The cleaning method selected for new PEX pipe installation can affect short-term drinking water quality

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ABSTRACT

The influence of four different cleaning methods used for newly installed polyethylene (PEX) pipes on chemical and odor quality was determined. Bench-scale testing of two PEX (type b) pipe brands showed that the California Plumbing Code PEX installation method does not maximize total organic carbon (TOC) removal. TOC concentration and threshold odor number values significantly varied between two pipe brands. Different cleaning methods impacted carbon release, odor, as well the level of drinking water odorant ethyl *tert*-butyl ether. Both pipes caused odor values up to eight times greater than the US federal drinking water odor limit. Unique to this project was that organic chemicals released by PEX pipe were affected by pipe brand, fill/empty cycle frequency, and the pipe cleaning method selected by the installer.

Key words | drinking water, leaching, odor, PEX, plastic pipe

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INTRODUCTION

Cross-linked polyethylene (PEX) pipes are rapidly replacing conventional copper pipes throughout the USA because they are 75% and 50% less expensive than copper and chlorinated polyvinylchloride (cPVC) pipes, respectively (Connell *et al.* 2013). A 2011 US homeowner survey revealed 54% of residents replumbed their homes with PEX pipe compared to 9% for copper and 7% for cPVC (Juneseok *et al.* 2013). Life cycle assessment investigators have reported PEX pipe requires 25–60% less energy and produces 50–75% less CO_2 than copper pipe during its manufacture, transport, and installation but yields 45–65% more solid waste (Table 1) (Franklin Associates 2011). PEX plumbing systems have been reported to exhibit less thermal energy loss than copper plumbing systems (Wiehagen & Sikora 2003; Wendt *et al.* 2004).

It has been well documented that PEX pipes sold in Europe release chemicals into drinking water and alter odor quality. Two fairly limited scope studies were found that examined PEX pipes available in the USA, while a recent study has shown six brands sold in the USA can alter tap water chemical and odor quality for at least 30 days (Kelley *et al.* 2014). Other investigators found PEX pipes can alter drinking water chemical and odor quality (Durand & Dietrich 2007; Chemaxx 2007). Various types of PEX pipes (-a, -b, -c) exist and impart antioxidants and their degradation products, solvents used for resin production, manufacturing agents, and multiple unidentified organic contaminants into drinking water (Skjevrak *et al.* 2003; Koch 2004; Lund *et al.* 2011). Total organic carbon (TOC) concentration levels have been reported as high as 5 mg/L near room temperature after only 3 days of water contact (Koch 2004). Not all pipes released lesser levels of TOC at the end of the reported experiments. Some pipes released more TOC. For example, of 10 PEX brands tested in Europe for 9 days, five brands demonstrated a reduction in TOC after 9 days, two brands imparted more TOC, and three brands did not impart a detectable level of TOC at all during the studies (Skjevrak *et al.* 2003; Koch 2004). When European investigators examined multiple brands of PEX for 1 year, three of 11 brands imparted more TOC to tap water after 1

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Table 1 | Life cycle energy, solid waste and global warming potential and costs for cPVC, PEX, and copper pipes

	Environmental impact of CPVC, PEX, and copper potable water pipe[a]			
Type of pipe (1,000 ft, 3/4″)	**Energy consumed, million Btu**	**Solid waste generated, pounds**	**CO_2 equivalents produced, pounds**	**Cost, $/ft**
CPVC	4.03	184	444	0.53[b]
PEX	4.83	144	371	0.48[b]
Copper type K	12.6	78.1	1,520	4.08[c]
Copper type L	8.96	61.2	1,080	2.55[b]
Copper type M[c]	6.48	49.6	780	1.85[d]

[a]Franklin Associates (2011).
[b]Connell *et al.* (2013).
[c]Type M is the most commonly used copper pipe within home plumbing systems in the USA.
[d]Prices were obtained from visiting local plumbing stores in Southern Alabama, fall 2013.

year than during the first 3 days installed (Lund *et al.* 2011). These dissimilar responses lend themselves to question what compounds are being released in what quantity and why?

Short-duration experiments have found PEX pipes available in Europe altered drinking water odor for up to a year (Skjevrak *et al.* 2003; Koch 2004; Lund *et al.* 2011). Some PEX pipes caused threshold odor number (TON) values ranging from 2 to 128 TON (Skjevrak *et al.* 2003; Koch 2004; Lund *et al.* 2011). In the USA, gasoline-like odor issues have been found in homes plumbed with new PEX-b piping; *tert*-butanol (TBA) and methyl *tert*-butyl ether (MTBE) were detected in drinking water at 52,000 μg/L and 740 μg/L, respectively (Chemaxx 2007). Ethyl *tert*-butyl ether (ETBE) concentrations from 23 μg/L to greater than 100 μg/L were found leaching from a single brand of new PEX pipe for a 9–12 day exposure period causing the water to smell similar to alcohol, burning, plastic, and chemical (Durand & Dietrich 2007). It is notable that each of the published PEX leaching studies utilized a different pipe cleaning method before conducting their leaching tests.

A factor not considered in any past laboratory or field investigation is whether or not the method used to clean the newly installed PEX pipe alters that material's leaching response. If the cleaning method alters the pipe's impact on water quality, results of published studies may not be directly comparable to one another and the field. In addition, plumbers who clean the pipes may in fact affect chemical leaching. The existing PEX pipe migration literature is based on the application of a number of different cleaning methods (i.e., National Sanitation Foundation International (NSFI) Standard 61, Utility Quick Test (UQT), European EN 1420 and EN 12873).

In the USA, pipes are cleaned according to the International Plumbing Code (IPC 2009) and state-specific plumbing codes. Differences between cleaning methods include variations in disinfectant concentration and contact time (Table 2). Flushing and disinfection steps aim to remove sediment from the system and kill pathogenic organisms. An exception however is the State of California Plumbing Code (CPC 2010) whereby all PEX plumbing systems must undergo a specific cleaning method before use. Discussions with several plumbers and building contractors from the Mobile, Alabama metropolitan area revealed that some new potable water plumbing pipes are simply flushed with tap water for 30 min before use and not disinfected. Thus, there appears to be a wide range of different plumbing pipe cleaning methods applied throughout the USA. Owing to this variation, several questions cannot be answered. (1) Does a longer stagnation period result in more chemical extraction from a new pipe or should more frequent fill/empty cycles be conducted to maximize chemical removal? (2) Does the chlorine disinfectant's presence or concentration affect pipe chemical leaching? To answer these questions, PEX pipe cleaning methods need to be compared to determine the effect they have on contact water quality.

The goal of this study was to determine initial drinking water quality impacts of two brands of PEX pipes caused by three factors: water contact time, brand, and the pipe's cleaning method. Water quality was monitored by quantifying odor and chemical content before and after contact with PEX potable water pipes. Specific objectives were to: (1) determine the degree to which water stagnation time affected water quality; (2) compare how two brands of PEX pipe affected water quality during a 9 day period; and (3) identify how PEX pipes responded to four different cleaning methods.

MATERIALS AND METHODS

Principle

Water quality was described using head space-solid phase microextraction-gas chromatography mass spectrometry

Table 2 | Description of plumbing system cleaning methods used in the USA

Cleaning method	Description
Approved cleaning methods for newly installed potable water materials	
IPC (2009)	Disinfected in accordance with local jurisdiction requirements or AWWA Standard C651 or AWWA Standard C652 or one of the following approaches: (a) filled with 50 mg/L free chlorine concentration water allowed to stand for 24 h; (b) filled with 200 mg/L free chlorine concentration water allowed to stand for 3 h.
California Plumbing Code (CPC 2010)	Tap water flushed for 10 min then filled and allowed to stand for 7 days at 2 mg/L free chlorine concentration.
ANSI/AWWA Standard C651-99, Disinfecting Water Mains	Tap water flushed then underwent either the (a) tablet method – filled pipes with 25 mg/L free chlorine concentration water and let stand for 48 h, or (b) continuous feed method – continuously fed water at a constant rate at 25 mg/L free chlorine concentration measured at regular intervals, or (c) slug method – a slug of 100 mg/L free chlorine concentration was applied for 3 h.
ANSI/AWWA Standard C652-02, Disinfection of Water Storage Facilities	Disinfected with either (a) 10 mg/L free chlorine concentration for 6 h (gas feed or chemical pump) or 24 h (sodium or calcium hypochlorite), or (b) spraying surface with 200 mg/L free chlorine concentration, or (c) 50 mg/L free chlorine concentration at 5% of storage volume for 6 h then 2 mg/L free chlorine concentration at overflow for 24 h.
Cleaning method applied by voluntary potable water material premarket testing in the USA	
NSFI/ANSI 61	Stagnated for 14 days with a 2 mg/L free chlorine concentration. During this time there had to be at least 10 water contact periods of at least 24 h.
UQT	Reference water flushed for 1 h then stagnated for 3 h with a 50 mg/L free chlorine concentration.
European Committee for Standardization Potable Water Material Compliance Test Method	
EN-1420-1	One hour ultrapure water flush and stagnation for 24 h with ultrapure water.

Only the CPC and IPC methods refer directly to PEX piping systems. AWWA C651 and C652 are listed since the IPC lists them as an option despite not being required for PEX pipe specifically. NSFI/ANSI 61 is a standard used for testing PEX pipe and is mentioned for comparison (AWWA 1999, 2002; NSFI 61 2007; IPC 2009; CPC 2010).

(HS-SPME-GCMS), TON, and TOC methods. Three separate migration tests were conducted to examine the influence of exposure duration, cleaning method applied, and PEX pipe brand on water quality. Tap water from one newly installed PEX plumbing system was also characterized. Water was prepared and characterized in accordance with *Standard Methods* (APHA *et al.* 1995).

Glassware preparation and PEX pipes used for testing

Glass amber vials and bottles for sample collection were cleaned in a 10% v/v nitric acid bath and underwent rinsing with Ultrapure Milli-Q™ water. Caps were polytetrafluoroethylene (PTFE) and water samples were stored head space free at 4 °C until analysis. All pipes were stamped with NSFI Standard 61 certification and obtained at plumbing supply stores. Two brands of PEX-b potable water pipe (PEX-b1 and PEX-b2) underwent migration testing. Three meter length sections were used for each migration test. PEX-b1 pipe (17.0 mm I.D.) had a wall thickness of 2.67 mm and PEX-b2 pipe (16.8 mm I.D.) had a wall thickness of 2.74 mm. Each 3 m pipe section had a surface area to water volume ratio of 2.4 cm^2/mL. Pipes were filled with contact water and plugged with PTFE lined stoppers. All experiments were conducted at room temperature.

Laboratory migration tests

Migration testing was modeled after the UQT developed by Schweitzer *et al.* (2004) and previously applied by Durand &

Dietrich (2007) for one PEX pipe brand in the USA. PEX pipes examined in this study underwent three consecutive 72 h water exposure periods. Pipes were filled with water, allowed to stagnate for 72 h, and then emptied. Water was then collected and characterized. Three replicate pipes were used for each migration test. The UQT was originally developed to help water utilities to determine the expected water quality impacts caused by those materials such as taste and odor.

The effect of fill and empty frequency on PEX pipe contact water

The first migration test was conducted to determine if the frequency of fill and empty cycles influenced the amount of total TOC released from PEX-b1 pipe. This test involved two groups of PEX pipe fills with Ultrapure Milli-Q™ water: (1) for three consecutive 3 day exposure periods, water from a group of PEX-b1 pipes was collected and replaced with Ultrapure Milli-Q™ water; and (2) a group of PEX-b1 pipes was filled with water for 9 consecutive days. A single 9 consecutive day exposure was selected so that results could be directly compared to the three consecutive 3 day exposure experiment. TOC concentration was measured each time water was collected.

The effect of brand on PEX pipe contact water

The second migration test was carried out to compare water quality impacts caused by two brands of PEX pipe. Pipes were filled with Ultrapure Milli-Q™ water. During this test, PEX-b1 and PEX-b2 pipes underwent three consecutive 3 day exposure periods. Samples were collected after each exposure period and were analyzed for TOC concentration and TON.

The effect of cleaning method on PEX pipe contact water

The third migration test compared the effects of four different pipe cleaning methods on water quality impacts caused by PEX-b1 and PEX-b2 pipes. After each new pipe was cleaned using one of the four methods listed in Table 3, they were filled with synthetic tap water and exposed for one 3 day period. The methods examined represented a wide range of disinfectant concentrations and water contact times. The methods were Industry Survey (IS), International Plumbing Code (IPC), modified International Plumbing Code (mIPC), and State of California Plumbing Code (CPC). The mIPC method is identical to the IPC technique but with a 2.5-fold greater chlorine concentration. The increased chlorine level was chosen to better understand the impact of disinfectant level on PEX pipe water quality impacts. The IS method was selected because a survey of local plumbing contractors revealed no disinfection was used for newly installed plumbing systems. The synthetic tap water was prepared using Ultrapure Milli-Q™ water and salt concentrations typical of an Eastern US drinking water (Zhang & Edwards 2009): 3.4 mg/L Al^{3+}, 19.6 mg/L Ca^{2+}, 13.9 mg/L Cl^{2-}, 28.5 mg/L HCO^{3-}, 0.25 mg/L HPO_4^{2-}, 5.0 mg/L K^{+}, 19.8 mg/L Mg^{2+}, 41.9 mg/L Na^{+}, 4.9 mg/L NO_3^{-}, 13.0 mg/L SiO_3^{2-}, 34.9 mg/L SO_4^{2-}. The alkalinity was 22.3 mg/L as $CaCO_3$ and the water pH ranged from 7.4 to 7.6. The experimental tap water was characterized for TOC and TON levels. The application of HS-SPME-GCMS analysis was used to quantify ETBE.

Table 3 | Cleaning methods applied during migration test #3

Name of method	Description of applied pipe cleaning protocols
Industry Survey (IS)	30 min tap water flush
IPC[a]	200 mg/L as Cl_2 static for 3 h
mIPC[a]	500 mg/L as Cl_2 static for 3 h
CPC[b]	10 min tap water flush followed by 2 mg/L as Cl_2 static for 7 days

[a]IPC (2009).
[b]CPC (2010).

TOC analysis

TOC concentration was measured using a Shimadzu TOC-L CPH/CPN analyzer by characterizing non-purgeable organic carbon (NPOC) in accordance with USEPA method 415.1 (EPA 1999). Calibration standards of 0, 2, 4, and 5 mg/L concentration were used. A linear calibration curve was obtained with a coefficient of determination (r^2) of 0.9989. The limit of detection was determined to be 0.10 mg/L concentration.

TON

Water odor properties were described using TON values in accordance with USEPA method 140.1 (EPA 1971). The

TON method is a quantitative dilution method whereby sample water is diluted until the panelists can no longer detect an odor. Water utilities across the USA apply this method to monitor finished drinking water quality and sometimes to monitor changes to source water quality. This is why it was selected for the present study, despite it having limitations (Mallevialle & Suffet 1987). Ultrapure Milli-Q™ water was used as a reference and to dilute the water removed from the pipes. The TON training and research protocol was approved by the University of South Alabama Institutional Review Board.

Head space-solid phase microextraction-gas chromatography mass spectrometry

Volatile organic contaminants (VOCs) were detected by the application of HS-SPME-GCMS. Samples were prepared by adding 10 mL of sample water to 20 mL amber vials resulting in 10 mL of head space. Next, vials were agitated at 50 °C and 500 rpm alternating direction every 10 s for 30 min. A Gerstel MPS autosampler was used to insert a 75 μm Carboxen®-Polydimethylsiloxane (CAR/PDMS) fiber into the sample for the last 5 min of agitation for contaminant adsorption. The CAR/PDMS fiber was inserted into the GC port with a desorption time of 3 min at 280 °C. An Agilent 7890A GC was connected to an Agilent 5975C mass spectrometer detector and was operated in splitless mode. The column used for analysis was an Agilent HP-5 30 m × 320 μm × 0.25 μm. The GC oven program started at 40 °C for 4 min, then increased at 20 °C per minute to 300 °C which was sustained for 3 min for a total run time of 19 min. HS-SPME-GCMS methods were generated from previously developed methods (Cassada *et al.* 2000; Oh & Stringfellow 2003; Durand & Dietrich 2007). The helium carrier gas was used at a flow rate of 1.0 mL per minute. The mass spectrometer was operated in scan mode, from m/z 50 to 100. Identification was based on the 2011 National Institute for Standards and Technology database of mass spectra. ETBE was determined to be the primary compound leached from PEX-b piping by a literature review. The major identifying ions of ETBE are m/z 59, the base peak, and 87, the confirming peak. The ETBE calibration curve was prepared using ETBE standards at 5, 50, 100, and 150 μg/L concentrations and had a coefficient of determination of 0.9835.

Statistical analysis

Minitab 16 (Minitab, Inc., State College, PA) was used to perform analysis of variance (ANOVA) and Student *t*-tests statistical analysis. An alpha value of 0.05 was selected as the significance level for all data interpretation. For TON, means are reported as geometric mean and standard deviation in accordance with USEPA method 140.1 (EPA 1971).

RESULTS AND DISCUSSION

Fill and empty frequency

Removal and replacement of contact water every 3 days yielded a 39% greater quantity of total TOC released compared to the same brand of PEX pipe held static for 9 days (Figure 1) ($p < 0.001$). This finding is significant because the CPC method specifically requires that PEX pipe have a single 7 day contact period when cleaned prior to use. This concept is similar to well-established extraction principles. That is, more frequent extractions result in greater extraction efficiency. The reason for this increased extraction is that the concentration gradient between the pipe and water was reset every 3 days.

The results of the present study indicated that a lengthy, single stagnation period did not result in extra 'cleaning' or a greater quantity of contaminants removed from the pipe. In fact, this approach did the opposite; less carbon was released for the longer water contact period compared to the more frequently flushed pipes. TOC flux declined for the pipe that underwent three consecutive 72 h exposure periods (Figure 1(b)) ($p = 0.001$). PEX pipe installers, water utility staff, and homeowners should consider a series of multiple fill, stagnation, and empty cycles to reduce the new PEX pipe's ability to alter TOC drinking water levels.

Brand of pipe

Both pipe brands ($p < 0.001$) affected the contact water's TOC concentration differently during 9 days. PEX-b2 pipe's TOC flux was more than three-fold greater than

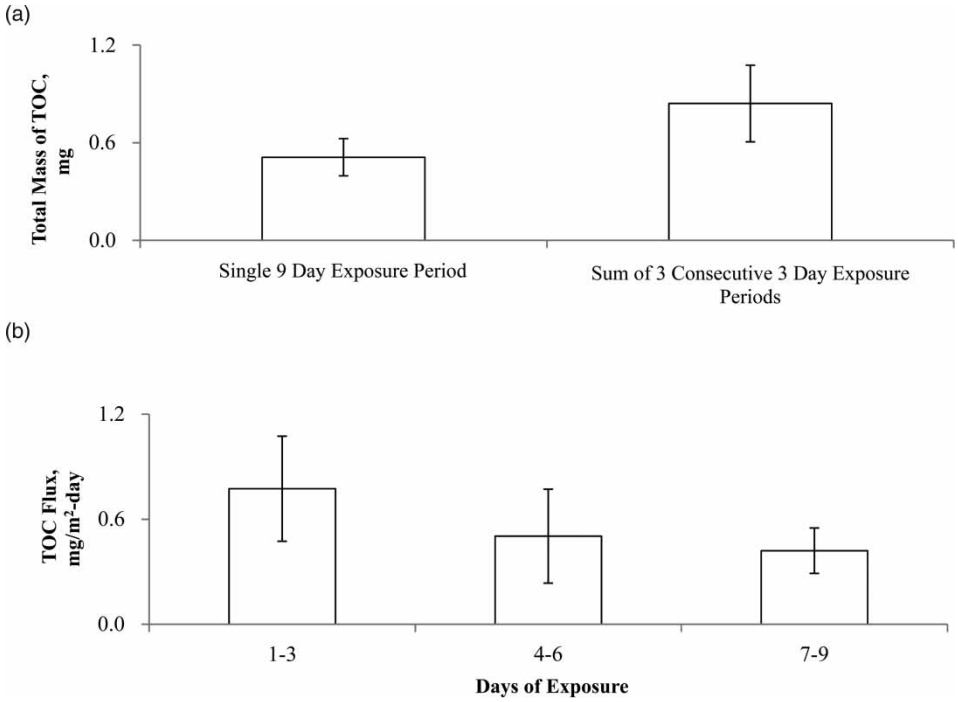

Figure 1 | Data summary for fill and empty frequency: (a) total mass of TOC and (b) TOC flux released from PEX-b1 pipe exposed to water for 9 days. Arithmetic mean and standard deviation values are shown. There is no PEX pipe TOC flux limit in the USA.

from PEX-b1 pipe's flux ($p < 0.001$) (Figure 2(a)). TOC flux changed for each pipe over the 9 day migration test ($p = 0.021$). This change is not as clearly pronounced as in Figure 1(a). PEX-b1 pipe flux ranged from 0.36 ± 0.12 mg/m^2-day to 0.46 ± 0.09 mg/m^2-day and PEX-b2 pipe flux ranged from 1.34 ± 0.10 mg/m^2-day to 1.59 ± 0.28 mg/m^2-day. Although the first and second migration tests showed changes in TOC flux over 9 days for PEX-b1 pipes, the rate of change differed between migration tests. This observed TOC flux difference for the same pipe brand during different migration tests indicates possible variations in PEX-b pipe manufacture between batches (Peacock 2001; Whelton & Nguyen 2013). Thus, it is possible the quality of the same pipe brand from the same manufacture may vary.

Odor results revealed that PEX-b1 pipe yielded a greater TON than PEX-b2 pipe at first (day 3) and last (day 9) fill and empty cycle. TON responses were similar for both pipes at the intermediate (day 6) fill and empty cycle. Both PEX-b pipe brands yielded TON responses greater than the USEPA SMCL for all exposure periods (Figure 3(a)). Other than those findings, no discernible odor pattern was found during the three exposure periods. Results indicate that longer PEX pipe investigations are needed to determine when contact water will meet the USEPA SMCL.

Newly installed pipe cleaning method

Results from the pipe cleaning method experiment revealed that certain cleaning methods caused the contact water to have greater TOC levels than other methods. Different combinations of brand and cleaning methods resulted in different degrees of TOC flux ($p = 0.006$) (Figure 2(b)). There was not a 'best' cleaning method identified. TOC flux values ranged from 1.1 to 3.8 mg/m^2-day and were similar to those reported by European investigators (Skjevrak *et al.* 2003; Koch 2004; Lund *et al.* 2011). When PEX-b2 pipe was cleaned using the IS method and PEX-b1 pipe was cleaned with the CPC method both contact waters yielded an average TOC flux greater than Norway's permissible TOC migration limit of 2.5 mg/m^2-day (Lund *et al.* 2011). TOC flux results were compared to Norway's TOC flux limit since there is no limit in the USA for polymer drinking water pipe. PEX-b1 pipe cleaned with the IS method exhibited the

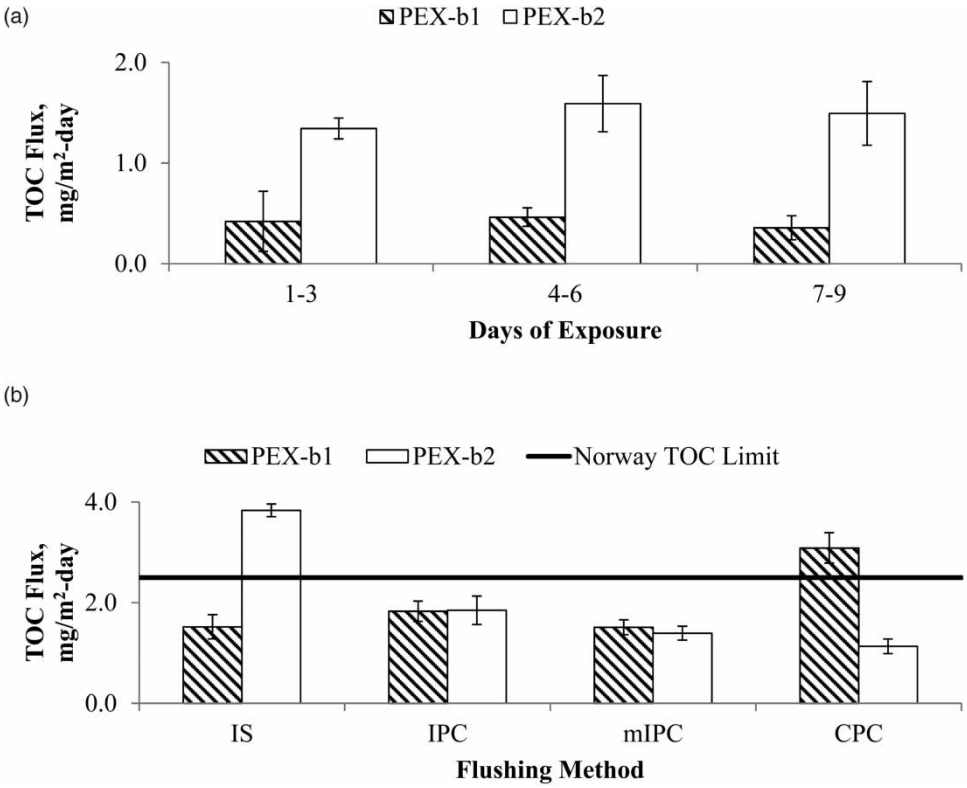

Figure 2 | Comparison of mean TOC flux from (a) two brands of PEX-b pipe exposed to water over 9 days with water changes every 3 days and (b) two brands of PEX-b pipe exposed to water for 3 days undergoing one of four cleaning methods. The shaded bar represents PEX-b1 pipe and the white bar represents PEX-b2 pipe. Arithmetic mean and standard deviation values are shown for TOC. The horizontal line for the TOC graph represents the Norwegian limit for TOC flux. There are no guidelines for TOC flux in the USA.

greatest TOC flux while PEX-b2 pipe cleaned with the CPC method exhibited the least TOC flux.

The TON data indicated that some brands imparted more odor when cleaned with specific methods. PEX-b2 pipe imparted more odor when combined with methods IS or mIPC. TON was unaffected by cleaning methods on PEX-b1 pipe. TON results for all brand method combinations exceeded the USEPA SMCL by at least a factor of five (Figure 4). Panelists described the PEX pipe contact water odor (no disinfectant was present) as having chemical, earthy, chlorine, and plastic smells. The TON responses from the brand and cleaning method experiments were similar to the TON response in the available literature. Skjevrak *et al.* (2003) and Lund *et al.* (2011) also measured TON responses greater than the USEPA SMCL for all exposure periods of 9 days or less. One limitation with these investigations is that they did not quantify TON values greater than five. Results in the present study quantified TON responses greater than five. No relationship was found between mean TOC flux and TON.

The crosslinking degradation byproduct ETBE was detected during the cleaning method study. Both PEX pipe brand ($p < 0.001$) and the cleaning method applied influenced ETBE results ($p < 0.001$). Ranking the cleaning method that generated the greatest to least ETBE concentration resulted in: mIPC for PEX-b1 pipe > CPC for PEX-b1 pipe > all remaining cleaning methods for both brands for which there was no statistical difference. Evidence suggests additional testing is needed to identify the chemicals responsible for PEX pipe drinking water odors. Results showed that ETBE was detected in PEX-b1 and PEX-b2 pipe contact waters and ranged from 6 to 20 μg/L (Figure 4). ETBE has been found by other investigators during PEX pipe migration experiments; Durand & Dietrich (2007) reported finding ETBE ranging from 23 to >100 μg/L in PEX-b pipe during a 9 day leaching study. Lund *et al.* (2011) detected ETBE concentrations ranging from 0.14 to 9.2 μg/L after a 9 day leaching studying two PEX-b pipes and three PEX-c pipes. ETBE was not detected in the six

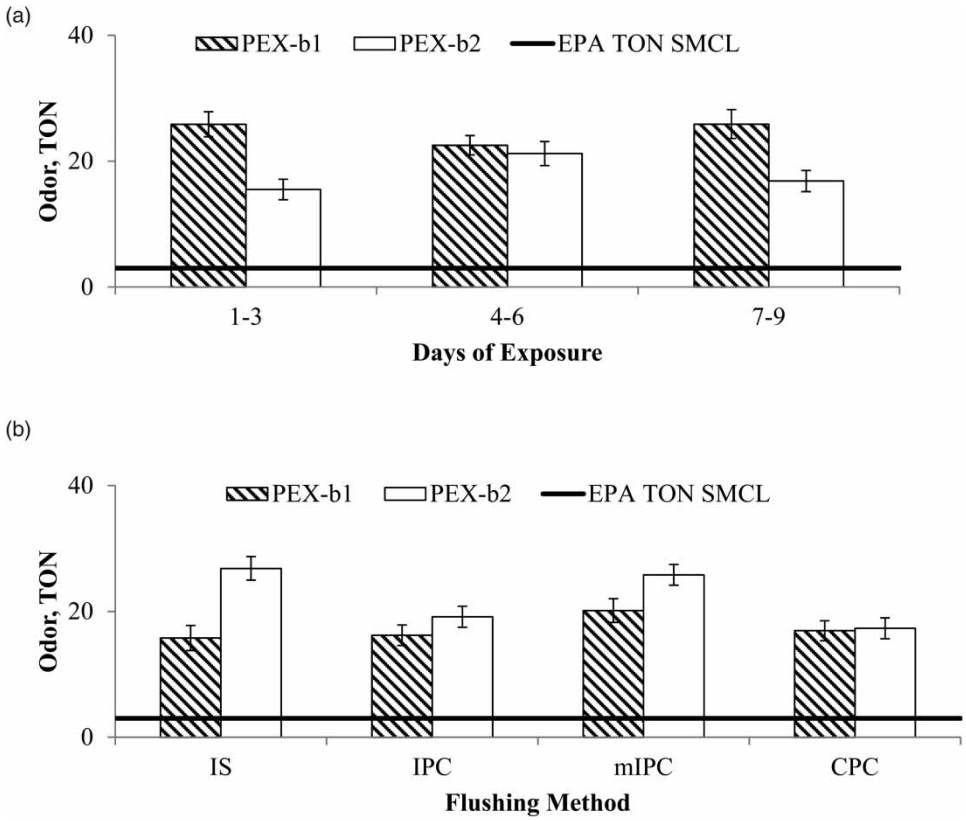

Figure 3 | Comparison of mean TON from (a) two PEX-b pipe brands exposed to water over 9 days with water changes every 3 days and (b) two PEX-b pipe brands exposed to water for 3 days after undergoing one of four cleaning methods. PEX-b1 pipe (shaded bar), PEX-b2 pipe (white bar); geometric mean and standard deviation values are shown. The horizontal line represents the USEPA SMCL = 3 TON.

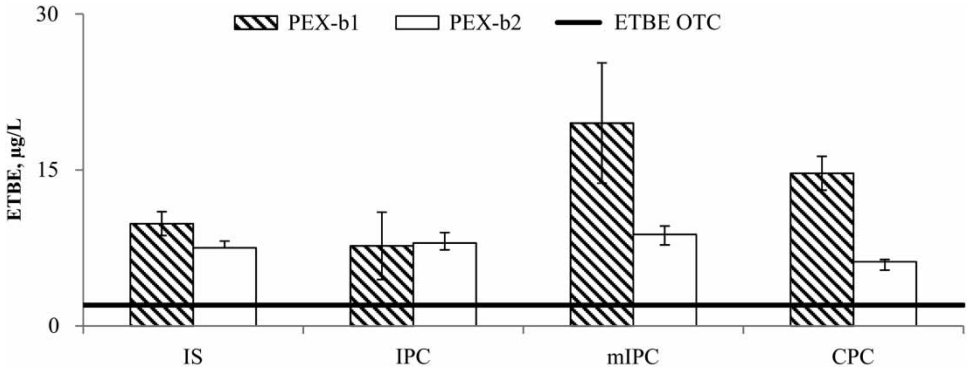

Figure 4 | ETBE results for two brands of PEX-b pipe were exposed to water for 3 days undergoing one of four cleaning methods. Shaded bar represents PEX-b1 pipe and white bar represents PEX-b2 pipe. Arithmetic mean and standard deviation values shown for ETBE concentration. The horizontal line for ETBE represents the concentration where people can detect an odor.

PEX-a brands tested, but odors were detected. Koch (2004) detected, but did not quantify ETBE in two multilayer pipes (PEX type not reported) and one PEX-c pipe.

Because ETBE's odor threshold concentration (OTC) is 2 µg/L (van Wezel *et al.* 2009), panelists likely detected ETBE odor during TON testing. However, panelists also

reported detecting odors in PEX pipe contact water that had been diluted five times below ETBE's 2 μg/L OTC. This result indicated that other contaminants were present in the water and were responsible for the panelists detecting drinking water odor. This finding was important since much of the literature has focused on quantification and odor characterization of ETBE in PEX pipe plumbing systems (Skjevrak *et al.* 2003; Koch 2004; Durand & Dietrich 2007; Chemaxx 2007; Lund *et al.* 2011). Additional drinking water odor examinations are needed to identify the agents responsible for PEX pipe caused odors. These efforts should consider flavor profile analysis (FPA) and use of a GC connected to an olfactory detector (ODP) called 'GC Sniff.' FPA is a highly sensitive chemical discrimination method that involves trained panelists (Khiari *et al.* 1999; Whelton & Dietrich 2004). The GC Sniff method has also been demonstrated to be effective at identifying contaminants present and determining their specific odors.

The observed TOC, TON, and ETBE differences are likely caused by differences in PEX pipe manufacture methods. Different amounts and types of organic contaminants are likely present in each material. Polymer characteristics (crosslink density and crystallinity) can also influence chemical leaching. Short-term exposure in the present study likely only represents contaminants being released into the water located near the polymer surface. Depth profiling contaminants through the pipe wall would provide additional understanding. The application of water testing methods capable of quantifying more polar organic and short-chain aliphatic contaminants may reveal additional understanding and help identify the odor agents.

CONCLUSION

Results showed that the cleaning method, exposure duration, and PEX-b pipe brand influenced contact water TOC and ETBE concentrations and odor quality with TON. Multiple 3 day stagnation periods for PEX pipe increased the total mass of organic carbon released compared to a single 9 day duration exposure. The 7 day stagnation period recommended by the CPC compared to a more frequent fill/empty cycle approach is not as effective if the purpose is to remove the greatest amount of organic chemicals before pipe use. To maximize TOC removal from newly installed pipes before use, pipe installers, homeowners, and water utility staff should consider filling and emptying the pipes repeatedly before use. Frequent water changes would provide greater TOC removal.

Two brands of PEX-b pipe caused initially odor free water to have odor ranging from 15 to 26 TON after 9 days. These values greatly exceeded the USEPA SMCL of 3 TON. The TON value represents the degree a drinking water must be diluted so that no detectable odor remains. While TON is a recognized drinking water standard in US federal and state drinking water regulations, it has its limitations. The primary limitation of the TON test is that the original water is diluted until odor is no longer detected and this phenomenon does not occur at customer taps.

Neither MTBE nor TBA were detected in PEX-b pipe contact waters during this study. ETBE was found ranging from 6.2 to 19.5 μg/L concentration for both PEX-b pipe brands. Panelists who conducted odor testing reported that water contained an odor when ETBE concentrations were below its 2 μg/L odor threshold concentration. This result implied contaminants other than ETBE were responsible for the drinking water odor. Future work specific to odor characterization should be carried out to identify the other odor causing contaminants. This action would enable PEX pipe manufacturing process optimization and assist building designers, homeowners, and water utilities to better understand how PEX pipes affect drinking water quality.

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