCUSSION

Concentration of VOCs in tap water samples

In this study, 50 tap water samples from different houses within the Al-Madinah Al-Munawwarah residential area were collected and analysed for the presence of selected VOCs. 10 samples were also obtained from the domestic water distribution network and analysed for the occurrence of target VOCs. Figure 1 depicts the location of samples and Table 1 summarizes the average concentrations along with occurrence frequency (percentage), maximum, minimum and standard deviation and WHO permissible limits.

The box plot diagram in Fig. 2 presents the variation in tap water VOC concentrations. The large variation between samples collected from different homes may be attributed to network length, size, pipe quality, existence of biofilms and time for which water was stagnant inside the pipes. Direct exposure to sunlight and the temperature of the pipes may vary from one home to another (Al-Malack and Sheikheldin, 2001; Lubrizol Advanced Materials, Inc., 2017). The storage tanks (either concrete or fibreglass, etc.,) and pipe connecting joint glueing resins can also be considerable sources for the occurrence of VOCs in tap water (Shaikh et al., 2019).

Figure 3 illustrates the number of VOCs and percentage contribution to the total VOC concentration by each VOC for each tap water sample. The pollutant counts per sample varied from 2 to 7, revealing an inconsistent distribution. The next paragraphs provide an overview of the concentration of each chemical and its frequency of occurrence in the investigated samples, along with its probable origin based on the available literature.

The most frequent pollutant in the tap water samples was benzene, which was detected in 39 (78%) of the examined water samples with a mean concentration of 3.01 µg/L (SD = 2.02) and a range of 0.26–7.51 µg/L. The guidelines provided by WHO (2003) and USEPA (2018b) have set a concentration of 5 µg/L as the maximum permissible level for benzene in drinking water. It is believed that benzene can cause leukaemia;, thus, the USEPA has set a goal of zero concentration in drinking water and surface water (ATSDR, 2007). Concentrations exceeding the permissible limits were observed in 5 (12.82%) of the analysed samples. Former work by this research group also detected high concentrations of benzene in water samples that were stagnant inside plastic pipes (Shaikh et al., 2018, 2019). High concentrations of benzene in water samples were found in buildings affected by wildfires (Proctor et al., 2020; Isaacson et al., 2021; Draper et al., 2022; Whelton et al., 2023) and in private wells (Jankowski et al., 2023) in regions that had been impacted by wildfires. These results could reflect the influence of stagnation time and ambient heat on the migration of benzene from polymeric pipes into water.

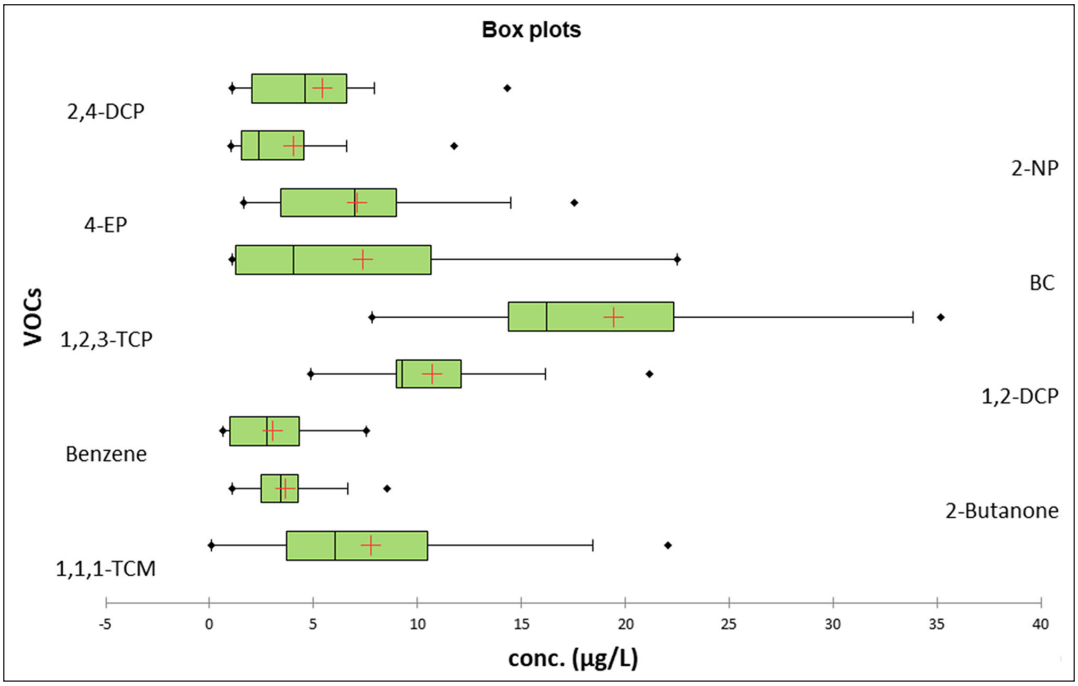

Figure 2. Box plot of VOC concentrations in tap water samples

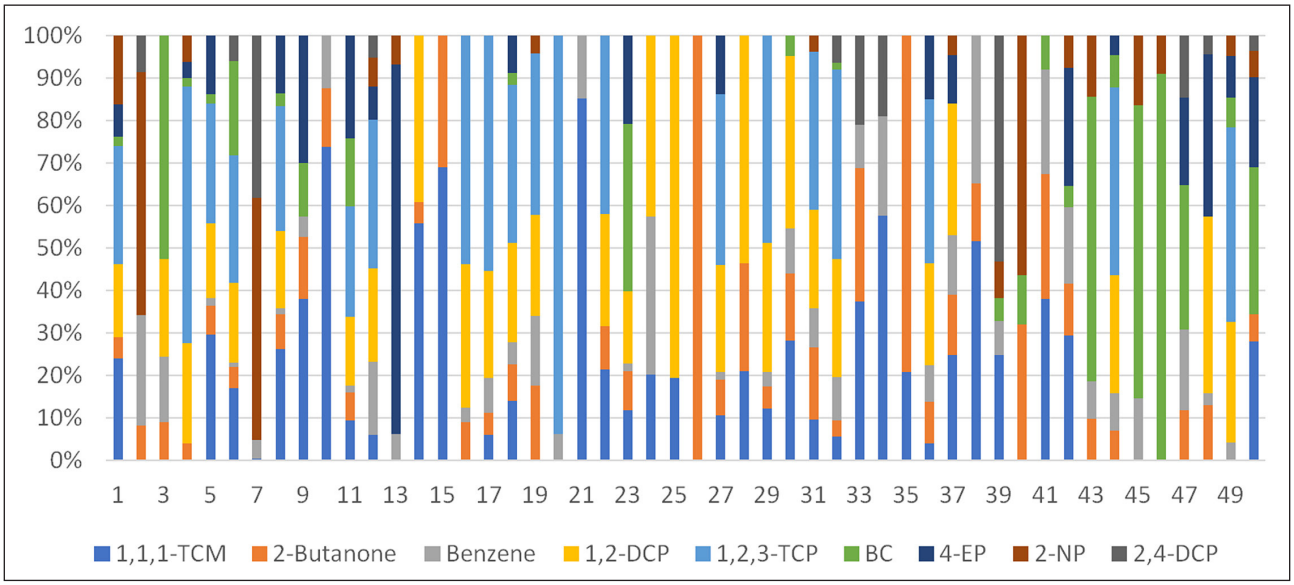

Figure 3. Number of VOCs and percentage contribution to the total VOC concentration per VOC for each tap water sample

2-Butanone was detected in 76% (38 samples) of the water samples, with values varying from 0.18 to 14.49 µg/L and a mean value of 4.36 µg/L (SD = 3.33). Concentrations in all samples were within the permissible limits established by WHO. 2-Butanone (MEK) and tetrahydrofuran (THF) were recorded at high levels in laboratory water outputs following the installation of PVC pipes. The solvents from the PVC pipe glue used for connecting the tubing are thought to leach these molecules into the water supply (Wang and Bricker, 1979). A considerable amount of this VOC was found in the water and plastic pipe debris collected from wells that suffered damage in wildfires. It is more likely that this pollutant is released due to the degradation of plastic pipes caused by heat (Jankowski et al., 2022). 2-Butanone has potential health effects in humans and animals, especially at high concentrations. Aguilar (2020) reported that butanone alone did not pose negative effects on the liver or nervous system, but it can convert other chemicals to be more harmful to these systems (Aguilar, 2020).

The next most frequently detected pollutant was 1,1,1-trichloroethane (1,1,1-TCA). It was identified in 34 (68%) of the water samples at concentrations ranging from 0.07 to 22.05 µg/L and a mean of 7.77 3 µg/L (SD =5.57). The International Agency for Research on Cancer (IARC) has isted 1,1,1-TCA in Group 3 (i.e. cannot be clearly classified as either carcinogenic or non-carcinogenic to humans) and the WHO recommends a limit in drinking water of 200 µg/L (USEPA, 2015). Certainly, the concentration of 1,1,1- TCA in the samples in which it was present was far below this limit. The USEPA has recently re-evaluated 1,1,1-TCA as hazardous after concluding that it is more hazardous than originally anticipated, with additional evidence linking it to human cancer and birth defects. The health risk increases proportionally with increased water volume and longer length of exposure. Despite the fact that the quantity of this pollutant was within the permissible WHO limit, it should be noted that even brief durations of exposure have the potential to cause a risk

to reproductive health (Chiu et al., 2013). Similar studies have reported the occurrence of 1,1,1-TCA in drinking water samples in the United States at concentrations ranging between 0.02 and 0.6 µg/L (USEPA, 1982), and a concentration of 0.37 µg/L was determined in drinking water samples from Italy (Aggazzotti, 1986). 1,1,1-TCA has been identified as one of the chemicals that can migrate from plastic pipes when they are subjected to hot temperatures. This finding, when paired with our previous results (Shaikh et al., 2019), suggests that this contaminant migrates from the plastic plumbing system.

The next most common molecule was 1,2-dichloropropane (1,2-DCP), which occurred in 29 (58%) of the total water samples. This pollutant is a colourless liquid with a pleasant odour that is soluble in water. When mixed with water, it can release harmful vapours that pose potential health risks (Proshad et al., 2018). The concentration of the contaminant varied between 4.88 and 21.97 µg/L with a mean of 11.20 µg/L (SD = 4.37). A recent study revealed a positive correlation between 1,2-DCP and cellular proliferation, anti-apoptotic effects, and DNA damage (Kimura et al., 2023). These traits are well-recognized as important characteristics of chemicals that have the potential to cause cancer. Earlier research conducted in our laboratory has verified the release of this contaminant from the commercial plastic pipes used in the construction of water systems (Shaikh et al., 2019). Furthermore, it has been identified in tap water samples from residences impacted by wildfire incidents (Whelton et al., 2023).

Half of the examined water samples (25 samples; 50%) were polluted with benzyl chloride (BC), with a concentration range from 1.06–22.50 µg/L (mean of 7.10 µg/L; SD= 7.41). The WHO limit was exceeded in 3 (6%) of the investigated tap water samples. BC is insoluble in water and the USEPA has estimated that extended use of water contaminated with this substance at an average concentration of 0.10 µg/L would increase the chance of acquiring cancer by more than one in a million (Budavari et al., 2001). BC is categorized as an emerging volatile disinfection byproduct (Krasner et al., 2006) and it has been identified in water incubated in polymeric pipes commonly used in plumbing (Shaikh et al., 2018, 2019).

1,2,3-Trichloropropane (1,2,3-TCP) was identified in 21 (42%) of the tap water samples. The concentration of 1,2,3-TCP in contaminated samples varied from 7.81 to 35.15 µg/L, with a mean of 19.42 µg/L (SD = 7.69). This is far beyond the WHO-advised threshold of around 0.03 µg/L for this pollutant. It is hypothesized that 1,2,3-TCP migrates from polymeric pipes into water due to the process of drinking water chlorination (Keith and Telliard, 1979). It often alters the taste and odour of drinking water due to its low odour-threshold concentration and has mild toxicity upon acute exposure (Sufett, 1999). Animal studies have demonstrated that prolonged exposure can result in renal failure. Its carcinogenicity in animals has been demonstrated by long-term exposure, affecting various locations. As per IARC, 1,2,3-TCP is classified as "probably carcinogenic to humans" and hence its maximum permissible limit is set at 0.005 µg/L in drinking water (Kleinman et al., 2017).Its average concentration in the tap water samples in this study was 0.34 µg/L. A published survey carried out in the United States revealed that 1,2,3-TCP was detected in around 6.5% of the analysed 1 237 water sources. Similarly, around 8% of private wells contained 1,2,3-TCP, but public-supply wells had a lower incidence of 5%. Furthermore, it was detected in 5.5% of the samples obtained from 7 787 public-supply sources. The observed concentrations varied between 0.005 and 2.7 µg/L (Burow et al., 2019). The existence of this contaminant in tap water samples collected from homes affected by wildfires suggests that its discharge rate may be correlated with temperature (Whelton et al., 2023).

2-Nitropropane (2-NP) was detected in 14 (28%) of the analysed tap water samples, ranging from 6.19 to 20.02 µg/L with a mean of 9.69 µg/L. Although ithe WHO does not provide guideline limits, exposure to this pollutant and similar nitrile compounds, such as acetonitrile, poses the risk of adverse effects, primarily through dermal and inhalation pathways. The toxicity of nitriles is contingent upon the absorbed amount and may affect the hepatic, renal, cardiovascular, gastrointestinal, and central nervous systems (Michałowicz and Duda, 2007).

4-Ethylphenol (4-EP) was found in 20 (40%) of the water samples, at concentrations ranging from 1.64 to 20.14 µg/L, and a mean of 7.54 µg/L (SD = 5.21). The USEPA has determined that lifetime exposure to 2 mg/L in drinking water is not expected to cause any adverse effects, but it is considered to be quite toxic to humans via oral exposure (at a dose of 5 000 mg/kg), causing anorexia, progressive weight loss, diarrhoea, vertigo, salivation, dark coloration of the urine (Kleinman et al., 2017). A study conducted on animals indicated that it reduced foetal body weight, causing growth retardation and abnormal development in the offspring of animals exposed to phenol by the oral route. Phenols have been classified by the USEPA as Group D (not assumed to be human carcinogens) (Kleinman et al., 2017). While it is doubtful that 4-EP will leak from plastic pipes, it could be formed by the reaction of a disinfectant with particular molecules encountered in biofilms, which are made up of microorganisms that adhere to the surfaces of polymeric materials in water systems (Papciak et al., 2022).

The least frequent pollutant identified in the screened tap water samples was 2,4-dichlorophenol (2,4-DCP). With a mean concentration of 5.44 µg/L (SD = 4.47) and a range of 1.07–13.97 µg/L, it occurred in 12 (24%) water samples, and in 8 samples breached the WHO permissible limit of 9 µg/L. Like 4-EP, this phenol is unlikely to leach from plastic pipes. However, it forms when the chlorination process interacts with organic molecules present in biofilms (HSDB, 2023). A recent study conducted on Korean people between the ages of 18 and 69 revealed that the levels of 2,4-DCP and 2,5-DCP in their urine exceeded 0.05 g/L. The average values were 0.14 mg/L (95% confidence interval of 0.13–0.16) and 0.44 mg/L (95% confidence interval of 0.41–0.48 mg/L), respectively (Park and Kim, 2018).

Correlation

The Pearson correlation coefficients in Table 2 indicate a significant positive association between 1,1,1-TCE and 2-butanone (R = 0.82), 2-NP (R = 0.76), 2,4-DCP (R = 0.55), and 1,2-TCP (R = 0.54). Furthermore, a weak correlation exists with benzene (R = 0.28). In addition, 2-butanone exhibited a moderate correlation with 1,2-DCP (R = 0.48) and 2-NP (0.49).

Benzene exhibits a weak correlation with 2-NP (R = 0.30) and 2,4-DCP (R = 0.25). The VOCs 1,2-DCP, BC, and 2-NP exhibited a moderate relationship to 2,4-DCP (R = 0.67), 2-NP (R = 0.68), and 2-DCP (R = 0.76) respectively, in the same sequence. The correlation values suggest that leaching of the correlated contaminants might be influenced by common factors.

Analysis of source water samples

To determine whether the VOCs in question originated from the water supply network or the residential plumbing system, 10 water samples were collected from the source supply network at a point before entering the plastic pipes in the residences. These samples were subsequently analysed for the target analytes, following the same sampling, preservation, and analytical protocols employed for samples obtained from households. The analysis indicated the presence of BC, 1,2-DCP, and phenol in 40% (4), 40% (4), and 30% (3) of the samples, respectively, with concentrations ranging from

Table 2. Pearson correlation between concentrations of VOCs in tap water samples

	1,1,1-TCE	2-Butanone	Benzene	1,2-DCP	1,2,3-TCP	BC	4-EP	2-NP	2,4-DCP
1,1,1-TCE	1.00								
2-Butanone	**0.82**	1.00							
Benzene	0.28	0.23	1.00						
1,2-DCP	**0.54**	**0.48**	0.05	1.00					
1,2,3-TCP	0.05	−0.03	0.16	−0.38	1.00				
BC	0.08	−0.12	−0.05	−0.40	0.04	1.00			
4-EP	-0.02	−0.19	0.20	−0.53	−0.02	**0.68**	1.00		
2-NP	**0.76**	**0.49**	**0.30**	0.13	0.29	−0.14	0.00	1.00	
2,4-DCP	**0.55**	0.27	0.25	**0.67**	0.13	−0.13	−0.23	**0.76**	1.00

14–19.4 µg/L, 0.53–4.8 µg/L, and 5.68–15.6 µg/L. Nevertheless, all detected levels remained below the WHO permissible limits. This observation may be attributed to the flushing and cleaning frequency in the public water network, which prevents VOC accumulation, whereas prolonged water stagnation and biofilm formation are more likely to occur within the home network.

CONCLUSIONS

The analysed tap water samples showed varying levels of VOC contamination, with some likely linked to plastic piping. Notably, 1,2,3-TCP, benzene, 2,4-DCP, and BC exceeded permissible limits in 43%, 10%, 8%, and 6% of samples, respectively. Nevertheless, the concentrations of most of the analysed VOCs remained within acceptable thresholds. Considering the significant health risks posed by prolonged exposure to water contaminated with these pollutants, including the potential buildup of VOCs in the human body, it is essential to conduct comprehensive research to pinpoint the sources of these contaminants in tap water and understand the specific mechanisms of their release.

ACKNOWLEDGEMENTS

The authors are grateful for the generous fund No 1-17-01-06-011 from King Abdul Aziz City for Science and Technology, Riyadh, Saudi Arabia.

AUTHOR CONTRIBUTIONS

Awadh AlSuhaimi: proposal design, methodology development, method validation, writing, supervision and editing. Ahad Fantoukh: Sampling and analysis, writing original draft. Eman AlHarbi: co-supervision, reviewing methodology and data representation. Mohammed Mansour: sample preparation and analysis. Imran Ali: scientific advisor, revising original draft and editing.

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