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SYSTEMATIC REVIEW

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Chemical and microbiological safety of drinking water in distribution networks made of plastic pipes

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Abstract

In recent years, metal alloys used for drinking water distribution are gradually being replaced by PVC and HDPE pipes. In areas of distribution networks made of plastic, consumer complaints related to a significant deterioration of organoleptic parameters of water are frequently recorded. The decline in water quality is most likely the result of chemical and biological processes occurring on the inner walls of the transmission pipes coexisting with the disappearance of disinfectant residues. Plastic pipes are also characterized by high failure rates associated with aging of polymeric materials under operating conditions. Published reports indicate disturbing phenomena occurring in plastic pipes: oxidative aging of polymers, degradation of antioxidant coatings, release of organic compounds to water as well as surface damage and scaling, generating microplastic particles. PE and PVC networks are also susceptible to biofilm formation, characterized by a high phylogenetic diversity of microorganisms. Studies presented in the literature, indicating the risks resulting from the exploitation of PE and PVC pipes, are mainly based on model tests. There is a lack of works, which would complementarily explain all the phenomena occurring in working water pipes made of plastics. The aim of this review is to present the current state of knowledge regarding the phenomena and processes that can occur in PE and PVC pipes in service and their relevance to the safety and quality of drinking water in distribution networks, as well as to identify areas that require further analysis to enable water producers to deliver an appropriately high-quality product to consumers.

This article is categorized under:

Engineering Water > Water, Health, and Sanitation
Science of Water > Water Quality
Water and Life > Conservation, Management, and Awareness

KEYWORDS

biofilm, disinfection, drinking water safety assessment, microplastic, PE and PVC pipes, plastic degradation

1 | INTRODUCTION

Water is one of the most valuable resources on earth, but not everyone recognizes how important it is for economic development and the growth of civilization. It is essential for the functioning of plants, animals, and humans, and is used in virtually all industries. The quality and safety of treated water for drinking largely depend on the purity of its source. Water resources worldwide are becoming increasingly polluted with a variety of chemical compounds of anthropogenic origin, among which pesticides, biocides, pharmaceuticals, personal care products, endocrine disruptors, heavy metals, perfluorinated compounds, or flame retardants are the most commonly described (Liu et al., 2017; Pivokonský et al., 2020; Schriks et al., 2010; Shannon et al., 2008; Ternes et al., 2015). Their effective removal in drinking water treatment depends on the increasingly complex technologies used for this purpose (Barbier et al., 2022; Chu et al., 2022; Moel et al., 2006; Sharifi & Movahedian Attar, 2022). Water producers are obliged to provide safe drinking water and protect public health. The quality of water leaving water treatment plants is usually high and in accordance with national (MH Regulation, 2017) and international (EU Directive, 2020) standards, which strictly specify the permissible values of numerous microbiological, chemical, and physical parameters (Fish et al., 2017). At a further stage, treated water is transported to consumers through often very extensive distribution networks (DWDNs), which include both underground pipelines with connections to buildings as well as internal networks in buildings (Ainsworth, 2013; Lam et al., 2020; Liu et al., 2017). The pipes that makeup DWDNs, with lengths often exceeding hundreds, or even thousands, of kilometers, are made of different materials (concrete, cast iron, steel, and plastics) that are joined by welds and valves (AWWA, 2012; Liu et al., 2017; Pratesi et al., 2021; Tao et al., 2023; Vreeburg & Boxall, 2007). Depending on the function performed in the system (main, building supply, etc.), pipes vary in diameter, and the prevalence of small-diameter pipes results in a very large ratio of their total surface area to the volume of water conveyed (Fish et al., 2017). Pipes in DWDNs are buried in the ground and form a system of feeds and loops where water can reside for a very short time (main transmission pipes) or longer periods (especially in dead-end nodes) (Ainsworth, 2013; Taghipour et al., 2023; Tong et al., 2020). In addition to pipes, DWDNs also include storage reservoirs, transmission pumps, pumping stations, and a variety of hydraulic equipment. Due to the composition of the treated water, the presence of residual disinfectant, nutrients (organic and mineral), and often bacterial spores, several biological and physicochemical processes occur in DWDNs resulting in a secondary decline in the quality of the transmitted water (Fish et al., 2017; Holder et al., 2019; Liu et al., 2013; Prest et al., 2016). This is most acutely felt by consumers in areas with prolonged water retention, during periods of low water demand, or at so-called dead-ends of the network (Ainsworth, 2013; Liu et al., 2013, 2017; Nawrocki et al., 2010; Pratesi et al., 2021; Proctor & Hammes, 2015; Świetlik et al., 2012; Taghipour et al., 2023; Tong et al., 2020; Vreeburg & Boxall, 2007). The worldwide observed decline in water quality in consumers' taps is mainly manifested by deterioration of olfactory parameters of water, increase in turbidity (Liu, Ling, et al., 2016; Verberk et al., 2007), presence of particulate matter (pipe corrosion products) (Li et al., 2010; Liu et al., 2017; Sly et al., 1990; Vreeburg & Boxall, 2007), as well as a deterioration of microbiological parameters associated with an increase in the bacterial cell content of the water (Hammes et al., 2010; Liu, Gunawan, et al., 2016; van der Kooij, 1992; van der Wielen & Lut, 2016; Wang et al., 2022) (Figure 1). All these processes are directly related to the gradual degradation of the materials that build the water supply network as a result of the physicochemical and microbiological processes that occur on their surface continuously over decades (Ainsworth, 2013; Liu et al., 2013, 2017; Nawrocki et al., 2010; Proctor & Hammes, 2015; Świetlik et al., 2012; Vreeburg & Boxall, 2007).

To counteract and reduce these phenomena, it is common practice worldwide to gradually replace pipes made of traditional materials such as metal alloys or concrete with pipes made of thermoplastics such as polyvinyl chloride (PVC), polypropylene (PP), high/ultrahigh density polyethylene (HD-PE, UHD-PE), and cross-linked polyethylene (PEX) (Biedroń et al., 2017; Diera et al., 2023; Liu et al., 2017; Pawlicki et al., 2019; Zhang et al., 2023). Among thermoplastics, polyethylene (PE) is the most commonly used polymer and its percentage share in the construction of drinking water distribution networks is increasing continuously (Diera et al., 2023; Holder et al., 2019; Rabaud & Rozental-Evesque, 2008). The popularity of thermoplastic materials is mainly related to their expected lifespan (over 100 years), as well as their corrosion resistance, flexibility, and low production costs (Davis et al., 2007a).

However, as studies conducted by researchers in various fields show, the introduction of plastic pipes is also not a perfect solution. Despite constant modifications and optimization of the composition of the plastics used, they continue to age, faster than expected, with a consequent negative impact on the final quality of drinking water. The aim of this review is to outline the phenomena and processes that can occur in PE and PVC pipes in service and their significance for the safety and quality of drinking water in distribution networks.

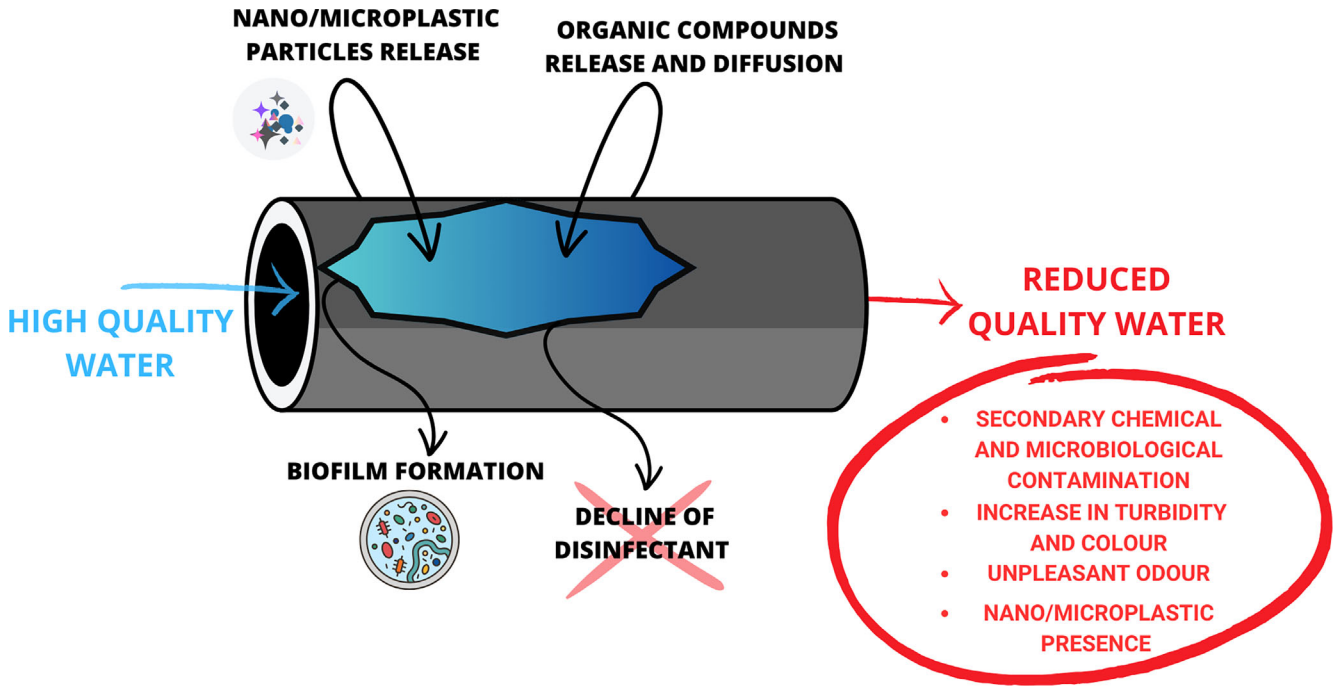

FIGURE 1 Phenomena observed in plastic pipes used for the transmission of drinking water resulting in a reduction of its quality in consumers' taps.

2 | THE MOST COMMON POLYMERIC MATERIALS USED IN THE CONSTRUCTION OF DRINKING WATER DISTRIBUTION NETWORKS

2.1 | Polyethylene pipes

Polyethylene is a thermoplastic material characterized by high resistance to acids, bases, salts, and most organic compounds. It found application in the production of, among others: packaging, bottles, and water pipes. It is formed as a result of the polymerization reaction of olefin gases (ethylene, propylene, and butylene) (Sixsmith & Hanselka, 1997). There are three types of polyethylene: high-density polyethylene (HDPE), which is formed from PE granules by low-pressure polymerization, in the presence of stabilizers in the form of antioxidants, and is characterized by high mechanical strength, plasticity, and stability at low temperatures; medium-density polyethylene (MDPE), and low-density polyethylene (LDPE), which is soft and flexible even at temperatures as low as −60°C. The polymer most commonly used for pipelines is HDPE, which over time has been modified to obtain the best mechanical properties (e.g., resistance to cracking, reduction of ion migration and low-molecular organic compounds from the external environment, resistance to oxidizing agents, etc.) (Denberg et al., 2007; Sixsmith & Hanselka, 1997). In addition, according to Holder et al., 2019, "crosslinking improves the ability of PE pipes to resist mechanical damage at elevated temperatures (e.g., better hot water transfer with PEX joints compared with HDPE pipes)." Effective chain bonding in PEX pipes can be achieved by cross-linking using: peroxides (PEX-A, the highest degree of cross-linking), silanes (PEX-B), and electron-beam (PEX-C, the lowest degree of cross-linking) (Holder et al., 2019; Whelton et al., 2011).

2.2 | Polyvinyl chloride pipes

The second most popular polymeric material is polyvinyl chloride (PVC) obtained by polymerization of vinyl chloride and combination with additives to obtain a material with excellent properties. It is characterized by high mechanical strength and has great thermoplastic properties (Sixsmith & Hanselka, 1997). PVC pipes are sensitive to the elevated temperature characteristic of the polymer processing/forming stage. Then many reactions occur, such as oxidation or crosslinking reactions, which cause its destruction. To prevent this, various additives are added to the polymer, including plasticizers (reducing the temperature of PVC forming), lubricants, fillers, impact modifiers, pigments, antioxidants,

and heat stabilizers (Sadiki et al., 1996; Sadiki & Williams, 1999; Sixsmith & Hanselka, 1997). Antioxidants used in polymer processing include: bisphenol A, bound phenols (BHT, BHA), and quinones (Sadiki et al., 1996; Sadiki & Williams, 1999). The addition of stabilizers (lead and tin) prevents thermal decomposition and also protects the material against UV radiation.

3 | MIGRATION OF ORGANIC COMPOUNDS FROM THERMOPLASTIC MATERIALS

In drinking water distribution systems, plastic pipes are used both for underground network areas and in indoor networks located in buildings (Holder et al., 2019). Unfortunately, as other researchers and practitioners show, these materials also have disadvantages and their use involves some risk. It was found that the compounds added to the polymer at the synthesis stage, migrate from the material to water. This can occur by direct diffusion of organic compounds into water or by their release into the water as a result of decomposition by microorganisms on the surface of pipes. The factors that cause the degradation of polymers include, among others, temperature, mechanical loads, UV radiation, and the presence of strong oxidants such as ozone, chlorine dioxide, or chlorine (Whelton et al., 2011). The addition of antioxidants to polymers is intended to prevent their degradation during processing and extend their service life (Denberg et al., 2007). Unfortunately, they generate numerous by-products as a result of oxidative degradation, including, for example, phenols or quinones (Denberg et al., 2007). The presence of volatile organic compounds (VOCs) from low-, medium-, and high-density polyethylene (LDPE, MDPE, and HDPE, respectively) and cross-linked polyethylene (PEX) has also been confirmed from laboratory studies (Rożej et al., 2015; Skjevrak et al., 2003). In the case of polyvinyl chloride (PVC) pipes, lead and tin compounds have been detected from the production of this material, which are responsible for serious diseases, especially in children (Whelton et al., 2011). The vast majority of published work on this topic is model, laboratory, or small-scale model system research. Their results indicate a high potential for the release of numerous chemicals of varying toxicity into the drinking water transferred through PE and PVC pipes, but do not show to what extent the presence of these secondary contaminants affects its quality and safety. Little is also known about the dynamics of these processes and the concentrations of the released compounds. This indicates an information gap that, given the widespread use of plastic pipes, should be filled.

3.1 | Migration from polyethylene (PE) pipes

In the case of water distributed in model systems made of high-density PE pipes (HDPE), a more intense smell and a more pronounced taste were observed, compared with water contacting with PVC. It has been shown that chemical, plastic and putrefactive dominated among the recognized aromas of water, while in the case of taste—plastic and chemical (Skjevrak et al., 2003). The source of smell in pipes made of HDPE are mainly alkylphenols, esters, aldehydes, and ketones, while in pipes made of LDPE the smell of water is determined by the presence of carbonyl compounds and alcohols (Whelton et al., 2011). In the tests, carried out under model conditions, it was found that pipes made of PE and PEX release about 100 different organic compounds, which are classified by Denberg et al. (2007) as: "(1) additives like antioxidants, (2) degradation products formed by radical reaction of the antioxidants, and (3) broken PE chains that in general have a functional polar oxygen group (e.g., esters and aldehydes)" (Table 1). The identified organic compounds migrating from the walls of polyethylene pipes to tap water and affecting its quality include primarily: 4-ethylphenol, 4-t-butylphenol, 2,6-di-t-butyl-p-benzoquinone, 2,4-di-t-butylphenol, 3,5-di-t-butyl-4-hydroxystyrene, 3,5-di-t-butyl-4-acetophenone, 3,5-di-t-butyl-4-hydroxyacetophenone (Brocca et al., 2002; Shaikh et al., 2019), tert-butyl methyl ether (MTBE) (Holder et al., 2019; Shaikh et al., 2019; Tang et al., 2013) as well as esters, aldehydes, ketones, aromatic hydrocarbons, and terpene (Biedroń et al., 2017; Diera et al., 2023) being degradation products of antioxidants or polymers used. Compounds migrating from PE pipes to water are also antioxidants: pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate (Irganox 1010), 3,5-Bis(1,1-dimethylethyl)-4-hydroxybenzenepropanoic acid thiodi-2,-1-ethanediyl ester (Irganox 1035), octadecyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate (Irganox 1076), 2,6-di-tert-butyl-4-methylphenol (BHT)) (Diera et al., 2023; Whelton et al., 2011). It was also found (Lundbäck, 2005), that migration of antioxidants from PE pipes depends on the environment (e.g., water with and without oxygen, presence of nitrogen) as well as the type of polyethylene (HDPE, LLDPE) and antioxidants (e.g., polar 4,4′-thiobis(3-methyl-6-tert-butylphenol) (Santonox R), and less polar 2,2′-thiobis(6-tert-butyl-p-cresol) (Irganox 1081)). It has been shown that in

TABLE 1 Compounds released into the water during the operation of pipes made of PE.

Material	Released compounds	Literature
Polyethylene (PE)	*Antioxidants*	
	2,6-di-tert-butyl-4-methylphenol (BHT)	Diera et al. (2023); Whelton et al. (2011)
	Pentaerythritol tetrakis(3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate (Irganox 1010))	
	3,5-Bis(1,1-dimethylethyl)-4-hydroxybenzenepropanoic acid thiodi-2,1-ethanediyl ester (Irganox 1035)	
	Octadecyl 3-(3,5-di-tert-butyl-4-hydroxyphenyl)propionate (Irganox 1076)	
	4,4′-thiobis(3-methyl-6-tert-butylphenol) (Santonox R)	Lundbäck (2005); Whelton et al. (2011)
	2,2′-thiobis(6-tert-butyl-p-cresol) (Irganox 1081)	
	Degradation products of antioxidants	
	4-ethylphenol	Brocca et al. (2002); Shaikh et al. (2019)
	4-t-butylphenol	
	2,6-di-t-butyl-p-benzoquinone	
	2,4-di-t-butylphenol	
	3,5-di-t-butyl-4-hydroxystyrene	
	3,5-di-t-butyl-4-acetophenone	
	3,5-di-t-butyl-4-hydroxyacetophenone	
	Tert-butyl methyl ether (MTBE)	Holder et al. (2019); Shaikh et al. (2019); Tang et al. (2013)
	Fragments of broken PE chains	
	Esters	Biedroń et al. (2017); Diera et al. (2023)
	Aldehydes	
	Ketones	
	Aromatic hydrocarbons	
	Terpenes	
	Alcohols	Whelton et al. (2011)

the aquatic environment, the migration of organic compounds is the most intense in the case of LLDPE. The fastest migrating antioxidant was Santonox R, and the slowest—Irganox 1081. Thus, it can be concluded that the degree of migration depends on both the structure of the polymer and the properties of the antioxidant itself (Whelton et al., 2011).

3.2 | Migration from polyvinyl chloride (PVC) pipes

PVC, in addition to releasing volatile organic compounds such as aldehydes (e.g., hexanal, octanal, etc.) into water, can also be a source of organotin compounds (Biedroń et al., 2017; García-Timermans et al., 2023; Skjevrak et al., 2003; Skjevrak et al., 2005) (Table 2). Tin-stabilized PVC is used when contact with drinking water can occur in pipes (Sixsmith & Hanselka, 1997). Research conducted by Sadiki et al. (1996) showed that lead compounds, organotin compounds, and unbound vinyl chloride monomers were found in water transported by PVC pipelines, as confirmed by other studies (Chen et al., 2019; Sun & Shang, 2013; Walter et al., 2011). Organotin compounds are iso-octyl sulfonylacetate derivatives (e.g., dimethyltin, butyltin, and octyltin). The concentration of these compounds depends, among other factors, on the condition of the pipelines and their changes over time. On the basis of tests conducted in model conditions (Al-Malack, 2001), consisting of PVC pipe in contact with test water (with variable temperature and dissolved compounds content) for 48 h, an increase in migration of lead and tin compounds from the pipe material into

TABLE 2 Compounds released into the water during the operation of pipes made of PVC.

Material	Released compounds	Literature
Poly(vinyl chloride) (PVC)	*Substrates*	
	Unbound vinyl chloride monomer (VCM)	Sun and Shang (2013); Sadiki et al. (1996); Walter et al. (2011)
	Stabilizers	
	Lead compounds	Al-Malack (2001)
	Organotin compounds—isooctyl sulfonylacetate derivatives (e.g., dimethyltin, butyltin, octyltin)	Biedroń et al. (2017); Kowalska et al. (2009); Skjevrak et al. (2003, 2005)
	Barium(II)/strontium(II)/calcium(II)	Fadel (2022); Kowalska et al. (2009); Mercea et al. (2021)
	Plasticizers	
	Dibutyl phthalate (DBP)	Chen et al. (2019); Liu et al. (2019); Ye et al. (2020); Zhang et al. (2023)
	Fragments of broken PVC chains	
	Aldehydes	Biedroń et al. (2017); Skjevrak et al. (2003, 2005)

water was observed. Moreover, it was noted that the factor that influences the leaching of stabilizers (e.g., barium(II), strontium(II), or calcium(II)) from the pipe material is the low pH of the water (Mercea et al., 2021). However, the highest concentrations of the above compounds occurred at the beginning of the analysis. Over time, their content significantly decreased, which was confirmed by laboratory tests (Fadel, 2022; Kowalska et al., 2009). A decrease in the content of tributyltin, dibutyltin, and monobutyltin was also observed in samples of water stagnant in PVC model pipes (Kowalska et al., 2009). Another undesirable compound in drinking water is dibutyl phthalate (DBP), used in the manufacturing process as a plasticizer (Liu et al., 2020; Ye et al., 2020; Zhang et al., 2023). The presence of DBP in water in contact with PVC fragments has been reported in laboratory studies. Ye et al. (2020) described a three-step mechanism for the release of DBP from PVC. This phenomenon is further favored by elevated temperature, exposure to light and the degree of fragmentation. Furthermore, the migration of DPB from PVC described by Ye et al. (2020) occurs continuously, indicating that the phthalate can be released into the transferred water throughout the many years of pipe life. It is noteworthy, however, that the migration of organic compounds from PVC pipes observed through laboratory studies is on a small scale, and no intense odor from organic compounds was found in the samples analyzed (Sadiki et al., 1996).

4 | DIFFUSION OF COMPOUNDS BY PE AND PVC

Another problem associated with the widespread use of PE and PVC materials is the permeability of these materials, as a result of which undesirable organic chemicals can diffuse into the transported drinking water from the external environment, adversely affecting its quality. The cross-linked structure of the pipes used for the distribution of drinking water is conducive to intentional or accidental contamination of the distributed water with organic chemicals, for example, organic solvents, petroleum derivatives, as well as inorganic ions (e.g., nitrites and nitrates, which can feed bacteria in biofilms). Soil organic contaminants adsorbed on PE pipes can be gradually released into water, resulting in long-term contamination (Saquing et al., 2010). As demonstrated by Whelton et al. (2010) the degree and rate of diffusion of impurities through polymers depends on their composition and cross-linking. It has been shown that both polar and non-polar compounds can permeate through synthetic materials and that the size of the impurity is an important parameter determining the rate of migration. In the case of polar compounds, diffusivity for compounds with low molar volumes, for example, acetonitrile ($M_v = 53.3\ cm^3$), as a function of polymer density, ranged from 6.38 to 30.0 [$10^{-9}\ cm^2/s$], while for larger particles, for example, benzyl alcohol ($M_v = 125.1\ cm^3$), it was only 4.03–7.40 [$10^{-9}\ cm^2/s$]. In contrast, for non-polar compounds, the determined diffusivities reached much higher values and were, for example, 64.4–132 [$10^{-9}\ cm^2/s$] for dichloromethane ($M_v = 60.6\ cm^3$) and 56.9–96.7 [$10^{-9}\ cm^2/s$] for m-xylene ($M_v = 135.9\ cm^3$). In determining the permeation potential of organic compounds through organic polymeric materials,

including PE and PVC, Zhang et al. (2018) showed that for hydrocarbon group polymers, organic compound-polymer interactions play a key role. In the case of PE, the organic compounds are much smaller in size (orders of Å) than the pores of the polymer (1.32 μm) and easily penetrate them. The situation is different for PVC, as it is a denser polymer and the exclusion effect dominates. This was confirmed by Song et al. (2021), who analyzed the course of sorption and desorption of petroleum hydrocarbons on microplastics. His results point to intermolecular diffusion and diffusion in the liquid layer as key steps in the sorption of organic compounds in the polymer. The results of available studies indicate that PE has a significantly higher sorption capacity than PVC, as a consequence of its lower crystallinity (Liu et al., 2019; Zhang et al., 2018). Studies of the adsorption and desorption processes of hydrophobic organic compounds from fuels on PE- and PVC-derived microplastic fragments have shown the possibility of storing hydrocarbons and releasing them back into the surrounding environment (Liu et al., 2019; Song et al., 2021). Unfortunately, most studies were based only on high concentrations of model compounds (Liu et al., 2019; Ryssel et al., 2015; Song et al., 2021; Tang et al., 2013), while none of the tests or developed models have yet assessed the mass transfer of contaminants occurring at low concentrations, corresponding to real conditions. In addition, an attempt to assess the phenomenon of permeation of organic compounds (pesticides, disinfection by-products or non-polar solvents) through PE has only been carried out on new pipes (Moser et al., 2005; Ong et al., 2008; Whelton et al., 2010, 2011; Zhang et al., 2018), which, unlike pipes in mains operation, have not been exposed to long-term continuous contact with oxidizing disinfectants. According to Davis et al. (2007b), pipes in distribution systems and domestic installations "remain 'new' for only a short period of their expected 50–100 year service life," and constant exposure to disinfectants significantly alters their usefulness, which may even shorten their lifespan (Dear & Mason, 2006; Whelton et al., 2011). It must therefore be assumed that organic contaminants can migrate through progressively aging plastic pipes, with the consequent deterioration of drinking water quality. Knowledge of the potential for different chemicals to migrate through plastics used for drinking water distribution is of great importance for the design of new and the operation of existing DWDNs (Holder et al., 2019), but at the moment only the results of model tests, carried out on plastic fragments or new pipes under strictly model conditions (high concentrations of the analyzed compounds, selected types of pollutants), are available. However, analyses illustrating actual operating conditions are lacking. On the other hand, there are more and more frequent situations when water supply companies receive complaints about unacceptable chemical smell of water distributed through PE or PVC pipes in the vicinity of, for example, old petrol stations or fuel tanks left in the ground, and so on. This confirms that there is a real risk to the quality and safety of drinking water and points to the need for testing under real operating conditions and/or on worn and aged pipe materials.

5 | MICROPLASTIC RELEASE

Production of various types of plastics is steadily increasing globally and reached more than 390 million tons in 2021 (Plastics Europe, 2022). For several years, the presence of small plastic fragments has been recorded in various aquatic environments—surface water, seas, and oceans. These fragments are classified into different categories based on their size and shape (Figure 2) (Anderson et al., 2017; Chu et al., 2022; da Costa et al., 2016; Di & Wang, 2018; Eerkes-Medrano et al., 2015; Feld et al., 2021; Hahladakis et al., 2018; Koelmans et al., 2015; Leslie et al., 2017; Mason et al., 2016; Mintenig et al., 2019; Mukotaka et al., 2021; Shen et al., 2021; Shruti et al., 2020; Strand et al., 2018; Su et al., 2016; Tong et al., 2020; Vibhatabandhu & Srithongouthai, 2022).

To date, the main focus of researchers has been on larger MP particles, whereas fine MP fractions and nanoplastics have only recently been characterized in terms of their quantitative content in natural waters and drinking water (da Costa et al., 2016; Pico et al., 2019; Pico & Barcelo, 2019; Wang & Wang, 2018). With regard to the pathway of migration into drinking water, nanoplastics and microplastics can be divided into primary (present in raw, untreated water) and secondary: migrating into treated water during the treatment process (as a result of contact with equipment containing components made of plastics) and/or migrating into treated water during its transmission, due to progressive degradation of the structure of the polymers from which the pipes are made (Figure 2). The main sources of primary MPs in drinking water sources are industrial plants, especially those producing plastics, the decomposition of plastic litter and associated surface runoff and leachate from landfills, abrasion from vehicle tyres during driving, and discharges of untreated and treated wastewater (Boucher & Friot, 2017; da Costa et al., 2016; Eerkes-Medrano et al., 2015; Mason et al., 2016; Mintenig et al., 2017, 2019). From domestic and industrial wastewater, MP can be partially removed in wastewater treatment plants (WWTPs), but only the largest fragments are effectively eliminated, while smaller particles freely pass through all treatment stages, representing an undesirable admixture of treated wastewater

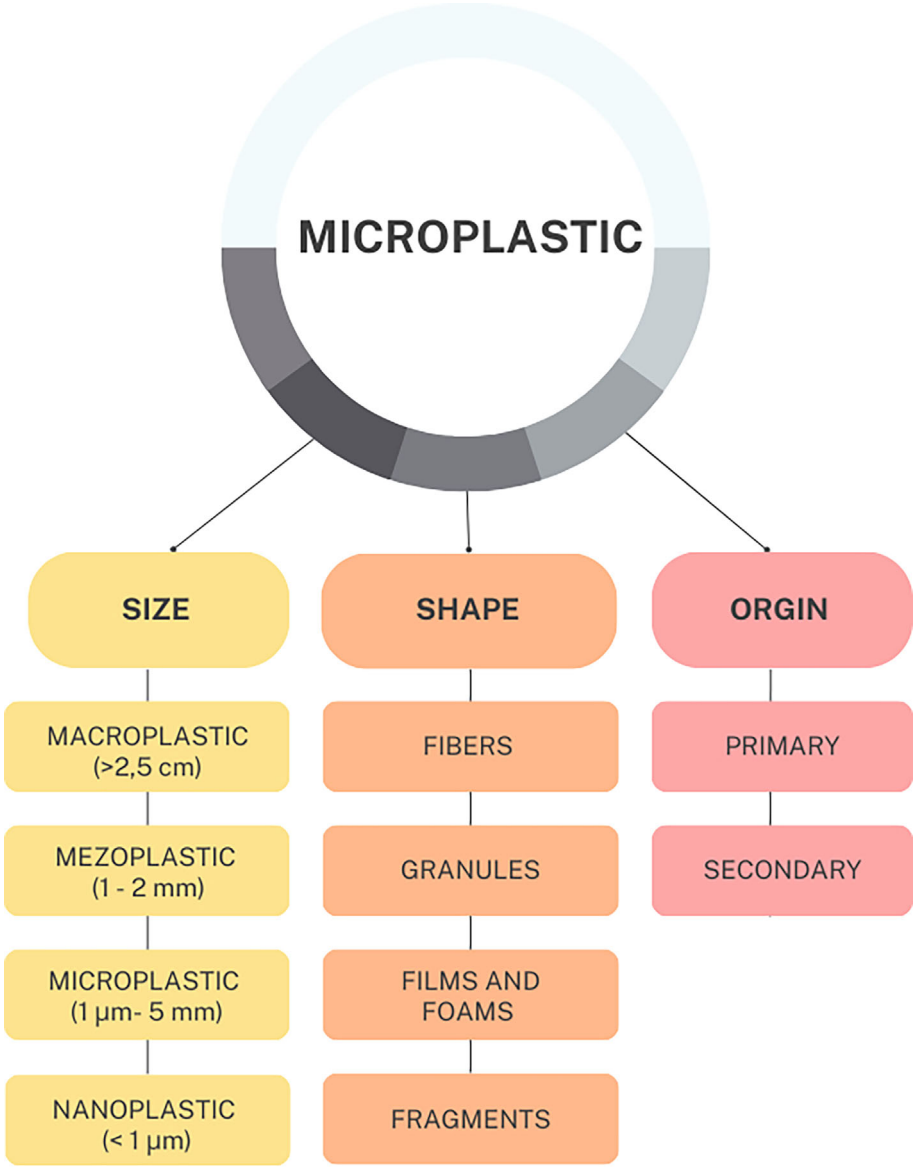

FIGURE 2 Classification of microplastics by size, shape and origin.

(up to several thousand particles per m^3 of treated wastewater) (da Costa et al., 2016; Fortin et al., 2019; Leslie et al., 2017; Mason et al., 2016; Mintenig et al., 2017, 2019; Novotna et al., 2019; Talvitie et al., 2017; Velasco et al., 2022).

The most commonly identified polymers in raw and treated waters, including tap water, are PE and PP (Feld et al., 2021; Mintenig et al., 2019; Mukotaka et al., 2021; Pico et al., 2019; Pittroff et al., 2021; Shen et al., 2021; Strand et al., 2018; Tong et al., 2020), less frequently polystyrene (PS) (Taghipour et al., 2023), PVC (Mukotaka et al., 2021; Pico et al., 2019; Shen et al., 2021) and polyethylene terephthalate (PET) (PE ≈ PP > PS > PVC > PET) (Bond et al., 2018; Koelmans et al., 2015; Tables 3–5). This largely coincides with results obtained for bottled waters, where the presence of numerous PE, PP, and styrene–butadiene copolymer fragments (MP >5 µm to 118 ± 88 MPs/L and MP >1 µm to 6292 ± 10,521 MPs/L) has been demonstrated (Oßmann et al., 2018; Schymanski et al., 2018), as well as analyses of other food and packaged beverage products (Liebezeit & Liebezeit, 2014; Oßmann et al., 2018; Schymanski et al., 2018; Sharma et al., 2022; van Cauwenberghe & Jenssen, 2014; Yang et al., 2015).

In recent years, more than numerous studies have been published on the presence of microplastics in treated and finished tap water (Bordós et al., 2018; Di et al., 2019; Di & Wang, 2018; Dris et al., 2015; Leslie et al., 2017; Luo, Zhang, et al., 2019; Mintenig et al., 2019; Pivokonsky et al., 2018; Semmouri et al., 2022; Shen et al., 2021; Su et al., 2016, 2018; Taghipour et al., 2023; Triebskorn et al., 2019; Wang et al., 2017; Zhao et al., 2014). Studies conducted on raw water

TABLE 4 Microplastic abundance in freshwater/raw water (surface water).

Water type	Size lower limit (μm)	Abundance (MPs/L) (*MPs/km^2)		Size distribution (μm)			Polymer type	Literature
		Range	Mean	<100	100–1000	1000–5000		
Thoothukudi river, south east India	500	54 ± 41–619 ± 377	263 ± 243	N	31.1%	68.9%	PE (49.83%); PP (37.33%); PS (10%); PA (2.83%)	Keerthika et al. (2022)
Karnaphuli river, Bangladesh	300	30,000–200,000*	145,592.59 ± 63,739.88*	N	77% (47%: 300–500; 30%: 500–1000)	23%	PET (22%); PA (15%); PE (12%); PS (13%); and others	Fatema et al. (2023)
Llobregat river, Catalonia, Spain	500	0–3.6	1.6	N	60%	40%	PP (41%); PES (30%); PE (9%); and others	Dalmau-Soler et al. (2021)
Baikal Lake, Siberia	20	–	291 ± 252	88% (<330)		22%	PP (65%); PET (16%); PE (4%); PVC (4%); and others	Moore et al. (2022)
Swat River, Hindu Kush Mountain, Pakistan	50	–	305.7 ± 289	18%	82% (62%: 300; 20%: 150)	N	—	Bilal et al. (2023)
Yangtze Estuary, China	500	0.5–10.2	4.1 ± 2.5	N	67%	33%	—	Zhao et al. (2014)
River Seine, France	100	<1	<1	N	51% (22%: 100–500; 29%: 500–1000)	49%	—	Dris et al. (2015)
Taihu Lake, China	5	3.4–25.8	—	10%	70% (40%: 100–333; 30%: 333–1000)	20%	—	Su et al. (2016)
Amsterdam canals, Holand	10	48–187	100	100% (61%: 10–300; 39%: >300)			—	Leslie et al. (2017)
Hanjiang River and Yangtze River, Wuhan	50	1.66 ± 0.64–8.93 ± 1.59	—	100% (>80%: <2000)			PET>PP > PE > PA > PS	Wang et al. (2017)
Three Gorges Reservoir, China	<50	1.6–12.6	4.7 ± 2.8	100% (31%–74%: <500)			PP (49%); PE (31%); PS (17%); PC (1.5%); PVC (1.5%)	Di and Wang (2018)
Dongting Lake, China	≤50	0.9–2.8	—	100% (27%: <330)			PE = PP > PS > PVC	Wang et al. (2018)
Hong Lake, China	50	1.5–4.7	2.9 ± 0.9	100% (27%: <330)			PE = PP > PS > PVC	Wang et al. (2018)
Carpathian Basin (rivers and reservoirs), Hungary	100	<1	<1	100%			PP > PE > PES > PS > PTFE > PAC	Bordós et al. (2018)
Danjiangkou Reservoir, China	48	0.5–15	2.6 ± 3.8	5.7%–44.4% (48–500); 8.3%–56.4% (500–1000)		15.6%–45.5% (1000–2000)	PP (43%); PS (36%); PE (21%)	Di et al. (2019)

(Continues)

TABLE 4 (Continued)

Water type	Size lower limit (μm)	Abundance (MPs/L) (*MPs/km^2)		Size distribution (μm)			Polymer type	Literature
		Range	Mean	<100	100–1000	1000–5000		
Suzhou and Huangpu River, including creeks, China	20	1.8–2.4	—	100%	N	N	—	Luo, Su, et al. (2019)
Poyang Lake, China	50	5–34	—	N	100% (73% < 500 μm)		PP (37%); PE (30%); Nylon (15%); PVC (8%)	Yuan et al. (2019)
The Inner Gulf of Thailand	125	1–96	9.97 ± 18.55	N	90% (68%: 125–300; 22%: 300–1000)	10%	PE (27%); PE/PP (21%); PP (16%); EPDM (12%); SEBS (6%); Polyacrylate (4%); PA (3%); PVC (0.2%); and other	Vibhatabandhu and Srithongouthai (2022)
Bueng Boraphet Wetland, Thailand	333	<1	<1	N	87.5%	12.5%	PES > PP > PET	Sarin and Klomjek (2022)
Wuliangsuhai Lake, China	330	3.12–11.25	—	N	100% (98.2%: <2000)		PS (39%); PP (28%); PE (17%); PVC (5%)	Mao et al. (2020)

Abbreviations: ABS, acrylonitrile butadiene styrene; CA, cellulose acetate; EPDM, ethylene–propylene diene monomer rubber; EPS, expanded polystyrene; PA, polyamide; PA6, nylon 6; PAN, polyacrylonitrile; PBA, polybutylacrylate; PC, polycarbonates; PE, polyethylene; PE/PP, poly(ethylene:propylene); PEO + PEG, polyethylene oxide + polyethylene glycol; PEST/PES, polyester; PET, polyethylene terephthalate; PEVA, ethylene (vinyl acetate) copolymer; PMMA, poly(methyl methacrylate); PP, polyprophylene; PP, polypropylene; PS, polystyrene; PTFE, polytetrafluoroethylene; PTT, polytrimethylene terephthalate; PU, polyurethane; PVAC, polyvinyl acetate; PVC, polyvinylchloride; SEBS, styrene–ethylene–butylene–styrene; VC/VA, vinyl chloride/vinyl acetate copolymer.

TABLE 4 Microplastic abundance in raw water supply drinking water treatment plants (DWTPs).

Water type	Size lower limit (μm)	Abundance (MPs/L)		Size distribution (μm)			Polymer type	Literature
		Range	Mean	<100	100–1000	1000–5000		
Jiangsu Province, China	1	377–1570.8 (76% decrease during transport)	—	100%	N	N	PVC > PET>PS > PE > PP	Tao et al. (2023)
WTP1, Zaheden, Iran	5	—	0.13	100%		N	PE; PET; PP; PS; EPS; PA; PVC; PMMA	Taghipour et al. (2023)
WTP2, Zaheden, Iran	5	—	0.078	100%	N	N	PE; PET; PP; PS; EPS; PA; PVC; PMMA	Taghipour et al. (2023)
DWTP in Tianjin (Yongding river), China	<50	—	134.79	50%	50% (>200)		Nylon (∼83%); PEST (∼17%)	Chu et al. (2022)
DWTP in Isfahan, Iran	<10	—	1597.7 ± 270.3	92.5% (49.9%: <10; 28.5%: 10–50; 14.1%: 50–100)	7.4%		PP (20.8%); PE (16.7%); PET (12.5%); Nylon 6 (12.5%); PVC (8.3%); PA (8.3%); PS (4.2%); and non-plastic (16.7%)	Sharifi and Movahedian Attar (2022)
DWTP in Catalonia, Spain	20	—	4230	38%	56%	6% (1000–2000)	PES (26%), PP (24%); Synthetic cellulose (24%); PAN (9%); and others	Dronjak et al. (2022)
DWTP in Paris (Seine/Marne/Oise river), France	25	7.4–45	—	100% (≤1271)			PET (52.3%); PE (31.7%); PP (13.1%); PVC; PS; PA; PU; PVAC; ABS	Barbier et al. (2022)
Sinos river, Southern Brazil	—	0–940	330.2	—	—	—	—	Ferraz et al. (2020)
Surabaya River, Indonesia	1	26.8–35	—	2%–4%	59%–77%	31%–37%	PE (LD-PE) and PP	Radityaningrum et al. (2021)
DWTP in Geneva, Switzerland	63	<1	<1	100% (76.7%: 63–125; 20.7%: 125–250)		N	PEVA > PE > PMMA > PP = PES	Velasco et al. (2022)
DWTP Milence (upper flow of the Úhlava River), the Czech Republic	1	—	23 ± 2	100% (50%: ≤5)			CA; PET; PVC; PE; PP; and other	Pivokonský et al. (2020)
DWTP Plzeň (lower flow of the Úhlava River), the Czech Republic	1	—	1296 ± 35	74%	26%		CA; PET; PVC; PE; PP; PS; PA6; PEO+ PEG; VC/VA; PTT; PTFE	Pivokonský et al. (2020)
	20	—	4.23 ± 1.26	38%	62% (<=2000)			

(Continues)

TABLE 4 (Continued)

Water type	Size lower limit (μm)	Abundance (MPs/L)		Size distribution (μm)			Polymer type	Literature
		Range	Mean	<100	100–1000	1000–5000		
DWTP in Catalonia, Spain							PES (25%); Synthetic cellulose (23%); PP (23%); PAN (9%); PET (4%); PE (3%); and other	Dronjak et al. (2022)
WTP1, Czech Republic	1	1383–1575	1473 ± 34	99%	1%	N	PET (60%); PP; PVC; PMMA; and others	Pivokonsky et al. (2018)
WTP2, Czech Republic	1	1648–2040	1812 ± 35	100%	N	N	PET (68%); PP; PVC; and others	Pivokonsky et al. (2018)
WTP3, Czech Republic	1	3123–4464	3605 ± 497	99%	1%	N	PET (27%); PE (24%); PP; PBA; PMMA; PS; PTT; and others	Pivokonsky et al. (2018)
DWTP Nethen (ground water), Germany	20	<1	<1	100% (50–150)		N	Epoxy resin; PVC	Mintenig et al. (2019)
DWTP Holdorf (ground water), Germany	20	<1	<1	100% (50–150)		N	PEST; PE	Mintenig et al. (2019)
DWTP Grossenkneten (ground water), Germany	20	0	0	N	N	N	—	Mintenig et al. (2019)
DWTP Sandelermoens (ground water), Germany	20	0	0	N	N	N	—	Mintenig et al. (2019)
DWTP Thuelsfelde (ground water), Germany	20	0	0	N	N	N	—	Mintenig et al. (2019)

Abbreviations: ABS, acrylonitrile butadiene styrene; CA, cellulose acetate; EPDM, ethylene–propylene diene monomer rubber; EPS, expanded polystyrene; PA, polyamide; PA6, nylon 6; PAN, polyacrylonitrile; PBA, polybutylacrylate; PC, polycarbonates; PE, polyethylene; PE/PP, poly(ethylene:propylene); PEO + PEG, polyethylene oxide + polyethylene glycol; PEST/PES, polyester; PET, polyethylene terephthalate; PEVA, ethylene(vinyl acetate) copolymer; PMMA, poly(methyl methacrylate); PP, polyprophylene; PP, polypropylene; PS, polystyrene; PTFE, polytetrafluoroethylene; PTT, polytrimethylene terephthalate; PU, polyurethane; PVAC, polyvinyl acetate; PVC, polyvinylchloride; SEBS, styrene–ethylene–butylene–styrene; VC/VA, vinyl chloride/vinyl acetate copolymer.

TABLE 5 Microplastic abundance in drinking water.

Water type ([1]sampling sites)	Size lower limit (μm)	Abundance (MPs/L) (*MPs/500 mL)	Size distribution (μm)				Polymer type	Literature
			<10	10–100	100–1000	1000–5000		
Treated water (at the exit of the DWTP)								
Catalonia, Spain	20	0.06 ± 0.04	N	~77.5%		~22.5% (≤2000)	PES > PP > PS > PAN>PVA > AR	Dalmau-Soler et al. (2021)
Tianjin (Yongding River), China	<50	95.63	N	~15% (50–100)	85% (50%: 100–200; ~35%: >200)		PEST (~50%); Nylon (~20%); PVC (~15%); PP (~15%)	Chu et al. (2022)
Isfahan, Iran	<10	260.5 ± 48.9	63.9%	35.1%	1%		PP (25%); PET (20.8%); PE (16.7%); PA (12.5%); Nylon 6 (8.3%); PVC (4.2%); and non-plastic	Sharifi and Movahedian Attar (2022)
Catalonia, Spain	20	0.075	N	61%	39%	<1% (1000–2000)	Synthetic cellulose (47%); PE (12%); PA (12%); PES (9%); PU (6%); Tygon B 44–4 polymer (6%); and others	Dronjak et al. (2022)
Choisy DWTP, (Seine river), Framce	25	<1	N	100% (majority 25–100)			PP (47.4%); PE (42.1%); PS (5.3%)	Barbier et al. (2022)
Neuilly DWTP (Marne river), France	25	<1	N	100% (majority 25–100)			PE (64.6%); PP (13.0%); PET (10.2%); PA (5.4%); and others	Barbier et al. (2022)
Mery DWTP (Oise river), France	25	<1	N	100% (majority 25–100)			PP (33.8%); PET (23.9%); PE (21.1%); PVC (9.9%); and others	Barbier et al. (2022)
WTP1, Zaheden, Iran	5	0.045	100%	N		N	PE; PET; PP; PS; EPS; PA; PVC; PMMA	Taghipour et al. (2023)
WTP2, Zaheden, Iran	5	0.02	100% (≤50)	N		N	PE; PET; PP; PS; EPS; PA; PVC; PMMA	Taghipour et al. (2023)
WTP1, Czech Republic	1	443 ± 10	100% (<50)	N		N	PET (41%); PP; PAM; PVC; and others	Pivokonsky et al. (2018)
WTP2, Czech Republic	1	338 ± 76	100% (<100)	N		N	PET (62%); PP; PAM; PVC; and others	Pivokonsky et al. (2018)
WTP3, Czech Republic	1	628 ± 28	100% (<100)	N		N	PE (35%); PET (26%); PP; PAM; and others	Pivokonsky et al. (2018)
Tap water								

(Continues)

TABLE 5 (Continued)

Water type ([1]sampling sites)	Size lower limit (μm)	Abundance (MPs/L) (*MPs/500 mL)	Size distribution (μm)				Polymer type	Literature
			<10	10–100	100–1000	1000–5000		
Zaheden, Iran	5	0.085–0.39 (WTP1) 0.075–0.4 (WTP2)	100% (90%: <50)			N	PE; PET; PP; PS; EPS; PA; PVC; PMMA	Taghipour et al. (2023)
Tianjin, China	<50	13.23	N	~18% (50–100)		82% (67%: 100–200; ~15%: >200)	PEST (~53%); Nylon (~25%); PS (~22%)	Chu et al. (2022)
Urban sources in Hong Kong	2.7	2181 ± 0.165	65.2%			34.8%	—	Lam et al. (2020)
Urban source in China (38 s.s.[1])	1	440 ± 275	31.25%–100%: 1–50; 1.47%–31.25%: 50–100	1.72–31.25%: 100–300; 1.18–7.69%: 300–500; 1.72–11.76%: 500–5000			PE (26.7%); PP (24.4%); PE/PP (22%); PPS (7.3%); PS (6.5%); PET (3.3%); and others	Tong et al. (2020)
Urban source in Brazil (32 s.s.[1])	6	97 ± 55* (South Wing) 219 ± 158* (North Wing)	100% (≤50)	N		N	-	Pratesi et al. (2021)
Residential districts of Qingdao, China	10	0.7 ± 0.6	N	75.4% (46.4%: 500–1000; 29%: ≤500)		24.6%	Rayon; PET; PE; PS; PAM; PDMS; PCL-diol; PI; PES; PMPS; PAA	Zhang et al. (2020)
Households and workplaces in Denmark (17 s.s.[1])	—	<1	100%	N		N	PET; PP; PS; ABS	Feld et al. (2021)

Abbreviations: ABS, acrylonitrile butadiene styrene; AR, alkyl resin; EPS, expanded polystyrene; ER, epoxy resin; PA, polyamide; PAA, polyacrylic acid; PAM, polyacrylamide; PAN, polyacrylonitrile; PCL, poly(caprolactone) diol; PDMS, polydimethylsiloxane; PE, polyethylene; PES/PEST, polyester; PET, polyethylene terephathalate; PEVA, polyethylene and ethylene-vinyl acetate; PI, poly(isoprene); PMPS, poly(methyl phenyl siloxane); PP, polypropylene; PPS, polyphenylene sulfite; PS, polystyrene; PTFE, polytetrafluoroethylene; PU, polyurethane; PVA, polyvinyl acetate; Tygon B 44-4 polymer, new generation polymer with high content of PVC and silicon, without phthalates.

TABLE 6 Toxic effects of MP/NP on life organisms.

Effect	Size	Type	Literature
Oxidative stress or mutagenic/carcinogenic	NP	PVC	Mahadevan and Valiyaveettil (2021); Taghipour et al. (2023)
	NP	PMMA	Mahadevan and Valiyaveettil (2021); Taghipour et al. (2023)
	NP	Plastic beads	Bhattacharya et al. (2010)
	MP (<20 μm)	PP	Hwang et al. (2019)
Bodily dysfunction or neurotoxicity	MP	HDPE and PP	Lagarde et al. (2016)
	MP (1–100 μm)	PE	Rehse et al. (2016)
	MP (3000 μm)	LDPE	Rochman et al. (2013)
	MP/NP	PS	Deng et al. (2017); Lehner et al. (2019)
Gastrointestinal problems	MP/NP (0.5–5 μm)	PS	Lehner et al. (2019); Luo, Su, et al. (2019)
	MP (29.5 μm)	PMMA	Imhof et al. (2013)

Abbreviations: HDPE, high density polyethylene; LDPE, low density polyethylene; PE, polyethylene; PMMA, poly(methyl methacrylate); PP, polypropylene; PS, polystyrene.

(groundwater [Mintenig et al., 2019; Pittroff et al., 2021; Shruti et al., 2020], surface water [Bordós et al., 2018; Sarin & Klomjek, 2022; Vibhatabandhu & Srithongouthai, 2022; Wang et al., 2017; Wang et al., 2018] and desalinated water [Almaiman et al., 2021]), during its treatment process (Mintenig et al., 2017, 2019; Novotna et al., 2019; Pivokonsky et al., 2018; Pivokonský et al., 2020) as well as on treated water distributed through the water supply network (including connections and domestic taps) (Feld et al., 2021; Mukotaka et al., 2021; Taghipour et al., 2023; Tong et al., 2020) showed the presence of all MP fractions: <10 μm with an average of 266 ± 56 MPs/L (e.g., Shen et al., 2021), 10 to 100 μm with an average of 0.2 ± 0.1–63 ± 11 MPs/L (e.g., Feld et al., 2021; Mintenig et al., 2019; Mukotaka et al., 2021; Shen et al., 2021; Shruti et al., 2020) and >100 μm with an average abundance of 0–18 ± 7 MPs/L (Feld et al., 2021; Mintenig et al., 2019; Mukotaka et al., 2021; Shen et al., 2021; Shruti et al., 2020) (see Tables 3–5 for more examples). It has also been observed that MP abundance in tap water increases with decreasing particle size.

Studies conducted at treatment plants have shown that the key to reducing the content of primary plastics in drinking water is the appropriate choice of process line (Novotna et al., 2019; Pivokonsky et al., 2018; Pivokonský et al., 2020; Velasco et al., 2022). The degree of microplastic removal achieved during water treatment ranged from 70% to 83%, with the highest degree of reduction achieved in multi-stage process trains including, for example, coagulation/flocculation, flotation and filtration, and GAC filtration (Chae & An, 2017; Mintenig et al., 2017, 2019; Novotna et al., 2019; Pivokonsky et al., 2018; Pivokonský et al., 2020; Velasco et al., 2022; Zhao et al., 2014). Unfortunately, in addition to the so-called primary MP, derived from raw water, the presence of secondary MP has also been reported in drinking water. Taghipour et al. (2023) reported an increase in the number of MP particles in tap water, relative to water leaving treatment plants. Furthermore, Mintenig et al. (2019) showed the presence of MP fragments in tap water in areas supplied with treated water produced from MP-free raw water, demonstrating that the source of microplastics is the thermoplastic materials used to construct the network. To date, however, there is a lack of studies assessing the potential for MP particles to enter water from plastic distribution pipes, which, due to progressive degradation, can undoubtedly be a significant source of secondary nano- and microplastics in consumers' taps. The available results concern either water leaving the treatment plants, containing mainly primary MP, or tap water only, in which it is difficult to assess clearly the origin of microplastics. There are also no studies on the presence and accumulation of microplastics in sludge/biofilms deposited on the inner surface of pipes, which can also enter drinking water during failure. And most importantly, the available literature describes almost exclusively microplastics, omitting smaller particles that are classified as nanoplastics.

However, it should be emphasized that the relatively small amounts of microplastics determined to date are not insignificant and drinking water may be an important source of nano- and microplastics for humans. The presence of microplastics in drinking water raises many concerns among the public due to the likely negative effects on human health (e.g., Chae & An, 2017; Deng et al., 2017; Hwang et al., 2019; Lehner et al., 2019; Lei et al., 2018; Mahadevan & Valiyaveettil, 2021; Mason et al., 2016; Taghipour et al., 2023). In vitro studies using human cells have shown that nanoplastics can penetrate cells and induce oxidative stress or proinflammatory responses (Lehner et al., 2019). Negative effects on living organisms, including humans, have also been shown by other authors (see Table 6). Among the

polymers studied, PE and PVC particles (especially nanoplastics), which are released into drinking water from aging pipes, occupy an important place, as the possibility of bodily dysfunction, gastrointestinal problems or even exposure-related neurotoxicity has been demonstrated (see Table 6). For this reason, the European Drinking Water Directive (DWD) requires the monitoring of microplastics in drinking water and the inclusion of microplastics in a "watch list" of potentially hazardous compounds by 2024 (EU directive). It also seems necessary to step up research to develop efficient technologies for removing the smallest plastic particles from treated water and for producing materials that are less susceptible to degradation.

6 | RESISTANCE OF PLASTIC PIPES TO DISINFECTANTS

Among the factors affecting the rate of polymer degradation one of the most important is their resistance to disinfectants. Polymers due to their structure are easily oxidized, which is why antioxidants added to pipes at the production stage are used, to protect the material against degradation (Whelton et al., 2011). Few studies on the behavior of the inner surfaces of polyethylene pipes in contact with water containing disinfectants have shown that the remaining disinfectant disappears as a result of reactions between the plastic and the free chlorine (Yang et al., 2022). This phenomenon has been reported for HDPE (Heim & Dietrich, 2007) as well as for cross-linked PEX (A and B) (Dietrich & Heim, 2007; Durand & Dietrich, 2007). The postulated mechanism of the occurring reaction involves, in the first step, the detachment of hydrogen from the PE structure by free radicals present in water. In the next stage molecular oxygen is attached and carbonyl groups are formed, which is presented in the Figure 3 (Colin et al., 2009; Hassinen et al., 2004). As a result of the successive oxidation of the PE surface under the influence of free chlorine, the polymer chains are torn apart, which in the course of time may lead to the formation of damage and even cracks in the pipe. The presence of carbonyl bonds on the inner surfaces of PE was also confirmed by other authors, both during the analysis of sections taken from distribution networks (Frank et al., 2009; Thompson et al., 1992) and during model tests involving exposure of pipes to water disinfected with chlorine dioxide (Chung et al., 2006; Colin et al., 2009), free chlorine, and chloramine (Chung et al., 2006). The application of extreme conditions in laboratory accelerated aging experiments in the presence of free chlorine solution, on the other hand, showed the formation of mainly carbonyl bonds as well as chloride, hydroxyl, and vinyl bonds (Chung et al., 2006; Whelton & Dietrich, 2009). An oxidation induction time (OIT) measurement, which is performed in bulk polymer, is used to assess the degree of PE oxidation. According to Gedde et al. (1994), a low OIT value indicates the depletion of antioxidants used to increase the oxidation resistance of PE, while at OIT = 0 the polymer may undergo massive degradation, resulting from the breaking of bonds in the carbon chains of the polymer and their gradual compaction. As a consequence, a decrease in mechanical strength of PE and an increase in susceptibility to damage are observed. OIT measurements for the assessment of PE resistance to oxidation are used in practice both for studies on the condition of pipes operating in distribution networks and in model studies (Chung et al., 2006; Thompson et al., 1992; Whelton et al., 2010; Whelton & Dietrich, 2009).

Changes in the surface and internal structure of polyethylene can significantly increase the ability of contaminants to settle in aging water pipes (Whelton et al., 2011). Furthermore, in the presence of compounds with oxidizing properties, for example, O_3, ClO_2, Cl_2, commonly used as disinfectants, the antioxidant concentration in materials decreases with time, which leads to so-called cracks on the surface of the polymer material. Devilliers et al. (2018), during the research on the assessment of the resistance of a PE pipe to the action of chlorine dioxide have found that the oxidation process taking place on the inner surface of the pipe causes chemical degradation of the layer to a depth of 200 μm (Devilliers et al., 2018). The results obtained by the authors indicate that as a consequence of the continuous impact of disinfectants on water supply pipes made of plastics, it is possible to destroy materials, causing the release of undesirable organic compounds into the water, as well as the release of microplastic particles. In addition, under model conditions, it was observed that ClO_2 attacks PE and PP pipes more aggressively than free chlorine or chloramines (Bredács et al., 2018; Colin et al., 2009; Vertova et al., 2019). This can be explained by the nature of chlorine dioxide, which, as a dissolved gas, can easily diffuse into the polymer. Additionally, chlorine dioxide readily reacts with phenolic stabilizers added at the PE pipe manufacturing stage, which significantly increases the material's susceptibility to degradation (Bredács et al., 2018; Colin et al., 2009; Vertova et al., 2019). Due to the release of organic compounds from plastics during degradation processes and with access to residual chlorine, plastic pipes can also be a "source" of THMs in drinking water. According to Cao et al. (2020) PEX has a high potential to form and sorb THMs. The intensity of the process is not affected by the disinfectant concentration, but is strongly temperature dependent.

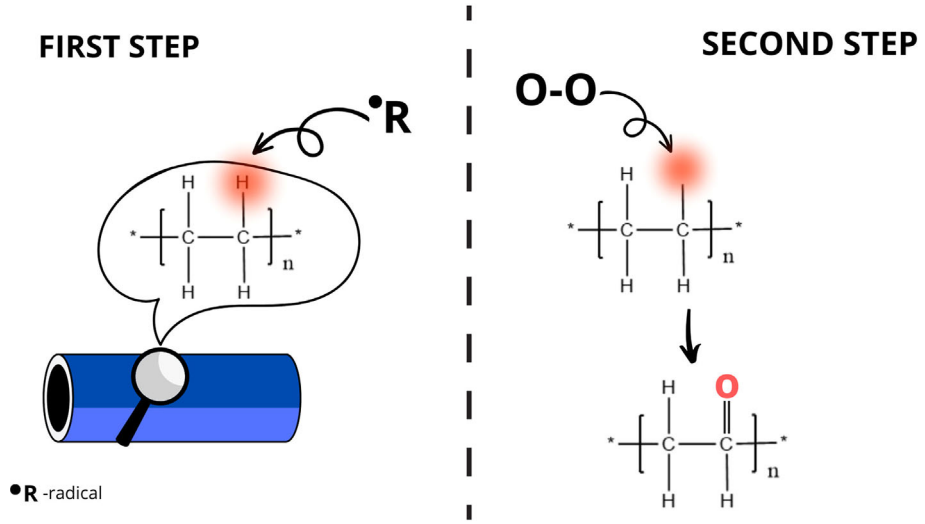

FIGURE 3 Mechanism of PE oxidative degradation.

Despite the awareness of the problems associated with the insufficient resistance of PE and PVC to the continuous action of disinfectants present in the transmitted water, there is still a lack of data on the analysis of these phenomena during pipe operation. In fact, almost all of the work published to date relates to studies carried out in laboratories, under conditions of accelerated aging of the materials, which makes direct transfer to real-world conditions impossible. This, in turn, clearly demonstrates the need to extend research to pipes operating in water supply networks, to understand the true extent of material degradation and implement appropriate remedial measures. This is of paramount importance for the safety and quality of drinking water, since, as the studies have shown regardless of the type of disinfectant used, the consequence of the reaction of the oxidant with the pipe surface is the disappearance of the disinfectant in the water, especially in the end areas of the distribution network. As a consequence, the quality and microbiological stability of water supplied to consumers may be impaired in areas of the distribution network made of PE and PVC (Zhang et al., 2014; Zhang & Liu, 2014).

7 | BIOFILM FORMATION

The use of plastics for the construction of pipelines was to minimize the risk of disturbing the biological and chemical stability of transported water due to their smooth surface and the elimination of corrosive processes. However, the conducted model tests showed that networks made of PE and PVC are also susceptible to biofilm formation, whose intensity depends on many factors. These include, among others: the pipe material (Biedroń et al., 2017; Eerkes-Medrano et al., 2015; Goraj et al., 2021; Liu et al., 2017; Rożej et al., 2015; Zhang & Liu, 2014), the content of chemical compounds that are nutrients for microorganisms (Denberg et al., 2007; Dong et al., 2018; Papciak et al., 2022; Piringer & Baner, 2000; Zhao et al., 2022), the concentration of disinfectant (Papciak et al., 2022; Yang et al., 2022; Zhang & Liu, 2014), water flow rate (Fish et al., 2017; Zhang et al., 2014), hydraulic conditions (Fish et al., 2017) and temperature (Inkinen et al., 2014; Lee, 2013; Papciak et al., 2022; Zhu et al., 2014) (Figure 4). The number of literature reports on the subject is increasing year by year, but the vast majority of published results involve studies conducted in systems that simulate conditions in DWDNs or mimic indoor distribution networks in buildings. Few data are obtained under real conditions. On the other hand, the number of data showing the huge potential for biofilm formation on plastic pipe surfaces is of great concern and points to the need for remedial action by water producers.

Bacterial biofilms are present in any environmental system with flowing water. Their presence in drinking water transfer pipes significantly affects the quality and stability of the transferred product. The term biofilm is used to describe the complex structures formed by microorganisms by adhesion, nucleation, and growth on various pipe materials (Eerkes-Medrano et al., 2015; Liu et al., 2017). Most commonly, these are flocs and aggregates of bacteria forming populations that have the ability to cover both the surface of pipe materials and the pores or microcracks present in their structure (Costerton et al., 1995; Yang et al., 2022). The average number of bacterial cells in a biofilm is assumed

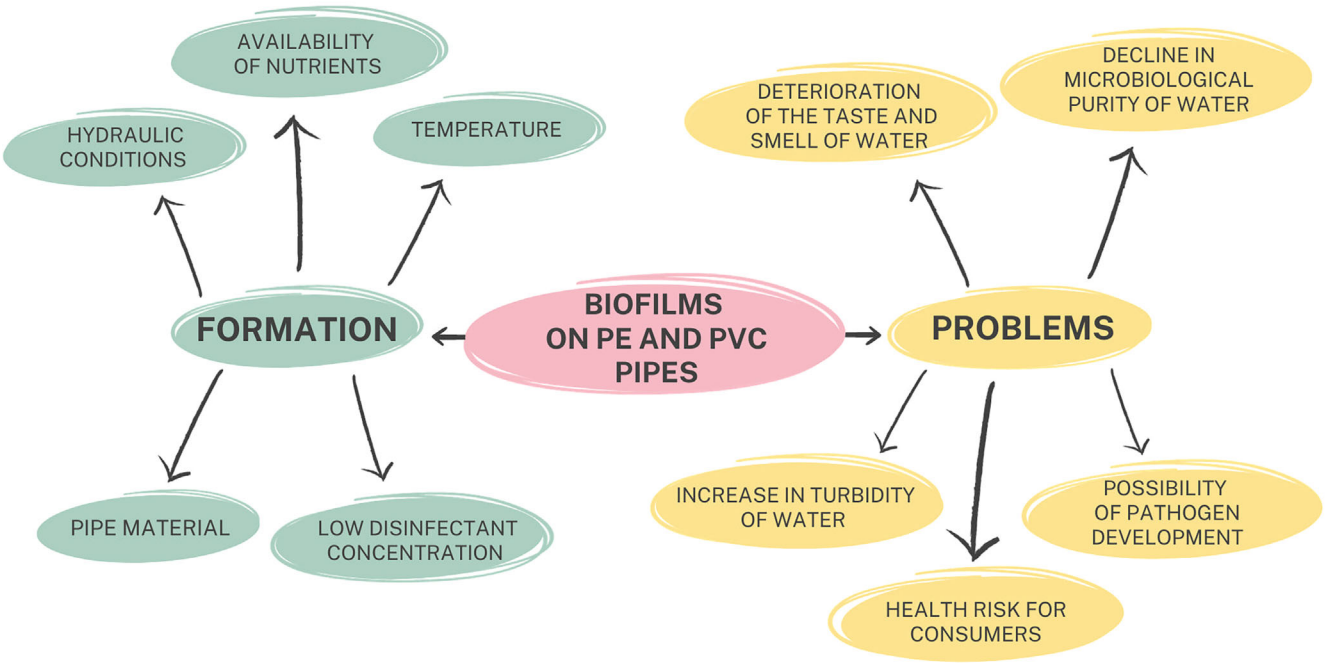

FIGURE 4 Biofilms—formation and impact on the final quality of drinking water in consumers' taps.

to be 10^4–10^8 cells/cm^2 (García-Timermans et al., 2023; Liu et al., 2013; Makris et al., 2014; Proctor & Hammes, 2015), representing approximately 10%–25% of the dry weight (Costerton et al., 1995; Flemming & Wingender, 2010; Liu, Gunawan, et al., 2016; Yang et al., 2022). The microorganisms are further protected from adverse environmental conditions, including the presence of disinfectants, by an extracellular polymeric substance (EPS) (Liu, Ling, et al., 2016) which in turn can account for up to 75%–90% of dry weight (Costerton et al., 1995; Flemming & Wingender, 2010; Liu, Ling, et al., 2016; Yang et al., 2022). This matrix consists primarily of polysaccharides, proteins, glycolipids, phospholipids, nucleic acids and enzymes that provide nutrients for bacteria in the early stages of biofilm development (Biedroń et al., 2017). The EPS also allows retention and accumulation of organic and inorganic matter (Liu et al., 2014; Peng et al., 2010; Peng & Korshin, 2011), heavy metals (e.g., As) (Liu et al., 2014), a variety of pathogens (Feazel et al., 2009; Fish et al., 2017; Liu et al., 2017; Vaerewijck et al., 2005) and possibly microplastic particles (Novotna et al., 2019; Pivokonsky et al., 2018; Tao et al., 2023). The process of biofilm development in drinking water distribution systems is multistep, and bacteria use intercellular signaling known as quorum sensing (QS) for its efficient expansion and stable functioning (Lami et al., 2022; Liu, Ling, et al., 2016; Shrout & Nerenberg, 2012).

However, the formation and growth of bacterial biofilms on the walls of pipes transporting drinking water, including PE and PVC pipes, is a serious problem for the quality and stability of the transmitted product. Biofilms can directly affect the turbidity, color, taste, and odor of drinking water and can be a source of bacterial contaminants, including pathogens. In addition, the presence of well-developed biofilms on pipe walls, which can be up to several millimeters thick, accelerates pipe degradation and increases water flow resistance, which, in the long term, can result in increased failure rates and reduced hydraulic performance of the distribution network (Liu, Ling, et al., 2016). On the other hand, an increase in the proportion of inorganic compounds and sediments in the matrix, usually caused by the deposition of corrosive contaminants carried by water from areas of the network constructed of metal alloys, increases the resistance of the biofilm to disinfectants due to its reduced penetration capacity (Liu et al., 2017).

Among the key factors for the formation and growth rate of biofilms in water mains, the pipe material plays an important role. Due to surface properties, such as roughness increasing with material degradation, and additives used in production (adhesives, plasticizers, stabilizers), which can be an important source of nutrients for bacteria (Biedroń et al., 2017; García-Timermans et al., 2023; Manuel et al., 2007; Momba & Makala, 2004; Papciak et al., 2022; Parizzi et al., 2004; Sitarska & Traczewska, 2009; Zhao et al., 2022), thermoplastics provide an excellent substrate for biofilm growth. Literature data cited in earlier chapters indicate that PE and PVC can release numerous organic compounds, which become a medium for microorganisms both present in the transferred water and attached to the inner wall of the pipes. Wang et al. (2022) conducted a study on the effects of exposure to low concentrations (1–10 μg/L) of the

phthalates dibutyl phthalate, di-*n*-hexane phthalate, and di-(ethylhexyl) phthalate released from HDPE and PVC pipes during aging on *Pseudomonas* biofilm growth. The results showed that already at lower phthalate concentrations (1–5 μg/L), the formation of more biofilm matrix and an increase in biofilm density (increase in volume fraction from 27.1% to as much as 50.6%) is observed. This thickening of the biofilm contributes to its resistance to disinfectants, due to the limited possibility of oxidant diffusion into the biofilm (Wang et al., 2022). Furthermore, the presence of phthalates, by accelerating physiological processes that stimulate the production of the antioxidant system, contributes significantly to the resistance of these microorganisms to disinfection (Wang et al., 2022). Unfortunately, phthalates are not the only group of compounds that promote biofilm growth. Indeed, the most bioavailable nutrients for microorganisms are compounds containing biodegradable organic carbon classified as assimilable organic carbon (AOC), including carboxylic acids and aldehydes (Biedroń et al., 2017; Duong et al., 2021; van der Kooij et al., 2017; Zhao et al., 2022). Pipes made of PE have been shown to have a high potential for generating AOCs in contact with water immediately after chlorine disinfection (Duong et al., 2021). PVC, on the other hand, has a much lower potential for the release of AOCs than PE. The presence of compounds containing biogenic elements in the water is also of great importance for the development of biofilms. In the case of ultra-high molecular weight polyethylene (UHMW-PE) pipes, nitrogen-containing organic compounds account for 16.84% of the total available nutrients, compared with 12.63% for PVC. In contrast, the availability of phosphorus- and sulfur-containing compounds in pipes made of UHMW-PE was estimated to be low (Biedroń et al., 2017; Inkinen et al., 2014).

The intensity of biofilm formation also depends on water temperature (Inkinen et al., 2014; Lee, 2013; Papciak et al., 2022; Zhu et al., 2014). Its increase intensifies the migration of chemical compounds from the inner layers of the material into the water and also promotes bacterial proliferation. The effect of temperature may be particularly important for the distribution of treated waters extracted from surface waters characterized by elevated temperatures during summer periods (Papciak et al., 2022).

Comparative studies performed on different plastics used for drinking water transmission have shown that the susceptibility of polymeric materials to biofilm formation can be ranked in the following order: PB > PP > HDPE > PEX > PVC (Eerkes-Medrano et al., 2015; Rożej et al., 2015), indicating that polyethylenes are more readily colonized by microorganisms than polyvinyl chloride. A similar relationship was observed in a study on the susceptibility of polymeric materials to colonization by microscopic fungi (Eerkes-Medrano et al., 2015). The type of pipe material also influences the phylogenetic diversity of bacteria included in biofilms (Papciak et al., 2022; Rożej et al., 2015; Schwartz et al., 2003; Skovhus et al., 2022; Zhao et al., 2022). Unfortunately, the vast majority of studies in this area were conducted in model systems simulating conditions in DWDNs and/or in so-called indoor networks in buildings, which, according to the authors, may have yielded results that do not fully coincide with the actual composition of biofilms in real water supply networks.

The results of studies published so far on the composition and growth rate of bacterial biofilms on plastic pipes have shown that bacteria bind very easily to the PE and PVC surface and start building biofilms very quickly. García-Timermans et al. (2023) noted that after just 8 days of running the model system, the number of bacteria in the water leaving the model increased by an order of magnitude, from 10^5 cells/mL at the feed to 10^6 cells/mL at the exit of the system. Similar results have been obtained by other authors (Papciak et al., 2022; Skovhus et al., 2022; Zhao et al., 2022), but Skovhus et al. (2022) showed that initially the number of bacterial cells determined in the water at the exit of the test system increases and then decreases, which correlates with an increase in the number of biofilm-building cells associated with the pipe surface. Other modeling studies mimicking conditions in indoor networks (in buildings), taking into account periods of water stagnation, have also shown that the biofilm in PVC pipes does not contain mineral deposits and is based on densely dispersed, single cells of *Pseudomonas aeruginosa* bacteria. In contrast, the biofilm taken from HDPE pipes has the highest bacterial diversity, while on the surface of cross-linked polyethylene (PEX) bacteria are most abundant but do not form large agglomerates (Rożej et al., 2015). The compositions of the biofilms characterized so far, growing on PE and PVC surfaces, indicate a high phylogenetic diversity of the microorganisms inhabiting them. The most abundant bacterial phyla were *Proteobacteria* (26.7%–60%), *Bacteroidetes* (2.3%–3.4%), and *Actinobacteria* (0.7%–1.9%) (Goraj et al., 2021; Rożej et al., 2015; Skovhus et al., 2022; Zhao et al., 2022). In contrast, *Pseudomonas*, *Bacillus*, *Aquabacterium*, and *Lactococcus* dominated among the identified genera (Skovhus et al., 2022; Zhao et al., 2022). The high percentages of *Bacillus*, *Pseudomonas*, and *Lactococcus* in the biofilms collected from PE and PVC, compared to the biofilms present on the other pipe materials tested, are, according to Zhao et al. (2022), a direct consequence of the release of large amounts of organic compounds from plastics acting as a medium for these particular microorganisms. Characterization of biofilms present on plastic pipes has been carried out using scanning electron microscopy,

polymerase chain reaction combined with denaturing agent electrophoresis (PCR-DGGE), next-generation sequencing (NGS) and measurement of heterotrophic bacterial counts (HPC), but, as all authors of the cited studies point out, a standardized protocol that can be applied in water supply laboratories needs to be developed to enable regular examination and characterization of biofilms.

Conditions favoring biofilm growth in PE and PVC pipes as well as the failure of water supply networks can also result in the uncontrolled proliferation of pathogenic bacteria. van der Kooij et al. (2003) documented the occurrence of opportunistic *Legionella pneumophila* pathogens in the biofilm present in underground parts of DWDN as well as in domestic water supply systems. These pathogenic microorganisms, which are dangerous to human health, can easily spread in water supply systems (van der Kooij & Veenendaal, 2014). To this end, *L. pneumophila* is even capable of proliferating in protozoa living in biofilms present on the walls of water pipes (Declerck et al., 2009; Kuiper et al., 2004; Lau & Ashbolt, 2009). Modeling studies in a system mimicking indoor network conditions in a building by van der Kooij et al. (2017) showed a linear logarithmic correlation between *L. pneumophila* abundance and biofilm density. On the other hand, Learbuch et al. (2019) showed in a model study that the use of pipes made of polymers such as PE or PVC for water distribution can increase the risk of *L. pneumophila* proliferation, as these materials intensify the growth potential of both biofilms and just *Legionella*.

Disinfectants have been used for decades to reduce the growth of microorganisms in drinking water distribution networks. Their main task is to destroy vegetative forms of bacteria, and the presence of a so-called residual disinfectant in the water significantly reduces the possibility of biofilm formation on the walls of the pipes. However, there are reports in the literature of disinfectant disappearance due to the interaction of the oxidant with organic compounds leaching from the pipe surface (Zhang & Liu, 2014), as well as with the material itself (Collin et al., 2009; Dietrich & Heim, 2007; Durand & Dietrich, 2007; Hassinen et al., 2004; Heim & Dietrich, 2007; Yang et al., 2022). The disappearance of the disinfectant in all cases leads to an increase in the concentration of total organic carbon (TOC) in the water and thus an increase in the availability of substances that provide a medium for microorganisms (Zhang & Liu, 2014; Zhao et al., 2022). Biofilm present on the walls of thermoplastic materials, although more susceptible to inactivation by disinfectant compared with biofilm attached to iron-containing materials, may contain oxidant-resistant bacteria. The presence of such microorganisms in biofilm located on the walls of PE pipes was demonstrated in a model study by Zhu et al. (2014).

Identification studies revealed the presence of bacteria belonging to the alpha- and gamma-proteobacteria species, whose representatives include *Moraxella osloensis*, *Sphingomonas* sp., *Bacillus* sp., and *Methylobacteriaceae*. High biofilm density and the presence of EPS have been identified by the authors as factors favoring increased disinfectant resistance (Zhang et al., 2014). Other authors have also signaled the presence in biofilms covering the surface of plastic pipes of other pathogens (including opportunistic fecal bacteria) also characterized by increased resistance to the disinfecting effects of chlorine (Abberton et al., 2016; Buswell et al., 1998; Goraj et al., 2021; Juhna et al., 2007; Percival & Walker, 1999; Torvinen et al., 2007). Another pathogen with the ability to generate biofilms in pipes building DWDNs is *Sphingomonas paucimobilis* (the bacterium responsible for nosocomial infections) (Gulati & Gosh, 2017). These bacteria readily proliferate on a variety of materials used for drinking water transmission, including PE and PVC, regardless of the conditions in the system and have a very high resistance to chlorine used for water disinfection (Gulati & Gosh, 2017). Pathogenic organisms characterized by increased resistance to disinfectants can exist in the aquatic environment for long periods of time. Their development occurs under conditions of nutrient availability and/or in the absence of other microorganisms. Bacterial resistance to disinfectants is primarily due to their high potential to rebuild damaged cells. If the action of disinfectants fails to fully inactivate the bacteria, under favorable conditions they begin to rebuild. For this purpose, bacteria use specific repair mechanisms, including a mechanism that proceeds by nucleotide excision repair (so-called "dark repair") (Jones & Baxter, 2017; Schwartz et al., 2003; Sommer et al., 2000). "Dark repair" mechanisms can be successfully exploited by bacteria under conditions in PE and PVC distribution networks due to increased nutrient availability and concomitant disappearance or very significant reduction in residual disinfectant concentration. The number of literature reports on the presence/possibility of pathogens and disinfectant-resistant bacterial strains attached to plastic pipe surfaces in biofilms clearly demonstrates the need for comprehensive studies to identify them and assess their vital activity.

In summary, the presence and high growth rate of biofilms on drinking water transmission pipes made of PE and PVC is a very negative phenomenon. Over time, fragments of the forming biofilms can detach from the walls of the pipelines, releasing bacteria back into the bulk water. Such secondary microbial contamination of water can result in both a decrease in water quality (e.g., increased turbidity, change in odor) and a decrease in microbiological stability, which in extreme cases can pose a health risk to consumers. It is also worth noting that uncontrolled microbial growth

in distribution networks is always a potential threat to consumer health. Consequently, it seems necessary to regularly carry out studies on the composition and disinfection susceptibility of biofilms present in actual distribution networks, to develop effective methods for the systematic cleaning of microbial deposits from pipes during their long-term operation, as well as to develop standardized analytical protocols for the continuous monitoring of the microbiological purity status of pipes under operating conditions.

8 | CONCLUSION

The studies cited in this article do not provide complete information on the chemical and microbiological safety of drinking water in distribution networks made of plastic pipes. For the most part, these are only model studies carried out in laboratories and not on real, working water supply networks. However, the information collected, signaling the numerous risks arising from the long-term use of plastic pipes, clearly indicates that, despite continuous improvements, the plastics used in the construction of distribution systems are not resistant to the degradation processes taking place in the water environment and, at the same time, are highly susceptible to biofilm formation. Consequently, the products of biological and chemical processes occurring on the inner surface of plastic pipes can significantly affect the quality and microbiological stability of transmitted water. In practice, complaints from consumers about reduced and sometimes even unacceptable organoleptic parameters of water supplied through plastic pipes are very frequent. However, to fully assess the course, rate, and hazards of the described phenomena under real conditions in a specific area, it is necessary to carry out comprehensive studies in cooperation with water producers, combining model tests with assessment of the degree of pipe degradation, release of microplastics and composition of biofilm in working pipes taken from the distribution network in operation. Unfortunately, such comprehensive studies are scarce.

AUTHOR CONTRIBUTIONS

Joanna Świetlik: Conceptualization (lead); resources (lead); writing – original draft (lead); writing – review and editing (equal). **Marta Magnucka:** Conceptualization (supporting); resources (supporting); writing – original draft (supporting); writing – review and editing (equal).

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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