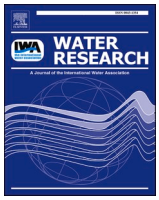
Water Research 253 (2024) 121273



Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres



Review



A review of research advances on disinfection strategies for biofilm control in drinking water distribution systems

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ARTICLE INFO

Keywords:
Biofilm control
Biofilm monitoring
Disinfection
Drinking water
Microbial contamination

ABSTRACT

The presence of biofilms in drinking water distribution systems (DWDS) is responsible for water quality deterioration and a possible source of public health risks. Different factors impact the biological stability of drinking water (DW) in the distribution networks, such as the presence and concentration of nutrients, water temperature, pipe material composition, hydrodynamic conditions, and levels of disinfectant residual. This review aimed to evaluate the current state of knowledge on strategies for DW biofilm disinfection through a qualitative and quantitative analysis of the literature published over the last decade. A systematic review method was performed on the 562 journal articles identified through database searching on Web of Science and Scopus, with 85 studies selected for detailed analysis. A variety of disinfectants were identified for DW biofilm control such as chlorine, chloramine, UV irradiation, hydrogen peroxide, chlorine dioxide, ozone, and others at a lower frequency, namely, electrolyzed water, bacteriophages, silver ions, and nanoparticles. The disinfectants can impact the microbial communities within biofilms, reduce the number of culturable cells and biofilm biomass, as well as interfere with the biofilm matrix components. The maintenance of an effective residual concentration in the water guarantees long-term prevention of biofilm formation and improves the inactivation of detached biofilm-associated opportunistic pathogens. Additionally, strategies based on multi-barrier processes by optimization of primary and secondary disinfection combined with other water treatment methods improve the control of opportunistic pathogens, reduce the chlorine-tolerance of biofilm-embedded cells, as well as decrease the corrosion rate in metal-based pipelines. Most of the studies used benchtop laboratory devices for biofilm research. Even though these devices mimic the conditions found in real DWDS, future investigations on strategies for DW biofilm control should include the validity of the promising strategies against biofilms formed in real DW networks.

1. Introduction

Biofilms are microbial communities established on any surface in contact with water and are responsible for several undesirable effects on the water quality, including a possible source of waterborne opportunistic pathogens (Hemdan et al., 2021; Ma et al., 2020; Simões and Simões, 2013). Although a multiple-barrier approach is applied in water treatment plants and for drinking water distribution systems (DWDS) management, biofilms are ubiquitous along the water networks. Community composition studies have revealed that drinking water (DW) microbiota is complex, with wide variation in the identity and composition of microbial communities in DW biofilms. Given the high growth rates of bacteria, their relatively small size, adaptation capabilities, and ability to produce extracellular polymeric substances (EPS), biofilm microbial communities in DWDS are generally dominated by bacteria (Characklis and Marshall, 1990; Liu et al., 2016). Bacteria belonging to the phylum Pseudomonadota, particularly those belonging to the α-, β-, γ-, and δ-proteobacteria subclasses, generally dominate biofilms in DWDS (Liu et al., 2016; Proctor and Hammes, 2015; Wu et al., 2015). However, viruses, filamentous fungi, algae, and protozoa may also be

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https://doi.org/10.1016/j.watres.2024.121273
Received 28 June 2023; Received in revised form 31 January 2024; Accepted 5 February 2024
Available online 7 February 2024
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present in DW biofilms. Single-species biofilms are rare, and in many cases, biofilm formation can be enhanced by the co-presence of microorganisms (Schwering et al., 2013; Simões et al., 2023, 2007). For instance, in a full-scale chloraminated DWDS composed of cast-iron water mains, *Mycobacteria* dominated the biofilm communities at the biofilm-bulk water interface, with the detection of both non-pathogenic *Mycobacterium frederiksbergense* and *Mycobacterium aurum* at a higher frequency, and the opportunistic pathogens *Mycobacterium haemophilum* and *Mycobacterium abscessus* at a low number (Gomez-Smith et al., 2015). On the other hand, underneath the corrosion tubercules, the biofilm communities were dominated by sulphate-reducing bacteria from the genus *Desulfovibrio* (Gomez-Smith et al., 2015).

The strategies implemented for biofilm prevention and control in DWDS are based on factors known to contribute to biofilm development, such as the concentration of nutrients in the water, type, and stability of the material used in DWDS, the hydrodynamic conditions, and levels of disinfectant residual through the distribution system (Gagnon et al., 2002; Liu et al., 2016; Simões and Simões, 2013). The balance between nutrient removal and the disinfectant residual concentration has been a high priority for many water utilities because the presence of organic matter in water increases the disinfectant demand (Gagnon et al., 2002; Simões and Simões, 2013). The biodegradable organic matter (BOM) in water is metabolized by most aquatic microorganisms for energy sources and the production of cellular materials (Liu et al., 2016). The levels of BOM are unique to each distribution system depending on the water source, which significantly shapes the microbial community in the water networks (Hozalski et al., 1999; Pan et al., 2021; Sun et al., 2014; Wan et al., 2019). The removal of BOM is mainly performed by biological treatment processes, including fluidized bed filters, slow sand filters, biological activated carbon (BAC) filters, and soil-aquifer treatment systems. Additionally, ozone can also be applied to water before filtration with either a rapid sand filter or a BAC biofilter (Gagnon et al., 2002; Mirnasab et al., 2021; Peterson and Summers, 2021; Sinha and Mukherji, 2022). Some European countries such as the Netherlands, Germany, Austria, and Switzerland, have taken the approach of distributing DW without the use of post-disinfection because of concerns associated with disinfection by-products (DBP), taste and odor complaints, and public perception (Gagnon et al., 2002; Simões and Simões, 2013). However, most water treatment plants strive to ensure the maintenance of a disinfectant residual concentration throughout the distribution system. Disinfectant residuals minimize the propensity of microorganisms for regrowth or re-inoculation from biofilms, reduce the risk of general contamination from exogenous intrusions, and serve as a sentinel of any rupture of the system integrity (Haas, 1999).

Chlorine is generally the preferred disinfectant for water treatment and is also applied to control microbial accumulation in pipes and tanks. Chlorine inhibits the reversible-to-irreversible transition of cell attachment to surfaces by degrading cell-membrane functional groups and associated polymers; however, it is incapable of guaranteeing complete biofilm inhibition (Xue and Seo, 2013). Alternatively, chloramines are often used in distribution systems where free chlorine residuals are difficult to maintain or to avoid excessive DBP formation (Liu et al., 2016). Although less reactive in comparison to chlorine against planktonic microorganisms, chloramines have been reported to have greater penetrating capacity in biofilms due to their relatively low tendency to react with EPS (LeChevallier et al., 1988; Lee et al., 2011; Liu et al., 2016). Nevertheless, the use of chloramine has been associated with the growth of certain nitrifying bacteria within the biofilm, due to the release of ammonia from chloramine decay (Li et al., 2014). Additionally, chlorine-resistant bacteria were also detected in full-scale chloraminated DWDS, including *Bdellovibrio, Bradyrhizobium, Peredibacter, Sphingomonas*, and *Hydrogenophaga* bacteria (Miao et al., 2022). The resistance was suggested to be modulated by glutaminyl-tRNA biosynthesis given the increase in the relative abundance of glutamate-tRNA ligase after chloramine disinfection (Miao et al., 2022). Other microbial inactivation strategies including ozonation or UV/H_2O_2 advanced oxidation can also be employed, although they are generally suitable for the primary disinfection stages of the DW treatment process (Prest et al., 2016).

Another important operational condition that potentially affects biofilm growth is the flow-rate variation in DWDS. Different locations along the DW network systems have variable hydrodynamic conditions, oscillating from laminar to turbulent and oppositely. To avoid zones in the distribution network with high organic material sedimentation, and consequently, abundant biofilm formation, the DWDS must be planned to reduce as much as possible the presence of zones of water stagnation and high water residence times in pipes (Liu et al., 2016; Simões and Simões, 2013). Flushing (increasing water flow rate to scour pipe inner walls), pigging (propelling a device through pipes for sediment removal), and air-water scouring (injecting filtered compressed air through pipes to propel water together with any suspended solids) are considered to be good routine management practices for biofilm control because they also remove any biomass killed or inactivated by disinfection (Liu et al., 2016).

A systematic review was conducted to assess the current state of knowledge regarding the disinfection of DW biofilms. The main aim of the present work was to draw reasonable conclusions across studies, through a qualitative and quantitative analysis of the literature on this topic over the last decade. The review includes the action of both conventional and novel strategies to control DW biofilms, as well as the analysis of the methods applied in the selected studies for biofilm formation and monitoring biofilms within DWDS. Finally, future research directions are highlighted to provide DW with effective microbial safety for consumers.

2. Methodology

The systematic quantitative literature review was accomplished according to the method described by Pickering and Byrne (2014) and Li et al. (2019). The application of a rigorous systematic methodology ensures that the current literature is adequately assessed, minimizing bias and random errors in the review of evidence from the individual studies (Pickering and Byrne, 2014; Li et al., 2019; Rousso et al., 2020). The methodology applied in this systematic literature review is schematized in Fig. 1.

Following the identification of the specific topic of study for literature review, *i.e.* state of the art in disinfection of DW biofilms, the identification of data sources and the definition of search criteria were performed. Research articles were searched on Web of Science™ (Clarivate) and Scopus (Elsevier) in the advanced topic search using the keywords ″drinking water″ OR ″potable water″ AND biofilm AND disinfection. Only original English written research articles published between January 2013 and December 2022 were considered. The present systematic quantitative literature review was focused on this subject matter over the last decade to present original and the most recent advances on the control of DW biofilms within DWDS that were not carefully addressed in the previous review studies performed by Kuo and Abustan (2009), Liu et al. (2016), Prest et al. (2016), Proctor and Hammes (2015), Rose and Rice (2014), and Simões and Simões (2013). The bibliographic information of the document search results was exported as BibTeX (bib), and comma separated (CSV Excel) or Excel (xls) file formats. This list included 562 journal articles identified through database searching, and after the removal of duplicates, it was reduced to 404 articles.

Then, the manual screening of the titles and abstracts in accordance with a set of arbitrary research questions relevant to the purpose of the study (Pickering and Byrne, 2014) allowed to pre-select 157 full-text articles for the next step of the systematic review process. This systematic quantitative literature review included the following research questions: Where, when, and by whom was the research published? What were the methods used for biofilm formation and monitoring biofilms within DWDS? What were the materials used as substrata for

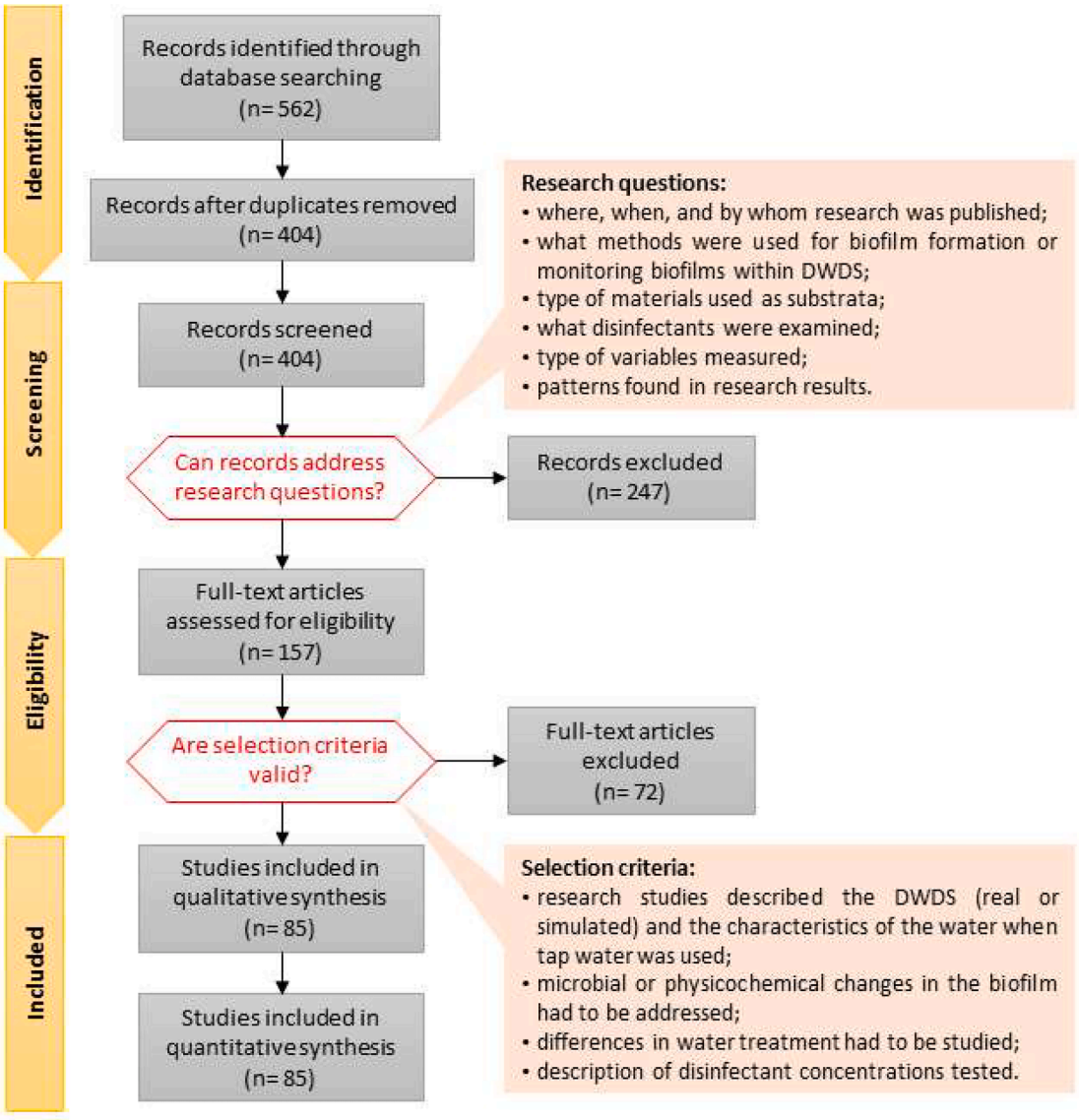

Fig. 1. Flow diagram of the different phases of the systematic review.

biofilm formation? What were the disinfectants tested? What were the variables typically measured? What were the patterns found in the research results? Finally, from the 157 full-text articles sample, eligibility criteria allowed to select 85 articles for detailed assessment. Selection criteria included the requirement that i) the research studies described the DWDS (real or simulated) and characteristics of the water when tap water was used for biofilm formation; ii) microbial or physicochemical changes in the biofilm had to be addressed; iii) differences in water treatment (preferable with primary or secondary disinfection) had to be studied, and iv) a clear definition of disinfectant concentrations tested.

3. Results and discussion

The 85 studies from the last decade included in this review were conducted in 23 different countries, with China and the United States of America being the two countries with the highest number of publications, with 21 and 19 articles, respectively (Figure S.1. Supplementary material). Following this rank were the United Kingdom, Canada, and Portugal, each with six publications, and France with five studies. From 2013 to 2022, the most prolific years were 2019 and 2022, with 14 and 11 articles, respectively.

3.1. Methods for biofilm formation and monitoring biofilms within DWDS

The preferable methods implemented to study DW biofilms were through the use of benchtop laboratory devices (Fig. 2(a)), particularly annular reactors, Centers for Disease Control (CDC) biofilm reactors, microtiter plates or Calgary biofilm devices, and microtiter plates with coupons of different materials. Other devices, such as the Propella™ reactor, rotating disc reactor, parallel plate flow chamber, flow cell system, and rotating cylinder reactor (RCR) were also applied, but at a lower frequency. The characterization and description of the limitations and advantages of these devices for studying biofilms in DWDS were extensively reviewed by Gomes et al. (2014). They are mainly used in laboratory-scale experiments, nevertheless, these devices mimic the conditions found in real DWDS, for example, environmental factors (temperature, concentration of nutrients and disinfectants), hydrodynamic conditions, and type of surface materials. Additionally, to promote biofilm formation, the benchtop laboratory devices can be supplied with tap water, supplemented water, or an appropriate broth medium. Table 1 summarizes the experimental conditions reported in

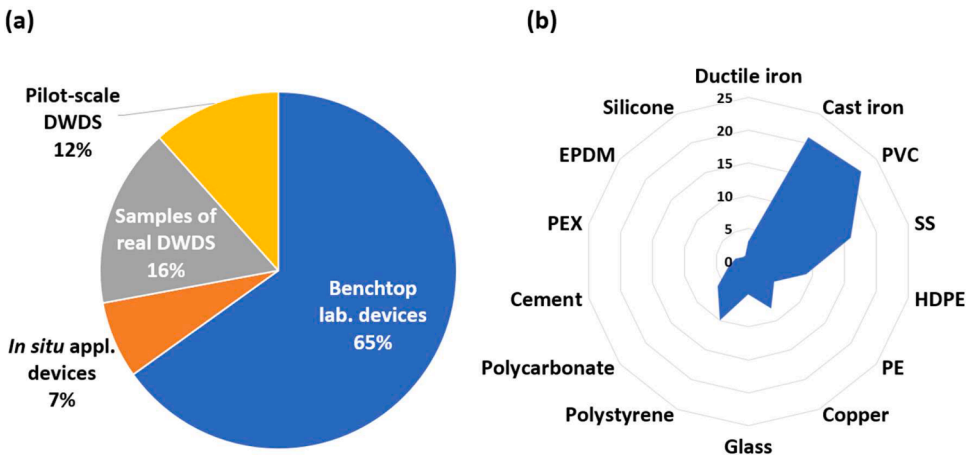

Fig. 2. Methods used to study DW biofilms (benchtop laboratory devices, pilot-scale DWDS, samples of real DWDS, and *in situ* application devices) (a) and different surface materials evaluated (b). The values in (b) represent the frequency of implementation of the different materials across the 85 research articles. PVC – polyvinyl chloride; SS – stainless steel; HDPE – high-density polyethylene; PE – polyethylene; PEX – cross-linked polyethylene; EPDM – ethylene-propylene-diene monomer rubber.

the selected articles to form and study the simulated DW biofilms with the use of benchtop laboratory devices. A variety of operational conditions were observed across the studies, with a duration of biofilm formation from 1 day to 2 years, under shear stress from 0.1 to 0.25 Pa, hydraulic retention time (HRT) from minutes to 48 h, and microbial colonization using the autochthonous microorganisms present in DW or with selected DW isolated bacteria.

Moreover, 16 % of the selected articles evaluated the biofilm growth in real DWDS by scraping the surfaces of water mains (Aggarwal et al., 2018; Alfredo, 2021; Cruz et al., 2020; Inkinen et al., 2021, 2019; Kelly et al., 2014; Waak et al., 2019a, 2019b; Wu et al., 2015) and household water meters (Ling et al., 2016); in hospital shower hoses through swab samples of the showerheads (Soto-Giron et al., 2016; Stüken et al., 2018); in dental units by cutting and collecting the polyvinyl chloride (PVC) tubes that supplied the units (Dallolio et al., 2014); in DWDS within broiler farms by swabbing the sample surface at the end of the pipes, openings at the drinking cups, and inside pressure regulators (Maes et al., 2019); and in an aircraft DW system through swab samples of coupling and tubing surfaces (Szabo et al., 2019). However, considering the heterogeneity of the biofilm distribution along the DW networks and the discrepancy of water properties in different locations, representative sampling constitutes a challenge (Liu et al., 2016). On the other hand, when it is intended to analyse biofilm samples of the water mains, the opportunities for the sampling process are dependent on pipe substitution and maintenance operations. Alternatively, the adaption of *in situ* devices placed as a by-pass or directly connected to the DWDS, and the biofilm formation in pilot-scale DW networks were also reported in the selected research articles. The *in situ* application devices included the Pennine Water Group coupon sampling device (Calero-Preciado et al., 2022; Fish et al., 2020; Fish and Boxall, 2018), biofilm incubators with glass beads (Bertelli et al., 2018), and an unconventional equipment analogous to a two-tiered "chandelier" with stainless steel (SS) coupons for biofilm formation in groundwater wells (Murray et al., 2015). The pilot-scale distribution facilities consisted of parallel loops of pipes with 0.5 to 270 m length from different materials and fed by DW (Álvarez-Arroyo et al., 2022; Farhat et al., 2022; Inkinen et al., 2017; Jungfer et al., 2013; Li et al., 2014; Meier and Bendinger, 2016; Pérez et al., 2019; Pérez and Susa, 2017; Zhang et al., 2019).

Among all the selected articles, the surface materials most studied for biofilm formation were PVC, cast iron, and SS (Fig. 2(b)). High-density polyethylene (HDPE), copper, and polystyrene were also tested, but at a lower frequency. These materials are representative of those used in DWDS pipes and household plumbing systems (Liu et al., 2016), except for polystyrene which reflected the limitation of the platform used for biofilm formation, *i.e.*, 96-well microtiter plates and Calgary biofilm device.

3.2. Disinfection strategies for biofilm prevention and control within DWDS

In the overall range of publications from the last decade, chlorination continues to be the most commonly studied strategy for biofilm prevention and control (Fig. 3). Chlorine in the form of chlorine gas, sodium hypochlorite, or calcium hypochlorite, was used for primary and secondary disinfection of water and subsequent control of microbial regrowth along the DW networks, as well as a direct strategy for control of pre-established biofilms. Nevertheless, it is important to mention that the use of chlorine as a reference disinfectant for comparison to other strategies or in combination with other disinfectants has contributed to its high relative frequency of implementation in the selected studies. Other disinfectants have been evaluated such as chloramine, UV irradiation, hydrogen peroxide, chlorine dioxide, ozone, and others, but at a lower frequency. Moreover, the different strategies have been tested alone or in combination with other treatments for the optimization of primary and secondary disinfection, as well as for studying the impacts of a multiple-barrier approach on the control of DW biofilms.

3.2.1. Chlorine

A significant number of studies have focused their objectives on evaluating the impact of chlorination on the microbial community present in DW biofilms. According to Pérez et al. (2019) in chlorinated DWDS with low flow conditions and high chlorine residuals, it is likely that a higher number of γ-proteobacteria can be observed than at sites further away from the treatment plant with lower chlorine residuals. On the other hand, fluctuations in the relative abundance of γ-proteobacteria probably will be higher at the end of the DW network if changes in water velocity do occur, as a consequence of bacterial detachment from the biofilm (Pérez et al., 2019). However, among the operational conditions evaluated in a pilot-scale DWDS with PVC pipelines, such as distance, time of stabilization, water velocity, and level of disinfectant residual, chlorine was found to be the most influential factor for the bacterial community, as it favoured the group characterized by its pathogenicity (Pérez et al., 2019). Reduced bacterial diversity populations dominated by *Pseudomonas,* including the opportunistic pathogen *Pseudomonas aeruginosa,* were found in biofilm samples developed in biofilm incubators with glass beads installed in chlorinated DWDS with 0.11 to 0.24 mg/L free chlorine (Bertelli et al., 2018). Zhang et al. (2022) also identified the genera *Rhodococcus* and *Sphingomonas* to have

Table 1
Methods for biofilm formation with benchtop laboratory devices.

Benchtop laboratory devices	Microbial colonization	Surface material	Primary water disinfection and/or residual disinfectant	Other operational conditions	References
Annular reactor	Autochthonous microorganisms present in groundwater source for DW	Cast iron	Chlorine at 0.1 mg/L or combined with UV pre-treatment (40 mJ/cm^2)	T = 25 °C Biofilm formation for 1 year Shear stress = 0.25 Pa HRT = 6 h	(Liu et al., 2019b)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron	Chorine concentration between 0 and 0.08 mg/L or combined with UV pre-treatment (40 mJ/cm^2)	Biofilm formation for 250 or 300 days Shear stress = 0.25 Pa (corresponding to a water velocity of 0.3 m/s in a 100 mm Ø smooth pipe) HRT = 6 h	(Wang et al., 2017; Zhu et al., 2014)
Annular reactor	Autochthonous microorganisms present in DW and further *L. pneumophila* inoculation (≈6.7 log CFU/mL)	Copper and PVC	Chlorine at 1 mg/L	T = 19–20 °C Biofilm formation for 1.5–2 years Rotation speed of 110 to 120 rpm (corresponding to a velocity of 0.3 m/s in a 12.7–25.4 mm Ø pipe) HRT = 10 min Then, 5 d incubation with *L. pneumophila* in batch mode in a beaker under agitation	(Buse et al., 2019)
Annular reactor	Autochthonous microorganisms present in DW	PVC	Chlorine concentration between 0.02 and 0.08 mg/L	T = 45 °C (lower limit for domestic hot water) Shear stress = 0.08 Pa HRT = 4 h	(Li et al., 2020b)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron	Chlorine at 1 mg/L or combined with UV/H_2O_2 pre-treatment (500 mJ/cm^2; 1 mg/L)	Biofilm formation for 90 days Rotation speed of 50 rpm HRT = 48 h	(Huo et al., 2021)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron	Chlorine at 0.04–0.1 mg/L or combined with ozone pre-treatment (0.55 mg/mg dissolved organic carbon)	Biofilm formation for 250 days Rotation speed of 50 rpm HRT = 6 h	(Wang et al., 2018)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron	Phosphate-enhanced ozone/biofiltration (2.18 mg O_3/mg dissolved organic carbon) and chlorine at 2.8 mg/L	Biofilm formation for 1.5–2 years Shear stress = 0.25 Pa HRT = 6 h	(Xing et al., 2018)
Annular reactor	Autochthonous microorganisms present in groundwater source for DW	Cast iron and polycarbonate	Untreated or groundwater treated with ion exchange, followed by chorine at 0.2 mg/L or combined with UV pre-treatment (40 mJ/cm^2)	Biofilm formation for 4 weeks without chlorination, followed by 12 weeks with disinfection Shear stress = 0.25 Pa	(Rand et al., 2013)
Annular reactor	Autochthonous microorganisms present in reclaimed water	Cast iron	Chorine at 0.05–1.10 mg/L or combined with UV pre-treatment (60 mJ/cm^2)	Biofilm formation for 305 days (first 30 days without disinfection) Shear stress = 0.25 Pa HRT = 6 h	(Wang et al., 2014)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron, SS, copper, PVC, and HDPE	Chlorine at 0.8 mg/L or chloramine at 1 mg/L	Biofilm formation for 8 weeks Shear stress = 0.25 Pa HRT = 1.7 h	(Li et al., 2020a)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron and polycarbonate	No disinfectant residual for 4 weeks, followed by 2 phases of chlorine at 0.2 and 1 mg/L	T = 21 °C Biofilm formation for 16 weeks Shear stress = 0.25 Pa HRT = 2 h	(Sharafimasooleh et al., 2016)
Annular reactor	Autochthonous microorganisms present in DW	PVC	No disinfectant residual, or chlorine at 0.4 mg/L or chloramine at 1.0 mg/L	T = 24 °C Biofilm formation for 6 weeks Shear stress = 0.154 Pa HRT = 1.9 h	(Wang et al., 2013)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron	Chlorine at 0.08 mg/L or combined with UV pre-treatment (40 mJ/cm^2)	Biofilm formation for 350 days	(Zhu et al., 2020a)
Annular reactor	Autochthonous microorganisms present in DW	Cast iron	Chorine at 0.05 mg/L or combined with ozone pre-treatment at 0.34 and 0.64 mg/L or O_3-BAC-Cl_2 system	T = 25 °C Biofilm formation for 6 months Rotation speed of 50 rpm HRT = 6 h	(Liu et al., 2019a)
Annular reactor	Autochthonous microorganisms present in DW	Polycarbonate	Chlorine at 1 mg/L with addition of either 1 mg/L PO_4^{3-} or 24–48 mg/L SiO_2	Biofilm formation for 1 year Rotation speed of 50 rpm HRT = 2 h	(Munoz et al., 2022)
Annular reactor	Autochthonous microorganisms present in DW	PVC	Total chlorine at 0.29 mg/L	T = 25 °C Biofilm formation for 2 years	(Chen et al., 2022)

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Table 1 (*continued*)

Benchtop laboratory devices	Microbial colonization	Surface material	Primary water disinfection and/or residual disinfectant	Other operational conditions	References
				Shear stress = 0.25 Pa HRT = 2 h	
Annular reactor	Autochthonous microorganisms present in DW	Ductile iron, SS, and PE	No chlorine residual or chlorine at 1.0 mg/L	Biofilm formation for 6 months HRT = 12 h	(Zhang et al., 2022)
CDC biofilm reactor	Multi-species cultures isolated from a local water utility (2×10^5 CFU/mL)	PVC	No chlorine residual or 3 phases of disinfection (Cl_2 or NH_2Cl): 50 days at 0.5 mg/L, followed by 25 days at 2 mg/L, and finally 25 days at 4 mg/L	T = 24 °C Biofilm formation for 6 months without disinfection, followed by 100 days with disinfection HRT = 12 h	(Wang et al., 2021)
CDC biofilm reactor	*P. aeruginosa* (≈ 10^{10} cells/mL)	Polycarbonate	No disinfectant residual	Biofilm formation for 5 days Stirred at 100 rpm HRT = 1.7 h	(Ma et al., 2022)
CDC biofilm reactor	Autochthonous microorganisms present in DW	Cement, PVC, and HDPE	No disinfectant residual or chloramine at 1.7 mg/L	Biofilm formation for 28 months Stirred at 125 rpm HRT = 4.5 h	(Aggarwal et al., 2018)
CDC biofilm reactor	Autochthonous microorganisms present in groundwater source for DW	PVC	No disinfectant residual for 1 year, then chlorine or chloramine at 4 mg/L	Biofilm formation for 1 year Stirred at 125 rpm (Re = 2384) Biofilm disinfection for 3 or 6 months in stirred or non-stirred conditions	(Shen et al., 2017, 2016)
CDC biofilm reactor	*P. aeruginosa*	Polycarbonate	No disinfectant residual	T = 23 °C Biofilm formation: 24 h in batch mode, followed by 24 h in CSTR* mode Stirred at 250 rpm HRT = 0.83 h	(Gora et al., 2019)
CDC biofilm reactor	Autochthonous microorganisms present in DW	SS and PE	Chlorine at 0.5 and 1.0 mg/L from chlorine gas or on-site generated chlorine	T = 21.6 °C Biofilm formation for 70 days Stirred at 100 rpm HRT = 30 min	(Choi et al., 2022)
CDC biofilm reactor	Autochthonous microorganisms present in groundwater source for DW	PVC	No disinfectant residual for 2 weeks, followed by chloramine at 7.5 to 9.1 mg/L for 8 weeks	Biofilm formation for 10 weeks Flow rate at 2.6 mL/min	(Ling and Liu, 2013)
CDC biofilm reactor	Single-species cultures of *P. aeruginosa* and *Staphylococcus aureus* (≈3 × 10^6 CFU/mL)	PVC	No disinfectant residual	T = 20 and 37 °C Biofilm formation for 24, 48 and 72 h Stirred at 125 rpm	(Garvey et al., 2015)
CDC biofilm reactor	*P. aeruginosa*	Polycarbonate	No disinfectant residual	T = 22.5 °C Biofilm formation: 24 h in batch mode, followed by 24 h in CSTR* mode Stirred at 125 rpm Flow rate at 11 mL/min	(Clayton et al., 2021)
Calgary biofilm device and microtiter plates	*P. alloputida* ($OD_{600\ nm}$=0.1)	Polystyrene	No disinfectant residual or 10 to 250 mg/L nZVI and its derivates (carboxymethyl cellulose- nZVI, oxidized-nZVI and Fe_3O_4)	T = 30 °C Biofilm formation for 24 h	(Yu et al., 2022)
Calgary biofilm device and microtiter plates	Single- and multi-species cultures of bacterial strains isolated from DWDS	Polystyrene	No disinfectant residual	T = 25 °C Biofilm formation between 20 h and 9 days Agitation at 125 rpm	(Schwering et al., 2013)
Calgary biofilm device and microtiter plates	Single- and multi-species cultures of *Sphingomonas* sp., *Acidovorax defluvii, Acinetobacter* sp., *B. cereus*, and *Microbacterium laevaniformans* (≈10^6 cells/mL)	Polystyrene	No disinfectant residual	T = 25 °C Biofilm formation for 24, 48, and 72 h Agitation at 150 rpm	(Zhu et al., 2020b; 2021)
Calgary biofilm device and microtiter plates	Single- and multi-species cultures of *A. calcoaceticus* (≈10^8 cells/mL) and filamentous fungi *Penicillium brevicompactum* and *P. expansum* (≈10^5 spores/mL)	Polystyrene	No disinfectant residual	T = 25 °C Adhesion for 2 or 4 h and biofilm formation for 24 or 48 h Shear stress = 0.05 and 1.6 Pa	(Simões et al., 2023)
Calgary biofilm device and microtiter plates	*P. aeruginosa*	Polystyrene	Chlorine at 0, 0.5, 0.7, and 1 mg/L	T = 37 °C Biofilm formation for 3 days	(Kekeç et al., 2016)
Calgary biofilm device and microtiter plates	Single-specie cultures of *Klebsiella* sp., *Pseudomonas* sp., *Flavobacterium* sp., and *Sphingomonas* sp. (≈10^7 cells/mL)	PVC	No disinfectant residual	T = 25 °C Biofilm formation for 48 h	(Lin et al., 2017)

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Table 1 (*continued*)

Benchtop laboratory devices	Microbial colonization	Surface material	Primary water disinfection and/or residual disinfectant	Other operational conditions	References
Calgary biofilm device and microtiter plates	Single-specie cultures of *P. putida* and mixed microbial community isolated from DW	Polystyrene	No disinfectant residual for 4 days, followed by chloramine at 0.5 to 32 mg/L for 2 days	$T = 30$ and 37 °C Biofilm formation for 6 days Static conditions	(Ng et al., 2021)
Calgary biofilm device and microtiter plates	Mixed-species nitrifying cultures	Polystyrene	No disinfectant residual	$T = 25$ °C Biofilm formation for 72 h Agitation at 100 rpm	(Keshvardoust et al., 2020)
Calgary biofilm device and microtiter plates	*P. aeruginosa* (≈10^6 CFU/mL)	Polystyrene	No disinfectant residual	$T = 37$ °C Biofilm formation for 24 h	(Stachler et al., 2021)
Calgary biofilm device and microtiter plates	Single-specie cultures of *Aspergillus niger, Penicillium polonicum*, and *Trichoderma harzianum* (≈10^5 CFU/mL)	Polystyrene	Chlorine, chlorine dioxide or chloramine from 0 to 1 mg/L	$T = 28$ °C Biofilm formation for 4 to 120 h	(Luo et al., 2021)
Propella™ reactor	Autochthonous microorganisms present in DW	Cast iron, PVC, and SS	No disinfectant residual	$T = 20$ °C Biofilm formation for 1 month in cast iron and 10 months in PVC and SS Water velocity = 0.13 m/s HRT = 12 h	(Gosselin et al., 2013)
Propella™ reactor	Autochthonous microorganisms present in DW and further *E. coli* inoculation (≈10^6 cells/mL)	SS	No disinfectant residual	Biofilm formation for 2–3 weeks (until 1.8–2 × 10^6 cells/cm^2) Then, the reactor was spiked with *E. coli* for bacterial adhesion for 1 h	(Mezule et al., 2015)
Parallel plate flow chamber	Single-species cultures of 3 *P. aeruginosa* strains and a wild-type *P. putida* (≈10^{10} cells/mL)	Glass	No disinfectant residual	$T = 22$ °C Biofilm formation for 6 days Flow rate = 0.2 mL/min	(Xue et al., 2014)
Parallel plate flow chamber	Single-species cultures of 3 *P. aeruginosa* strains, wild-type, alginate-deficient and alginate-overproducing mutants (≈10^{10} cells/mL)	Glass	No disinfectant residual or chlorine at 0.5 mg/L	Bacterial adhesion for 2 h without flow Biofilm formation for 6 days Flow rate = 1 mL/min HRT = 0.1 min	(Xue and Seo, 2013)
Flow cell system	Autochthonous microorganisms present in DW	HDPE	Dechlorinated DW containing 50 mg/L NH_3-N for stable nitrification process, then (3:1) and (5:1) Cl_2/NH_3-N mass ratios	$T = 16$ °C After the stable nitrification process, two phases of chloramination, each for 33 days Shear stress from 0.018 to 0.286 Pa	(Shi et al., 2019)
Rotating disc reactor	Autochthonous microorganisms present in DW	HDPE and glass	Chlorine concentration less than 0.02 mg/L	$T = 20$ °C Biofilm formation for 2 months Shear stress from 0.2 to 1 Pa	(Mathieu et al., 2014)
Rotating disc reactor	Autochthonous microorganisms present in DW and further bacteriophage (MS2, GA, and Qβ) inoculation (≈10^6 eqPFU/mL)	HDPE	Chlorine concentration less than 0.05 mg/L	Biofilm formation for 2 months Shear stress = 1 Pa (corresponding to a velocity of 0.5 m/s in a 20 cm Ø pipe) HRT = 24 h Then, the reactor was spiked with phages for adhesion in batch mode for 3 h	(Pelleieux et al., 2016)
RCR	Single- and dual-species cultures of *A. calcoaceticus* and *S. maltophilia* (≈10^7 CFU/mL)	PVC	No disinfectant residual	Biofilm formation for 7 days Shear stress = 1 Pa (0.34 m/s water velocity on the cylinder surface) HRT = 10 h	(Gomes et al., 2018)
RCR	*S. maltophilia* (2 × 10^7 cells/mL)	Copper alloys and SS	No disinfectant residual	Biofilm formation for 7 days Shear stress = 0.1 Pa HRT = 10 h	(Gomes et al., 2020)
Microtiter plates with coupons	Single-species cultures of *A. calcoaceticus* and *S. maltophilia* (≈10^6 CFU/mL)	PVC and SS	No disinfectant residual	$T = 25$ °C Biofilm formation for 48 h Agitation 150 rpm	(Oliveira et al., 2022)
Microtiter plates with coupons	Single-species cultures of *L. pneumophila* sg 1 and *L. pneumophila* sg 2–15 (≈10^6 CFU/mL)	Galvanized steel and PVC	No disinfectant residual or, after 18 or 30 days, chlorine at 50, 100, 150, and 200 mg/L	$T = 37$ °C Biofilm formation for 45 days	(Assaidi et al., 2020)
Microtiter plates with coupons	Single- and dual-species cultures of *A. calcoaceticus* and *S. maltophilia* (≈10^8 CFU/mL)	PVC	No disinfectant residual	$T = 23$ °C Adhesion for 2 h and biofilm formation for 24 h Agitation 120 rpm	(Gomes et al., 2016)

(*continued on next page*)

Table 1 (*continued*)

Benchtop laboratory devices	Microbial colonization	Surface material	Primary water disinfection and/or residual disinfectant	Other operational conditions	References
Microtiter plates with coupons	Single-species cultures of *Aeromonas* sp. isolated from DW, *Aeromonas hydrophila* and *P. aeruginosa* (≈10^8 CFU/mL)	SS	No disinfectant residual or disinfection with 1 % of amphoteric surfactants and diamines or 0.75 % of chlorine compounds	T = 4 and 20 °C Biofilm formation for 48 h	(Craveiro et al., 2015)
Microtiter plates with coupons	*P. aeruginosa* ($OD_{600\ nm}$=0.4)	HDPE coated with encapsulated phages	No disinfectant residual	T = 30 °C Biofilm formation for 72 h	(Zuo et al., 2022)

* CSTR – Continuous-flow Stirred Tank Reactor.

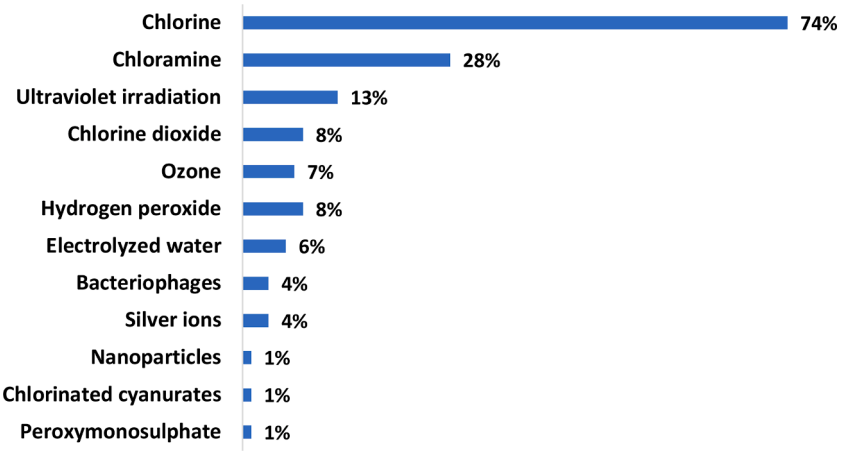

Fig. 3. Disinfection strategies reported in the last decade for biofilm prevention and control in DW. The values represent the relative frequency of implementation in the literature.

a growth advantage in biofilms formed on ductile iron, SS, and polyethylene using annular reactors fed by DW with 1.0 mg/L free chlorine. The impact of chlorine on DW biofilm prevention also included a reduction of the amount of heterotrophic plate counts and changes in the EPS spatial distribution within biofilms, in comparison to unchlorinated systems (Zhang et al., 2022). However, the influence of pipe materials was shown to be the principal factor for the biofilm community composition rather than the effect of chlorination (Zhang et al., 2022). Performing a metagenomic approach, Soto-Giron et al. (2016) demonstrated that the predominant taxon in microbial communities growing on hospital shower hoses supplied by DW containing 0.8 mg/L free chlorine was *Mycobacterium* sp., closely related to *Mycobacterium rhodesiae* and *Mycobacterium tusciae*. Additionally, genes associated with disinfectant tolerance and a lower abundance of virulence determinants associated with colonization and evasion of the host immune system were also detected in the biofilm community (Soto-Giron et al., 2016). Furthermore, sub-inhibitory concentrations of chlorine and type of pipe material (PVC and copper) collectively resulted in a selective pressure to enrich antibiotic-resistant bacteria within the microbial biofilm populations (Khan et al., 2019; Soto-Giron et al., 2016).

Chlorine was demonstrated to be effective for the control of a biofilm-associated opportunistic pathogen, *Legionella pneumophila* serogroup 1 (sg1), through reduction of culturable cells colonized in 1.5–2 year-old chlorinated DW biofilms developed on PVC by the use of annular reactors (Buse et al., 2019). After 15 min exposure of the biofilms to chlorine at 2 mg/L, a 3.9 log reduction of *L. pneumophila* sg1 and a 2.9 log reduction of the levels of heterotrophic plate counts were observed. The chlorine treatment also negatively impacted *L. pneumophila* sg1 16S rRNA gene transcript levels in biofilms formed on copper and PVC (Buse et al., 2019). However, culturable *L. pneumophila* sg1 cells detached from biofilms into the bulk water were still detected after 5 to 30 min of disinfection, demonstrating to be more tolerant to chlorine than planktonic *L. pneumophila* sg1 cells, which could be inactivated after 3 to 5 min of exposure (Buse et al., 2019). The inactivation of detached biofilm-associated *L. pneumophila* seems to be more critical when disinfection measures are applied to control *L. pneumophila* colonized in DW biofilms developed in locations where chlorine residual is lacking or low. For instance, Shen et al. (2017) demonstrated that the inactivation ratio of the *L. pneumophila* released from DW biofilms formed under no disinfectant conditions was up to 2 times lower, and infectivity to amoebae was up to 29 times higher than those from biofilms developed under biofilm prevention measures by exposure to chlorine or monochloramine at 4 mg/L for 6 months. The long-term disinfected autochthonous DW biofilms were suggested to provide less protection for the biofilm-colonized pathogens by altering the biofilm properties and minimizing the detachment of larger biofilm clusters (Shen et al., 2017). Indeed, after 3 months of chlorine or monochloramine exposure at 4 mg Cl_2/L, autochthonous DW biofilms formed on PVC in CDC reactors became more rigid with higher mean stiffness and higher ratio of protein over polysaccharide amount in the EPS than those DW biofilms without exposure to disinfectant residual (Shen et al., 2016). So, long-term disinfectant exposure seemed to promote biofilms more resistant to detachment and reduce the release of biofilm-associated pathogens (Shen et al., 2016). Conversely, biofilm control treatment through shock chlorination with 10 mg/L chlorine for 1 h decreased the biofilm cohesiveness of 2 month-old DW biofilms formed in a rotating disc reactor, by reducing the number of contact points within the biofilm EPS network structure (Mathieu et al., 2014). The damages also included a decrease in biofilm cluster volumes and detachment of bacterial cells in combination with low shear stress (Mathieu et al., 2014). Nevertheless, Xue and Seo (2013) highlighted that detached cell clusters from 6 days-old *P. aeruginosa* biofilms formed in a parallel plate flow chamber were still able to survive and initiate biofilm redistribution, even with biofilm prevention measures by

continuous chlorine disinfection at recommended minimal residual for DWDS (0.5 mg/L). Moreover, a high concentration of chlorine can lead to high water quality deterioration, which can be observed by the increase of inorganic loads and discoloration, a major cause of water quality complaints (Fish et al., 2020).

A recent study evaluated the impacts of water temperature increase due to climate change on the efficacy of biofilm control by shock chlorination combined with flushing (Calero-Preciado et al., 2022). An increase in water discoloration and alterations in the biofilm community structure were observed by the increase of water temperature from 16 to 24 °C, using a pilot-scale system with Pennine Water Group coupons. The implementation of flushing procedures alone or combined with a high concentration of chlorine decreased the discoloration potential and allowed a reduction of the relative abundance of bacterial biofilm community (Calero-Preciado et al., 2022). However, the authors concluded that the addition of shock chlorination as a strategy for managing biofilms seemed to be not beneficial because no difference between the interventions was observed (Calero-Preciado et al., 2022).

3.2.2. Chloramine

The effects of chloramination on microbial communities of DW biofilms are also widely reported in the literature (Aggarwal et al., 2018; Cruz et al., 2020; Li et al., 2020a; Ling and Liu, 2013; Wang et al., 2013). A preventive biofilm formation strategy through the presence of a chloramine residual concentration shaped the biofilm community formed on cement, PVC, and HDPE coupons in CDC reactors operating for more than two years by selecting *Mycobacterium*- and *Shingopyxis*--like taxon, while the biofilm community developed without chloramine was more diverse and dominated by *Nitrospira* population (Aggarwal et al., 2018). Additionally, chloramination also allowed a reduction of biofilm accumulation in these systems (Aggarwal et al., 2018). Nevertheless, the biofilm communities from the chloraminated CDC reactors differed significantly when compared to those on full-scale water mains that supplied water to the bench-scale system. The cement-lined water mains, which had been in service for approximately 52 years, also harbored biofilms dominated by *Mycobacterium* spp., but the overall communities were very distinct (Aggarwal et al., 2018). Similarly, Waak et al. (2019a) reported that biofilms on full-scale water mains with ages of 40–100 years from chloraminated DWDS presented lower biofilm biomass and lower alpha diversity (given by the Shannon and inverse Simpson indices) than those on no-residual DWDS, but chloramine selected for *Mycobacterium* spp. and *Nitrosomonas oligotropha* within the biofilm communities. Additionally, under corrosion tubercles present in the water mains, corrosion associated *Desulfovibrio* spp. were detected principally in the chloraminated DWDS (Waak et al., 2019a). Conversely, another study revealed that biofilm communities developed for about two months in chloraminated annular reactors were dominated by α-proteobacteria and β-proteobacteria (Li et al., 2020a). The presence of antibiotic biosynthesis-related pathways, such as tetracycline, bovobiocin, ansamycin, butirosin, and neomycin biosynthesis, were also found in the biofilm communities (Li et al., 2020a). High relative abundances of Pseudomonadota communities within 2 month-old biofilms formed under chloraminated tap water, specifically α-proteobacteria and β-proteobacteria, were also observed by Mi et al. (2015) using a custom-made bench-scale pipe section reactors constructed with cast iron pipes from a full-scale DWDS, which had been in service for approximately 27 years. Chloraminated DWDS located in urbanized metropolis with tropical conditions were affected by the auto-decomposition of chloramine to free ammonia, promoting the growth of nitrifiers within the biofilms of full-scale water mains (Cruz et al., 2020). Furthermore, metabolically active ammonia-oxidizing bacteria were responsible for mediating the decay of chloramine and protecting the members of mixed-species biofilms from the biofilm control treatment through disinfection with chloramine at 2 mg/L for 1 h in a microtiter biofilm modelling system (Keshvardoust et al., 2020).

A comparative study between chlorinated and chloraminated DW biofilms formed on PVC in CDC reactors demonstrated the lower efficacy of chloramine in biofilm removal than chlorine, even at the highest concentration tested (4 mg/L) for both chlorine and monochloramine (Wang et al., 2021). However, chloramine disinfection showed to be beneficial for the prevention of high levels of DBPs at different chloramine residuals (Wang et al., 2021), as well as for the control of *Legionella* spp. in the DW biofilms (Wang et al., 2013). A significant reduction in biofilm biomass and thickness of more than 80 % was reported after 10 weeks of preventive DW biofilm regrowth process by disinfection with high concentrations of chloramine (between 7 and 9 mg/L), even though membrane-intact cells within the biofilms were still detected (Ling and Liu, 2013). After a biofilm control treatment with chloramine disinfection for 2 days in 4 days-old microtiter biofilm models, Ng et al. (2021) suggested that the persistent bacteria could easily enter a viable but non-culturable state and form biofilms mainly constituted by protein EPS. Additionally, sub-lethal disinfection with chloramine resulted in biofilms being more resistant to chloramination, given the increase of the inhibitory concentration of the exposed biofilm cultures in comparison to the untreated biofilm (Ng et al., 2021). There is a consensus among previous studies that chloramine has a good diffusion capability through the biofilm matrix because it is more stable and less reactive than chlorine (Fang et al., 2010; LeChevallier et al., 1990, 1988; Lee et al., 2011). However, Xue et al. (2014) demonstrated that the composition of the biofilm matrix affects the chloramine penetration, biofilm inactivation, and the viability of detached clusters. The comparison of the chloramine treatment (at 2 mg/L for 2 h) against 6 days-old biofilms formed in a parallel plate flow chamber by protein-based EPS producing *Pseudomonas putida* and polysaccharide-based EPS producing *P. aeruginosa* revealed that the selective reaction with proteins was unfavourable for disinfectant penetration (Xue et al., 2014).

3.2.3. UV irradiation

The effects of combined UV irradiation for primary disinfection of water followed by the addition of chlorine residuals for secondary disinfection have been evaluated on biofilms developed in DWDS. Valuable results were reflected in the water quality, with the inactivation of heterotrophic bacteria and opportunistic pathogens in the bulk phase, reduction of the required initial chlorine dose, as well as decreased iron release from cast iron surfaces in annular reactors (Liu et al., 2019b; Wang et al., 2014). However, no significant differences were observed in the autochthonous DW biofilm growth (Rand et al., 2013; Wang et al., 2014). Therefore, the results suggested an inefficiency of UV irradiation and residual chlorine for preventing microbial regrowth and biofilm formation in cast iron distribution networks, even when comparing DW from untreated hard groundwater and groundwater treated with granular-activated carbon (GAC) filter followed by ion exchange to remove hardness (Rand et al., 2013). Moreover, opportunistic pathogens such as *Legionella* spp., *Mycobacterium* spp., *P. aeruginosa, Acanthamoeba* spp., and *Aeromonas* spp. present in the biofilms, corrosion products, and loose deposits were shown to be tolerant to combined UV and chlorine or chlorine alone disinfection (Liu et al., 2019b). Within biofilms developed on copper and SS surfaces of biofilm devices installed in modular pilot-scale systems fed with UV-disinfected DW, the expression of *rec*A SOS responsive gene, which is the main mechanism to repair DNA injuries, was also reported (Jungfer et al., 2013).

The impacts of UV/chlorine disinfection have also been studied on the microbial composition of the autochthonous DW biofilm communities formed on cast iron surfaces of annular reactors (Wang et al., 2014, 2017; Zhu et al., 2014). The preventive biofilm formation strategy through combined UV (primary) and chlorine (secondary) disinfection induced bacteria from the genus *Dechloromonas* to be dominant in the biofilms, which were responsible for the decrease of corrosion rate through their redox cycling of iron, enhancing the precipitation of iron oxides and formation of Fe_3O_4 (Wang et al., 2017; Zhu et al., 2014).

Additionally, Wang et al. (2014) also detected the presence of the iron-oxidizing bacterium *A. defluvii* and the iron-reducing bacteria uncultured *Rhodoferax* sp. and uncultured *Geobacter* sp. in biofilms developed in UV/chlorine distribution systems.

A recent study indicated that the use of an advanced oxidation process with the combination of UV (500 mJ/cm^2) and hydrogen peroxide (1 mg/L) before GAC filtration followed by post-chlorination enhanced the control of opportunistic pathogens in autochthonous DW biofilms formed on cast iron surfaces of annular reactors (Huo et al., 2021). This multi-barrier process (UV/H_2O_2-GAC-chlorine) promoted the reduction of the number of *L. pneumophila, Mycobacteria avium*, and *P. aeruginosa* in the bulk water and biofilms, as well as induced a lower chlorine-tolerance of the biofilm-embedded cells by decreasing the content of proteins found within the biofilm matrix (Huo et al., 2021). Indeed, both water treatments with GAC filtration or UV/H_2O_2-GAC filtration allowed to improve the removal of the tryptophan-like proteins, and fulvic acid-like and humic acid-like compounds from the inlet water, which was suggested to cause the lower diversity and lower richness of the biofilm bacterial community in the two DWDS (Huo et al., 2021).

3.2.4. Other disinfection strategies

New disinfection strategies have been explored for application on DW and their impact on DW biofilms has been evaluated under defined water processing systems or at pilot or laboratory scale. For example, dental units supplied by municipal DW are also subjected to biofilm formation within their water networks. Dallolio et al. (2014) investigated the efficacy of different strategies to control autochthonous DW biofilms on PVC tubes from dental units, including an intermittent disinfection protocol with a peroxidic system (peracetic acid, peracetyl ions, and hydrogen peroxide) and two continuous disinfection protocols with hydrogen peroxide combined with silver ions and chloride dioxide, respectively. Compared to non-disinfected dental units, the different protocols allowed the decrease of the number of heterotrophic bacteria in the bulk water and the reduction of biofilm thickness (Dallolio et al., 2014). However, the continuous disinfection protocols were demonstrated to be more efficient, promoting the total eradication of culturable *P. aeruginosa* cells (Dallolio et al., 2014). Conversely, Meier and Bendinger (2016) reported that the efficacy of chlorine, hydrogen peroxide, or chlorine dioxide in controlling the regrowth of opportunistic pathogens in DW plumbing systems was affected by the operating temperature (11 or 37 °C), pipe surface material (copper, SS, polyethylene, or ethylene-propylene-diene monomer (EPDM) rubber), and water quality (nutrient concentration of N, P, and assimilable organic carbon). Generally, at 11 °C all the disinfectants were able to suppress the regrowth of inoculated *L. pneumophila* and *P. aeruginosa* in autochthonous DW biofilms developed in a pilot-scale pipeline system and bulk water, while at 37 °C both pathogens were detected in a culturable state (Meier and Bendinger, 2016). The presence of high nutrient levels in the water and the use of EPDM rubber pipes also limited the action of these disinfectants. Nevertheless, non-culturable cells were observed in treated biofilms even in favourable disinfectant operating conditions (Meier and Bendinger, 2016).

Since the water quality (*i.e.* diversity and level of nutrients) has a significant impact on the performance of the disinfectants, a previous reduction of the organic load from the water may be a relevant step to improve disinfection performance. Therefore, the application of chemical (ozone) or physical (*e.g.* UV irradiation, biofiltration or ultrafiltration) pretreatments before the application of the mentioned disinfectants may be a promising strategy for an improved biofilm control. For instance, the impacts of primary disinfection of water with ozone followed by post-chlorination have also been evaluated on the development of biofilms in DW networks (Álvarez-Arroyo et al., 2022; Liu et al., 2019a; Wang et al., 2018). Likewise UV/chlorine disinfection, the ozone/chlorine disinfection demonstrated to promote changes in the content of corrosion-related bacteria within autochthonous DW biofilms formed on cast iron surfaces in annular reactors (Wang et al., 2018). An abundance of iron-oxidizing and iron-reducing bacteria were detected in the water system disinfected with ozone combined with chlorination, in comparison to those only disinfected with chlorine (Wang et al., 2018). The alterations in the microbial community of biofilms in the ozone/chlorine systems promoted an increase of Fe_3O_4 formation in the corrosion scales of cast iron surfaces that became more stable than the ones formed in the chlorinated systems. Therefore, ozone/chlorine disinfection was beneficial to inhibit corrosion and iron release in these bench-scale DWDS (Wang et al., 2018). Even though a decrease in the number of gene copies of *M. avium* and *L. pneumophila* within the biofilms was observed (Wang et al., 2018), typical opportunistic pathogens, such as *Legionella* spp., *Mycobacterium* spp., *P. aeruginosa, Acanthamoeba* spp., and *Aeromonas* spp. were still positively detected in biofilms of DW treated with ozone/chlorine disinfection or ozone combined with BAC biofiltration followed by chlorination (Liu et al., 2019a; Wang et al., 2018). Besides the inability to prevent autochthonous DW biofilm formation in chlorinated systems, the use of ozone before water ultrafiltration resulted in the increase of DBPs formation, such as trihalomethanes and haloacetic acids, in a pilot-scale polyethylene pipeline system (Álvarez-Arroyo et al., 2022).

Electrochemical water disinfection is an alternative to conventional DW chlorination, as it can generate free chlorine from the electrolysis of water in the presence of a high concentration of salts (Choi et al., 2022; Clayton et al., 2021; Mezule et al., 2015; Murray et al., 2015). Other oxidative species such as ozone, hydrogen peroxide, and oxygen free radicals can also be formed (Choi et al., 2022; Mezule et al., 2015), and, therefore, the term ″mixed oxidants" disinfectant solution has been similarly reported in the literature to designate this disinfection strategy (Choi et al., 2022; Murray et al., 2015; Szabo et al., 2019). Mezule et al. (2015) indicated that electrolyzed water was efficient in decreasing the culturability and respiratory activity of *E. coli* in the planktonic state up to 5 and 2 log reduction, respectively. However, biofilm-associated *E. coli* cells, which had been inoculated in autochthonous DW biofilms formed on SS through the use of Propella™ reactors, were more tolerant to disinfection with a 3 log decrease in culturability and the presence of 30 % of cells able to divide (Mezule et al., 2015). Moreover, electrolyzed water was more effective than chlorine gas in reducing the total heterotrophic bacteria present within autochthonous DW biofilms formed on polyethylene surfaces in CDC biofilm reactors (Choi et al., 2022). Although this strategy resulted in a lower HOCl/OCl^- ratio, the weak reactivity of OCl^- with the biofilm matrix allowed it to effectively penetrate the biofilms (Choi et al., 2022).

A comparative study between different disinfection strategies, such as UV irradiation, hydrogen peroxide, ozone, and electrolyzed water, was performed for the control of pre-established autochthonous biofilms on SS surfaces from groundwater wells (Murray et al., 2015). The authors concluded that hydrogen peroxide at 1 % or 6 % (v/v) presented the most effective disinfection with a reduction of biofilm culturability up to 3.1 log, followed by electrolyzed water and ozone with 1.4 and 1.0 log reduction, respectively (Murray et al., 2015).

Bacteriophages, also known as phages, are small viruses that selectively target prokaryotic cells. Specifically, lytic phages have a cost-effective bactericidal capacity, even at a low single dosage, and are considered an environment-friendly strategy for biofilm control (D'Accolti et al., 2021; Parasion et al., 2014). The mechanism of action can be summarized in the following steps: (a) phages are first absorbed on the bacterial surface by a viral tail strand that binds to specific receptors, such as lipopolysaccharides, proteins, sugar molecules, and fimbriae; (b) then they enter and take over the metabolism of the host cell; (c) after lytic phage replication, new phages are released by endolysin-mediated cell lysis (an enzyme encoded by phage capable of degrading the bacterial cell wall), making a new cycle of infection possible (Parasion et al., 2014; Tian et al., 2021). Bacteriophages have been used in several fields for controlling bacterial pathogens in agriculture, the food industry, aquaculture, and medicine (D'Accolti et al., 2021; Moye et al., 2018).

Some investigations with bacteriophages for water systems have been recently conducted (Magin et al., 2019; Stachler et al., 2021; Zuo et al., 2022). After 14 h of exposure to specific lytic bacteriophages, a 1.7 log reduction of 24 h-old *P. aeruginosa* biofilms formed on SS coupons in plastic flasks was observed (Magin et al., 2019). Additionally, the authors also observed that bacteriophages were effective in limiting the spread of detached biofilm cells in the bulk phase (Magin et al., 2019). However, similarly to other disinfectant strategies, the action of bacteriophages was higher against planktonic bacteria than in biofilms. To circumvent the diffusion limitations through the biofilm matrix, Zuo et al. (2022) proposed a targeted delivery of bacteriophages by encapsulation of phages in chitosan crosslinked with tri-polyphosphate and 3-glycidoxypropyltrimethoxysilane. The encapsulated-phage coating on HDPE surfaces placed in microtiter plates allowed a biomass reduction of more than 90 % of 72 h-old *P. aeruginosa* biofilms, as well as a significant reduction of the biofilm surface area coverage and the ratio of the viable/damaged cells (Zuo et al., 2022). Moreover, Stachler et al. (2021) evaluated the combinatory effects of phages and chemical disinfectant treatments on 24 h-old *P. aeruginosa* biofilms formed on microtiter plates. The bacteriophage treatment for 4 h at 37 °C followed by chlorine disinfection at 200 mg/L for 10 min at room temperature could decrease the number of non-damaged biofilm cells by more than 3 log, which was demonstrated to be more efficacious than each treatment alone (Stachler et al., 2021). However, the impact of the phage treatment was reduced when bacteriophages were applied after chemical disinfection, even with a lower chlorine concentration of 5 mg/L (Stachler et al., 2021). Sodium hypochlorite concentrations of 5 and 20 mg/L for 10 min were found to cause phage inactivation, but the authors suggested that this was not the reason for hindering the impact of phage treatment when chemical disinfection was applied first, since chlorine was removed and quenched before the application of phages (Stachler et al., 2021). Stachler et al. (2021) further proposed that the previous exposure of bacterial cells to chlorine could induce them to enter an inactive state, inhibiting phage infection and self-propagation. Although the effects of the combination of bacteriophages followed by chlorine disinfection are interesting, the benefits and practicability of this approach for pathogen control in DW networks are questionable, principally in chlorinated DWDS. The simultaneous application of bacteriophages and chemical disinfection requires that the phage would be resistant to the disinfectant, but phage inactivation events were observed with chlorine concentrations used for DW disinfection (5 mg/L) (Stachler et al., 2021). Additionally, residual disinfectant concentrations in the bulk water or biofilm matrix may invalidate phage treatment. Nevertheless, it is uncertain whether phage may affect the environmental microbiome, principally in the case of phage release into the environment without regulation. The indiscriminate use of bacteriophages, which are considered one of the last resources to face antibiotic resistance, can promote the rise of bacterial resistance to phage treatments (Brockhurst et al., 2021; Hussain et al., 2021; MacCallin and Oechslin, 2019; Sousa and Rocha, 2019). Bacteriophages are not suitable for the replacement of broad-spectrum disinfectants in DW treatment. However, their use can represent a promising strategy for target-oriented disinfection. In particular, attending the selectivity of bacteriophages, they could be used to control/inactivate specific problematic bacteria tolerant to conventional disinfection strategies.

A promising strategy has been recently proposed to control biofilm formation in water systems and to prevent the emergence of antimicrobial resistance through the use of a nanomaterial-based approach (Yu et al., 2022). The exposure of *Pseudomonas alloputida* to 10 mg/L of engineered nanoscale zero-valent iron (nZVI) and derivates, including carboxymethyl cellulose-modified nZVI and oxidized nZVI nanoparticles, revealed a significant inhibitory effect on biofilm formation measured by crystal violet biomass quantification in a microtiter biofilm model (Yu et al., 2022). The nZVI nanoparticles also promoted the removal of pre-established 24 h-old *P. alloputida* biofilms. Moreover, both nZVI and carboxymethyl cellulose-modified nZVI hindered the acquisition of *P. alloputida* resistance to ampicillin, ciprofloxacin, and tetracycline during a 30-day antimicrobial resistance emergence assay. The mechanism of action of nZVI nanoparticles was suggested to be through the overproduction of reactive oxygen species, cytoplasmic membrane destabilization, and inhibition of efflux pumps (Yu et al., 2022). Gosselin et al. (2013) had already demonstrated that DW biofilm disinfection could be improved by Fenton-like oxidation with the presence of H_2O_2 at pH 5 and using iron present in the attached biomass on fully corroded cast iron pipes as a catalyst of the Fenton reaction. This reaction is an advanced oxidation process that through a sequence of reactions with iron and H_2O_2 at acidic pH generates oxidative species such as hydroxyl radicals (Gosselin et al., 2013).

Arrays of microchannel plasma jets were claimed to provide a chlorine-free and *in situ* tool for the control and removal of biofilms in commercial or residential plumbing systems (Sun et al., 2018). The experimental 9 × 9 array of helium plasma jets consisted of microchannel/electrode structures fabricated by 3D printing. After 20 min exposure of simulated DW biofilms to the plasma array, non-thermal disruption and deactivation of biofilm cells was observed (Sun et al., 2018). These authors proposed that several oxygen-bearing species, such as hydroxyl radical, singlet oxygen, hydrogen peroxide, and ozone, produced by the interaction of the helium plasma microcolumns with room air were primarily responsible for the destruction of the biofilms and the deactivation of the biofilm-embedded microorganisms. Although the experimental geometry of the microplasma array was not suitable for application in DWDS, a cylindrical geometry system comprising multiple cylindrical microplasma jet arrays integrated with a modified plumbing snake was described in the U.S. Patent No. 8957572. This technology can provide a degree of specificity in terms of spatial localization and customized treatment to specific biofilm compositions or structures, as well as appears as an alternative to control DW biofilms in plumbing systems where previous interventions have been unsuccessful (Sun et al., 2018).

The scientific community has evaluated all these mentioned strategies which may be relevant for application in DW disinfection to control biofilms. However, due to associated costs and specificity, their use may be limited for restricted conditions. For example, the use of nZVI has been described as important for combating the emergence of antimicrobial resistance. Therefore, their application in hospital-associated DWDS could be justifiable, while bacteriophages may be applied as a specific and/or complementary treatment. Also, the characterization of the DW chemical composition, the monitoring and characterization of planktonic and sessile microbial communities in DWDS are essential to apply adequate disinfection strategies and pre-treatments for an improved water safety and biofilm control.

4. Challenges for innovation in DW biofilm disinfection

The presence of biofilms in DWDS constitutes an important problem for DW suppliers given the potential source of microbial contamination, deterioration of water quality, including the taste and odour, and promotion of pipe corrosion. The biofilm matrix protects the embedded cells from disinfection and facilitates the recovery and growth of microbial cells injured by environmental stress and disinfection (Buse et al., 2019; Liu et al., 2016; Simões and Simões, 2013). Moreover, the higher biofilm tolerance to disinfection in comparison to the planktonic cell state (Mezule et al., 2015; Rand et al., 2013; Wang et al., 2014) poses a significant difficulty in the surveillance of public health risks present in the DW networks. The presence of opportunistic pathogens namely *Legionella* spp., *Mycobacterium* spp., *P. aeruginosa, Acanthamoeba* spp., and *Aeromonas* spp. (Liu et al., 2019a; 2019b; Wang et al., 2018) and detection of antibiotic biosynthesis-related pathways and virulence determinants (Li et al., 2020a; Soto-Giron et al., 2016) in microbial communities of DW biofilms developed in conventional disinfected DWDS have been frequently reported. Additionally, sub-inhibitory concentrations of chlorine or chloramine, which are present in network locations

further away from the treatment plants, may create a selective pressure to enrich antibiotic-resistant bacteria in the DW biofilms (Khan et al., 2019; Soto-Giron et al., 2016) or promote biofilm resistance to disinfection (Ng et al., 2021). Therefore, to ensure an optimized control of microbial recontamination in DWDS it is important to choose a disinfectant with adequate chemical stability through the DW network. On the other hand, it has been observed that an effective strategy for biofilm control is not necessarily achieved by the use of a disinfectant with the best activity against microbial cells in a planktonic state (Choi et al., 2022). The reaction with the EPS components and consequent lower chemical diffusion through the biofilm hinders the action of disinfectants against biofilms (LeChevallier et al., 1990; Lee et al., 2011; Xue et al., 2014). For that reason, an appropriate understanding of the mechanisms involved in the interaction of disinfectants with biofilms, including biofilm matrix and embedded cells, will advance the accomplishment of effective strategies for biofilm control in DWDS.

The scientific community should develop through consensus and internationally adopt guidelines for the formation and monitoring of DW biofilms to improve consistency and better inform the findings of these investigations. The complexity of the DWDS environment combined with the application of diverse methods and experimental systems for biofilm formation can result in ambiguous or difficult to compare results between studies. The majority of the research studies used benchtop laboratory devices for DW biofilm investigations. These devices allow a realism-based assessment of the effectiveness of the disinfectants on biofilm control under controlled experimental conditions. Nevertheless, promising alternatives to conventional disinfectants should also be validated by conducting experiments using *in situ* devices placed as a bypass or directly connected to the DWDS, or alternatively, using pilot-scale DW networks.

Lastly, when designing a new approach for the disinfection of DW biofilms, specifically with the use of chemical agents, it is important to not undervalue the public perception of the solution and the requirements for approval under national policies and regulations. Within this regulatory context in the European Union, chemical agents for water disinfection are also classified as biocidal products, and so, the practical application of these strategies is dependent on the approval process defined by the Biocidal Product Directive (Regulation (EU) No 528/2012) on the supply and use of biocidal products. The Biocidal Product Directive ensures that the biocidal products are effective and do not present unacceptable risks to humans, animals, or the environment (Regulation (EU) No 528/2012). Similarly, disinfectant products for DW use in the United States of America must be licensed by the U.S. Environmental Protection Agency (U.S. EPA) under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (U.S. EPA, 2023).

5. Conclusion

This systematic review qualitatively and quantitatively analysed the research advances in the disinfection of DW biofilms over the last decade. The studies were mainly performed using benchtop laboratory devices that mimic the conditions found in real DWDS, and, to a lesser extent, by monitoring the biofilm growth in real DWDS and in pilot-scale systems. Conventional disinfection with chlorine or chloramine continues to be the most frequently explored strategy for biofilm prevention and control, but other alternatives were also reported. The diversity of operational conditions applied across the studies challenged the ability to derive reliable comparisons between studies. Changes in microbial biofilm communities, culturability, biofilm biomass, and biofilm matrix components can be achieved by the application of disinfectants. The presence of chlorine or chloramine residual concentrations and the type of pipe materials used in the DWDS represent the main factors that impact the DW biofilm community composition, resulting in a lower diversity and selective pressure to favour opportunistic pathogens. Nevertheless, the maintenance of an effective residual concentration in the water guarantees long-term prevention of biofilm formation and improves the inactivation of detached biofilm-associated opportunistic pathogens. Additionally, disinfection strategies based on multi-barrier processes by optimization of primary and secondary disinfection combined with other water treatment methods, such as filtration, improve the control of opportunistic pathogens, reduce the chlorine-tolerance of biofilm-embedded cells, as well as decrease the corrosion rate in metal-based pipelines. Although, no effective strategy has been demonstrated for the complete eradication of DW biofilms, as regrowth is detected after disinfection, new and promising strategies have been evaluated at laboratorial scale, such as the use of bacteriophages and nanoparticles. These developing strategies may be of great potential for application in restricted DWDS and as response to specific microbial problems.

CRediT authorship contribution statement

Isabel Maria Oliveira: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Inês Bezerra Gomes:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lúcia Chaves Simões:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Formal analysis, Conceptualization. **Manuel Simões:** Conceptualization, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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 paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was financially supported by: LA/P/0045/2020 (ALiCE), UIDB/00511/2020, UIDP/00511/2020 (LEPABE) UIDB/BIO/04469/2020 (CEB), and LA/P/0029/2020 (LABBELS), PRESAGE - Aquatic/0007/2020, funded by national funds through FCT/MCTES (PIDDAC); project Germirrad – POCI-01-0247-FEDER-072237 supported by COMPETE2020 – Programa Operacional Competitividade e Internacionalização (POCI) and FCT/MCTES (PIDDAC); FCT PhD grant awarded to Isabel Maria Oliveira (SFRH/BD/138117/2018) and the Inês B. Gomes' contract supported by FCT (2022.06488.CEECIND).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121273.

References

Aggarwal, S., Gomez-smith, C.K., Jeon, Y., LaPara, T.M., Waak, M.B., Hozalski, R.M., 2018. Effects of chloramine and coupon material on biofilm abundance and community composition in bench-scale simulated water distribution systems and comparison with full-scale water mains. Environ. Sci. Technol. 52, 13077–13088. https://doi.org/10.1021/acs.est.8b02607.

Alfredo, K., 2021. The "Burn": water quality and microbiological impacts related to limited free chlorine disinfection periods in a chloramine system. Water Res. 197, 117044 https://doi.org/10.1016/j.watres.2021.117044.

Álvarez-Arroyo, R., Pérez, J.I., Ruiz, L.M., Gómez, M.A., 2022. Chlorination by-products formation in a drinking water distribution system treated by ultrafiltration associated with pre-ozonation or coagulation/flocculation. J. Water Process Eng. 47, 102779 https://doi.org/10.1016/j.jwpe.2022.102779.

Assaidi, A., Ellouali, M., Latrache, H., Zahir, H., Karoumi, A., Mliji, E.M., 2020. Chlorine disinfection against *Legionella pneumophila* biofilms. J. Water, Sanit. Hyg. Dev. 10, 885–893. https://doi.org/10.2166/washdev.2020.151.

Bertelli, C., Courtois, S., Rosikiewicz, M., Piriou, P., Aeby, S., Robert, S., Loret, J.F., Greub, G., 2018. Reduced chlorine in drinking water distribution systems impacts bacterial biodiversity in biofilms. Front. Microbiol. 9, 2520. https://doi.org/10.3389/fmicb.2018.02520.

Brockhurst, M.A., Koskella, B., Zhang, Q.-G., 2021. Bacteria-phage antagonistic coevolution and the implications for phage therapy. In: Harper, D.R., Abedon, S.T., Burrowes, B.H., MacConville, M.L. (Eds.), Bacteriophages. Springer, Cham, Switzerland, pp. 231–251. https://doi.org/10.1007/978-3-319-41986-2_7.

Buse, H.Y., Morris, B.J., Struewing, I.T., Szabo, J.G., 2019. Chlorine and monochloramine disinfection of *Legionella pneumophila* colonizing copper and polyvinyl chloride drinking water biofilms. Appl. Environ. Microbiol. 85, 1–16. https://doi.org/10.1128/AEM .02956-18.

Calero-Preciado, C., Soria-Carrasco, V., Boxall, J., Douterelo, I., 2022. Climate change and management of biofilms within drinking water distribution systems. Front. Environ. Sci. 10, 962514 https://doi.org/10.3389/fenvs.2022.962514.

Characklis, W.G., Marshall, K.C., 1990. Biofilms: a basis for an interdisciplinary approach. In: Characklis, W.G., Marshall, K. (Eds.), Biofilms. John Wiley & Sons, Inc, New York, pp. 3–15.

Chen, J., Li, W., Tan, Q., Sheng, D., Li, Y., Chen, S., Zhou, W., 2022. Effect of disinfectant exposure and starvation treatment on the detachment of simulated drinking water biofilms. Sci. Total Environ. 807, 150896 https://doi.org/10.1016/j.scitotenv.2021.150896.

Choi, Yonkyu, Byun, S.-H., Jang, H.-J., Kim, S.-E., Choi, Y., 2022. Comparison of disinfectants for drinking water: chlorine gas *vs.* on-site generated chlorine. Environ. Eng. Res. 27, 200543 https://doi.org/10.4491/eer.2020.543.

Clayton, G.E., Thorn, R.M.S., Reynolds, D.M., 2021. The Efficacy of chlorine-based disinfectants against planktonic and biofilm bacteria for decentralised point-of-use drinking water. In: NPJ Clean Water, 4, p. 48. https://doi.org/10.1038/s41545-021-00139-w.

Craveiro, S., Alves-Barroco, C., Crespo, M.T.B., Barreto, A.S., Semedo-Lemsaddek, T., 2015. *Aeromonas* biofilm on stainless steel: efficiency of commonly used disinfectants. Int. J. Food Sci. Technol. 50, 851–856. https://doi.org/10.1111/ijfs.12731.

Cruz, M.C., Woo, Y., Flemming, H.C., Wuertz, S., 2020. Nitrifying niche differentiation in biofilms from full-scale chloraminated drinking water distribution system. Water Res. 176, 115738 https://doi.org/10.1016/j.watres.2020.115738.

D'Accolti, M., Soffritti, I., Mazzacane, S., Caselli, E., 2021. Bacteriophages as a potential 360-degree pathogen control strategy. Microorganisms 9, 261. https://doi.org/10.3390/microorganisms9020261.

Dallolio, L., Scuderi, A., Rini, M.S., Valente, S., Farruggia, P., Sabattini, M.A.B., Pasquinelli, G., Acacci, A., Roncarati, G., Leoni, E., 2014. Effect of different disinfection protocols on microbial and biofilm contamination of dental unit waterlines in community dental practices. Int. J. Environ. Res. Public Health 11, 2064–2076. https://doi.org/10.3390/ijerph110202064.

Fang, W., Hu, J.Y., Ong, S.L., 2010. Effects of phosphorus on biofilm disinfections in model drinking water distribution systems. J. Water Health 8, 446–454. https://doi.org/10.2166/wh.2009.303.

Farhat, N., Kim, L., Mineta, K., Alarawi, M., Gojobori, T., Saikaly, P., Vrouwenvelder, J., 2022. Seawater desalination based drinking water: microbial characterization during distribution with and without residual chlorine. Water Res. 210, 117975 https://doi.org/10.1016/j.watres.2021.117975.

Fish, K.E., Boxall, J.B., 2018. Biofilm microbiome (re)growth dynamics in drinking water distribution systems are impacted by chlorine concentration. Front. Microbiol. 9, 2519. https://doi.org/10.3389/fmicb.2018.02519.

Fish, K.E., Reeves-McLaren, N., Husband, S., Boxall, J., 2020. Uncharted waters: the unintended impacts of residual chlorine on water quality and biofilms. NPJ Biofilms Microbiomes 6, 34. https://doi.org/10.1038/s41522-020-00144-w.

Gagnon, G.A., 2002. Biofilm control in drinking water distribution systems, in: american chemistry council, sodium chlorite-chlorine dioxide panel, Awwa Research Foundation (Eds.), Chlorine dioxide: The state of science, regulatory, environmental issues, and case histories - Proceedings of the fourth international symposium. Awwa Research Foundation and the American Water Works Association, Las Vegas, 71–86. ISBN: 1-58321-180-2.

Garvey, M., Rabbitt, D., Stocca, A., Rowan, N., 2015. Pulsed ultraviolet light inactivation of *Pseudomonas aeruginosa* and *Staphylococcus aureus* biofilms. Water Environ. J. 29, 36–42. https://doi.org/10.1111/wej.12088.

Gomes, I.B., Lemos, M., Mathieu, L., Simões, M., Simões, L.C., 2018. The action of chemical and mechanical stresses on single and dual species biofilm removal of drinking water bacteria. Sci. Total Environ. 631–632, 987–993. https://doi.org/10.1016/j.scitotenv.2018.03.042.

Gomes, I.B., Simões, L.C., Simões, M., 2020. Influence of surface copper content on *Stenotrophomonas maltophilia* biofilm control using chlorine and mechanical stress. Biofouling 36, 1–13. https://doi.org/10.1080/08927014.2019.1708334.

Gomes, I.B., Simões, M., Simões, L.C., 2016. The effects of sodium hypochlorite against selected drinking water-isolated bacteria in planktonic and sessile states. Sci. Total Environ. 565, 40–48. https://doi.org/10.1016/j.scitotenv.2016.04.136.

Gomes, I.B., Simões, M., Simões, L.C., 2014. An overview on the reactors to study drinking water biofilms. Water Res. 62, 63–87. https://doi.org/10.1016/j.watres.2014.05.039.

Gomez-Smith, C.K., LaPara, T.M., Hozalski, R.M., 2015. Sulfate reducing bacteria and mycobacteria dominate the biofilm communities in a chloraminated drinking water distribution system. Environ. Sci. Technol. 49, 8432–8440. https://doi.org/10.1021/acs.est.5b00555.

Gora, S.L., Rauch, K.D., Ontiveros, C.C., Stoddart, A.K., Gagnon, G.A., 2019. Inactivation of biofilm-bound *Pseudomonas aeruginosa* bacteria using UVC light emitting diodes (UVC LEDs). Water Res. 151, 193–202. https://doi.org/10.1016/j.watres.2018.12.021.

Gosselin, F., Madeira, L.M., Juhna, T., Block, J.C., 2013. Drinking water and biofilm disinfection by Fenton-like reaction. Water Res. 47, 5631–5638. https://doi.org/10.1016/j.watres.2013.06.036.

Haas, C.N., 1999. Benefits of using a disinfectant residual. J. Am. Water Work. Assoc. 91, 65–69. https://doi.org/10.1002/j.1551-8833.1999.tb08569.x.

Hemdan, B.A., El-Taweel, G.E., Goswami, P., Pant, D., Sevda, S., 2021. The role of biofilm in the development and dissemination of ubiquitous pathogens in drinking water distribution systems: an overview of surveillance, outbreaks, and prevention. World J. Microbiol. Biotechnol. 37, 1–18. https://doi.org/10.1007/s11274-021-03008-3.

Hozalski, R.M., Bouwer, E.J., Goel, S., 1999. Removal of natural organic matter (NOM) from drinking water supplies by ozone-biofiltration. Water Sci. Technol. 40, 157–163. https://doi.org/10.1016/S0273-1223(99)00652-6.

Huo, L., Zhao, S., Shi, B., He, S., Wang, H., 2021. Effects of GAC and UV/H_2O_2 -GAC filtration on the bacterial community and opportunistic pathogens in simulated drinking water systems. Environ. Sci. Water Res. Technol. 7, 1611–1621. https://doi.org/10.1039/D1EW00222H.

Hussain, F.A., Dubert, J., Elsherbini, J., Murphy, M., Vaninsbergue, D., Arevalo, P., Kauffman, K., Rodino-Janeiro, B.K., Gavin, H., Gomez, A., Lopatina, A., Le Roux, F., Polz, M.F., 2021. Rapid evolutionary turnover of mobile genetic elements drives bacterial resistance to phages. Science 374, 488–492. https://doi.org/10.1126/science.abb1083.

Inkinen, J., Jayaprakash, B., Ahonen, M., Pitkänen, T., Mäkinen, R., Pursiainen, A., Domingo, J.W.S., Salonen, H., Elk, M., Keinänen-Toivola, M.M., 2017. Bacterial community changes in copper and PEX drinking water pipeline biofilms under extra disinfection and magnetic water treatment. J. Appl. Microbiol. 124, 611–624. https://doi.org/10.1111/jam.13662.

Inkinen, J., Jayaprakash, B., Siponen, S., Hokajarvi, A.M., Pursiainen, A., Ikonen, J., Ryzhikov, I., Taubel, M., Kauppinen, A., Paananen, J., Miettinen, I.T., Torvinen, E., Kolehmainen, M., Pitkanen, T., 2019. Active eukaryotes in drinking water distribution systems of ground and surface waterworks. Microbiome 7, 99. https://doi.org/10.1186/s40168-019-0715-5.

Inkinen, J., Siponen, S., Jayaprakash, B., Tiwari, A., Hokajärvi, A.-M., Pursiainen, A., Ikonen, J., Kauppinen, A., Miettinen, I.T., Paananen, J., Torvinen, E., Kolehmainen, M., Pitkänen, T., 2021. Diverse and active archaea communities occur in non-disinfected drinking water systems–Less activity revealed in disinfected and hot water systems. Water Res. X 12, 100101. https://doi.org/10.1016/j.wroa.2021.100101.

Jungfer, C., Friedrich, F., Villarreal, J.V., Brändle, K., Gross, H.-J., Obst, U., Schwartz, T., 2013. Drinking water biofilms on copper and stainless steel exhibit specific molecular responses towards different disinfection regimes at waterworks. Biofouling 29, 891–907. https://doi.org/10.1080/08927014.2013.813936.

Kekeç, Ö., Gökalsin, B., Karalti, I., Kayhan, F.E., Sesal, N.C., 2016. Effects of chlorine stress on *Pseudomonas aeruginosa* biofilm and analysis of related gene expressions. Curr. Microbiol. 73, 228–235. https://doi.org/10.1007/s00284-016-1056-2.

Kelly, J.J., Minalt, N., Culotti, A., Pryor, M., Packman, A., 2014. Temporal variations in the abundance and composition of biofilm communities colonizing drinking water distribution pipes. PLoS One 9, e98542. https://doi.org/10.1371/journal.pone.0098542.

Keshvardoust, P., Huron, V.A.A., Clemson, M., Barraud, N., Rice, S.A., 2020. Nitrite production by ammonia-oxidizing bacteria mediates chloramine decay and resistance in a mixed-species community. Microb. Biotechnol. 13, 1847–1859. https://doi.org/10.1111/1751-7915.13628.

Khan, S., Beattie, T.K., Knapp, C.W., 2019. Rapid selection of antimicrobial-resistant bacteria in complex water systems by chlorine and pipe materials. Environ. Chem. Lett. 17, 1367–1373. https://doi.org/10.1007/s10311-019-00867-z.

Kuo, J., Abustan, L., 2009. Disinfection and antimicrobial processes. Water Environ. Res. 81, 1361–1375. https://doi.org/10.2175/106143009X12445568399695.

LeChevallier, M.W., Cawthon, C.D., Lee, R.G., 1988. Inactivation of biofilm bacteria. Appl. Environ. Microbiol. 54, 2492–2499. https://doi.org/10.1128/aem.54.10.2492-2499.1988.

LeChevallier, M.W., Lowry, C.D., Lee, R.G., 1990. Disinfecting biofilms in a model distribution system. J. Am. Water Work. Assoc. 82, 87–99. https://doi.org/10.1002/j.1551-8833.1990.tb06996.x.

Lee, W.H., Wahman, D.G., Bishop, P.L., Pressman, J.G., 2011. Free chlorine and monochloramine application to nitrifying biofilm: comparison of biofilm penetration, activity, and viability. Environ. Sci. Technol. 45, 1412–1419. https://doi.org/10.1021/es1035305.

Li, N., Li, X., Yang, Y., Shang, S., Fan, X., Liu, Y., Zhao, L., Zhou, Z., 2020b. Secondary disinfection ensures biosafety of domestic hot water and its impact on biofilm bacterial community. Desalin. Water Treat. 173, 186–196. https://doi.org/10.5004/dwt.2020.24818.

Li, R.A., McDonald, J.A., Sathasivan, A., Khan, S.J., 2019. Disinfectant residual stability leading to disinfectant decay and by-product formation in drinking water distribution systems: a systematic review. Water Res. 153, 335–348. https://doi.org/10.1016/j.watres.2019.01.020.

Li, W., Tan, Q., Zhou, W., Chen, J., Li, Y., Wang, F., Zhang, J., 2020a. Impact of substrate material and chlorine/chloramine on the composition and function of a young biofilm microbial community as revealed by high-throughput 16S rRNA sequencing. Chemosphere 242, 125310. https://doi.org/10.1016/j.chemosphere.2019.125310.

Li, X.X., Wang, H.B., Zhang, Y., Hu, C., Yang, M., 2014. Characterization of the bacterial communities and iron corrosion scales in drinking groundwater distribution systems

with chlorine/chloramine. Int. Biodeterior. Biodegrad. 96, 71–79. https://doi.org/10.1016/j.ibiod.2014.09.014.
Lin, H., Zhu, X., Wang, Y., Yu, X., 2017. Effect of sodium hypochlorite on typical biofilms formed in drinking water distribution systems. J. Water Health 15, 218–227. https://doi.org/10.2166/wh.2017.141.
Ling, F., Hwang, C., LeChevallier, M.W., Andersen, G.L., Liu, W.-T., 2016. Core-satellite populations and seasonality of water meter biofilms in a metropolitan drinking water distribution system. ISME J. 10, 582–595. https://doi.org/10.1038/ismej.2015.136.
Ling, F.Q., Liu, W.T., 2013. Impact of chloramination on the development of laboratory-grown biofilms fed with filter-pretreated groundwater. Microbes Environ. 28, 50–57. https://doi.org/10.1264/jsme2.ME12095.
Liu, L., Xing, X., Hu, C., Wang, H., 2019a. O_3-BAC-Cl_2: a multi-barrier process controlling the regrowth of opportunistic waterborne pathogens in drinking water distribution systems. J. Environ. Sci. 76, 142–153. https://doi.org/10.1016/j.jes.2018.04.017.
Liu, L., Xing, X., Hu, C., Wang, H., Lyu, L., 2019b. Effect of sequential UV/free chlorine disinfection on opportunistic pathogens and microbial community structure in simulated drinking water distribution systems. Chemosphere 219, 971–980. https://doi.org/10.1016/j.chemosphere.2018.12.067.
Liu, S., Gunawan, C., Barraud, N., Rice, S.A., Harry, E.J., Amal, R., 2016. Understanding, monitoring, and controlling biofilm growth in drinking water distribution systems. Environ. Sci. Technol. 50, 8954–8976. https://doi.org/10.1021/acs.est.6b00835.
Luo, X., Xu, X., Cao, R., Wan, Q., Wang, J., Xu, H., Lin, Y., Wen, G., Huang, T., 2021. The formation kinetics and control of biofilms by three dominant fungi species isolated from groundwater. J. Environ. Sci. (China) 109, 148–160. https://doi.org/10.1016/j.jes.2021.04.002.
Ma, B., Seyedi, S., Wells, E., McCarthy, D., Crosbie, N., Linden, K.G., 2022. Inactivation of biofilm-bound bacterial cells using irradiation across UVC wavelengths. Water Res. 217, 118379 https://doi.org/10.1016/j.watres.2022.118379.
Ma, X., Li, G., Chen, R., Yu, Y., Tao, H., Zhang, G., Shi, B., 2020. Revealing the changes of bacterial community from water source to consumers tap: a full-scale investigation in eastern city of China. J. Environ. Sci. 87, 331–340. https://doi.org/10.1016/j.jes.2019.07.017.
Maes, S., Vackier, T., Huu, S.N., Heyndrickx, M., Steenackers, H., Sampers, I., Raes, K., Verplaetse, A., De Reu, K., 2019. Occurrence and characterisation of biofilms in drinking water systems of broiler houses. BMC Microbiol. 19, 77. https://doi.org/10.1186/s12866-019-1451-5.
Magin, V., Garrec, N., Andrés, Y., 2019. Selection of bacteriophages to control *in vitro* 24h old biofilm of *Pseudomonas aeruginosa* isolated from drinking and thermal water. Viruses 11, 749. https://doi.org/10.3390/v11080749.
Mathieu, L., Bertrand, I., Abe, Y., Angel, E., Block, J.C., Skali-Lami, S., Francius, G., 2014. Drinking water biofilm cohesiveness changes under chlorination or hydrodynamic stress. Water Res. 55, 175–184. https://doi.org/10.1016/j.watres.2014.01.054.
McCallin, S., Oechslin, F., 2019. Bacterial resistance to phage and its impact on clinical therapy. In: Górski, A., Międzybrodzki, R., Borysowski, J. (Eds.), Phage therapy: A practical Approach. Springer, Cham. Switzerland, pp. 59–88. https://doi.org/10.1007/978-3-030-26736-0_3.
Meier, T., Bendinger, B., 2016. Survival of pathogens in drinking water plumbing systems: impact factors and sanitation options. Water Sci. Technol. Supply 16, 931–941. https://doi.org/10.2166/ws.2016.040.
Mezule, L., Denisova, V., Briedis, A., Reimanis, M., Ozolins, J., Juhna, T., 2015. Disinfection effect of electrochemically generated chlorine on surface associated *Escherichia coli* in a drinking water system. Desalin. Water Treat. 53, 3704–3710. https://doi.org/10.1080/19443994.2013.873742.
Mi, Z.L., Dai, Y., Xie, S.G., Chen, C., Zhang, X.J., 2015. Impact of disinfection on drinking water biofilm bacterial community. J. Environ. Sci. 37, 200–205. https://doi.org/10.1016/j.jes.2015.04.008.
Miao, X., Han, X., Liu, C., Bai, X., 2022. Intrinsic chlorine resistance of bacteria modulated by glutaminyl-tRNA biosynthesis in drinking water supply systems. Chemosphere 308, 136322. https://doi.org/10.1016/j.chemosphere.2022.136322.
Mirnasab, M.A., Hashemi, H., Samaei, M.R., Azhdarpoor, A., 2021. Advanced removal of water NOM by pre-ozonation, enhanced coagulation and bio-augmented granular activated carbon. Int. J. Environ. Sci. Technol. 18, 3143–3152. https://doi.org/10.1007/s13762-020-03039-7.
Moye, Z.D., Woolston, J., Sulakvelidze, A., 2018. Bacteriophage applications for food production and processing. Viruses 10, 205. https://doi.org/10.3390/v10040205.
Munoz, S., Trueman, B.F., Li, B., Gagnon, G.A., 2022. Effect of sodium silicate on drinking water biofilm development. Environ. Sci. Water Res. Technol. 8, 1300–1311. https://doi.org/10.1039/D1EW00682G.
Murray, K.E., Manitou-Alvarez, E.I., Inniss, E.C., Healy, F.G., Bodour, A.A., 2015. Assessment of oxidative and UV-C treatments for inactivating bacterial biofilms from groundwater wells. Front. Environ. Sci. Eng. 9, 39–49. https://doi.org/10.1007/s11783-014-0699-0.
Ng, W.J., Tan, C.T., Bae, S., 2021. Effects of monochloramine on culturability, viability and persistence of *Pseudomonas putida* and tap water mixed bacterial community. Appl. Microbiol. Biotechnol. 105, 3799–3810. https://doi.org/10.1007/s00253-021-11251-9.
Oliveira, I.M., Gomes, I.B., Simões, L.C., Simões, M., 2022. Chlorinated cyanurates and potassium salt of peroxymonosulphate as antimicrobial and antibiofilm agents for drinking water disinfection. Sci. Total Environ. 811, 152355 https://doi.org/10.1016/j.scitotenv.2021.152355.
Pan, R., Zhang, K., Cen, C., Zhou, X., Xu, J., Wu, J., Wu, X., 2021. Characteristics of biostability of drinking water in aged pipes after water source switching: ATP evaluation, biofilms niches and microbial community transition. Environ. Pollut. 271, 116293 https://doi.org/10.1016/j.envpol.2020.116293.
Parasion, S., Kwiatek, M., Gryko, R., Mizak, L., Malm, A., 2014. Bacteriophages as an alternative strategy for fighting biofilm development. Polish J. Microbiol. 63, 137–145. https://doi.org/10.33073/pjm-2014-019.
Pelleieux, S., Mathieu, L., Block, J.C., Gantzer, C., Bertrand, I., 2016. The effect of chlorination and hydrodynamic shear stress on the persistence of bacteriophages associated with drinking water biofilms. J. Appl. Microbiol. 121, 1189–1197. https://doi.org/10.1111/jam.13243.
Pérez, M.F.L., Cárdenas, J.A., Leon, A.J.M., Susa, M.S.R., 2019. Changes on Eubacteria 338I, Gamma-, Betaproteobacteria in biofilms from drinking water systems according to operational conditions. Environ. Process. 6, 85–106. https://doi.org/10.1007/s40710-019-00355-0.
Pérez, M.F.L., Susa, M.R., 2017. Exopolymeric substances from drinking water biofilms: dynamics of production and relation with disinfection by products. Water Res. 116, 304–315. https://doi.org/10.1016/j.watres.2017.03.036.
Peterson, E.S., Summers, R.S., 2021. Removal of effluent organic matter with biofiltration for potable reuse: a review and meta-analysis. Water Res. 199, 117180 https://doi.org/10.1016/j.watres.2021.117180.
Pickering, C., Byrne, J., 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High. Educ. Res. Dev. 33, 534–548. https://doi.org/10.1080/07294360.2013.841651.
Prest, E.I., Hammes, F., van Loosdrecht, M.C.M., Vrouwenvelder, J.S., 2016. Biological stability of drinking water: controlling factors, methods, and challenges. Front. Microbiol. 7 (75), 1–24. https://doi.org/10.3389/fmicb.2016.00045.
Proctor, C.R., Hammes, F., 2015. Drinking water microbiology - from measurement to management. Curr. Opin. Biotechnol. 33, 87–94. https://doi.org/10.1016/j.copbio.2014.12.014.
Rand, J.L., Sharafimasooleh, M., Walsh, M.E., 2013. Effect of water hardness and pipe material on enhanced disinfection with UV light and chlorine. J. Water Supply Res. Technol. 62, 426–432. https://doi.org/10.2166/aqua.2013.060.
Regulation (EU) No 528/2012 of the European Parliament and of the Council of 22 May 2012 concerning the making available on the market and use of biocidal products (Text with EEA relevance) (OJ L 167, 27.6.2012, p. 1–123, ELI: http://data.europa.eu/eli/reg/2012/528/oj).
Rose, L.J., Rice, E.W., 2014. Inactivation of bacterial biothreat agents in water, a review. J. Water Health 12, 618–633. https://doi.org/10.2166/wh.2014.038.
Rousso, B.Z., Bertone, E., Stewart, R., Hamilton, D.P., 2020. A systematic literature review of forecasting and predictive models for cyanobacteria blooms in freshwater lakes. Water Res. 182, 115959 https://doi.org/10.1016/j.watres.2020.115959.
Schwering, M., Song, J., Louie, M., Turner, R.J., Ceri, H., 2013. Multi-species biofilms defined from drinking water microorganisms provide increased protection against chlorine disinfection. Biofouling 29, 917–928. https://doi.org/10.1080/08927014.2013.816298.
Sharafimasooleh, M., Rand, J.L., Walsh, M.E., 2016. Effect of high chloride concentrations on microbial regrowth in drinking water distribution systems. J. Environ. Eng. 142, 1–7. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001027.
Shen, Y., Huang, C., Lin, J., Wu, W., Ashbolt, N.J., Liu, W.-T., Nguyen, T.H., 2017. Effect of disinfectant exposure on *Legionella pneumophila* associated with simulated drinking water biofilms: release, inactivation, and infectivity. Environ. Sci. Technol. 51, 2087–2095. https://doi.org/10.1021/acs.est.6b04754.
Shen, Y., Huang, C., Monroy, G.L., Janjaroen, D., Derlon, N., Lin, J., Espinosa-Marzal, R., Morgenroth, E., Boppart, S.A., Ashbolt, N.J., Liu, W.-T., Nguyen, T.H., 2016. Response of simulated drinking water biofilm mechanical and structural properties to long-term disinfectant exposure. Environ. Sci. Technol. 50, 1779–1787. https://doi.org/10.1021/acs.est.5b04653.
Shi, Y., Babatunde, A., Bockelmann-Evans, B., Webster, G., 2019. Influence of hydraulic regimes and Cl_2/NH_3-N mass ratios on the bacterial structure and composition in an experimental flow cell chloraminated drinking water system. Environ. Sci. Water Res. Technol. 5, 977–992. https://doi.org/10.1039/c9ew00015a.
Simões, L.C., Chaves, A.F.A., Simões, M., Lima, N., 2023. Interactions between *Penicillium brevicompactum/Penicillium expansum* and *Acinetobacter calcoaceticus* isolated from drinking water in biofilm development and control. Int. J. Food Microbiol. 384, 109980 https://doi.org/10.1016/j.ijfoodmicro.2022.109980.
Simões, L.C., Simões, M., 2013. Biofilms in drinking water: problems and solutions. RSC Adv. 3, 2520–2533. https://doi.org/10.1039/c2ra22243d.
Simões, L.C., Simões, M., Vieira, M.J., 2007. Biofilm interactions between distinct bacterial genera isolated from drinking water. Appl. Environ. Microbiol. 73, 6192–6200. https://doi.org/10.1128/AEM.00837-07.
Sinha, P., Mukherji, S., 2022. Biofiltration process for treatment of water and wastewater. Trans. Indian Natl. Acad. Eng. 7, 1069–1091. https://doi.org/10.1007/s41403-022-00360-0.
Soto-Giron, M.J., Rodriguez-R, L.M., Luo, C.W., Elk, M., Ryu, H., Hoelle, J., Domingo, J.W.S., Konstantinidis, K.T., 2016. Biofilms on hospital shower hoses: characterization and implications for nosocomial infections. Appl. Environ. Microbiol. 82, 2872–2883. https://doi.org/10.1128/AEM.03529-15.
Sousa, J.A.M.d., Rocha, E.P.C., 2019. Environmental structure drives resistance to phages and antibiotics during phage therapy and to invading lysogens during colonisation. Sci. Rep. 9, 3149. https://doi.org/10.1038/s41598-019-39773-3.
Stachler, E., Kull, A., Julian, T.R., 2021. Bacteriophage treatment before chemical disinfection can enhance removal of plastic-surface-associated *Pseudomonas aeruginosa*. Appl. Environ. Microbiol. 87 https://doi.org/10.1128/AEM.00980-21 e00980-21.
Stüken, A., Haverkamp, T.H.A., Dirven, H.A.A.M., Gilfillan, G.D., Leithaug, M., Lund, V., 2018. Microbial community composition of tap water and biofilms treated with or without copper-silver ionization. Environ. Sci. Technol. 52, 3354–3364. https://doi.org/10.1021/acs.est.7b05963.

Sun, H., Shi, B., Bai, Y., Wang, D., 2014. Bacterial community of biofilms developed under different water supply conditions in a distribution system. Sci. Total Environ. 472, 99–107. https://doi.org/10.1016/j.scitotenv.2013.11.017.

Sun, P.P., Araud, E.M., Huang, C., Shen, Y., Monroy, G.L., Zhong, S., Tong, Z., Boppart, S. A., Eden, J.G., Nguyen, T.H., 2018. Disintegration of simulated drinking water biofilms with arrays of microchannel plasma jets. NPJ Biofilms Microbiom. 4, 24. https://doi.org/10.1038/s41522-018-0063-4.

Szabo, J., Rodgers, M., Mistry, J., Steenbock, J., Hall, J., 2019. The effectiveness of disinfection and flushing procedures to prevent coliform persistence in aircraft water systems. Water Supply 19, 1339–1346. https://doi.org/10.2166/ws.2018.195.

Tian, F., Li, J., Nazir, A., Tong, Y., 2021. Bacteriophage - A promising alternative measure for bacterial biofilm control. Infect. Drug Resist. 14, 205–217. https://doi.org/10.2147/IDR.S290093.

U.S. EPA, 2023. Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and Federal Facilities [WWW Document]. URL https://www.epa.gov/enforcement/federal-insecticide-fungicide-and-rodenticide-act-fifra-and-federal-facilities (Accessed 16 June 2023).

Waak, M.B., Hozalski, R.M., Halle, C., LaPara, T.M., 2019a. Comparison of the microbiomes of two drinking water distribution systemswith and without residual chloramine disinfection. Microbiome 7, 87. https://doi.org/10.1186/s40168-019-0707-5.

Waak, M.B., LaPara, T.M., Hallé, C., Hozalski, R.M., 2019b. Nontuberculous mycobacteria in two drinking water distribution systems and the role of residual disinfection. Environ. Sci. Technol. 53, 8563–8573. https://doi.org/10.1021/acs.est.9b01945.

Wan, K., Zhang, M., Ye, C., Lin, W., Guo, L., Chen, S., Yu, X., 2019. Organic carbon: an overlooked factor that determines the antibiotic resistome in drinking water sand filter biofilm. Environ. Int. 125, 117–124. https://doi.org/10.1016/j.envint.2019.01.054.

Wang, H., Hu, C., Zhang, S., Liu, L., Xing, X., 2018. Effects of O_3/Cl_2 disinfection on corrosion and opportunistic pathogens growth in drinking water distribution systems. J. Environ. Sci. 73, 38–46. https://doi.org/10.1016/j.jes.2018.01.009.

Wang, H., Pryor, M.A., Edwards, M.A., Falkinham, J.O., Pruden, A., 2013. Effect of GAC pre-treatment and disinfectant on microbial community structure and opportunistic pathogen occurrence. Water Res. 47, 5760–5772. https://doi.org/10.1016/j.watres.2013.06.052.

Wang, H., Zhu, Y., Hu, C., 2017. Impacts of bacteria and corrosion on removal of natural organic matter and disinfection byproducts in different drinking water distribution systems. Int. Biodeterior. Biodegrad. 117, 52–59. https://doi.org/10.1016/j.ibiod.2016.11.023.

Wang, H.B., Hu, C., Hu, X.X., 2014. Effects of combined UV and chlorine disinfection on corrosion and water quality within reclaimed water distribution systems. Eng. Fail. Anal. 39, 12–20. https://doi.org/10.1016/j.engfailanal.2014.01.009.

Wang, Z., Li, L., Ariss, R.W., Coburn, K.M., Behbahani, M., Xue, Z., Seo, Y., 2021. The role of biofilms on the formation and decay of disinfection by-products in chlor(am)inated water distribution systems. Sci. Total Environ. 753, 141606 https://doi.org/10.1016/j.scitotenv.2020.141606.

Wu, H.T., Zhang, J.X., Mi, Z.L., Xie, S.G., Chen, C., Zhang, X.J., 2015. Biofilm bacterial communities in urban drinking water distribution systems transporting waters with different purification strategies. Appl. Microbiol. Biotechnol. 99, 1947–1955. https://doi.org/10.1007/s00253-014-6095-7.

Xing, X.C., Wang, H.B., Hu, C., Liu, L.Z., 2018. Effects of phosphate-enhanced ozone/biofiltration on formation of disinfection byproducts and occurrence of opportunistic pathogens in drinking water distribution systems. Water Res. 139, 168–176. https://doi.org/10.1016/j.watres.2018.03.073.

Xue, Z., Lee, W.H., Coburn, K.M., Seo, Y., 2014. Selective reactivity of monochloramine with extracellular matrix components affects the disinfection of biofilm and detached clusters. Environ. Sci. Technol. 48, 3832–3839. https://doi.org/10.1021/es405353h.

Xue, Z., Seo, Y., 2013. Impact of chlorine disinfection on redistribution of cell clusters from biofilms. Environ. Sci. Technol. 47, 1365–1372. https://doi.org/10.1021/es304113e.

Yu, Z., Li, X., Guo, J., 2022. Combat antimicrobial resistance emergence and biofilm formation through nanoscale zero-valent iron particles. Chem. Eng. J. 444, 136569 https://doi.org/10.1016/j.cej.2022.136569.

Zhang, J., Li, W., Chen, J., Wang, F., Qi, W., Li, Y., 2019. Impact of disinfectant on bacterial antibiotic resistance transfer between biofilm and tap water in a simulated distribution network. Environ. Pollut. 246, 131–140. https://doi.org/10.1016/j.envpol.2018.11.077.

Zhang, Xinyue, Lin, T., Jiang, F., Zhang, Xue, Wang, S., Zhang, S., 2022. Impact of pipe material and chlorination on the biofilm structure and microbial communities. Chemosphere 289, 133218. https://doi.org/10.1016/j.chemosphere.2021.133218.

Zhu, Y., Chen, L., Xiao, H., Shen, F., Deng, S.H., Zhang, S.R., He, J.S., Song, C., Wang, X., Zhang, J.H., Gong, L., Hu, C., 2020a. Effects of disinfection efficiency on microbial communities and corrosion processes in drinking water distribution systems simulated with actual running conditions. J. Environ. Sci. 88, 273–282. https://doi.org/10.1016/j.jes.2019.09.009.

Zhu, Y., Wang, H.B., Li, X.X., Hu, C., Yang, M., Qu, J.H., 2014. Characterization of biofilm and corrosion of cast iron pipes in drinking water distribution system with UV/Cl_2 disinfection. Water Res. 60, 174–181. https://doi.org/10.1016/j.watres.2014.04.035.

Zhu, Z., Shan, L., Hu, F., Li, Z., Zhong, D., Yuan, Y., Zhang, J., 2020b. Biofilm formation potential and chlorine resistance of typical bacteria isolated from drinking water distribution systems. RSC Adv. 10, 31295–31304. https://doi.org/10.1039/D0RA04985A.

Zhu, Z., Shan, L., Zhang, X., Hu, F., Zhong, D., Yuan, Y., Zhang, J., 2021. Effects of bacterial community composition and structure in drinking water distribution systems on biofilm formation and chlorine resistance. Chemosphere 264, 128410. https://doi.org/10.1016/j.chemosphere.2020.128410.

Zuo, P., Metz, J., Yu, P., Alvarez, P.J.J., 2022. Biofilm-responsive encapsulated-phage coating for autonomous biofouling mitigation in water storage systems. Water Res. 224, 119070 https://doi.org/10.1016/j.watres.2022.119070.