White Paper: A Review of Chemical Substances Shown to Leach from Common Drinking Water Piping Materials

Abstract

The use of plastic piping materials for residential and commercial drinking water, as well as concerns regarding the presence of substances potentially leaching into drinking water from such materials, are increasing worldwide. Here, we reviewed the literature regarding substances potentially leached from six plastic piping materials (polyethylene, cross-linked polyethylene, high-density polyethylene, polypropylene, chlorinated polyvinyl chloride, polyvinyl chloride) into drinking water, then identified data availability for these substances through evaluation of drinking water quality criteria or standards from a variety of sources. We compiled a list of 163 such substances and found that drinking water criteria or standards are available for 89 of 163. Conversely, 74 of 163 do not have established drinking water criteria/standards, including 17 of the 37 most frequently reported substances potentially leached from various plastic piping materials. These results can be used to prioritize substances or chemical groups for which further evaluation and research efforts may be warranted.

1. Introduction

The demand for piping material is increasing in the United States (US)[1] and abroad, driven by growth in the oil and natural gas industry as well as residential and non-residential building construction. In the US, for example, the demand for plastic piping materials in particular is expected to expand rapidly through 2018 (The Freedonia Group, 2016). Plastic piping materials are used for a variety of systems, including water mains; hot and cold water distribution; drain, waste, and vent (DWV); and sewer (PPFA, 2014a). Polyvinyl chloride (PVC) and high-density polyethylene (HDPE) are the leading plastic resins for piping due to their durability, flexibility, and corrosion resistance properties (The Freedonia Group, 2016).

In recent years, the public, consumers, industry, and government agencies have become increasingly interested in environmental exposures to chemical substances and the potential impact of these exposures on human health. This desire for transparency and an understanding of the presence and potential health effects of chemical substances in drinking water systems is demonstrated by recent efforts from government agencies that have prioritized drinking water quality and infrastructure for new policy and management programs in public works buildings (*e.g.*, CDC, 2013, 2014) and public water systems (PCAST, 2016; United States, Office of the White House, 2015). Recent analyses in the peer-reviewed

[1] US, United States; DWV, Drain, Waste, and Vent; PVC, Polyvinyl Chloride; HDPE, High-Density Polyethylene; PE, Polyethylene; PEX, Cross-linked Polyethylene; PP, Polypropylene; CPVC, Chlorinated Polyvinyl Chloride; TOC, Total Organic Carbon; AOC, Assimilable Organic Carbon; VOC, Volatile Organic Compound; UV, Ultraviolet; US EPA, US Environmental Protection Agency; MCL, Maximum Contaminant Level; GLI, Great Lakes Initiative; RSL, Regional Screening Level; PHG, Public Health Goal; WHO, World Health Organization; NSF, National Sanitation Foundation; ANSI, American National Standards Institute; TSCA, Toxic Substances Control Act; CCL 4, Contaminant Candidate List 4); UN, United Nations; MTBE, Methyl Tert-Butyl Ether; GC-MS, Gas Chromatography Coupled with Mass Spectrometry; GC-FID, Gas Chromatography Coupled with Flame Ionization Detector; MCLG, Maximum Contaminant Level Goal; LCR, Lead and Copper Rule.

literature further accentuate public and consumer requests for such information. Lee (2015), for example, developed a framework for selecting domestic piping materials and reported that "health considerations" had the greatest impact on consumer choice of piping material over all other factors (*e.g.*, environmental impact, cost, taste, and odor). Therefore, the aim of this analysis was to evaluate data availability for substances that can potentially leach into drinking water from these piping materials to assist in prioritizing substances for future research efforts and drinking water monitoring programs. Toxicological data assessment for individual substances is very time- and labor-intensive; for this analysis, we relied on the presence of drinking water standards or criteria from a combination of international and US-based lists as a proxy for the available toxicological data.

To this end, we performed a systematic survey of the published literature regarding substances potentially leaching from commonly used drinking water system piping materials. The analysis focused on six plastic piping materials: polyethylene (PE), cross-linked polyethylene (PEX), HDPE, polypropylene (PP), chlorinated polyvinyl chloride (CPVC), and PVC. The goals of the analysis were to: (1) compile a comprehensive list of substances cited as leaching from these materials, with the understanding that the methodology and collection techniques used in the studies surveyed would not be critically evaluated; and (2) identify drinking water standards and human health criteria related to these substances. As a result, we compiled an extensive list of substances that can potentially leach into drinking water systems from various piping materials. From this information, which piping products may influence drinking water quality as well as substances potentially leaching from those products that either have or lack established health-protective criteria can be identified. This information does not, however, allow for an evaluation of potential risks associated with these exposures. Detailed information on exposures (*e.g.*, levels in drinking water, other potential routes of exposure) and toxicity (*e.g.*, identifying target organ and endpoint, deriving safe exposure levels) is required for proper risk assessment regarding these substances in drinking water, and is not provided in this review.

It is worth noting that the pipe materials themselves are not the only materials that come into contact with drinking water throughout a piping system. The plastic piping materials, for example, often contain plastic fittings and solvent cement joints (PPFA, 2014b), which may be comprised of substances and materials that are different from that of the actual piping and may also contribute substances that can potentially leach into drinking water. For the purposes of this analysis, we focused on the pipe material itself, when possible, and excluded the presence of substances that have been explicitly reported as leaching from such additional materials.

2. Methods

2.1. Literature Review

We performed a comprehensive and systematic review of the literature on chemical substances potentially leaching from the six plastic piping materials (PE, PEX, HDPE, PP, CPVC, PVC) using the Scopus database, which is a comprehensive and expansive abstract and citation database of peer-reviewed scientific literature that captures over 21,500 peer-reviewed journals, 360 trade publications, and over 7.2 million conference papers (Elsevier B.V., 2016). We searched with terms that included the material name (*e.g.*, TITLE-ABS-KEY [*e.g.*, PVC OR "polyvinyl chloride"]) in conjunction with the following search terms: TITLE-ABS-KEY (pipes OR piping OR plumbing OR tubing) AND TITLE-ABS KEY (leaching OR leach OR leachate OR odor OR taste OR contaminated OR contaminants OR "water quality" OR chemicals OR chemical OR microbiological OR "byproducts" OR "bay products" OR microbial OR "organic carbon" OR "organic compounds" OR solvents). For completeness, we also reviewed the secondary references in the relevant studies identified.

From a review of the abstracts, 79 studies evaluating the six plastic piping materials that were potentially relevant to this analysis's objectives were identified. A full-text review of those 79 articles revealed a final 39 studies for inclusion in the analysis. Our inclusion criteria deemed a study relevant if it identified individual substances leaching from piping materials under conditions of the study and was presented in a peer-reviewed or government agency study or review article. Excluded studies included those that: did not measure individual substances (*e.g.*, provided measurements of total organic carbon [TOC], assimilable organic carbon [AOC], or volatile organic compounds [VOCs]); reported substances permeating through pipes or from dissolved piping materials; were not peer-reviewed (*e.g.*, academic dissertations); were reviews of studies already captured in the analysis; evaluated piping materials after significant physical manipulation (*e.g.*, after ultraviolet [UV] radiation exposure or material maceration); and/or evaluated substances specifically indicated as leaching from materials other than the piping (*e.g.*, cement joints).

2.2. Water Quality Criteria and Standards Screening

We screened all the identified substances against a comprehensive body of US-based and international water quality criteria and standards, including:

- US Environmental Protection Agency (US EPA) Maximum Contaminant Levels (MCLs) (US EPA, 2009);
- US EPA Great Lakes Initiative (GLI) Clearinghouse Database (US EPA, 2015, 2016a);
- US EPA Regional Screening Levels (RSLs) Table (US EPA, 2016b);
- California Environmental Protection Agency Public Health Goals (PHGs) (Howd *et al*., 2000; CalOEHHA, 2016);
- World Health Organization (WHO) Guidelines for Drinking-Water Quality (WHO, 2017);
- National Sanitation Foundation (NSF) International/American National Standards Institute (ANSI) for Drinking Water Additives Standard 61 (NSF International, 2015); and
- Health Canada Guidelines for Canadian Drinking Water Quality (Health Canada, 2017).

We also noted whether the substance was included in the US EPA Toxic Substances Control Act (TSCA) 2014 Work Plan (US EPA, 2014) or the US EPA Contaminant Candidate List 4 (CCL 4) (US EPA, 2016c), because inclusion in these sources is an indicator of potential future criteria being developed or investigation being conducted.

We primarily focused on federal (*e.g*., US EPA MCL list) and international lists, (*e.g*., NSF International standards and WHO criteria), and further included other lists (*e.g.*, from US state agencies and the TSCA Work Plan) to provide a representative array of chemical criteria. The NSF is a consortium led by NSF International to develop voluntary third-party consensus standards and a certification program for all direct and indirect drinking water additives. The NSF/ANSI Standard 61 is a voluntary protocol used to establish minimum requirements for substances and components that come into contact with drinking water, such as polymeric pipes (NSF International, 2015). Because the International Plumbing Code permits pipes to be used for potable water if they are NSF International 61-certified (International Code Council, Inc., 2009), the NSF standards are considered internationally relevant. The WHO's Guidelines for Drinking-Water Quality (WHO, 2017) are included to provide a broader perspective, because they pertain to issues of drinking water quality and health considered by "UN-Water," a body that coordinates among the 24 United Nations (UN) agencies and programs concerned with water issues.

The criteria and standards referenced in this effort are varied and have different objectives and derivation methodologies. The compilation of criteria serves to elucidate what toxicological data may be available for the individual chemical substances as well as to highlight data gaps. Brief descriptions of each of the criteria/standards and their threshold derivations are provided in Table 1. For the purposes of this analysis, we do not discuss which are most relevant for health or risk evaluation.

3. Results

3.1. Leachable Substances from Plastic Piping Materials

A total of 163 unique substances were identified from 39 studies as reportedly leaching from the six plastic piping materials evaluated (Table 2). This count includes four agents identified in studies with a generic or chemical group name, including: "aldehydes," "phenolics," "alkyl naphthalene," and "various C3- and C4-alkylated benzenes." As shown in Table 2, when stratified by piping material, the substances identified as having leached from PEX are the most common, followed by PVC and HDPE materials. We further characterized the substances by chemical structure and identified 38 separate chemical groups to which the 163 total identified substances belong. Some patterns emerge from this categorization – for example, halogenated compounds and hydrocarbons represent a sizable fraction of all the substances identified and are reported as having leached predominantly from CPVC and PVC materials. Similarly, the organotins are reported as having leached from PVC and CPVC only, and not from HDPE, PP, PE, or PEX. In contrast, the alkyl phenols (including alkyl phenol esters, acids, ester amides, aldehydes, and ketones) and quinones are all reported as having leached from HDPE, PE, PEX and/or PP materials, but not from PVC or CPVC. For other chemical groups, clear patterns regarding the types of plastic from which the chemicals have reportedly leached are not as easily discernable: aromatic hydrocarbons, phthalates, and vinyl compounds, for example, are reported as having leached from a variety of material types.

Due to the large number of identified substances (n = 163) reportedly leaching from plastic piping materials, we used a tiered approach to prioritize the substances based on the frequency with which they were identified in the studies surveyed. Frequency was assessed by counting the number of different plastic materials the substance reportedly leached from as well as the number of individual studies that identified that specific substance (see Table 3). As shown in Table 2, some of the most frequently identified substances included the alkyl phenols butylated hydroxytoluene and 2,4-di-tert-butylphenol, and the quinones 2,6-di-t-butyl-p-benzoquinone and 7,9-di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione, all of which are antioxidants and/or antioxidant degradation products. Such substances are intentionally added to and/or identified as degradation products present in certain plastic piping materials (*e.g.*, Denberg *et al*., 2009). Other frequently identified substances included solvents (*e.g.*, methyl tert-butyl ether [MTBE], toluene, tert-butyl alcohol) and various organotins (including butyltin, dimethyltin, dibutyltin, tributyltin, and trimethyltin). We note that many of the organotin substances were reported and discussed in the study text as the parent compound (*e.g.*, "dibutyltin"), but were actually detected as some derivatized tin species or the chloride salt. For consistency, we report the parent compound name as it is reported in the study text.

3.2. Drinking Water Criteria and Data Availability

We screened the 163 identified substances against each of the lists described above, in the water quality criteria and standards screening section, and discovered that drinking water criteria and/or standards are available for 55% of the identified substances (89 of 163), while 74 of the 163 identified substances did not have existing drinking water criteria from any authoritative agency or industry standard. Table 4 presents the drinking water criteria availability for the most commonly reported substances leaching from plastic piping materials in frequency tiers I, II, III (described in Table 3). Drinking water criteria and/or standards were available for the majority of these 56 substances (45 of 56), although the types of criteria/standards varied among substances. While many of the 45 substances in frequency tiers I, II, or III had established screening values from the US EPA (*i.e.*, RSLs; 29 of 45), only 14 had legally enforceable criteria put forth by the US EPA (*i.e.*, MCL values). Moreover, 15 of these 45 substances had only non-enforceable information from the NSF/ANSI industry standard. NSF/ANSI Standard 61 is a private industrial set of criteria that is intended to protect public health from short-term exposures to certain substances. These standards may not necessarily equate to compliance with current or future environmental regulations for the respective substances, due to the differences in derivation processes. For the most commonly reported substances leached from the largest number of plastic materials (*i.e.*, those in frequency tier I), about half (17 of 37) had either no criteria whatsoever, or no established drinking water criteria from any state or federal environmental agency (*e.g.*, US EPA).

In addition to the criteria and standards provided in Table 4, several of the substances are listed on US EPA priority lists, including the US EPA CCL 4 (US EPA, 2016c), a list of substances that are known or anticipated to be present in public water systems and for which no regulatory determinations exist (see Table 1), and the US EPA TSCA 2014 Work Plan (US EPA, 2014), which is a list of substances identified by the US EPA as warranting further assessment based on its high exposure and hazard potential. Of the 163 identified substances, 5 have been nominated for review on the CCL 4: methanol, formaldehyde, MTBE, 1,1,1,2-tetrachloroethane, and 1,3-butadiene. Twenty-four identified substances are listed in the TSCA 2014 Work Plan (US EPA, 2014): formaldehyde, bis(2-ethylhexyl)hexanedioate, benzene, ethyl benzene, naphthalene, m-xylene, o-xylene, p-xylene, styrene, bisphenol A, 1,2-dichloroethane, bromoform, carbon tetrachloride, dichloromethane, tetrachloroethylene, trichloroethylene, vinyl chloride, paraffin, antimony, lead, bis(2-ethylhexyl)phthalate, dibutyl phthalate, diisononyl phthalate, and 1,3-butadiene.

3.3. Leaching Test Methods

The evaluated studies utilized a wide variety of methodologies to measure substances leaching from plastic piping materials. For example, water samples were collected in distilled or deionized water under laboratory settings (*e.g.*, Connell *et al*., 2016) as well as from tap water in contact with operational and in-use drinking water systems (*e.g.*, Kowalska *et al.*, 2013; Walter *et al*., 2011). Samples were left in contact with piping materials over a multitude of durations, ranging from 20 minutes (Adams *et al*., 2011), to 30 days (*e.g.*, Kelley *et al*., 2014), to 2 years (Walter *et al*., 2011). Other factors that varied across studies included temperature, pH, water quality/hardness, as well as the detection methods used to analyze the samples (most frequently, gas chromatography coupled with mass spectrometry [GC-MS] or with flame ionization detector [GC-FID]). In addition, some studies evaluated the effects of various types of manipulation, including co-exposure to UV radiation or maceration of the piping material; the results of these manipulations were excluded from this analysis, based on the fact that these scenarios do not represent normal use conditions in drinking water systems.

Importantly, some of the conditions employed in these studies may not reflect typical environmental conditions; a critical review of the methodology and its impact on individual study results is beyond the scope of this review but can be found elsewhere (*e.g.*, Stern and Lagos, 2008). Therefore, the substances identified in Table 2 may be released from piping materials under certain chemical or physical conditions, but should not be assumed to always be present in drinking water when a particular piping material is utilized.

4. Discussion

This analysis compiled relevant studies that evaluated leachable substances from common drinking water piping materials. In doing so, it provides a comprehensive list of potential chemical substances that are capable of leaching from these plastic piping materials and the availability of drinking water criteria and standards for each identified substance from a variety of US-based and international lists.

For the purposes of this analysis and based on our knowledge of the derivation of the environmental health criteria and standards used here, we assumed that the existing water quality criteria and standards are indicative of at least a minimal set of toxicological data for the substances of interest (or similar analogue/chemical group) from which the health-based value was derived. However, the presence of such a value alone does not signify the robustness or quality of the available toxicological data. Due to the time and effort needed to develop and/or promulgate a state or federal criterion, some substances may not have an existing criterion even though there is an underlying toxicological database available for that substance. Therefore, this evaluation may underrepresent the toxicity data available for the substances listed in Tables 2 and 4. Conversely, a criterion may be based on a minimal dataset (*e.g.*, one chronic oral exposure study), while additional information on the substances' potential health effects (*e.g.*, reproductive, developmental, endocrine) may be lacking; thus, the presence of a criterion does not necessarily indicate the robustness of the underlying toxicological data.

There are some limitations to this analysis. Specifically, we did not critically evaluate the methods used for sample collection and processing in the studies surveyed, both of which can significantly influence the types and concentrations of the substances identified in those studies. Some of the key factors that affect substances leaching from piping materials include water quality, pH, sampling duration, the age of the materials, temperature, and exposure to UV radiation or other gross manipulations (reviewed in Stern and Lagos, 2008; Whelton and Nguyen, 2013). In some cases (*e.g.*, analysis of tap water samples), some of the substances identified in water may be present in the water supply itself, rather than leached from the pipe material being study. A critical review of these factors for the studies included here is beyond the scope of this analysis, but would provide more information on the applicability and "generalizability" of this analysis's results to typical environmental conditions.

Even with these limitations, the results of this analysis may help identify and prioritize substances for future drinking water quality monitoring. Specifically, the presence or absence of drinking water criteria and standards from an group of international and US-based sources, such as the six presented here, provide a robust snapshot of the current regulatory landscape pertaining to these substances within the US and abroad. In doing so, this review provides an easily accessible list that can help prioritize future monitoring and research efforts for substances that are potentially present in drinking water systems around the world for which drinking water and human health criteria do not currently exist. In addition to prioritizing substances that have been identified by multiple studies and as leaching from multiple different plastic piping materials (frequency criteria described in Table 1), the results in Table 2 further allow the identified substances to be divided into several chemical groups. This grouping may contribute to prioritizing chemical classes or indications of other chemicals in the same class for future evaluation, which may aid in streamlining future assessments for industries and governmental agencies saddled with hundreds to thousands of potential chemical substances to review for drinking water evaluations.

As different substances were detected across different polymeric materials, these results may also help characterize profiles of potentially leachable substances from the different classes of materials (*i.e.*, PE, PEX, HDPE, PP, CPVC, and PVC). However, as discussed by Stern and Lagos (2008), different substance profiles have been measured in water from pipe segments of the same polymeric materials from different manufacturers, and thus such observations appear to depend not only on material type and the aforementioned factors (*e.g.*, pH, water quality, use conditions), but also on the processes by which they are manufactured. This point requires further investigation into manufacturing processes and standards in place that may result in different formulations and the ultimate reactivity of the materials.

Importantly, the lists of substances provided in Tables 2 and 4 neither identify toxicological hazards nor indicate or imply risks to human health. Detailed analysis of the toxicological information for each substance, as well as substantial exposure characterization, is necessary to perform a proper assessment of any associated health hazards or risks to human health potentially posed by these substances. In addition, the water quality criteria and standards used in this analysis cover a broad range of criteria with diverse objectives. While the majority of the criteria are based in some way on health effects, many of these values are screening-level criteria and/or purposefully derived to reflect conservative assumptions. The US EPA MCL Goal (MCLG) for lead, for example, is zero, but enforces an action level of 0.015 mg/L based on technical feasibility limitations. A detailed review and understanding of each criterion is needed before any conclusions can be drawn about the significance of the measured substance concentrations in drinking water.

Lastly, the results of this analysis are useful to contrast with what is known for other commonly used piping materials, such as copper. Plastic and copper piping materials represent the most commonly used materials for residential plumbing since the decline of other kinds of piping for these uses, such as a galvanized steel piping (WHO and World Plumbing Council, 2006). Copper has been used extensively for residential and non-residential tubing and piping purposes for over 75 years, typically because of its corrosion resistance, machinability, antibacterial properties, and high level of heat transfer (CDA, 2016a). The majority of copper tubing produced is manufactured with a specific copper alloy, C12200, which is comprised of ≥99.9% copper and ≤0.04% phosphorous (CDA, 2016a,b). Studies evaluating copper piping materials generally do not discuss leaching in the same way as those evaluating plastic piping materials, but rather focus on characterizing and measuring factors that contribute to the corrosion and pitting of copper pipes, which is considered a multifaceted and complex phenomenon (see, for example, Dietrich *et al*., 2004; Merkel and Pehkonen, 2006; NRC, 2000). These factors include water quality parameters (*e.g.*, pH, hardness, temperature, dissolved oxygen, oxidizing and complexing agents, other ion concentration) as well as use conditions, such as the duration of water stagnation and the age of the pipes (NRC, 2000; Turek *et al*., 2011; Lagos *et al*., 2001; Gonzalez *et al*., 2013). As with the leaching of substances in plastic pipes, these parameters will ultimately affect the rate and extent of scaling and oxidation on the copper pipes, which in turn contributes to the amount and types of byproducts, ions, and/or particulates that may leach into the water from the pipes. As such, current regulations and research efforts regarding the use of copper plumbing in drinking water systems largely focus on corrosion control and monitoring (US EPA, 1991, 2008; Nyongbela and Johannsen, 2015; Lytle *et al*., 2012).

Because copper is primarily composed of one substance (*i.e*., 99.9% copper) and tightly constrained by alloy specifications (CDA, 2016a), the majority of solid corrosion byproducts reported to form on and leach from copper piping include numerous soluble and insoluble copper compounds (reviewed in Merkel and Pehkonen, 2006; Lagos *et al*., 2001). In pure water, substances containing the copper(II) ion, such as cuprite and tenorite, are the most common and readily form hydroxide and carbonate ion complexes (WHO 2004; US EPA, 1995; Lagos *et al*., 2001). Other copper substances, such as copper sulfate or phosphate compounds, are formed to a lesser degree, and the addition of agents (*e.g.*, orthophosphate) affecting copper solubility and compound formation has been explored as a means of controlling copper pipe corrosion (US EPA, 1995).

Lead has also been identified as a corrosion byproduct in drinking water systems that use copper pipes; however, this substance is likely leaching from older lead pipes in the same system, lead solders and fluxes used to connect copper pipes, and/or alloys containing lead (*e.g.*, brass), and not from the copper material itself (US EPA, 1991; Kimbrough, 2007; Vilarinho *et al.*, 2004). Lead and copper substances in drinking water are regulated by US EPA under their established action levels or MCL/MCLGs, respectively, and the Lead and Copper Rule (LCR), which provides extensive guidance and rules for lead and copper treatment, monitoring, and control (US EPA, 1991; NDWAC, 2015).

Our review of the literature highlights a number of substances that can potentially leach from commonly used plastic piping materials (under certain environmental conditions) into drinking water. It is important to emphasize that the substances identified in this analysis have not all been identified under actual use scenarios in drinking water systems, and that the mere presence of such substances in water do not necessarily present a health risk. Future research efforts may build upon this analysis to prioritize substances or chemical groups for additional data collection. In order to adequately assess public health risks, additional characterization of the exposure levels and potential health hazards of leachable substances in drinking water systems is warranted.

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Table 1. Drinking Water Quality Criteria and Standards

Organization (Reference)	Criteria	Criteria Basis	Enforcement and General Information
US EPA (2009, 2015, 2016a,b,c)	MCL	Derived based on the US EPA MCLGs (Health Goals); considers treatment technologies, costs, and other feasibility factors.	• Maximum concentration of a chemical that is allowed in public drinking water systems. • Legally enforceable.
	GLI Clearinghouse	Compilation of criteria provided by US state environmental agencies (Indiana, Minnesota, New York, Ohio, and Wisconsin).	• Provides human health, aquatic life, and wildlife criteria. • Human health criteria are based on water consumption, fish consumption, and/or fish and water consumption. • Not legally enforceable.
	RSL	Derived from standardized equations combining exposure assumptions with US EPA toxicity data.	• Media-specific (air, soil, water) health-protective values over a lifetime of exposure. • RSLs are screening values, not *de facto* cleanup standards. • Practical risk management factors are not considered. • Not legally enforceable.

Organization (Reference)	**Criteria**	**Criteria Basis**	**Enforcement and General Information**
	CCL 4	A list of substances for which no regulatory determinations exist, are known or anticipated to occur in public water systems, and have been nominated for review.	• Publication of the CCL does not impose any requirements on public water systems. • May require future regulation under the Safe Drinking Water Act (SDWA); SDWA requires US EPA to publish the CCL every 5 years.
CalEPA (Howd *et al*., 2000; CalOEHHA, 2016)	PHG	Health-protective value in drinking water set by CalEPA (US).	• Practical risk management factors are not considered. • Not legally enforceable.
WHO (2017)	Health-based targets	Established based on international risk assessments of health effects associated with exposure to the chemical in water.	• Scientifically based point of departure for development of national or regional drinking water quality standards. • Not legally enforceable.
NSF/ANSI (NSF International, 2015)	MCL; MAC; TAC; SPAC; STEL	Provides a reference of known and derived water quality criteria, including: MCLs (US EPA); MACs (Health Canada); and TACs, SPACs, and STELs derived by NSF.	• NSF/ANSI 61 establishes minimum requirements to protect against potential adverse human health effects from products that come into contact with drinking water (*e.g.*, piping systems). • Not legally enforceable.

Organization (Reference)	Criteria	Criteria Basis	Enforcement and General Information
Health Canada (2017)	MAC; AO; OG	Derived based on a comprehensive review of health effects associated with each contaminant; considers treatment technologies and the benefit of the substance in the disinfection processes.	• The Guidelines for Canadian Drinking Water Quality are established by the Federal-Provincial-Territorial Committee on Drinking Water (CDW) and published by Health Canada. • It is largely the responsibility of municipal governments to maintain drinking water quality standards set out by the Federal-Provincial-Territorial Committee on Drinking Water. • Not legally enforceable.

Notes:

ANSI = American National Standard Institute; AO = Aesthetic Objective; CalEPA = California Environmental Protection Agency; CalOEHHA = California Office of Environmental Health Hazard Assessment; CCL 4 = Contaminant Candidate List 4; GLI = Great Lakes Initiative; MAC = Maximum Allowable/Acceptable Concentration; MCL = Maximum Contaminant Level; MCLG = Maximum Contaminant Level Goal; NSF = National Sanitation Foundation; OG = Operational Guidance Value; PHG = Public Health Goal; RSL = Regional Screening Level; SPAC = Single Product Allowable Concentration; STEL = Short-term Exposure Level; TAC = Total Allowable Concentration; US = United States; US EPA = US Environmental Protection Agency; WHO = World Health Organization.

Table 2. Substances Potentially Leaching from Commonly Used Plastic Piping Materials

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Acetophenone derivatives	1378888-43-7	1-(3-Ethyl-4-(hydroxymethyl) phenyl)ethanone	✓	✓	✓				36[b]
Acetophenone derivatives	30773-71-8	1,1'-(Phenylene)bisethanone	✓	✓	✓				36[b]
Acetophenone derivatives	98-86-2	Acetophenone	✓	✓	✓				27, 36[b]
Acrylates/methacrylates	140-88-5	Ethyl acrylate					✓	✓	36[b]
Alcohols	19550-30-2	1-Butanol, 2,3-dimethyl				✓			27
Alcohols	137-32-6	1-Butanol, 2-methyl-				✓			27
Alcohols	110-03-2	2,5-dimethyl-2,5-hexanediol	✓	✓	✓				12, 36[b]
Alcohols	104-76-7	2-Ethyl-1-hexanol			✓		✓	✓	12, 21, 27
Alcohols	58175-57-8	2-Propyl-1-pentanol		✓					25
Alcohols	67-56-1	Methanol	✓	✓	✓				36[b]
Alcohols	111-87-5	n-Octanol			✓				27
Alcohols	75-65-0	tert-Butyl alcohol	✓	✓	✓				19, 28, 34, 36[b]
Aldehydes	96-17-3	2-Methylbutanal						✓	21
Aldehydes	78-84-2	2-Methylpropanal						✓	21

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Aldehydes	107-86-8	3-Methyl-2-butenal	✓	✓	✓				36[b]
Aldehydes	Generic name	Aldehydes	✓						3, 4, 5[c]
Aldehydes	112-31-2	Decanal	✓		✓			✓	12, 21, 34
Aldehydes	50-00-0	Formaldehyde					✓	✓	36[b]
Aldehydes	66-25-1	Hexanal						✓	34
Aldehydes	124-19-6	Nonanal	✓		✓			✓	12, 21, 34
Aldehydes	124-13-0	Octanal						✓	34
Aldehydes	110-62-3	Pentanal						✓	21
Aldehydes, aromatic	22927-13-5	2-Ethylbenzaldehyde				✓			27
Aldehydes, aromatic	4748-78-1	4-Ethylbenzaldehyde				✓			27
Alkanes	1560-93-6	2-Methyl pentadecane			✓				9, 19
Alkanes	2882-96-4	3-Methyl pentadecane			✓				9, 19
Alkanes	629-78-7	n-Heptadecane			✓				9, 19
Alkanes	544-76-3	n-Hexadecane			✓				9, 19
Alkanes	629-62-9	n-Pentadecane			✓				9, 19
Alkyl phenol	128-37-0	Butylated hydroxytoluene	✓	✓	✓				30, 34, 36,[b] 39

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Alkyl phenol acids/esters	20170-32-5	3-(3,5-Di-tert-butyl-4-hydroxyphenyl)propanoic acid			✓				27
Alkyl phenol acids/esters	6683-19-8	Benzenepropanoic acid, 3,5-bis(1,1-dimethylethyl)-4-hydroxy-, 1,1'-(2,2-bis((3-(3,5-bis(1,1-dimethylethyl)-4-hydroxyphenyl)-1-oxopropoxy)methyl)-1,3-propanediyl) ester		✓					22
Alkyl phenol acids/esters	6386-38-5	Methyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate	✓	✓	✓				9, 10, 19, 27, 32, 36[b]
Alkyl phenol acid/ester (oxidized)	No CAS No.	Cyclohexa-1,4-diene-1,5-bis(tert-butyl), 6-one, 4-(2-carboxy-ethylidene)			✓				8
Alkyl phenol aldehydes	1620-98-0	3,5-Di-tert-butyl-4-hydroxybenzaldehyde		✓	✓	✓			8, 10, 25, 27, 32

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Alkyl phenol ester amides	70331-94-1	Naugard XL-1		✓					22
Alkyl phenol ketone	14035-33-7	3,5-Di-tert-butyl-4-hydroxyacetophenone		✓	✓				8, 10, 32
Alkyl phenols	96-76-4	2,4-Di-tert-butylphenol	✓	✓	✓	✓			9, 10, 16, 19, 25, 27, 28, 32, 34, 35
Alkyl phenols	4130-42-1	2,6-Di-tert-butyl-4-ethylphenol	✓						3, 4, 5[c]
Alkyl phenols	128-39-2	2,6-Di-tert-butylphenol		✓	✓				25, 28
Alkyl phenols	2409-55-4	2-t-Butyl-4-methylphenol	✓						20
Alkyl phenols	121-00-6	2-tert-Butyl-4-methoxyphenol			✓				29
Alkyl phenols	122-94-1	4-Butoxyphenol			✓				34
Alkyl phenols	1709-70-2	Irganox 1330		✓					22
Alkyl phenols	Generic name	Phenolics	✓	✓	✓				36[b]
Amides	No CAS No.	Diazadiketo-cyclo-tetradecane	✓	✓	✓				36[b]
Aniline derivatives	101-67-7	4,4'-Dioctyldiphenylamine			✓				9, 19

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Aniline derivatives	121-69-7	N,N-Dimethylaniline					✓	✓	24
Aromatic hydrocarbons	1014-60-4	1,3-Di-tert-butylbenzene			✓				9, 28
Aromatic hydrocarbons	1012-72-2	1,4-Di-tert-butylbenzene	✓	✓	✓				36[b]
Aromatic hydrocarbons	Generic name	Alkyl naphthalene	✓						3, 4, 5[c]
Aromatic hydrocarbons	71-43-2	Benzene	✓	✓	✓			✓	20, 21, 34, 36[b]
Aromatic hydrocarbons	110-82-7	Cyclohexane			✓				9
Aromatic hydrocarbons	100-41-4	Ethyl benzene	✓					✓	21, 34
Aromatic hydrocarbons	1319-73-9	Methylstyrene	✓						20
Aromatic hydrocarbons	108-38-3	m-Xylene						✓	21
Aromatic hydrocarbons	91-20-3	Naphthalene	✓						34
Aromatic hydrocarbons	95-47-6	o-Xylene			✓			✓	9, 21
Aromatic hydrocarbons	106-44-4	p-Cresol			✓				9
Aromatic hydrocarbons	106-42-3	p-xylene			✓			✓	9, 21
Aromatic hydrocarbons	108-88-3	Toluene	✓		✓	✓		✓	9, 19, 20, 21, 27, 34
Aromatic hydrocarbons	Generic name	Various C3- and C4-alkylated	✓						34

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
		benzenes							
Aromatic hydrocarbons	1330-20-7	Xylene(s)	✓		✓				12, 34
Aromatic hydrocarbons, phosphite	31570-04-4	Tris(2,4-ditert-butylphenyl) phosphite		✓					22
Aromatic hydrocarbons/ vinyl compounds	100-42-5	Styrene	✓				✓	✓	20, 21, 24, 34
Biolefinic steroid	1224-94-8	Androsta-5,16-dien-3beta-ol			✓				9
Bisphenol compounds	80-05-7	Bisphenol A	✓	✓	✓				36[b]
Epoxides	106-89-8	Epichlorohydrin					✓	✓	24
Epoxides	106-92-3	Oxirane, ((2-propenyloxy)methyl)-	✓	✓	✓				36[b]
Esters	No CAS No.	1,3-diol diisobutyrate	✓						3, 4, 5[c]
Esters	6846-50-0	2,2,4-trimethyl-1,3-pentanediol diisobutyrate	✓						34
Esters	103-23-1	Bis(2-ethylhexyl) hexanedioate			✓				9, 19
Esters	123-86-4	Butyl acetate	✓						34

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Esters	109-21-7	Butyl butyrate			✓				12
Esters	626-82-4	Butyl hexanoate	✓						34
Esters	3025-30-7	Ethyl decadienoate	✓						34
Esters	123-66-0	Ethyl hexanoate	✓						34
Esters	106-32-1	Ethyl octanoate	✓						34
Esters	142-92-7	Hexyl acetate	✓						34
Esters	2639-63-6	Hexyl butanoate	✓						34
Esters	6378-65-0	Hexyl hexanoate	✓						34
Esters	108-21-4	Isopropyl acetate	✓						34
Esters	626-77-7	Propyl hexanoate	✓						34
Esters	540-88-5	tert-Butyl acetate			✓				27
Esters	77-93-0	Triethyl citrate			✓				9
Ethers	629-82-3	1-Oxtoxyoctane			✓				27
Ethers	126-84-1	2,2-Diethoxypropane			✓				12
Ethers	637-92-3	Ethyl tert-butyl ether			✓				9, 12, 18, 19, 28

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Ethers	33021-02-2	Isopropyl tert-butyl ether			✓				34
Ethers	1634-04-4	Methyl tert-butyl ether	✓		✓				10, 19, 20, 28, 34
Fatty acids	1592-23-0	Calcium stearate					✓	✓	36[b]
Fatty acids	334-48-5	Decanoic acid			✓				27
Fatty acids	143-07-7	Dodecanoic acid			✓				27
Fatty acids	124-07-2	Octanoic acid			✓				27
Halogenated	25167-80-0	Chlorophenol					✓	✓	36[b]
Halogenated	598-99-2	Methyl trichloroacetate			✓				9, 19
Halogenated hydrocarbons	630-20-6	1,1,1,2-Tetrachloroethane			✓				9, 19
Halogenated hydrocarbons	71-55-6	1,1,1-Trichloroethane						✓	21
Halogenated hydrocarbons	107-06-2	1,2-Dichloroethane						✓	21
Halogenated hydrocarbons	75-25-2	Bromoform						✓	21
Halogenated hydrocarbons	56-23-5	Carbon tetrachloride					✓	✓	11, 21
Halogenated hydrocarbons	67-66-3	Chloroform					✓	✓	11, 21
Halogenated hydrocarbons	156-59-2	cis-1,2-Dichloroethylene					✓	✓	24

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Halogenated hydrocarbons	124-48-1	Dibromochloromethane						✓	21
Halogenated hydrocarbons	75-27-4	Dichlorobromomethane						✓	21
Halogenated hydrocarbons	75-09-2	Dichloromethane						✓	21
Halogenated hydrocarbons	127-18-4	Tetrachloroethylene						✓	21
Halogenated hydrocarbons	79-01-6	Trichloroethylene	✓	✓	✓			✓	21, 36[b]
Halogenated hydrocarbons	27154-33-2	Trichlorofluoroethane						✓	21
Halogenated hydrocarbons	75-69-4	Trichlorofluoromethane						✓	21
Halogenated/vinyl compounds	75-01-4	Vinyl chloride					✓	✓	2, 6, 13, 36,[b] 37
Heterocycles	102-06-7	1,3-Diphenylguanidine	✓						35
Heterocycles	15045-43-9	2,2,5,5-Tetramethyloxolane			✓				27
Heterocycles	95-16-9	Benzothiazole	✓	✓	✓				36[b]
Heterocycles	110-86-1	Pyridine			✓				9, 19
Heterocycles	109-99-9	Tetrahydrofuran	✓	✓	✓		✓	✓	7, 36,[b] 38
Hydrocarbons	74663-85-7	Nonylcyclopropane	✓	✓	✓				36[b]
Hydrocarbons	8002-74-2	Paraffin					✓	✓	36[b]

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Hydrocarbons	9002-88-4	Polyethylene wax					✓	✓	36[b]
Inorganic	471-34-1	Calcium carbonate					✓	✓	36[b]
Inorganic	1333-86-4	Carbon black					✓	✓	36[b]
Inorganic	75-15-0	Carbon disulfide	✓	✓	✓				36[b]
Inorganic	13463-67-7	Titanium dioxide					✓	✓	36[b]
Ketones	693-54-9	2-Decanone	✓						34
Ketones	6175-49-1	2-Dodecanone	✓						34
Ketones	6137-06-0	2-Heptanone, 4-methyl-				✓			27
Ketones	112-12-9	2-Undecanone	✓						34
Ketones	110-12-3	5-Methyl-2-hexanone			✓				10, 28, 34
Ketones	830-13-7	Cyclododecanone		✓					27
Ketones	108-94-1	Cyclohexanone	✓	✓	✓		✓	✓	7, 36[b]
Ketones	120-92-3	Cyclopentanone	✓	✓	✓				36[b]
Ketones	No CAS	Dicyclopentylone	✓	✓	✓				36[b]
Ketones	141-79-7	Mesityl oxide			✓				34
Ketones	78-93-3	Methyl ethyl ketone					✓	✓	7, 38

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Metals	7440-36-0	Antimony					✓	✓	36[b]
Metals	7439-89-6	Iron				✓		✓	23
Metals	7439-92-1	Lead				✓			23
Metals	7440-31-5	Tin						✓	31
Organotins	2406-65-7	Butyltin					✓	✓	7, 14, 15, 17, 31, 33, 36[b]
Organotins	1002-53-5	Dibutyltin					✓	✓	1, 14, 15, 17, 31, 33, 36[b]
Organotins	23120-99-2	Dimethyltin					✓	✓	1, 7, 33
Organotins	15231-44-4	Di-n-octyltin						✓	15
Organotins	16408-15-4	Methyltin						✓	33
Organotins	688-73-3	Tributyltin					✓	✓	15, 17, 36[b]
Organotins	1631-73-8	Trimethyltin					✓	✓	7, 33
Peroxides	110-05-4	Di-tert-butyl peroxide			✓				28
Phthalates	117-81-7	Bis(2-ethylhexyl)phthalate					✓	✓	26, 36[b]
Phthalates	No CAS No.	Butyl-2-methoxyethyl-			✓				9

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
		phthalate							
Phthalates	84-74-2	Dibutyl phthalate		✓			✓		25, 27
Phthalates	28553-12-0	Diisononyl phthalate					✓	✓	36[b]
Quinones/quinone derivatives	106-51-4	1,4-Benzoquinone	✓	✓	✓				36[b]
Quinones/quinone derivatives	719-22-2	2,6-Di-t-butyl-p-benzoquinone	✓	✓	✓				3, 4, 5,[c] 10, 27, 28, 29, 32, 34
Quinones/quinone derivatives	82304-66-3	7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione	✓	✓	✓	✓			9, 10, 19, 25, 27, 36[b]
Terpenoids	502-61-4	alpha-Farnesene	✓						34
Terpenoids	80-56-8	alpha-Pinene	✓						34
Terpenoids	13466-78-9	delta-Carene	✓						34
Terpenoids	138-86-3	Limonene	✓						34
Terpenoids	586-62-9	Terpinolene	✓						34
Vinyl compounds	106-99-0	1,3-Butadiene					✓	✓	36[b]
Vinyl compounds	763-32-6	3-Methylbut-3-en-1-ol			✓				27

Chemical Grouping	CAS No.	Substance Name	Piping Material						Source[a]
			HDPE	PE	PEX	PP	CPVC	PVC	
Vinyl compounds	115-11-7	Isobutylene	✓	✓	✓				28, 36[b]
Vinyl compounds	60766-00-9/ 115-18-4	Methylbutenol	✓	✓	✓				36[b]
Vinyl compounds	108-05-4	Vinylacetate					✓	✓	24

Notes:

CPVC = Chlorinated Polyvinyl Chloride; HDPE = High-density Polyvinyl Chloride; PE = Polyethylene; PEX = Cross-linked Polyethylene; PP = Polypropylene; PVC = Polyvinyl Chloride.

[a]Corresponding reference list provided in Supplemental Table S1.

[b]Study did not specify whether substances were identified from individual materials and grouped plastic materials together. The groups included: "HDPE; PE; PEX" and "PVC; CPVC" and, in the absence of clarifying information, we conservatively assumed the identified substances are leached from all materials listed in the group.

[c]References 3, 4, and 5 are separate publications presenting the same data and should not be considered separate studies.

Table 3. Substance Identification Frequency

Frequency Tier[a]	Substance Identification Criteria				Number of Substances
	One Material	Two or More Materials	One Study	Two or More Studies	
I		X		X	37
II	X			X	13
III		X	X		6
IV	X		X		107
				Total:	**163**

Note:

[a]Tier I = Highest frequency, to Tier IV = Lowest frequency.

Table 4. Available Drinking Water Quality Criteria and Standards for Select Substances

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
Tier I											
Acetophenone derivatives	98-86-2	Acetophenone	HDPE; PE; PEX		✓	✓		✓			27, 36[b]
Alcohols	110-03-2	2,5-Dimethyl-2,5-hexanediol	HDPE; PE; PEX					✓			12, 36[b]
Alcohols	104-76-7	2-Ethyl-1-hexanol	CPVC; PVC; PEX					✓			12, 21, 27
Alcohols	75-65-0	tert-Butyl alcohol	HDPE; PE; PEX					✓			19, 28, 34, 36[b]
Aldehydes	112-31-2	Decanal	HDPE; PEX; PVC								12, 21, 34
Aldehydes	124-19-6	Nonanal	HDPE; PEX; PVC					✓			12, 21, 34
Alkyl phenol acids/esters	6386-38-5	Methyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate	HDPE; PE; PEX					✓			9, 10, 19, 27, 32, 36[b]
Alkyl phenol aldehydes	1620-98-0	3,5-Di-tert-butyl-4-	PE; PEX; PP					✓			8, 10, 25, 27,

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
		hydroxybenzaldehyde									32
Alkyl phenol ketones	14035-33-7	3,5-Di-tert-butyl-4-hydroxyacetophenone	PE; PEX								8, 10, 32
Alkyl phenols	96-76-4	2,4-Di-tert-butylphenol	HDPE; PE; PEX; PP					✓			9, 10, 16, 25, 27, 28, 32, 34, 35, 36[b]
Alkyl phenols	128-39-2	2,6-Di-tert-butylphenol	PE; PEX					✓			25, 28
Alkyl phenols	128-37-0	Butylated hydroxytoluene	HDPE; PE; PEX			✓					30, 34, 36,[b] 39
Aromatic hydrocarbons	71-43-2	Benzene	HDPE; PE; PEX; PVC	✓	✓	✓	✓	✓	✓	✓	20, 21, 34, 36[b]
Aromatic hydrocarbons	100-41-4	Ethyl benzene	HDPE; PVC	✓	✓	✓	✓	✓	✓	✓	21, 34
Aromatic hydrocarbons	95-47-6	o-Xylene	PEX; PVC	✓	✓	✓	✓	✓			9, 21
Aromatic hydrocarbons	106-42-3	p-xylene	PEX; PVC	✓	✓	✓	✓	✓			9, 21
Aromatic hydrocarbons	108-88-3	Toluene	HDPE; PEX; PP;	✓	✓	✓	✓	✓	✓	✓	9, 19, 20, 21,

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
			PVC								27, 34
Aromatic hydrocarbons	1330-20-7	Xylene(s)	HDPE; PEX	✓	✓	✓	✓		✓	✓	12, 34
Aromatic hydrocarbons/ vinyl compounds	100-42-5	Styrene	HDPE; CPVC; PVC	✓	✓	✓	✓	✓	✓		20, 21, 24, 34
Ethers	1634-04-4	Methyl tert-butyl ether	HDPE; PEX		✓	✓	✓			✓	10, 19, 20, 28, 34
Halogenated hydrocarbons	56-23-5	Carbon tetrachloride	CPVC; PVC	✓	✓	✓	✓	✓	✓	✓	11, 21
Halogenated hydrocarbons	67-66-3	Chloroform	CPVC; PVC		✓	✓		✓	✓		11, 21
Halogenated hydrocarbons	79-01-6	Trichloroethylene	HDPE; PE; PEX; PVC	✓	✓	✓	✓	✓	✓	✓	21, 36[b]
Halogenated vinyl compounds	75-01-4	Vinyl chloride	CPVC; PVC	✓	✓	✓	✓	✓	✓	✓	2, 6, 13, 36,[b] 37
Heterocycles	109-99-9	Tetrahydrofuran	HDPE; PE; PEX; CPVC; PVC		✓	✓		✓			7, 36,[b] 38
Ketones	108-94-1	Cyclohexanone	HDPE; PE; PEX;			✓		✓			7, 36[b]

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
			CPVC; PVC								
Ketones	78-93-3	Methyl ethyl ketone	CPVC; PVC		✓	✓		✓			7, 38
Organotins	2406-65-7	Butyltin	CPVC; PVC								7, 14, 15, 17, 31, 33, 36[b]
Organotins	23120-99-2	Dimethyltin	CPVC; PVC								1, 7, 33
Organotins	1002-53-5	Dibutyltin	CPVC; PVC								1, 7, 14, 15, 17, 31, 33, 36[b]
Organotins	688-73-3	Tributyltin	CPVC; PVC			✓					15, 17, 36[b]
Organotins	1631-73-8	Trimethyltin	CPVC; PVC								7, 33
Phthalates	117-81-7	Bis(2-ethylhexyl)phthalate	CPVC; PVC		✓	✓		✓			26, 36[b]
Phthalates	84-74-2	Dibutyl phthalate	PE; CPVC		✓	✓		✓			25, 27
Quinones/quinone derivatives	719-22-2	2,6-Di-t-butyl-p-benzoquinone	HDPE; PE; PEX					✓			3, 4, 5,[c] 10, 27, 28, 29, 32, 34

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
Quinones/quinone derivatives	82304-66-3	7,9-Di-tert-butyl-1-oxaspiro(4,5)deca-6,9-diene-2,8-dione	HDPE; PE; PEX; PP					✓			9, 10, 19, 25, 27, 36[b]
Vinyl compounds	115-11-7	Isobutylene	HDPE; PE; PEX					✓			28, 36[b]
Tier II											
Alkanes	2882-96-4	3-Methyl pentadecane	PEX								9, 19
Alkanes	629-78-7	n-Heptadecane	PEX					✓			9, 19
Alkanes	544-76-3	n-Hexadecane	PEX								9, 19
Alkanes	629-62-9	n-Pentadecane	PEX								9, 19
Alkanes	1560-93-6	2-Methyl pentadecane	PEX								9, 19
Aniline derivatives	101-67-7	4,4'-Dioctyldiphenylamine	PEX					✓			9, 19
Aromatic hydrocarbons	1014-60-4	1,3-Di-tert-butylbenzene	PEX					✓			9, 28
Esters	103-23-1	Bis(2-ethylhexyl) hexanedioate	PEX			✓		✓			9, 19
Ethers	637-92-3	Ethyl tert-butyl ether (ETBE)	PEX		✓			✓			9, 12, 18, 19,

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
											28
Halogenated	598-99-2	Methyl trichloroacetate	PEX								9, 19
Halogenated hydrocarbons	630-20-6	1,1,1,2-Tetrachloroethane	PEX		✓	✓		✓			9, 19
Heterocycles	110-86-1	Pyridine	PEX		✓	✓		✓			9, 19
Ketones	110-12-3	5-Methyl-2-hexanone	PEX					✓			10, 28, 34
Tier III											
Aniline derivatives	121-69-7	N,N-Dimethylaniline	CPVC; PVC		✓	✓					24
Epoxides	106-89-8	Epichlorohydrin	CPVC; PVC	✓		✓		✓	✓		24
Halogenated hydrocarbons	156-59-2	cis-1,2-Dichloroethylene	CPVC; PVC	✓	✓	✓	✓	✓			24
Metals	7439-89-6	Iron	PP; PVC	✓	✓	✓					23

Chemical Grouping	CAS No.	Substance Name	Piping Material	Drinking Water Criteria and Standards Sources							Source[a]
				US EPA MCL	US EPA GLI	US EPA RSL	CalOEHHA PHG	NSF	WHO	Health Canada	
Metals	7439-92-1	Lead	PP; PVC	✓	✓	✓	✓	✓	✓	✓	23
Vinyl compounds	108-05-4	Vinylacetate	CPVC; PVC			✓		✓			24

Notes:

CalOEHHA = California Office of Environmental Health Hazard Assessment; CPVC = Chlorinated Polyvinyl Chloride; GLI = Great Lakes Initiative; HDPE = High-density Polyvinyl Chloride; MCL = Maximum Contaminant Level; NSF = National Sanitation Foundation; PE = Polyethylene; PEX = Cross-linked Polyethylene; PHG = Public Health Goal; PP = Polypropylene; PVC = Polyvinyl Chloride; RSL = Regional Screening Level; US EPA = United States Environmental Protection Agency; WHO = World Health Organization.

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[b]Study did not specify whether substances were identified from individual materials and grouped plastic materials together. The groups included: "HDPE; PE; PEX" and "PVC; CPVC" and, in the absence of clarifying information, we conservatively assumed the identified substances are leached from all materials listed in the group.

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