ORIGINAL RESEARCH

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Plastic water supply connectors: Leaching, hydrocarbon contamination, and decontamination

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Abstract

Disasters can prompt hydrocarbon contaminants to reach building water systems, and ultimately customer fixtures. Here, seven water supply connectors (e.g., ice-maker lines, faucet connectors, washing machine hoses) were exposed to contaminated water, and were subsequently decontaminated by water flushing. After a 24 h contamination period, water samples were collected after three consecutive 72 h exposure periods. Samples were characterized for volatile organic compound, semi-volatile organic compound, and total organic carbon concentrations. New, uncontaminated, PVC tubing leached phenol at concentrations that exceeded the health advisory. All materials sorbed more than 90% of hydrocarbon contaminants during the initial exposure period. All materials then released the contaminants into the water during decontamination, at times above health-based limits. The majority of sorbed mass remained in the plastics at the end of the decontamination effort, indicating the products posed continued leaching risks. Public health guidance considerations and research needs were identified.

KEYWORDS

contamination, decontamination, drinking water, plastic, plumbing

1 | INTRODUCTION

Water supply connectors often transport water from rigid plumbing components to another plumbing asset nearby. These metal and flexible plastic components are used for a variety of applications such as ice-makers, coffee machines, refrigerators, kitchen sink spray hoses, water fountains, water softeners, and shower wands. Compared to copper and stainless steel, plastic connectors are the least expensive. Some of the plastics used include poly(1-butene) (PB), polyethylene (PE), plasticized polyvinylchloride (PVC), and ethylene propylene diene

monomer (EPDM). Because connectors are often close to the water use location, the type and magnitude of chemicals they leach into the water can be of human health importance.

A growing number of studies have reported volatile organic compound (VOC) and semi-volatile organic compound (SVOC) leaching from plastic plumbing pipes, but no studies were found that had evaluated connector leaching. Prior studies have shown PE pipes released up to 83 mg/L organic carbon into drinking water and up to 4.96 mg/L for unplasticized PVC pipes (Koch, 2004; Kowalska, 2011; Lund et al., 2011; Skjevrak et al., 2003). Hydrocarbons like benzene, toluene, ethylbenzene, xylenes, naphthalene (NAP), alkylated NAP, and phenol have been observed to leach from high density polyethylene (HDPE) and cross-linked polyethylene (PEX) pipes in Poland, the United States, and France (Anselme et al., 1985; Heim and Dietrich, 2006; Kowalska et al., 2011). Although existing studies have identified some organic compounds leaching from these pipes, it is estimated that up to 98% of leached organic mass remains unidentified (Ryssel et al., 2015). Less chemical leaching data was found for unplasticized PVC pipes, but PVC well casings were previously shown to leach o-cresol and NAP (Junk et al., 1974). Many compounds identified are used in resin synthesis, are processing lubricants, or are antioxidant degradation products (Whelton and Nguyen 2013). The flexible plastics used as connectors have different formulations than the rigid materials evaluated previously, which can impact the compounds released into water under normal use conditions.

Another health concern with connectors is that building drinking water contamination caused by chemical spills, wildfires, and chemical backflow incidents can make connectors long-term sources of contamination. No studies were found that examined connector contamination and decontamination. Due to the lack of information, in 2014, a local West Virginia health department encouraged restaurants to discard their plastic connectors after a drinking water contamination incident. Wildfires can cause drinking water VOC levels sometimes as high as 40,000 μg/L of benzene and other compounds exceeding 1,000 μg/L (Proctor et al., 2020; Whelton et al., 2023; Whelton et al., 2024). Following numerous wildfires, organizations have advised that "the first two cups (16 ounces) of water [be discarded] from the tap before taking the sample for analysis..." "...to help ensure that the sample represents water in contact with the building pipes" (SWRCB, 2019). By discarding the initial volume of water, contamination of the fixture and water supply connector is not being evaluated. Chemical incidents can also cause drinking water contamination, such as the 2021 incident in Texas, which resulted in a 177 μg/L benzene concentration in drinking water (Casteloes et al., 2015; Douglas, 2021; Huang et al., 2017; Troeschel

> **Article Impact Statement**
> New plastic tubing exceeded an acute drinking water limit, and after contaminated drinking water exposure, many products were unable to be decontaminated by water flushing.

et al. 2022; Whelton et al., 2015). Flushing contaminated water from impacted plumbing has been the most popular approach for reducing post-incident chemical exposure risks (Casteloes et al., 2015; Troeschel et al., 2022).

Evidence is clear that some hydrocarbons can diffuse into and out of plastic drinking water pipes and gaskets, and thus connectors may be equally vulnerable. The only study available pertaining to connectors was conducted in 2017. Here, investigators found that dishwasher and refrigerator plumbing remained contaminated after a VOC exposure experiment (Szabo et al., 2017). Though the study did not describe the materials present in the water supply connectors. Previous works evaluating drinking water have shown that HDPE, PEX, and unplasticized PVC (uPVC) pipes can sorb and desorb hydrocarbons (Haupert et al., 2023; Haupert & Magnuson, 2019; Huang et al., 2017). uPVC pipes have demonstrated greater resistance to VOC uptake compared to PE pipes (Mao, 2008). Unlike uPVC pipes, PVC water supply connectors are often plasticized which would enable chemical diffusion to occur more readily (Martin & Young, 2003; Pal et al., 1992; Suleman et al., 2016).

The study objective was to better understand the role water supply connectors have in influencing tap water quality following a contamination event. Specific objectives were to (1) quantify hydrocarbon uptake when the products were exposed to petroleum contaminated water, and (2) identify the degree to which sorbed contaminants are removed during three decontamination periods. In addition to those objectives, this study sought to (1) identify the chemicals leach from new products into drinking water and (2) identify practical sampling and public health guidance considerations and research needs. Due to the absence of any prior studies, results were intended to help public health officials, building owners, and insurance companies.

2 | MATERIALS AND METHODS

2.1 | Standards and reagents

Mixed standards of benzene, toluene, ethylbenzene, o-xylene, m-xylene, and p-xylene (2000 mg/L in methanol

TABLE 1 Material characteristics of the water supply connectors used in this study.

Description (color, inner diameter as cm)	Label	SA/V ratio (cm²/mL)	Identification by FTIR (% crystallinity)[a]	Thermal properties			
				Onset T_{deg} (°C)	T_{deg}, (°C)	wt% remain at 100°C	wt% remain at 800°C
Vinyl multipurpose tubing (black, 0.952)	PVC-Black	4.2	PVC (−)	198	251	100	2.6
Vinyl multipurpose tubing (clear, 0.952)	PVC-Clear	4.2	PVC (−)	157	263	99.8	13.7
PE multipurpose tubing (translucent, 0.410)	PE-MP	9.8	LDPE (31.7)	421	462	99.3	0
PE ice-maker supply line (translucent, 0.438)	PE-Ice	9.1	LDPE (27.5)	419	464	99.9	0
PVC faucet supply line (white, 0.757)	PVC-Faucet	5.3	PVC (−)	194	271	99.9	11.6
Washing machine hose (red (hot)/ blue (cold), 0.830)	EPDM-Hot, EPDM- Cold	4.8	EPDM (−)	192/191	273 /276	99.9 /99.9	17.1 /29.3
PEX ice-maker supply line (blue, 0.381)	PEX-Ice	10.5	HDPE (61.7)	437	469	99.8	0

[a]PVC and EPDM materials did not contain detectable crystallinity.

(MeOH)), polyaromatic hydrocarbon (PAH) mix B (200 mg/L in acetone), and 8270 MegaMix (1000 mg/L in dichloromethane (DCM)) were purchased from Restek Corporation. Acetone, DCM, MeOH, sodium hypochlorite, sodium chloride, trace metal grade hydrochloric acid, NAP-d8, and chlorobenzene d5 were purchased from Fischer Scientific. Phenol d-6 and pyrene-d10 were purchased from SPEX CertiPrep. Louisiana light sweet crude oil was obtained from a crude oil processing facility in Mobile, AL. Reagent grade water (18.2 MΩ cm) was produced from a Thermo Scientific Barnstead™ Nanopure™ water purification system.

2.2 | Materials

Plumbing items were purchased from a regional pipe supply store and all items were reported to be certified by NSF/ANSI Standard 61, which is an industry drinking water contact testing procedure. Items were made of different polymers such as PE, PEX, PVC, and ethylene propylene diene monomer (EPDM) and served various functions: ice-maker supply line, faucet supply line, dishwasher supply line, washing machine connector (Table 1, Figure SI-1). Some components (e.g., dishwasher supply line, washing machine

connector) were removed from the braided steel covering before conducting tests.

2.3 | Material characterization

Materials were characterized using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy. These characterization methods were applied to better understand material composition, so their water quality impact performance results could be better interpreted. Thermal transitions of all plastic materials and residue generated with similar heating conditions were evaluated using TGA (TA Instruments Q50). A sample of each material (20–30 mg) was placed in an alumina pan, and heated from ambient temperature to 600°C at 10°C/min under 50 mL/min of nitrogen, and held at 600°C for 2 min. The gas flow was then switched to oxygen, and the temperature was increased to 800°C at 10°C/min. The onset temperature of degradation (onset T_{deg}) and degradation temperature (T_{deg}) were identified from the thermograms. The onset temperature of degradation represents the temperature at which the plastic first starts to decompose and is commonly determined by intercepting the baseline with the start of the derivative peak. The

degradation temperature was the midpoint of the derivative peak. These parameters are often used to help compare the type of polymer materials (i.e., PEX has a greater T_{deg} than LDPE). Sample weight remaining after TGA can sometimes be attributed to noncombusted materials (carbon black, inorganics, etc.), depending on the carrier gas and temperature.

Differential scanning calorimetry (TA Instruments Q2000) was used to determine the melting point and crystallinity of the samples. Approximately 10 mg of each material was added to an aluminum pan, and the temperature was ramped from 30 to 200°C at a rate of 10°C/min, the temperature was held at 200°C for 2 min, then cooled to 30°C. The samples were held at 30°C for 2 min and then underwent a second increase to 200°C at a rate of 10°C/min, held at 200°C for 2 min, then cooled to 30°C. The heating and cooling were performed under 50 mL/min of nitrogen. Percent crystallinity for the polyethylene materials was calculated based upon 293 J/g for the heat of melting for a 100% crystalline material (Wunderlich, 1980). The second melting curve was used to reduce the effects of any previous heat treatments (Figure SI-2).

ATR-FTIR spectroscopy (Perkin Elmer Spectrum 100) was performed to confirm material compositions as not all manufacturer disclosures listed the type of plastic used. Twenty scans were performed from 4000 cm^{-1} to 600–500 cm^{-1} in transmission mode and with the resolution of 2 cm^{-1}. A diamond/zinc selenide crystal was employed for the spectroscopic analysis.

2.4 | Material and solution preparation

All materials were rinsed with synthetic tap water (STW) and disinfected with 200 mg/L as Cl$_2$ free chlorine (made from 5.65 to 6 wt% of sodium hypochlorite) for 3 h as described in the International Plumbing Code and Uniform Plumbing Code for new potable drinking water systems (ICC 2024; Kelley et al., 2015). The STW was a low alkalinity water adopted from prior work, and the water pH was adjusted to the range of 6.5–7.5 (Huang et al., 2017) (Table SI-1). The components were filled and capped with Teflon-wrapped rubber and silicon stoppers. After disinfection, materials were drained and rinsed again.

Hydrocarbon contamination was conducted using a 0.3% v/v solution. The oil-water solution procedure was adopted from a prior study examining hydrocarbon contamination of metal and plastic service lines (Huang et al., 2017). To prepare the solution, crude oil and synthetic tap water were mixed in aspirator bottles for 20 h followed by 5 h stagnation. Crude oil was chosen as a contaminant because spills of crude oil derived products and crude oil itself have impacted drinking water

systems previously (Casteloes et al., 2015). Additionally, many of the hydrocarbons detected in water systems following wildfires are constituents in crude oil. The soluble fraction of oil-water was collected using the aspirator valve. Next, the materials were filled with the hydrocarbon contaminated water, sealed, and stagnated for 24 h. The length of each material filled for analysis was similar across replicates but differed across materials (0.73–3.78 m). Different lengths were needed to obtain enough water for chemical analysis because inner diameters of the materials also differed. The surface area to water volume ratio ranged from 4.2 to 10.5 cm^2/mL across material types (Table 1). Control experiments were performed in glass vials with no headspace to determine analyte loss during experiments and sample preparation. Synthetic tap water with no hydrocarbons was placed in each of the materials to determine initial leaching that may occur from each connector. After the 24 h contamination period, materials were drained and rinsed with synthetic tap water to remove oil-water residue. Next, the materials underwent the "Utility Quick Test," which is a migration/leaching protocol developed to assess leaching from plastic materials prior to installation in potable drinking water systems (Schweitzer et al., 2004). Materials were filled with new STW and stagnated for three consecutive 72 h periods. After each leaching period the STW was removed and replaced.

2.5 | Water quality analysis

Water samples were analyzed for VOCs and SVOCs using gas chromatography-mass spectrometry (GC-MS) headspace (Agilent GC-7890B coupled to 7000C MS) and liquid injections (Shimadzu GC-2010 Plus coupled to Shimadzu TQ8040 MS). Two separate analytical methods were used as two contaminants of interest, benzene and toluene, eluted in the solvent front of the liquid injection analytical method. The GC-MS headspace method involved incubating a 5 mL aqueous sample in a 10 mL vial at 50°C and agitating for 10 min. A 500 μL headspace sample is then injected using a 10:1 split mode. The injection temperature is set at 280°C. GC separation is carried out using an Agilent HP-5MSUI column (30 m × 0.32 mm × 0.25 μm) with a flow rate of 1 mL/min of helium gas. The oven program is held at 40°C for 4 min before increasing to 121°C at 12°C/min, where it is held for another 4 min. Finally, the oven temperature is ramped to 250°C at 25°C/min and held for an additional 2 min. The ion source is held at 250°C. The instrument was operated in selective ion monitoring (SIM) mode. Two of the isomers of xylene elute simultaneously,

the two signals are combined; subsequently, the three xylene isomers are treated as one compound. Chlorobenzene-d5 was used as an internal standard. Method detection limits are listed in Table SI-2.

Analysis of less volatile compounds required liquid-liquid extraction of the water samples prior to GC-MS analysis. Approximately 38 mL of effluent was extracted with 2 mL of DCM in a 40 mL volatile analysis vial, and 12 g of sodium chloride was added prior to vigorous shaking for 5 min as described in EPA Method 3511. NAP-d8 and phenol-d6 were added prior to liquid-liquid extraction and used as surrogate standards. GC separation is carried out using an Agilent HP-5MSUI column (30 m × 0.32 mm × 0.25 μm) with a flow rate of 1 mL/min of helium gas. Chlorobenzene-d5 and pyrene-d10 were used as internal standards. The extract was analyzed with GC-MS with the injector being operated in splitless mode and held at 310°C. The oven temperature was held at 40°C for 4 min, ramped to 320°C at 12°C/min, then held at 320°C for 10 min. The ion source is held at 280°C. The instrument was operated in selective ion monitoring mode, and the percent recovery and method detection limits of all 38 compounds quantified are listed in Table SI-2.

TOC was measured as non-purgeable organic carbon using TOC analyzer (Shimadzu TOC-V) with a high sensitivity catalyst. Samples were collected in 40 mL acid-washed carbon-free amber vials. Water was then acidified to a pH <2 using 3 N hydrochloric acid.

2.6 | Statistical analysis

One-way analysis of variance (ANOVA) tests were used to determine if differences between sample means were significant. Post hoc pairwise comparisons were made using the Bonferroni correction. Results with p-values below .05 were considered significant. Prior to ANOVA testing, normality and homogeneity of variance was confirmed using the Shapiro–Wilks and Levene tests, respectively (Tables SI-3, SI-4, SI-5, SI-6). All statistical analyses were performed in OriginLab.

3 | RESULTS AND DISCUSSION

3.1 | Chemical identification and properties of the plastics examined

The water supply connectors examined were found to be PVC, PE, and EPDM. The two PE materials, an ice-maker line and multipurpose tubing, were found to be LDPE. A
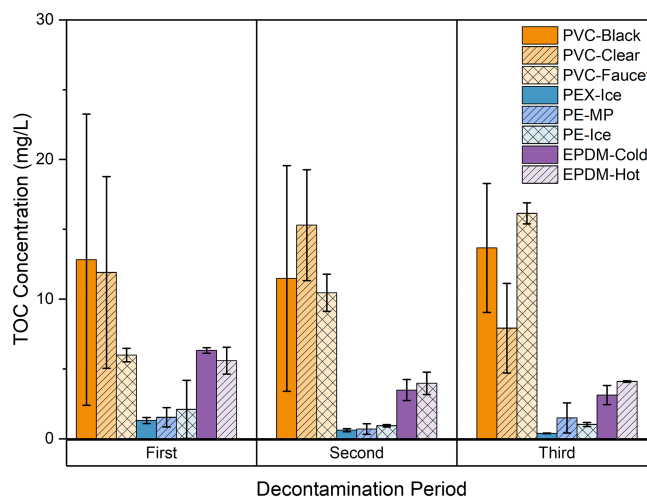

FIGURE 1 After shock disinfection and rinsing of each new material, organic carbon leaching was measured from each water supply connector into non-contaminated water mimicking the product being placed into service.

separate icemaker line was found to be cross-linked HDPE. Both the cold and hot water washing machine supply lines were found to be EPDM. Thermograms for each material can be found in Figure SI-2.

3.2 | Chemical leaching from new connectors

Connector exposure to the non-contaminated synthetic tap water indicated that all materials released organic carbon, and the release was greatest from new PVC materials. Organic carbon levels in plumbing are important to consider as various plastic pipes have been shown to release TOC, which reacts with residual chlorine and forms disinfection by-products such as trihalomethanes (Cao et al., 2020). Throughout the three decontamination periods, the PVC materials imparted the most carbon (10–17 mg/L), followed by EPDM (3–5 mg/L), and PE materials (1.3–2.1 mg/L) (Figure 1). Unlike all other products examined here where organic carbon levels decreased or were unchanged during the decontamination periods, the PVC faucet connector imparted increasing levels of organic carbon in subsequent stagnation periods. Organic carbon leaching varied greatly across some replicates. The two PVC tubing materials had the greatest variation between replicates, up to 110%. However, as decontamination continued this variation decreased, indicating the variability observed was likely within the product and not the instrumentation replicates. Organic carbon migration from plastics can be influenced by formulation and manufacturing differences, as well as storage conditions (Matthews et al., 2023; Cao et al., 2020).

TABLE 2 The concentrations of compounds detected in contaminated water solution and their respective chemical characteristics and USEPA drinking water levels.

Compound				Contaminated water conc. (μg/L)	USEPA drinking water levels	
Name	Boiling point (°C)	Solubility (g/L)	Log K_{ow}		MCL/1 day HA/RSL	Exceeded?
Benzene (B)†,Δ	80	1.792	2.1	6210	5/200/80	Yes
Toluene (T)†,Δ	110	0.532	2.7	6620	1000/20,000/1600	Yes
Ethylbenzene (E)†,Δ	136	0.175	3.1	292	700/30,000/1000	–
Total Xylenes (X) (o-, m-, p-)†,Δ	137	0.18, 0.16, 0.16	3.1, 3.2, 3.2	2513	10,000/40,000/4000	–
Phenol	181	82.80	1.5	6.9	–/6000/6000	–
o-Cresol	191	25.90	2.0	15.7	–/–/1000	–
p-Cresol	201	21.50	1.9	9.1	–/–/400	–
2,4-Dimethylphenol (DMP)	211	7.877	2.3	11.1	–/–/400	–
Naphthalene (NAP)†,Δ	217	0.031	3.3	180	–/500/400	–
2-Methylnaphthalene (MNAP)*,†	240	0.026	3.9	79.6	–/–/80	Yes
1-Methylnaphthalene (MNAP)*	241	0.025	3.9	60.1	–/–/1400	–
Fluorene*,†	294	0.0017	4.2	2.1	–/–/800	–
Phenanthrene*,†	338	0.015	4.5	2.8	–/–/Not found	–

Note: Cross symbol (†) represents a fire-related compound associated with post-wildfire drinking water contamination identified by Whelton et al. (2024), Jankowski, Isaacson, et al. (2023), Whelton et al. (2023), and Proctor et al. (2020); Delta (Δ) symbol indicates the chemical was discovered by drawing contaminated air into stainless steel plumbing during a structure fire by Horn et al. (2023). Asterix (*) represents a compound classified as a SVOC by a USEPA definition (USEPA, 2023); The USEPA health advisory (HA) is for a 1 day exposure for a 10 kg child; USEPA regional screening level (RSL) represents the non-cancer child hazard index ingestion exposure route. Based on the USEPA definition, a boiling point of 240°C was the transition from VOCs to SVOCs; nine contaminants did not have a formal MCL and seven did not have a USEPA 1-day health advisory, which are sometimes used for drinking water safety assessments post-disaster. USEPA regional screening levels (RSLs) for tap water ingestion risk were also considered at the recommendation of a state health department for a prior contaminated drinking water investigation (Jankowski, Isaacson, et al., 2023). RSLs are risk-based concentrations derived from standardized equations combining exposure assumptions with EPA specific toxicity values and are used for site screening.

Only a few VOCs were chemically identified after leaching from the new materials into control water. Identified compounds included phenol, o-cresol, and p-cresol. Similar to TOC results, the PVC-black and PVC-clear materials prompted the greatest phenol concentrations (1.3–6.4 mg/L), with EPDM hoses leaching lower concentrations (0.15–0.5 mg/L), and the PE materials leached the lowest levels (ND to 0.002 mg/L) (Table SI-7). The PVC faucet connector leached 100- to 1000-fold less phenol than the PVC clear tubing products. The PVC-clear tubing prompted an exceedance of the USEPA 1 day health advisory level of 6 mg/L for phenol during the first 24 h exposure period (USEPA, 2018). Phenol levels decreased with subsequent exposure periods, but remained above 1 mg/L for the PVC tubing materials throughout all decontamination periods. The drinking water odor threshold concentration of phenol was determined to be 0.009–0.035 mg/L by Young et al. (1996), which was exceeded

by all materials except the PVC faucet connector and PE materials. Both PVC tubing materials released o-cresol (ND to 0.001 mg/L) and p-cresol (ND to 0.003 mg/L), but levels were not detected after the three stagnation periods. o-Cresol and p-cresol did not reach levels that USEPA identifies as posing a health risk (1 and 0.4 mg/L, respectively) (USEPA, 2022). EPDM cold and hot water hoses from the same manufacturer had similar leaching responses, indicating that the only apparent difference between them may be the colorant used (Table 1).

3.3 | Hydrocarbon uptake by the connectors

Water used for connector contamination contained a moderate level of VOCs and SVOCs compared to levels found after some wildfires (Table 2). For example, the benzene level that the materials were exposed to in

the present study was 6.2 mg/L, whereas after the 2017 Tubbs Fire and 2018 Camp Fire in California, maximum benzene levels ranged from 2.2 to 40 mg/L (Proctor et al., 2020; Whelton et al., 2023). However, an important consideration is that samples from contaminated drinking water systems may have been taken weeks or months after the wildfire and may not represent the peak concentrations present in the water systems. All contaminants detected in the present study have health-based drinking water limits with exception of phenanthrene. For the present study, both benzene and toluene exceeded federal Maximum Contaminant Levels (MCL), and 2-methylnaphthalene (2-MNAP) exceeded regional screening levels (USEPA, 2018; USEPA, 2023).

During the 24 h stagnation period, aqueous concentrations of all contaminants except those with hydroxyl functional groups were reduced by 90% or more across all materials (Table SI-8). Concentration in glass control experiments decreased up to 13.4% for VOCs, and up to 100% for select SVOCs. These control experiment losses could likely be attributed to either sorption to the glass surface and/or volatilization of the analytes during sample extraction and preparation. Initial concentrations of fluorene and phenanthrene were very close to their respective method detection limits. As a result, a small decrease in the concentration of either compound would yield a concentration below their method detection limit. This factor may have strongly influenced the removal rates that were observed across all samples. Other than fluorene and phenanthrene, the mass uptake by the plastic materials was substantially higher than the glass controls.

Although the materials sorbed the majority of contaminants during the exposure period, additional uptake may have occurred if the length of stagnation period was increased. Following contamination incidents, water systems often issue Do Not Use orders. However, the length of time that these orders are left in place can vary. A 2015 survey of contamination events found that many lasted between 3 and 30 days, indicating that a risk of further sorption is possible (Casteloes et al., 2015). The polymer-water partitioning coefficient (K_{pw}) values for HDPE, LDPE, and plasticized PVC geomembranes have been reported for BTEX (Table SI-12). These partitioning values can be used to estimate the amount of BTEX uptake when the contaminated water and plastic materials are at equilibrium. It was calculated that an HDPE material, such as the PEX-ice product, would uptake approximately 97.5% of the benzene from the contaminated water solution. Whereas 99% benzene uptake would be expected in LDPE and plasticized PVC materials. No reported K_{pw} values were found for EPDM. Experimental results found that benzene uptake was lower than estimated values in all but one
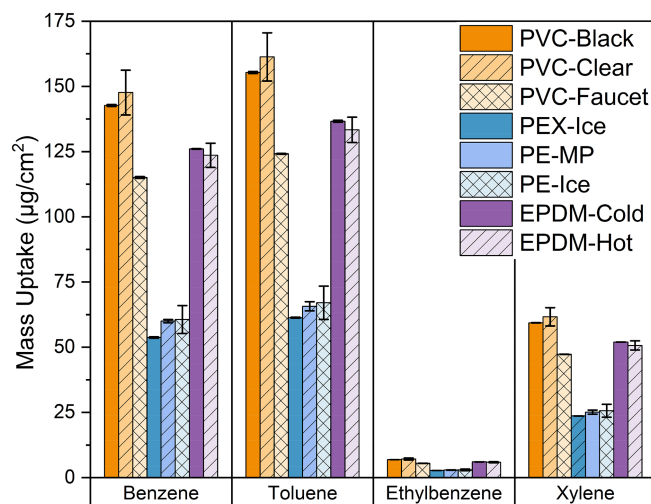

FIGURE 2 Average mass uptake normalized to inner wall surface area of BTEX compounds during 24 h contamination period. Error bars represent standard deviation ($n = 3$).

material, the PVC-faucet. This could indicate that equilibrium between the two phases may not have been reached in most materials and additional hydrocarbon sorption may occur with longer stagnation. Alternatively, the reported K_{pw} values were for geomembranes and not plastic connectors, and difference in material properties such as crystallinity has been shown to impact K_{pw} (Islam & Rowe, 2009).

To determine the influence of material type on mass uptake, BTEX concentrations were normalized to each material's inner wall surface area. Surface area was calculated using geometric properties which would not account for potential differences in surface roughness between materials. Though the surface roughness of both PE and PVC pipes is often considered equal to glass, and rubber would have 66 times greater roughness than those materials (Hydraulic Institute, 2024). PVC and EPDM materials sorbed approximately two times more mass than the PE materials across all BTEX compounds (Figure 2). The uptake of the two PVC multipurpose tubing materials was significantly higher than the EPDM and PE materials (Figure 2, Table SI-10). There was also a significant difference between the PVC faucet connector and the two PVC multipurpose tubing materials, indicating that material type is not the only variable impacting uptake. The PVC faucet connector was more rigid than the multipurpose tubing, and although plasticizer content was not analyzed, the level of plasticization may have impacted the rate of uptake. Surprisingly, there were no significant differences observed between PE materials when accounting for surface area differences. Previous studies have shown that contaminant partitioning and diffusion coefficients for PE can be influenced by

crystallinity, bulk density, and cross-link density (Whelton et al., 2009; Whelton et al., 2011).

The near complete BTEX sorption (≥90%) by all connectors was significantly greater than what has been observed in other plastic building plumbing assets. For example, residential water softeners often use polydivinylbenzene resin beads which have been shown to uptake approximately 44%–56% of hydrocarbons during a 72 h stagnation period following exposure (Jankowski, Gustafson, et al., 2023). Similarly, a study examining HDPE and PEX drinking water pipes showed 53%–91% sorption of BTEX over a 72 h exposure period (Huang et al., 2017). Compared to the larger diameter pipes, the smaller diameter connectors had a higher surface area to volume ratio. This factor is known to account for increased sorption relative to larger diameter materials.

Differences in uptake across contaminants may be due to chemical characteristics such as hydrophobicity and solubility (Figure SI-3). Polarity is well known to influence contaminant diffusion and solubility in hydrophobic polymers (Comyn, 1985). In the present study, similar results were observed with the hydroxyl group bearing compounds sorbing, on average, less than the other nonpolar contaminants. There is a strong correlation between increasing octanol-water partition coefficients (K_{ow}) values and increased K_{pw} for a variety of organic compounds (Haupert & Magnuson, 2019; Joo et al., 2004; Whelton et al., 2010). However, this trend did not fully describe the permeation observed in this study. For the non-phenolic compounds, permeation increased as the K_{ow} value of the compound increased. However, when considering the phenolic compounds this was not the case. For example, 2,4-DMP has a higher K_{ow} value than benzene (2.3 vs. 2.1), however, the uptake of 2,4-DMP was lower than benzene in all materials tested.

3.4 | Hydrocarbon leaching during decontamination

Decontamination by flushing did not remove a majority of VOCs and SVOCs from any of the materials tested. BTEX were the most abundant contaminants, and their leaching varied across material types, likely due to material property differences. Benzene was the only compound that exceeded a US federal MCL (benzene's MCL is 5 μg/L), although toluene, ethylbenzene, and xylene concentrations did sometimes exceed reported odor thresholds of 24, 2, and 200 μg/L, respectively (World Health Organization, 2022). After three decontamination periods, the plasticized PVC materials leached the greatest benzene concentrations, followed by the EPDM and PE materials (Figure 3). When
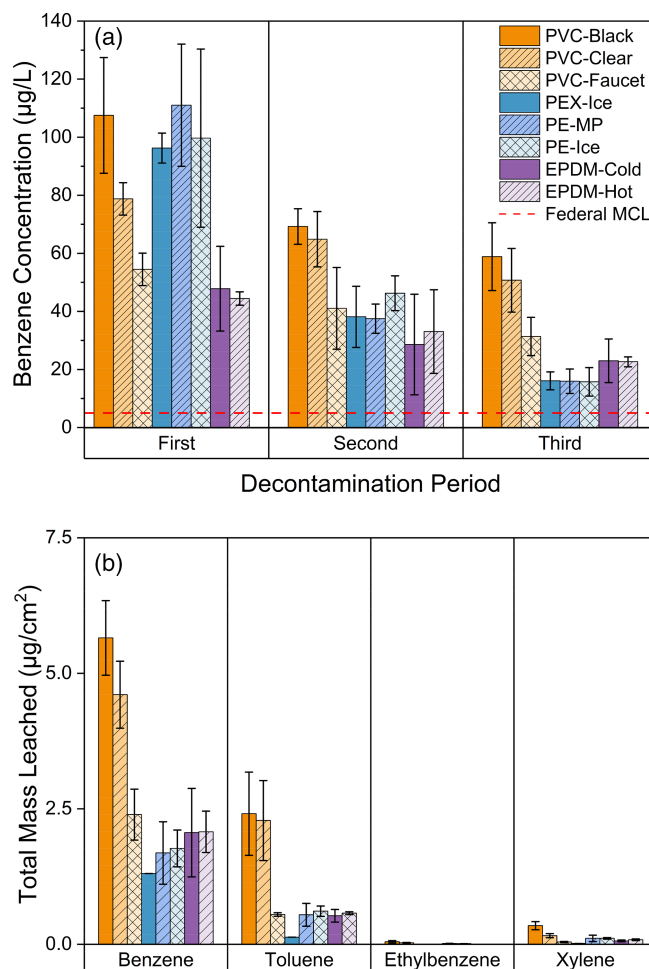

FIGURE 3 (a) Concentration of benzene released across material types during the three 72 h stagnation periods, (b) Total mass of BTEX leached over all three decontamination periods normalized by surface area. Mean and standard deviation values shown ($n = 3$).

considering the total mass of BTEX uptake, only a fraction of the BTEX had been removed from the materials by leaching. The highest proportion of benzene leaching was from EPDM hoses (7.5%) (Figure 3, Table 3). Interestingly, it was found that for the EPDM materials there was no significant decrease in leached concentration of benzene across all three decontamination periods (Table SI-13). For the PVC and PE materials there was no significant difference between the second and third decontamination periods. This is noteworthy, as in all materials at all decontamination periods, benzene leaching was above the health based federal MCL. With over 90% of benzene remaining in all materials, there exists a risk of prolonged leaching of concentrations of human health concern.

Using previously reported K_{pw} values (Table SI-12), the total amount of expected contaminant removal throughout decontamination was estimated. Assuming equilibrium

TABLE 3 Percent of sorbed mass removed from each of the materials during decontamination.

Description (color)	Benzene	Toluene	Ethyl benzene	Xylenes	NAP	1-MNAP*	2-MNAP*	p-cresol	o-cresol	2,4-DMP	Fluorene*	Phenanthrene*
	Contaminant mass removed from the material during decontamination, %											
PVC-Black	5.9	1.6	0.7	0.6	0.6	1.6	1.4	59.2	–	26.7	ND	ND
PVC- Clear	6.6	2.2	1.4	1.1	0.7	ND	ND	–	–	25.5	ND	ND
PVC- Faucet	2.7	0.7	0.6	0.3	0.4	1.0	0.9	24.9	23.7	17.1	ND	ND
PEX-Ice	5.4	1.4	0.7	0.6	ND	ND	ND	ND	ND	ND	ND	ND
PE-MP	3.6	1.0	0.7	0.5	0.7	ND	ND	6.7	8.3	12.1	ND	ND
PE-Ice	2.9	0.9	0.4	0.4	ND	ND	ND	ND	2.2	16.7	ND	ND
EPDM	7.5, 6.5	1.6, 1.6	0.8, 0.9	0.8, 0.8	0.6, 0.5	4.6, 0.8	2.6, 1.3	–	–	46.5, 42.5	ND	ND

Note: Asterix (*) represents a compound classified as a SVOC by a USEPA definition (USEPA, 2023); fluorene and phenanthrene were not detected above MDL. (–) represents that the material leached this compound. ND represents the compound was not detected in any decontamination solution. Standard deviation of samples with hydroxyl group ranged from 1.5% to 9.7%, between 0.1% and 1.3% for all other compounds.

was reached during each of the 72 h decontamination periods it was calculated that up to 4.1%, 1.9%, and 2.6% of the sorbed benzene mass would be removed from the HDPE, LDPE, and PVC materials, respectively. Decontamination results showed that up to 5.4% and 6.6% of the sorbed benzene mass was leached into the water from the PE and PVC material, respectively (Table 3). Deviation from estimated values could be attributed to a few factors including differences in materials characteristics impacting K_{pw} as discussed previously. A lower K_{pw} value would result in additional desorption. Alternatively, if equilibrium was not achieved during the contamination period, contaminants may not have been equally distributed throughout material. This uneven distribution would result in localized concentration gradients near the surface of the material in contact with the water prompting greater aqueous leaching.

To evaluate the impact that material type had on leaching, the total mass of benzene leached from each of the materials was normalized to the inner wall surface area. The two PVC multipurpose tubing materials leached significantly higher mass throughout the three decontamination periods of all components of BTEX than any other material (Figure 3, Table SI-15). This was unsurprising as these two materials had the highest uptake of any material. However, unlike the uptake experiments, there was no significant difference in total mass leached among the rest of the materials. This was surprising, as the EPDM hoses sorbed over two times the mass as the PE materials (Figure 2). Previous studies have found that benzene diffusion constants in EPDM are two to three orders of magnitude higher than in PE (Cheng et al., 2012; Mao et al., 2015; Prasad et al., 1994). However, other characteristics impact desorption as well, such as K_{pw}. Although no published K_{pw} values were found for EPDM, a higher value than that of PE would mean a larger proportion of benzene would remain in the material.

Leached concentrations of the hydroxyl group containing compounds were low relative to BTEX compounds, in part because the initial sorbed mass was smaller. It was found that material type had a significant impact on compound leaching, however, there was no clear trend based on the type of plastic (PVC vs. EDPM vs. PE) (Table SI-9). Additionally, some of the compounds such as phenol, o-cresol, and p-cresol leached from several of the new, uncontaminated materials. This phenomena made it difficult to differentiate the post-contamination leaching of these compounds from the new product leaching.

Similar to BTEX, the mass of PAHs remaining in the plastic materials was much greater than the mass that was leached over 9 days (Table 3). This may be due to the relative hydrophobicity of these compounds, which is

linked to K_{pw}. For example, the K_{pw} of phenanthrene has been found to be up to four orders of magnitude larger than that of benzene, indicating that a significantly higher proportion of phenanthrene would partition into PE relative to the concentration in the water (Choi et al., 2013). The results from the present study show a similar trend. Benzene, which has the lowest K_{ow} value, had the lowest percentage of mass remaining in the materials, which would be expected as it would partition most readily into the water. As K_{ow} increases from benzene to phenanthrene, the mass percentage of compound remaining in the material increased up to 100%. Additionally, compounds with greater K_{ow} values have been associated with lower diffusivity values for HDPE, meaning that the diffusion of bulkier compounds like NAP and phenanthrene will be much slower than benzene (Britton et al., 1989; Joo et al., 2004; Touze-Foltz et al., 2012).

4 | CONCLUSION

This study provides insights into drinking water chemical contamination and leaching potential of water supply connectors. Connectors examined were found to be comprised of PVC, HDPE, LDPE, PEX, and EPDM. After disinfection and the product being placed into service, all new connectors released organic compounds into drinking water. Material leaching was generally ranked greatest to least from PVC > EDPM > PE materials. One PVC faucet connector performed differently than the other six materials tested as increasing carbon leaching was observed during each exposure period. Of the total carbon released, only a small amount of mass was chemically identified by the author's analytical method. The PVC-clear tubing prompted an exceedance of the USEPA 1 day health advisory level of 6 mg/L phenol for the first 24 h exposure period.

All connectors completely or near completely sorbed the studied contaminants during a 24 h exposure period at room temperature, except for the more water soluble hydroxyl group containing VOCs. The contaminated water solution contained benzene, toluene, and 2-MNAP exceeding health-based drinking water levels, and several other VOC (6) and SVOC (3) contaminants were also identified. All nine contaminants have been detected in water systems following wildfires, in some cases at concentrations exceeding those used in the present study. Material type impacted both contaminant uptake and desorption, with PVC and EPDM products releasing the largest percentage of sorbed mass, and PE products releasing the least. However, leaching was not consistent within material type as the two multipurpose PVC tubing

products released the greatest amount of sorbed mass, whereas the PVC faucet connector released the second lowest amount. These results emphasize that material characteristics such as plasticizer content, density, and cross-linking may be responsible for marked differences in uptake and leaching for connectors. After the final decontamination period, only benzene, one of the three chemicals that initially exceeded federal health-based drinking water limits exceeded its drinking water limit. Though this exceedance was found for all products during all decontamination periods.

There are several implications for the decontamination discoveries. In actual buildings hydrocarbon desorption differences seen here could prompt different exposures at different fixtures. For example, the PE connectors evaluated in this work reached lower levels of benzene leaching faster than the PVC connectors. Therefore, under similar stagnation times, water used at a kitchen or bathroom faucet with a PVC connector may contain greater levels of benzene than water exiting a PE ice-maker line. However, it is important to note that material type alone is not a sufficient indicator of relative contamination. Significant differences in benzene leaching were observed between different PVC connectors. Overall, only a fraction of sorbed VOCs and SVOCs were removed by the 9 days of decontamination effort from all materials. Contaminants remaining in the plastics would continue to leach out if the materials were returned to use.

Another implication of the results is that before plumbing contamination investigations are conducted, the degree to which contaminated connectors influence sampling results should be considered. For example, standard first draw water samples for VOC analysis (i.e., 40 mL vial) could contain water in contact with the fixture, connector, and plumbing pipe. In contrast, first draw water samples for SVOC analysis (i.e., 1 L bottle) may be more influenced by the water in the plumbing pipe (by volume) than the connector. If, as California previously recommended, homeowners flush two cups of water (437 mL) before collecting a water sample at their kitchen sink and they would be unable to determine if using 2 cups of water or less from that fixture (indicative of water in contact with the water supply connector) posed a health risk. Evidence from the present work indicates connectors can uptake much greater levels of hydrocarbons from contaminated water than larger plumbing pipes tested (Huang et al., 2017). Secondly, some buildings have multiple types of plumbing pipes (i.e., copper, poly(1-butene), PVC, HDPE, PEX, etc.) and connectors at different locations. For larger plumbing pipes, material type influenced benzene leaching and benzene was still detected after 30 days of tap water rinsing decontamination (Huang et al., 2017). Although a

longer stagnation period was not tested in the present study, similar impacts would be expected for the smaller diameter connectors.

Future work should examine chemical leaching from new water supply connectors, connector contaminant uptake, and leaching responses to contaminated waters. Connector responses to these phenomena at different water temperatures and water use frequencies should be evaluated. Initial contaminant exposure concentration can influence the observed contaminant levels during desorption (Huang et al., 2017), and a single concentration was examined in the present study. The potential for contaminants to exceed health-based drinking water levels will also be related to the exposure temperature and duration. The present study examined three successive 72 h stagnation periods at room temperature, so results could be directly compared across prior studies. However, fixture water use may fluctuate throughout the day (Salehi et al., 2020). Following a wildfire or other disaster, plumbing stagnation periods can last weeks or even months (Odimayomi et al., 2021). Long stagnation periods, even after decontamination steps have been taken, could result in higher VOC and SVOC levels than found in the present study. Additionally, future work should consider more types of connectors and materials such as softener connectors, appliance lines, kitchen faucet spray hoses, and shower wand hoses. The degree at which hydrocarbons interact with scale and biofilm should be examined. Hydrocarbon interactions with fixture and valve components (i.e., gaskets) should be examined. For applications where hot water is being used (i.e., water heater, shower hoses, coffee-makers), there is a need to better understand the degree heat influences contaminant diffusion into and out of the connectors. For warm and hot water applications, VOCs leached from the connector may volatilize and lead to an inhalation exposure risk. Evidence here indicates that contaminated water supply connectors can pose a health risk and should be considered during plumbing safety investigations. Because many plastic connectors are inexpensive, often accessible compared to other plumbing components, and flushing and water sampling may increase costs and take long times, connector replacement after an incident may be the least expensive remediation option.

AUTHOR CONTRIBUTIONS

Kristofer P. Isaacson: Conceptualization; data curation; formal analysis; validation; investigation; visualization; methodology; writing – original draft; writing – review and editing. **Halley Le:** Data curation; formal analysis; investigation; methodology; writing – original draft; writing – review and editing. **Akshat Verma:** Data curation; formal analysis; investigation; methodology; writing – original draft; writing – review and editing. **Jeffrey P. Youngblood:** Resources; data curation; formal analysis; supervision; investigation; visualization; methodology; writing – original draft. **Amisha D. Shah:** Data curation; formal analysis; supervision; funding acquisition; investigation; visualization; methodology; writing – original draft; writing – review and editing. **Andrew J. Whelton:** Conceptualization; resources; data curation; formal analysis; supervision; funding acquisition; validation; investigation; visualization; methodology; writing – original draft; project administration; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.