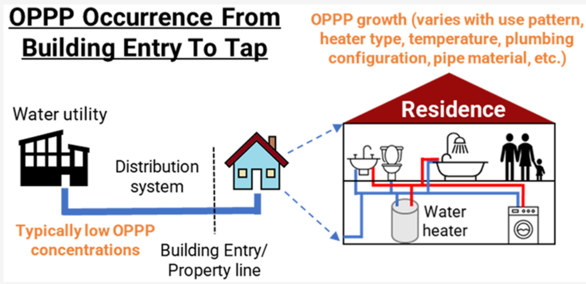
Environmental Science & Technology
pubs.acs.org/est
Critical Review

A Critical Review on the Factors that Influence Opportunistic Premise Plumbing Pathogens: From Building Entry to Fixtures in Residences

Alshae' R. Logan-Jackson,* Marylia Duarte Batista, William Healy, Tania Ullah, Andrew J. Whelton, Timothy A. Bartrand, and Caitlin Proctor

Cite This: Environ. Sci. Technol. 2023, 57, 6360−6372
Read Online

ABSTRACT: Residential buildings provide unique conditions for opportunistic premise plumbing pathogen (OPPP) exposure via aerosolized water droplets produced by showerheads, faucets, and tubs. The objective of this review was to critically evaluate the existing literature that assessed the impact of potentially enhancing conditions to OPPP occurrence associated with residential plumbing and to point out knowledge gaps. Comprehensive studies on the topic were found to be lacking. Major knowledge gaps identified include the assessment of OPPP growth in the residential plumbing, from building entry to fixtures, and evaluation of the extent of the impact of typical residential plumbing design (e.g., trunk and branch and manifold), components (e.g., valves and fixtures), water heater types and temperature setting of operation, and common pipe materials (copper, PEX, and PVC/CPVC). In addition, impacts of the current plumbing code requirements on OPPP responses have not been assessed by any study and a lack of guidelines for OPPP risk management in residences was identified. Finally, the research required to expand knowledge on OPPP amplification in residences was discussed.



KEYWORDS: *opportunistic premise plumbing pathogens, Legionella, residences, water quality, plumbing design, water use pattern, water heaters, pipe material, fixtures*

1. INTRODUCTION TO SINGLE- AND MULTIFAMILY RESIDENCES

Health risks from residential plumbing were made clear in a National Academies of Sciences, Engineering, and Medicine (NASEM) report.[1] This report focused on *Legionella*, but a host of microbes, termed opportunistic premise plumbing pathogens (OPPPs), are a concern. For example, OPPPs listed as concerning by the United States (U.S.) Environmental Protection Agency (EPA) Contaminant Candidate List (CCL) 5[2] were three bacterial species, *Legionella pneumophila* (*L. pneumophila*), *Mycobacterium avium* (*M. avium*), and *Pseudomonas aeruginosa* (*P. aeruginosa*), as well as one amoebae species, *Naegleria fowleri* (*N. fowleri*). OPPPs were defined by Falkinham et al.[3] as "waterborne microorganisms that are normal inhabitants of premise plumbing and cause infections in individuals with predisposing conditions, such as advanced age (>70 years), cancer, or immunodeficiency."[3] Residential water use can be conducive to the release of OPPPs via aerosolized water droplets.[3] It has been estimated that 96% of one type of OPPP disease, Legionnaires' Disease (caused primarily by *Legionella pneumophila*) may be caused by sporadic residential exposure from sites such as showers, tubs, and hot water faucets.[4]

Water heating system equipment, design, and usage impact water quality at fixtures because of their direct influence on water temperature, water age, and disinfectant residual concentration.[5,6] Operations may involve trade-offs between water quality, water conservation, and energy conservation. While energy efficiency measures (e.g., reduced hot water set point temperatures [48 °C or less]) and water conservation strategies (e.g., low flow fixtures) in residences are effective in reducing energy and water usage,[7] they can promote OPPP proliferation and pose public health challenges[8] if they are implemented without understanding their influence on the system.

There are several review papers on topics related to OPPPs,[9−11,3,12−25] and each review has taken a different approach to advancing knowledge in this field. For example, one review identified and characterized emerging OPPPs,[3] and

Received: June 14, 2022
Revised: March 2, 2023
Accepted: March 3, 2023
Published: April 10, 2023

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

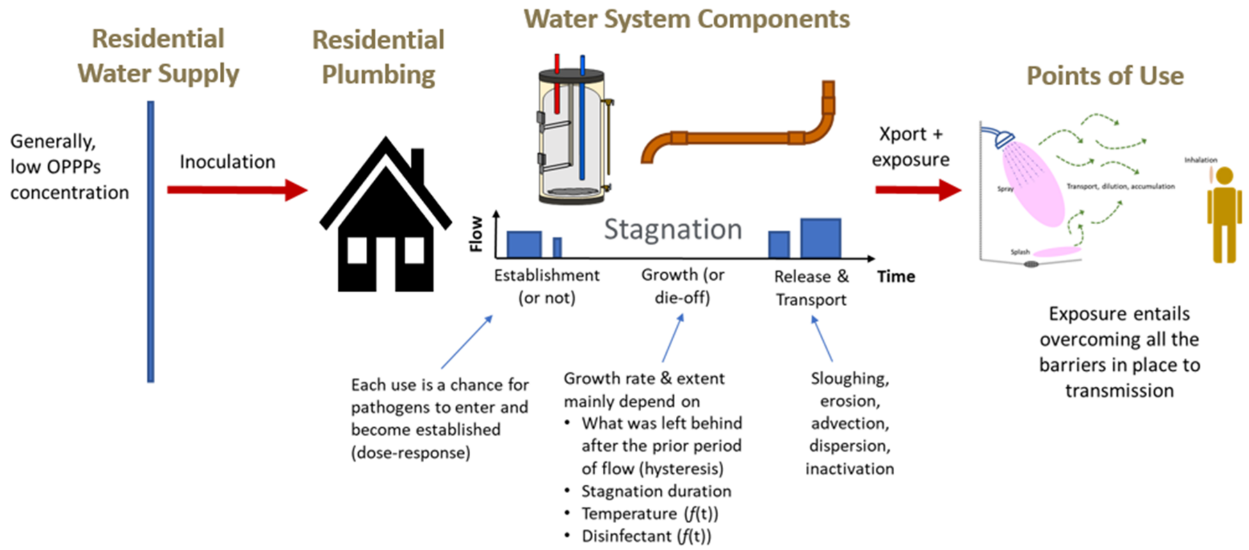


Figure 1. OPPP story line in residential plumbing.

another manuscript focused on understanding how *L. pneumophila*, *M. avium*, and *P. aeruginosa* grow, survive, and persist in drinking water systems.[12] Wang et al.[17] critically evaluated bulk water and biofilm sampling procedures to bring awareness to the issue by developing a standardized sampling approach. In addition, Proctor et al.[24] discussed a holistic approach in managing different OPPPs in drinking water systems.[24] Other researchers critically reviewed how pipe materials impact OPPP growth,[19] and the most recent review systematically reviewed OPPPs in residences and discussed their transmission of infection and how to control for their occurrence.[25] From each review mentioned above, it is evident that plumbing contains several different features that can select for a certain microbial community (e.g., disinfectant residual type and concentration, plumbing material, age of the system). However, there is a gap in critically and holistically reviewing the current knowledge regarding conditions that may impact OPPP growth in both cold and hot water residential plumbing.

To date there is no specific guideline on OPPP risk management applied to the point of entry (POE) or at the points of use (POU) of any type of residential building. While the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 188 provides guidance to manage the risk of Legionellosis, its scope does not include single-family dwellings nor does it address other OPPPs. It cannot be assumed that single-family residences are immune from OPPP concerns because even water provided by a public utility that meets all regulatory requirements can contain OPPP and potentially degrade in quality over time after it enters plumbing and pose a health risk at the POU.[26] To create better guidance, there is a critical need to identify and characterize residential plumbing configurations (e.g., trunk−branch vs manifold systems), their components (e.g., valves and fittings), water heater types (e.g., electric vs gas, storage vs on-demand), plumbing material (metal vs plastic), and type of fixture (e.g., faucets, showerheads, and tub spouts). All of the above-mentioned factors can impact the growth risk of the OPPPs listed on the U.S. EPA CCL 5.[2] Because these organisms can grow in cold and hot water systems and cause disease, the authors believe that residential water systems may benefit from control strategies to minimize OPPP risk. This review aims to bring awareness to the science community, building managers, the plumbing industry, and the public at-large regarding the importance of studying their occurrence in residences.

2. BASELINE WATER QUALITY IN RESIDENCES

OPPPs can be present at every location within dwellings, including water at the POE and at cold water fixtures. In a study conducted on a retrofitted net-zero energy efficient single-family residence,[27] the authors found that the total *Legionella* (average concentration: 1.82 log GC/100 mL) and *Mycobacterium* (average concentration: 3.11 log GC/100 mL) species were the lowest at the influent line but increased by 2 and 4 logs, respectively, in the cold water fixtures.[27] The authors did not detect *L. pneumophila* and *M. avium* at the POE or cold water taps.[27] Additionally, several studies have detected these OPPPs only in cold water faucet samples in residences.[28−31] While there is a data gap in assessing OPPP from the POE to the fixtures, there is an understanding that these OPPPs are naturally present in the cold water environment, and the survival rate and proliferation of these bacteria generally increases when the water stagnates or within the hot water fixtures.[32,29,33,34] The paucity of data suggests that there is a lack of systematic studies in residences. To this point, there is a need to assess the entire residential plumbing to determine OPPP amplification hot spots (Figure 1). Once these locations are determined, strategies to reduce OPPP growth can be identified. Such studies should include residences with different water supplies (e.g., untreated groundwater or treated surface water).

2.1. OPPP Detection in Residential Plumbing.

L. pneumophila,[35−39] *P. aeruginosa*,[40,41] *M. avium*,[30,42,43] and *N. fowelri*[31,44−48] all have been detected in residential plumbing. These organisms all respond differently to various environmental factors[37,39,42,49] (i.e., building age, water age, water temperature, heater type, disinfectant type/concentration, and symbiotic relationships), which may cause them to proliferate within drinking water systems.[50] While there is some understanding about how each OPPP responds to the environmental factors, no systematic study was found that investigated all OPPPs in one type of residential plumbing. For example, having some knowledge about how four different

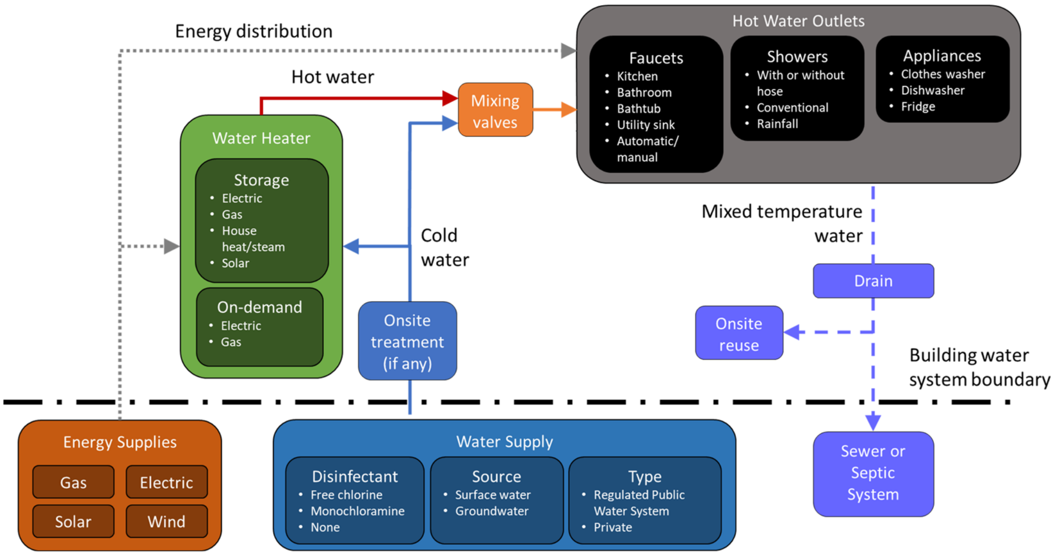


Figure 2. Simple hot water system components, water flows, and energy flows (modified from Gary Klein, Gary Klein and Associates, Inc.).

OPPPs respond to various water heater set point temperatures in one study could open opportunities to develop new water heating systems that better limit their growth. Additional residential plumbing investigations should be conducted, especially in storage water heaters and at the POU, to identify environments conducive to growth for a range of OPPPs. Another area of research should be conducted to identify potential control mechanisms in residential plumbing for these OPPPs.

3. RESIDENTIAL PLUMBING DESIGN AND OPERATION

Typical residential plumbing consists of four main components: water supply, water heaters, piping including valves and manifolds, and end-use fixtures (Figure 2). Ensuring adequate hot water delivery (i.e., the necessary volume at the desired flow rate and temperatures) in a safe manner is of paramount interest. Striving to deliver hot water in the most energy- and water-efficient manner is also a key aspect of water heating and delivery system design. In the United States, water heating accounts for 19% of total site energy use in households.[51]

3.1. Plumbing Design. While trunk-and-branch designs are common in existing residences, manifold systems that use direct pipe runs from the cold or hot water source to end uses are becoming more popular. Because a traditional trunk-and-branch system has a large main supply (Figure 3), this configuration may lead to water sitting in the pipes longer than for manifold systems (Figure 3) during periods of low or no water use due to the diameter and longer pipe length. As reviewed by Wang et al, however, most water quality studies focus on only the fixtures[17] rather than surveying the plumbing configuration,[52] especially for residences. Since OPPP growth can be partly induced by water stagnations,[53] it is important to understand plumbing configuration so areas of potential concern can be identified. There has been a historical lack of descriptions of plumbing configurations on past water quality studies, as well as plumbing design documentation, and their impact on OPPPs.

3.2. Residence Types and Water Use Patterns. The median size of residential dwellings, both single- and multifamily, is 139 m^2, and 31% of residences have three or more stories. About 57% of the residences surveyed in the 2019 American Housing Survey (AHS) were built with two or more bathrooms within the dwelling.[54] Single-family residences are also getting larger, with the average size of a home built in the 1970s being 164 m^2 and that of a home built in 2019 at 232 m^2.[55] The larger the size and number of stories of a building, the larger the water heating system, pipe networks, and number of fixtures and water-utilizing appliances. The median build year for residences in the AHS was 1971, indicating that many existing residences may include larger plumbing pipes for the flow rates and usage patterns typical of today's occupants.

Single- and multifamily residences also differ in the number of occupants, which can impact total daily water consumption as well as use pattern and frequency. Use patterns can be highly variable within buildings due to particularities associated with consumer behavior.[56] These factors lead to large variations in plumbing water age compared to that in the distribution system.[56] Water age influences OPPP growth.[57,58,6,59−62]

Several studies investigated the impacts of water use pattern and/or stagnation in either residences or simulated residential hot water systems on OPPPs.[57,58,6,59−62] Although most studies have included other factors in the analysis (i.e., temperature, pipe materials, and building age), stagnation is one of the most impactful conditions that leads to increased OPPP growth.[59−61] It is worth mentioning the pilot-scale study by Rhoads et al., which found that a low use pattern (can be compared to stagnation in the system) and water heater set point of 51 °C led to higher concentrations of *L. pneumophila* at the fixture.[6] However, in terms of weekly yield (total amount of cells delivered at the fixture per week), the high use pattern resulted in higher yield than the low use likely due to increased nutrient delivery combined with ideal temperature conditions. In addition, different microorganisms may behave differently depending on use pattern and temperature. Tolofari et al.[62] found that a combination of high use pattern and the highest temperature setting was effective in inactivating HPCs but not NTM. While several studies give an indication of how the water use pattern and/or stagnation influence the OPPP growth, no studies were found that described whether resident

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

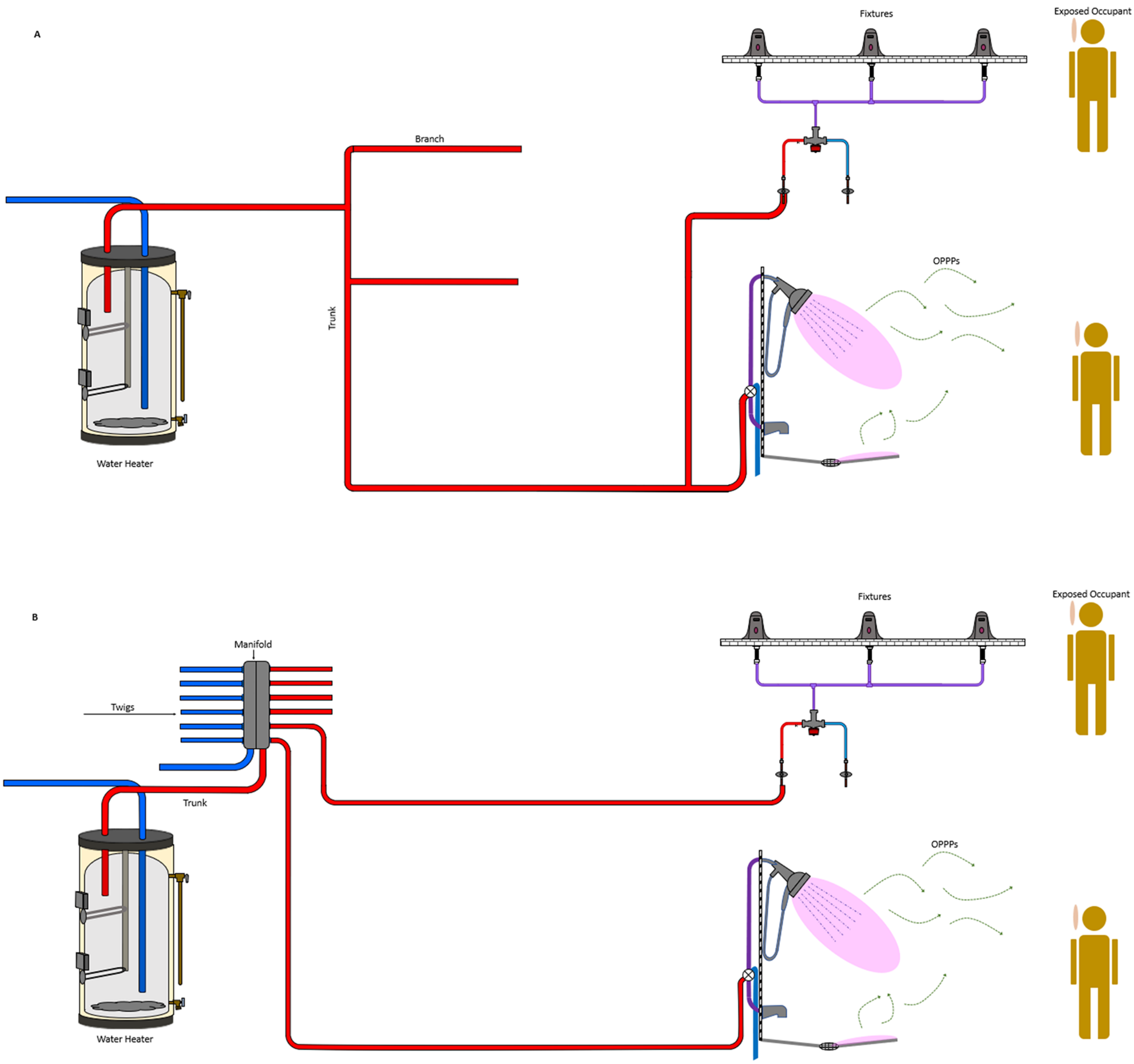


Figure 3. (A) Trunk and branch system with storage tank. (B) Manifold home run system with storage tank.

behavior (e.g., vacations, weekend trips, work routine) played a role in the stagnation as it relates to the OPPP growth outcome. Hayes-Phillips et al.[61] surveyed residents about the type of water heater and its temperature setting and found a significant association between temperature, frequency of use, and building age with *Legionella* spp. detection. Water stagnation is an important factor to assess, but daily water stagnation in any water system is a challenging parameter to measure. Future research should survey resident user behavior to determine low and high water usage patterns and use real-time data to identify risk factors associated with OPPP contamination. In addition, recent studies were conducted following extended stagnation (weeks to months) due to stay-at-home orders associated with the COVID-19 pandemic, including field studies and review papers.[63−65,52,66−70] The published studies to-date mostly focus on university buildings, schools, or other commercial-scale buildings. Nevertheless, those studies indicate that stagnation is critical to consider when evaluating OPPP growth in buildings.

3.3. Residential Water Heaters. Water heaters carry out the function of raising incoming cold water to a usable hot water temperature in a residence. A variety of water heater types exist on the market, and some are designed to be centrally located and provide water to an entire residence. Other water heaters available are meant to heat water at the POU. Different applications in a home require different hot water temperature, and central water heaters will be set to exceed that temperature to provide all hot water service to the residence. Producing hot water, especially within tank-type water heaters, can increase the potential for OPPP growth. Therefore, water heaters are a key plumbing component to evaluate for OPPP-related health risks.

3.3.1. Types. Water heaters are typically categorized into storage and tankless (also referred to as "on-demand" or

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

"instantaneous"). The most common residential water heater fuels are electric and natural gas. Electric and gas storage water heaters make up approximately 94% of residential water heaters, while gas tankless heaters make up about 5%; all other types of heaters make up the remaining percentage.[71,72] Several studies[73−76] have investigated the impact of residential water heater type and design on OPPP prevalence. Water heater type and design can lead to conducive environments for *L. pneumophila*[74] growth, but such factors can also impact other OPPPs. Researchers have shown an increased presence of *L. pneumophila* in electric water heaters compared to gas water heaters.[74,75] A group in Germany determined the occurrence and concentration of *Legionella* spp. in hot water systems (district heating vs solar) of single-family residences in the suburbs of two different cities.[76] Residences that utilized district heating systems were colonized with 667 CFU/100 mL, while solar heating systems contained lower levels of *Legionella* species (223 CFU/100 mL) and instantaneous water heaters resulted in samples that were below the detection limit for *Legionella* spp. There is data that associates certain types of water heaters with OPPPs, but the studies listed above were not exhaustive. For example, no study was found that described the association between a heat-pump water heater and OPPP growth. While heat-pump water heaters are not yet common in residences, incentives for consumers to upgrade their conventional heaters to an energy-efficient water heater will likely lead to an increase in their popularity. Thus, gaining knowledge on whether heat pump water heaters influence OPPP growth in residences is warranted.

There have been several laboratory studies[5,6,77−83] and a field-study[84] aiming to understand how heater design and operation impact opportunistic pathogens. Most studies have found that water usage patterns and water heater design influence the chemical and microbial water quality.[5,20,94,136] One study compared three configurations of residential electric water heating systems—standard, recirculation, and tankless heaters—in terms of volumes at risk for pathogen growth based on temperature measurements and water quality parameters while operating them at different use patterns. Another study showed that lower water temperatures were associated with OPPP colonization in water heaters and POU (faucets, showerheads, and tubs).[6] While there is some understanding on how different water heaters contribute to the growth of OPPPs spatially, there is a clear need to understand how different water heaters impact OPPPs temporally and spatially in residences.

3.3.2. Temperature Setting. The temperature at which water heaters deliver water is a complicated issue due to the need to balance hot water demand, safety, and energy efficiency. That decision, however, is important for OPPPs since most pathogens have temperature ranges in which they survive or proliferate. For example, the ideal temperature range for *L. pneumophila* to proliferate is between 25 and 45 °C.[85,86] The U.S. Department of Energy (DOE) recommends that water heaters be set to 46−49 °C to minimize energy consumption[7] and scalding[87] while still providing the hot water service demanded by end users.

Other recommendations suggest a higher set point temperature to mitigate the risk of pathogen growth. For example, the NASEM suggests that water should not be stored any lower than 60 °C to reduce the risk of *L. pneumophila* growth and that temperatures within recirculation loops should be maintained above 55 °C.[1] The World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC) recommend that hot water temperature should be maintained above the *Legionella* spp. optimal growth range. CDC recommends maintaining hot water temperature at the highest possible level allowed by plumbing codes and/or above 45 °C,[88] while the WHO suggests temperatures above 50 °C.[89]

Research shows that set point temperatures below 48.8 °C promoted the colonization of *L. pneumophila* in residential plumbing.[39] Brazeau et al.[5] found that standard and recirculation heating systems have different water volumes at temperatures at risk of pathogen growth depending on the heater temperature set point, while tankless heaters had small volumes at risk.[5] Other studies validated that low water temperatures were the most critical factor for the growth of *Legionella* spp. in residential plumbing.[90,91] The balance between water delivery capacity, scalding potential, OPPP growth, and energy consumption involves multiple design and operation factors. This issue is important, however, as certain OPPP growth appears to occur more in hot water systems than cold water systems.[92] More research is needed to understand the balance between these factors for all OPPPs mentioned in this review to understand what environmental factors are more conducive for certain species. Thus, it is important to monitor such OPPPs to understand how different OPPPs respond to various set point temperatures in residences. Having data and knowledge on this topic will provide opportunities for future innovations—to save energy while reducing the risk of pathogen growth in water heaters and residential plumbing.

4. RESIDENTIAL PIPE MATERIALS AND OPPPS

Pipe materials can affect OPPPs directly, by providing organic or inorganic nutrients to enhance growth or act as a growth-inhibitor, or indirectly, by interacting with disinfectant residue to promote the growth of pathogens in distal sites such as faucets, showers, and tubs. The type of material can also affect water chemistry,[58] biological stability,[93] and the microbiome[78,94] of the water inside plumbing. More specifically, pipe material selection (metals vs plastics) is also known to influence biofilm formation,[95] rate,[96] density,[97] and bacterial diversity.[98] Microbial performance variation within different types of plastics (e.g., varying by brand, production batch, shock disinfectant exposure, etc.) are just beginning to be explored. Data on how different pipe materials affect specific bacteriological growth in bulk water, relative to biofilm density, is limited. Here we review the common pipe materials used for residential plumbing and discuss how each material directly or indirectly affects OPPPs in bulk water and biofilms present in residences.

4.1. Copper. Three studies have shown an association between copper pipes and OPPPs in bulk water samples collected from single-family residences, but their results were not consistent.[76,99,100] One study showed that copper piped hot water systems, with an aqueous copper concentration of 0.5 mg/L or more, had higher concentrations of *L. pneumophila* than PEX pipes.[76] Another study also isolated *L. pneumophila* only from copper piped hot water systems but did not find an association between the copper pipes and *L. pneumophila*.[99] Borella et al.[100] found an inverse association between copper levels of 50 μg/L or more and *Legionella* spp. counts, while there was a positive correlation between copper concentrations and *Pseudomonas* spp. Since copper can be growth-promoting or growth-inhibiting, more work is needed

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

to determine which residential copper plumbing conditions enhance or inhibit OPPP growth.

The association between biofilm growth on copper pipe and OPPPs has been investigated in laboratory-scale studies,[101−105] in part because of the difficulty of extracting biofilms for analysis. Laboratory study results are mixed, with some researchers observing a higher abundance of *L. pneumophila* in copper pipe biofilms compared with biofilms on polyvinyl chloride (PVC) and steel pipes.[101,105] Other investigators have observed lower concentrations of *L. pneumophila* in biofilms on copper than on steel, cross-linked polyethylene (PEX), and chlorinated polyvinyl chloride pipe materials.[102,103] There is a gap in research describing the conditions for observations on plumbing operation (i.e., water use pattern) and environmental factors (i.e., water temperature) and how each impact the occurrence and concentration of OPPPs in biofilms isolated from copper pipes and fixtures in residences. Thus, future research should be conducted in copper plumbed residences to systematically study the interactive effects of design, use, and materials (i.e., copper, pipe length, water use pattern, and water temperature) on biofilm formation and OPPPs. Results could inform decisions about which materials are best for specific design and plumbing use conditions.

4.2. Cross-Linked Polyethylene and Polyvinyl Chloride. PEX and PVC pipes are commonly used plastics for potable water piping in new and renovated construction. PEX and PVC materials have been associated with increased OPPP growth in bulk hot water[78,102,106−108] and biofilm formation relative to copper pipe.[79,102,109−111,93] One important microbial growth observation has been attributed to carbon compound leaching into drinking water.[112] For example, new PEX pipes have been shown to leach 77,000 μg/L of total organic carbon (TOC).[113] Moreover, PVC pipes can leach 60 to 50,000 μg/L of TOC with 50% of that total estimated to be assimilable carbon.[94] Leaching of TOC from PVC material has the potential to promote or inhibit OPPPs biofilm and planktonic growth.[110,111,114−120] While these studies add value to the literature by understanding how PEX and PVC pipe materials affect different OPPPs in a laboratory setting, no data were found on the interactive effects on OPPP growth in a residential setting. Thus, there is a critical need in evaluating PEX and PVC on OPPP growth temporally (years of data) as well as understanding this phenomenon in household water supply systems. In addition, many other plastic materials may be used for small pipes or connectors (e.g., shower hoses, faucet connectors, ice machine lines, sealing rings), and carbon leaching is also a concern.[121] The caveat with plastics used in plumbing is that the quality assurance and quality control of the product water quality impact variations have not been investigated; this is due to the fact that researchers and the water industry both have not recognized the importance of defining the fitness and how the variations of PEX and PVC leaching potential can impact OPPP growth. Thus, to understand how plastics, which are increasingly being used in plumbing, affect water quality, a better understanding of water quality performance between and within brands and production batches is needed. Care will be needed to document products tested because material from the same roll of pipe that sits unused can perform differently than those installed used months earlier.[122]

5. HOT WATER DISTRIBUTION

In addition to the water heater, other components of residential plumbing deserve attention as potential locations where OPPPs can grow, such as fixtures and temperature control valves. These components can impact microbial dynamics through their impact on hydrodynamics and constituent materials.

5.1. Fixtures. Hot water plumbing in residences is typically limited to bathrooms, kitchens, and laundry areas. Table 1 shows the fraction of daily hot water use by end use in North America,[123] with showers and faucets accounting for the most hot water use. Temperatures at these fixtures vary, but the ASHRAE indicates that a typical temperature for hand washing is 40 °C and showering is 43 °C.[124] Another key characteristic of end use is flow rate. Currently in the U.S., federal standards require showerheads to deliver water at no greater than 9.5 L/min and faucets at no greater than 8.3 L/min.[71] There is momentum, however, for fixtures with even lower flow rates. The U.S. EPA WaterSense product labeling program is one that assists consumers in identifying water-efficient fixtures on the market, and its requirements are more stringent than minimum federal standards. For example, WaterSense showerheads and sink faucets must deliver water at rates no more than 7.6 L/min and 5.7 L/min, respectively.[125] It is important to recognize that at a given point in the day, fixtures are typically not operating. Salehi et al., in a study of a net-zero energy residence, found that fixtures were generally stagnant well over 90% of the time.[113] These three features—temperature, flow rate, and stagnation time—all impact OPPP growth.

Table 1. Average Daily Hot Water Use by End-Use[123]

End Use	Percent (%)	L
Shower	41.1%	67.4
Faucet	35.6%	58.3
Clothes Washer	10.2%	16.7
Bathtub	6.0%	9.8
Dishwasher	5.1%	8.3
Other	2.1%	3.4
Total	100.0%	163.9

OPPPs have been detected in household fixtures such as showerheads and hoses, faucets, and tub spouts.[126,59,127,128,61,30] Those fixtures are located at distal residential plumbing sites and have characteristics conducive to pathogen growth and biofilm formation: (1) the presence of a variety of materials, (2) large surface-to-volume ratios that create regions for biofilm attachment, and (3) regions of water stagnation that can lead to temperature and disinfectant residual decay.[128,1] No studies to date have conducted direct comparisons of fixture designs to understand which ones are more likely to support OPPP growth and biofilm formation. However, some specific types of fixtures have been associated with higher risk of contamination by OPPPs and different risks of subsequent infection. Hamilton et al.[129] proposed risk-based critical concentrations for *L. pneumophila* that vary by fixture type (i.e., toilets vs shower heads). Design features of spray nozzles in showers may also affect aerosolization rates[130] and thus potentially infection rates.

5.2. Temperature Control Mixing Valves. Thermostatic Mixing Valves (TMVs) have been associated with a higher risk for *Legionella* spp. growth in plumbing. Reasons that have been proposed include the presence of various types of materials in

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

their composition, as well as their complex internal structure with interstices where biofilms can develop.[1] The mixing of hot and cold water in plumbing may also create favorable temperature conditions for pathogen growth.[131,132] Finally, Rhoads et al.[133] suggests that these valves are subject to mechanical failure, which can cause mixing and contamination between cold and hot water lines.

There is a lack of guidance on TMV use and their role in pathogen growth at plumbing zones downstream of the valve.[132] No studies were found that assessed the impact of the most used types of TMVs in residences (such as those in shower and bathtubs) and the implications of their use on microbial water quality at the POU compared to the water supply. Temperature control devices are required for shower and bathtub fixtures for one- and two-family dwellings according to the 2021 International Residential Code (IRC).[134] Thus, research is needed on the contribution of those valves to enhancing not only growth of *Legionella* species but also other OPPPs in residences at the POU in comparison with the cold water supply. The results of those studies could support the development of alternative valve designs and guidelines for maintenance and decontaminating, as well as the review of current plumbing codes to incorporate better installation locations and temperature settings to reduce both OPPP growth potential and scalding risk.

6. PLUMBING CODES AND GUIDELINES FOR OPPP MANAGEMENT IN PLUMBING

This section reviews existing plumbing codes and OPPP management plans to help identify how future research can support their continuous update and improvement. In the United States, the design, installation, and inspection of plumbing is based largely on the requirements contained in either the Uniform Plumbing Code (UPC) or International Plumbing Code (IPC), published by IAPMO and the International Code Council (ICC), respectively, although specific requirements vary among states.[135,136] The ICC also developed the IRC, which "establishes minimum requirements for one- and two-family dwellings and townhouses using prescriptive provisions".[134]

Tables S1 and S2 summarize some of the requirements of the most recent versions of the UPC, IPC, and IRC that could potentially impact microbial water quality.[135,136] For example, pressure/temperature control valves are required for some specific types of fixtures such as showers, tub/shower combinations, and bathtubs, and a maximum temperature setting of 49 °C was established for those valves. In addition, the IPC and IRC set forth requirements related to maximum water heater temperature settings for water heaters used as space heaters, and the IPC requires a maximum outlet temperature of 60 °C for tankless water heaters. As described in Section 5, TMVs have been associated with *Legionella* spp. growth under plumbing conditions, and their use in residences require further research. In Section 3, the impact of temperature on different OPPPs was also discussed, although their interactions with other factors may support conditions for increased growth. Finally, all codes list requirements for insulation of hot water piping under certain conditions. Adding insulation to hot water pipes (an energy savings measure) should be carefully considered as it reduces heat losses during stagnation, which can cause temperatures to stay within optimal *L. pneumophila* growth ranges for longer periods of time.[137]

Currently, there is a lack of comprehensive residential plumbing codes and guidelines for OPPP management. The recommendations that do exist are based on documents, such as ASHRAE Guideline 12 and ANSI/ASHRAE Standard 188-2018, developed for commercial, institutional, multiunit residential, and industrial buildings.[138,139] Single-family residences do not typically contain open- or closed-circuit cooling towers, evaporative condensers, or hot water recirculation systems as many commercial buildings[138,139] and multifamily residences do.[140,141] However, they likely have water heater storage units, plumbing configurations, and stagnation periods that can contribute to OPPP proliferation in residential plumbing. Furthermore, single-family residences can have showers, whirlpools, spas, water features, or humidification systems that release water aerosols within the building. These may pose an OPPP infection risk to occupants. Therefore, it is important that residential versions of these guidelines exist to assist the design and inspection of new residences and resumption of operation of existing plumbing after long periods of stagnation or detection of the presence of OPPPs.

ANSI/ASHRAE Standard 188 focuses on developing a building water management plan to manage the risk of legionellosis.[138] While single-family residences do not have building operators or water quality monitoring systems to implement such plans continually, builders and occupants can use similar approaches. One approach could be to manage water quality on a periodic basis and when renovations, additions, or modifications are made to the residence. Water management plans, however, are more relevant to multifamily dwellings. The first steps recommended are conducting a building survey to describe the water systems, creating flow diagrams, and conducting evaluations of hazardous (or potentially hazardous) conditions to determine where control measures should be applied (Figure 4). The next steps are to establish monitoring procedures with control measures that are within established limits and document them in a risk management plan. These steps are more applicable to commercial, institutional buildings, and multifamily residences, but changes can be made to make them more realistic and appropriate for residences. If control measures (i.e., microbiological testing) reveal that control limits for what is safe and acceptable in buildings are exceeded, then appropriate corrective actions, such as flushing or disinfection, need to be taken.

Therefore, future research should address the impact of the current plumbing code requirements on potential for OPPP growth while considering scalding risks. More specifically, the use of temperature control devices, their required outlet temperatures, and the use of insulation should be reviewed for different types of residences. In addition, updates of future standards should include guidelines for design, installation, and maintenance of plumbing and its components in a variety of building types, including single-family residences. Finally, updated guidelines on building water management plans could include measures for preventing the risk of legionellosis and other disease-causing OPPPs in not only commercial, industrial, and multifamily residences but also single-family residences.

7. CHARTING A COURSE FOR THE FUTURE: IDENTIFYING RESEARCH GAPS AND NEEDS

Despite the knowledge gained by nearly 50 years of study, questions remain about predicting health risks associated with

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

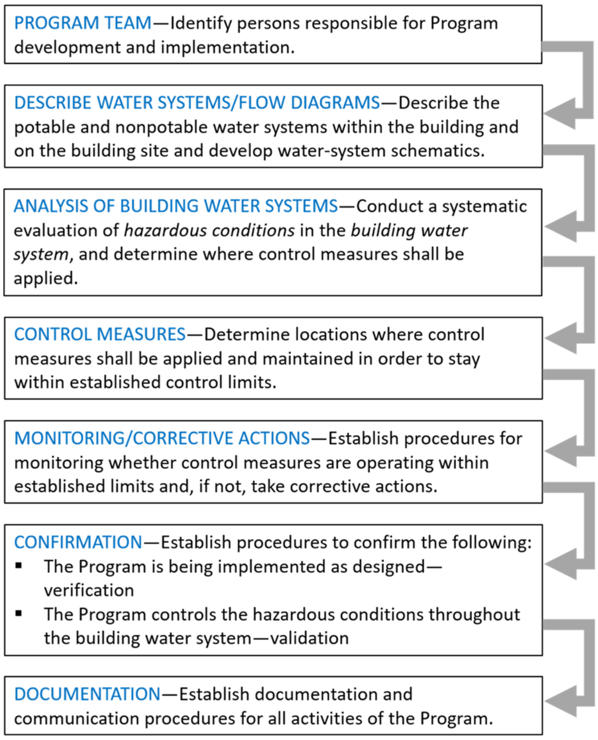


Figure 4. Elements of a water management program for commercial, industrial, or multifamily residences. Copyright 2018, ASHRAE, www.ashrae.org. ASHRAE Standard-188.

residential plumbing. A prioritized approach is needed to support plumbing design and use practices that minimize microbial risks in building water. Persily et al.[136] identified measurement science needs on water and energy efficiency and water quality in plumbing and developed a list of research topics to be explored in the future.[136] Although the document was not specifically intended for residential plumbing applications, some listed topics overlap with the research gaps identified in this study.[136] Another knowledge gap study identified the need to understand how water use and water quality vary with plumbing characteristics, with different uses, and over time and space.[142]

Comprehensive, controlled studies on the impact of different types, configurations, and use frequencies of residential water heaters and fixtures are needed to support recommendations that address concerns related to water efficiency, energy efficiency, and public health. In addition, more research is needed on different types (i.e., storage vs on demand., etc.) of residential water heating systems to better understand the magnitude of the impacts of the resulting temperature on water quality,[143] particularly on OPPP growth.

Although the pathogenic species of *Legionella* are often the focus of concern and investigations, other OPPPs can cause diseases and should be investigated in residences. Proctor et al.[24] emphasized the importance of looking at multiple organisms simultaneously, as the effects of a treatment for one organism cannot necessarily be extrapolated to all organisms.[24] More attention should be dedicated to the detection of *N. fowleri*, known as the brain-eating amoeba, in residential plumbing, which is a thermotolerant microorganism that can cause a lethal disease in humans.[144] A more complete investigation should be conducted throughout residential plumbing to identify environments conductive to OPPP growth since different conditions may favor the growth of different species.

Overall, a finding repeated throughout this review was the lack of studies in actual residences. Much work has been undertaken in laboratory settings, but extrapolation of those results to residential settings was not always clear. Additionally, work has been done in commercial buildings, but it was not apparent how relevant those studies are to residences. Water use patterns vary greatly, and consideration should be given to how scientific studies translate to water quality and the hazards of OPPPs in actual residences. The topics identified in this review highlighted the research needs that will help understand OPPPs holistically in residences. Once more research is conducted, communicating and translating of research findings to building owners and occupants may bring awareness to the residents.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c04277.

> Tables summarizing plumbing code requirements for operating temperatures associated with fixtures, thermostatic mixing valves, and water heaters; requirements for length of tempered water piping and insulation (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Alshae' R. Logan-Jackson − *Building Energy and Environment Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, United States;* orcid.org/0000-0002-2154-3261; Email: alshae.logan@nist.gov

Authors

Marylia Duarte Batista − *Building Energy and Environment Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, United States;* orcid.org/0000-0002-5200-7963

William Healy − *Building Energy and Environment Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, United States;* orcid.org/0000-0001-7711-7301

Tania Ullah − *Building Energy and Environment Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, United States;* orcid.org/0000-0001-6588-8977

Andrew J. Whelton − *Lyles School of Civil Engineering, Division of Environmental and Ecological Engineering, Purdue University, West Lafayette, Indiana 47907, United States;* orcid.org/0000-0001-5934-3081

Timothy A. Bartrand − *Environmental Science, Policy, and Research Institute, Bala Cynwyd, Pennsylvania 19004, United States;* orcid.org/0000-0002-2978-254X

Caitlin Proctor − *Agricultural and Biological Engineering, Division of Environmental and Ecological Engineering, Purdue University, West Lafayette, Indiana 47907, United States;* orcid.org/0000-0002-7868-4057

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.2c04277

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372

Funding

This work was supported through the National Institute of Standards and Technology (NIST) Strategic and Emerging Research Initiative; and for A.J.W. and C.P. by the U.S. National Science Foundation RAPID Grant 2027049 and U.S. Environmental Protection Agency contract R836890; and for T.A.B. by the Environmental Science, Policy, and Research Institute.

Notes

The contents of this publication are solely the responsibility of the authors and do not represent the official views of NIST.

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors thank the NIST librarians for their assistance in compiling the literature for the author's review. The authors also thank Andrew Persily, Dave Yashar, and Stephanie Servetas for their reviews.

■ REFERENCES

(1) *Management of Legionella in Water Systems*; A consensus study report of the National Academies of Sciences, Engineering, Medicine; National Academies of Sciences, Engineering, and Medicine (NASEM), Ed.; The National Academies Press: Washington, DC, 2020.

(2) U.S. Environmental Protection Agency (EPA). *Drinking Water Contaminant Candidate List 5—Draft*; 2021; Vol. 40 CFR Part 141, pp 37948−37972. https://www.epa.gov/ccl/contaminant-candidate-list-5-ccl-5.

(3) Falkinham, J. O.; Pruden, A.; Edwards, M. Opportunistic Premise Plumbing Pathogens: Increasingly Important Pathogens in Drinking Water. *Pathogens* **2015**, *4* (2), 373−386.

(4) *Legionellosis — United States, 2000−2009. Weekly August 19, 2011 /60(32); 1083−1086 [WWW Document]*. URL https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6032a3.htm (accessed 2022-08-04).

(5) Brazeau, R. H.; Edwards, M. A. Role of Hot Water System Design on Factors Influential to Pathogen Regrowth: Temperature, Chlorine Residual, Hydrogen Evolution, and Sediment. *Environ. Eng. Sci.* **2013**, *30* (10), 617−627.

(6) Rhoads, W. J.; Ji, P.; Pruden, A.; Edwards, M. A. Water Heater Temperature Set Point and Water Use Patterns Influence Legionella Pneumophila and Associated Microorganisms at the Tap. *Microbiome* **2015**, *3* (1), 67.

(7) U.S. Department of Energy (DOE). *Savings Project: Lower Water Heating Temperature*. Energy.gov. https://www.energy.gov/energysaver/services/do-it-yourself-energy-savings-projects/savings-project-lower-water-heating (accessed 2021-07-27).

(8) Naumova, E. N.; Liss, A.; Jagai, J. S.; Behlau, I.; Griffiths, J. K. Hospitalizations Due to Selected Infections Caused by Opportunistic Premise Plumbing Pathogens (OPPP) and Reported Drug Resistance in the United States Older Adult Population in 1991−2006. *J. Public Health Pol* **2016**, *37* (4), 500−513.

(9) Emmerson, A. Emerging Waterborne Infections in Health-Care Settings. *Emerg. Infect. Dis.* **2001**, *7* (2), 272−276.

(10) Wang, H.; Edwards, M. A.; Falkinham, J. O.; Pruden, A. Probiotic Approach to Pathogen Control in Premise Plumbing Systems? A Review. *Environ. Sci. Technol.* **2013**, *47* (18), 10117−10128.

(11) Williams, M. M.; Armbruster, C. R.; Arduino, M. J. Plumbing of Hospital Premises Is a Reservoir for Opportunistically Pathogenic Microorganisms: A Review. *Biofouling* **2013**, *29* (2), 147−162.

(12) Falkinham, J. Common Features of Opportunistic Premise Plumbing Pathogens. *IJERPH* **2015**, *12* (5), 4533−4545.

(13) Falkinham, J. O.; Hilborn, E. D.; Arduino, M. J.; Pruden, A.; Edwards, M. A. Epidemiology and Ecology of Opportunistic Premise Plumbing Pathogens: *Legionella Pneumophila*, *Mycobacterium Avium*, and *Pseudomonas Aeruginosa*. *Environ. Health Perspect* **2015**, *123* (8), 749−758.

(14) Gamage, S. D.; Ambrose, M.; Kralovic, S. M.; Roselle, G. A. Water Safety and Legionella in Health Care: Priorities, Policy, and Practice. *Infectious Disease Clinics of North America* **2016**, *30* (3), 689−712.

(15) Prest, E. I.; Hammes, F.; van Loosdrecht, M. C. M.; Vrouwenvelder, J. S. Biological Stability of Drinking Water: Controlling Factors, Methods, and Challenges. *Front Microbiol* **2016**, *7*, 45.

(16) United States Environmental Protection Agency (EPA). Technologies for Legionella Control in Premise Plumbing Systems: Scientific Literature Review, 2016. https://www.epa.gov/sites/default/files/2016-09/documents/placeholder.pdf (accessed 2021-08-12).

(17) Wang, H.; Bédard, E.; Prévost, M.; Camper, A. K.; Hill, V. R.; Pruden, A. Methodological Approaches for Monitoring Opportunistic Pathogens in Premise Plumbing: A Review. *Water Res.* **2017**, *117*, 68−86.

(18) Cates, E. L.; Torkzadeh, H. Can Incorporation of UVC LEDs into Showerheads Prevent Opportunistic Respiratory Pathogens? - Microbial Behavior and Device Design Considerations. *Water Res.* **2020**, *168*, 115163.

(19) Cullom, A. C.; Martin, R. L.; Song, Y.; Williams, K.; Williams, A.; Pruden, A.; Edwards, M. A. Critical Review: Propensity of Premise Plumbing Pipe Materials to Enhance or Diminish Growth of *Legionella* and Other Opportunistic Pathogens. *Pathogens* **2020**, *9* (11), 957.

(20) Falkinham, J. O. Living with Legionella and Other Waterborne Pathogens. *Microorganisms* **2020**, *8* (12), 2026.

(21) Weinbren, M. J. Dissemination of Antibiotic Resistance and Other Healthcare Waterborne Pathogens. The Price of Poor Design, Construction, Usage and Maintenance of Modern Water/Sanitation Services. *Journal of Hospital Infection* **2020**, *105* (3), 406−411.

(22) Gamage, S. D.; Ambrose, M.; Kralovic, S. M.; Roselle, G. A. Water Safety and Health Care: Preventing Infections Caused by Opportunistic Premise Plumbing Pathogens. *Infectious Disease Clinics of North America* **2021**, *35* (3), 667−695.

(23) Leslie, E.; Hinds, J.; Hai, F. I. Causes, Factors, and Control Measures of Opportunistic Premise Plumbing Pathogens—A Critical Review. *Applied Sciences* **2021**, *11* (10), 4474.

(24) Proctor, C.; Garner, E.; Hamilton, K. A.; Ashbolt, N. J.; Caverly, L. J.; Falkinham, J. O.; Haas, C. N.; Prevost, M.; Prevots, D. R.; Pruden, A.; Raskin, L.; Stout, J.; Haig, S.-J. Tenets of a Holistic Approach to Drinking Water-Associated Pathogen Research, Management, and Communication. *Water Res.* **2022**, *211*, 117997.

(25) Hayward, C.; Ross, K. E.; Brown, M. H.; Bentham, R.; Whiley, H. The Presence of Opportunistic Premise Plumbing Pathogens in Residential Buildings: A Literature Review. *Water* **2022**, *14* (7), 1129.

(26) Collier, S. A.; Deng, L.; Adam, E. A.; Benedict, K. M.; Beshearse, E. M.; Blackstock, A. J.; Bruce, B. B.; Derado, G.; Edens, C.; Fullerton, K. E.; Gargano, J. W.; Geissler, A. L.; Hall, A. J.; Havelaar, A. H.; Hill, V. R.; Hoekstra, R. M.; Reddy, S. C.; Scallan, E.; Stokes, E. K.; Yoder, J. S.; Beach, M. J. Estimate of Burden and Direct Healthcare Cost of Infectious Waterborne Disease in the United States. *Emerging Infectious Diseases Journal* **2021**, *27* (1), 140.

(27) Ley, C. J.; Proctor, C. R.; Jordan, K.; Ra, K.; Noh, Y.; Odimayomi, T.; Julien, R.; Kropp, I.; Mitchell, J.; Nejadhashemi, A. P.; Whelton, A. J.; Aw, T. G. Impacts of Municipal Water-Rainwater Source Transitions on Microbial and Chemical Water Quality Dynamics at the Tap. *Environ. Sci. Technol.* **2020**, *54* (18), 11453−11463.

(28) Charron, D.; Bédard, E.; Lalancette, C.; Laferrière, C.; Prévost, M. Impact of Electronic Faucets and Water Quality on the Occurrence of Pseudomonas Aeruginosa in Water: A Multi-Hospital Study. *Infect Control Hosp Epidemiol* **2015**, *36* (3), 311−319.

(29) Donohue, M. J.; O'Connell, K.; Vesper, S. J.; Mistry, J. H.; King, D.; Kostich, M.; Pfaller, S. Widespread Molecular Detection of

Legionella Pneumophila Serogroup 1 in Cold Water Taps across the United States. *Environ. Sci. Technol.* **2014**, *48* (6), 3145−3152.
(30) Falkinham, J. O.; Iseman, M. D.; de Haas, P.; van Soolingen, D. Mycobacterium Avium in a Shower Linked to Pulmonary Disease. *J. Water Health* **2008**, *6* (2), 209−213.
(31) Cope, J. R.; Ratard, R. C.; Hill, V. R.; Sokol, T.; Causey, J. J.; Yoder, J. S.; Mirani, G.; Mull, B.; Mukerjee, K. A.; Narayanan, J.; Doucet, M.; Qvarnstrom, Y.; Poole, C. N.; Akingbola, O. A.; Ritter, J. M.; Xiong, Z.; da Silva, A. J.; Roellig, D.; Van Dyke, R. B.; Stern, H.; Xiao, L.; Beach, M. J. The First Association of a Primary Amebic Meningoencephalitis Death With Culturable Naegleria Fowleri in Tap Water From a US Treated Public Drinking Water System. *Clinical Infectious Diseases* **2015**, *60* (8), e36−e42.
(32) Falkinham, J. O.; Norton, C. D.; LeChevallier, M. W. Factors Influencing Numbers of *Mycobacterium Avium*, *Mycobacterium Intracellulare*, and Other *Mycobacteria* in Drinking Water Distribution Systems. *Appl. Environ. Microbiol.* **2001**, *67* (3), 1225−1231.
(33) Bédard, E.; Prévost, M.; Déziel, E. Pseudomonas Aeruginosa in Premise Plumbing of Large Buildings. *Microbiologyopen* **2016**, *5* (6), 937−956.
(34) Donohue, M. J.; Vesper, S.; Mistry, J.; Donohue, J. M. Impact of Chlorine and Chloramine on the Detection and Quantification of Legionella Pneumophila and Mycobacterium Species. *Appl. Environ. Microbiol.* **2019**, *85* (24), e01942-19 DOI: 10.1128/AEM.01942-19.
(35) Mapili, K.; Pieper, K. J.; Dai, D.; Pruden, A.; Edwards, M. A.; Tang, M.; Rhoads, W. J. *Legionella Pneumophila* Occurrence in Drinking Water Supplied by Private Wells. *Lett. Appl. Microbiol* **2020**, *70* (4), 232−240.
(36) De Filippis, P.; Mozzetti, C.; Messina, A.; D'Alò, G. L. Prevalence of Legionella in Retirement Homes and Group Homes Water Distribution Systems. *Sci. Total Environ.* **2018**, *643*, 715−724.
(37) Rhoads, W. J.; Bradley, T. N.; Mantha, A.; Buttling, L.; Keane, T.; Pruden, A.; Edwards, M. A. Residential Water Heater Cleaning and Occurrence of Legionella in Flint, MI. *Water Res.* **2020**, *171*, 115439.
(38) Stout, J. E.; Yu, V. L.; Yee, Y. C.; Vaccarello, S.; Diven, W.; Lee, T. C. Legionella Pneumophila in Residential Water Supplies: Environmental Surveillance with Clinical Assessment for Legionnaires' Disease. *Epidemiol Infect* **1992**, *109* (1), 49−57.
(39) Lee, T. C.; Stout, J. E.; Yu, V. L. Factors Predisposing to Legionella Pneumophila Colonization in Residential Water Systems. *Archives of Environmental Health: An International Journal* **1988**, *43* (1), 59−62.
(40) Longtin, Y.; Troillet, N.; Touveneau, S.; Boillat, N.; Rimensberger, P.; Dharan, S.; Gervaix, A.; Pittet, D.; Harbarth, S. Pseudomonas Aeruginosa Outbreak in a Pediatric Intensive Care Unit Linked to a Humanitarian Organization Residential Center. *Pediatr Infect Dis J.* **2010**, *29* (3), 233−237.
(41) Schelstraete, P.; Daele, S. V.; Boeck, K. D.; Proesmans, M.; Lebecque, P.; Leclercq-Foucart, J.; Malfroot, A.; Vaneechoutte, M.; Baets, F. D. Pseudomonas Aeruginosa in the Home Environment of Newly Infected Cystic Fibrosis Patients. *Eur. Respir. J.* **2008**, *31* (4), 822−829.
(42) Donohue, M. J.; King, D.; Pfaller, S.; Mistry, J. H. The Sporadic Nature of Legionella Pneumophila, Legionella Pneumophila Sg1 and Mycobacterium Avium Occurrence within Residences and Office Buildings across 36 States in the United States. *J. Appl. Microbiol.* **2019**, *126* (5), 1568−1579.
(43) Nishiuchi, Y.; Maekura, R.; Kitada, S.; Tamaru, A.; Taguri, T.; Kira, Y.; Hiraga, T.; Hirotani, A.; Yoshimura, K.; Miki, M.; Ito, M. The Recovery of Mycobacterium Avium-Intracellulare Complex (MAC) from the Residential Bathrooms of Patients with Pulmonary MAC. *Clinical Infectious Diseases* **2007**, *45* (3), 347−351.
(44) Blair, B.; Sarkar, P.; Bright, K. R.; Marciano-Cabral, F.; Gerba, C. P. Naegleria Fowleri in Well Water. *Emerg Infect Dis* **2008**, *14* (9), 1499−1501.
(45) Dai, D.; Rhoads, W. J.; Katner, A.; Strom, L.; Edwards, M. A.; Pruden, A.; Pieper, K. J. Molecular Survey of *Legionella* and *Naegleria Fowleri* in Private Well Water and Premise Plumbing Following the 2016 Louisiana Flood. *Environ. Sci.: Water Res. Technol.* **2019**, *5* (8), 1464−1477.
(46) Xue, J.; Zhang, B.; Lamori, J.; Shah, K.; Zabaleta, J.; Garai, J.; Taylor, C. M.; Sherchan, S. P. Molecular Detection of Opportunistic Pathogens and Insights into Microbial Diversity in Private Well Water and Premise Plumbing. *Journal of Water and Health* **2020**, *18* (5), 820−834.
(47) Yoder, J. S.; Straif-Bourgeois, S.; Roy, S. L.; Moore, T. A.; Visvesvara, G. S.; Ratard, R. C.; Hill, V. R.; Wilson, J. D.; Linscott, A. J.; Crager, R.; Kozak, N. A.; Sriram, R.; Narayanan, J.; Mull, B.; Kahler, A. M.; Schneeberger, C.; da Silva, A. J.; Poudel, M.; Baumgarten, K. L.; Xiao, L.; Beach, M. J. Primary Amebic Meningoencephalitis Deaths Associated With Sinus Irrigation Using Contaminated Tap Water. *Clinical Infectious Diseases* **2012**, *55* (9), e79−e85.
(48) Kelly, R. B.; Francine, M.-C.; Charles, P. G. Occurrence of Naegleria Fowleri in Arizona Drinking Water Supply Wells. *Journal AWWA* **2009**, *101* (11), 43−50.
(49) Stout, J. E.; Yu, V. L.; Best, M. G. Ecology of Legionella Pneumophila within Water Distribution Systems. *Appl. Environ. Microbiol.* **1985**, *49* (1), 221−228.
(50) Ley, C. J.; Proctor, C. R.; Singh, G.; Ra, K.; Noh, Y.; Odimayomi, T.; Salehi, M.; Julien, R.; Mitchell, J.; Nejadhashemi, A. P.; Whelton, A. J.; Aw, T. G. Drinking Water Microbiology in a Water-Efficient Building: Stagnation, Seasonality, and Physicochemical Effects on Opportunistic Pathogen and Total Bacteria Proliferation. *Environ. Sci.: Water Res. Technol.* **2020**, *6* (10), 2902−2913.
(51) United States Energy Information Administration. *Residential Energy Consumption Survey (RECS) - Data*. U.S. Department of Energy. https://www.eia.gov/consumption/residential/data/2015/index.php?view=consumption#by%20end%20uses (accessed 2021-07-01).
(52) Proctor, C. R.; Rhoads, W. J.; Keane, T.; Salehi, M.; Hamilton, K.; Pieper, K. J.; Cwiertny, D. M.; Prévost, M.; Whelton, A. J. Considerations for Large Building Water Quality after Extended Stagnation. *AWWA Water Science* **2020**, *2* (4), e1186 DOI: 10.1002/aws2.1186.
(53) Ling, F.; Whitaker, R.; LeChevallier, M. W.; Liu, W.-T. Drinking Water Microbiome Assembly Induced by Water Stagnation. *ISME J.* **2018**, *12* (6), 1520−1531.
(54) United States Census Bureau. *American Housing Survey. 2019 National - Housing Unit Characteristics - All Housing Units*. https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html (accessed 2021-08-11).
(55) Center for Sustainable Systems, University of Michigan. *Residential Buildings Factsheet*. https://css.umich.edu/publications/factsheets/built-environment/residential-buildings-factsheet (accessed 2021-08-11).
(56) *Drinking Water Distribution Systems: Assessing and Reducing Risks*; National Research Council (NRC), Ed.; National Academies Press: Washington, DC, 2006.
(57) Lautenschlager, K.; Boon, N.; Wang, Y.; Egli, T.; Hammes, F. Overnight Stagnation of Drinking Water in Household Taps Induces Microbial Growth and Changes in Community Composition. *Water Res.* **2010**, *44* (17), 4868−4877.
(58) Ji, P.; Parks, J.; Edwards, M. A.; Pruden, A. Impact of Water Chemistry, Pipe Material and Stagnation on the Building Plumbing Microbiome. *PLoS One* **2015**, *10* (10), No. e0141087.
(59) Collins, S.; Stevenson, D.; Bennett, A.; Walker, J. Occurrence of Legionella in UK Household Showers. *International Journal of Hygiene and Environmental Health* **2017**, *220* (2), 401−406.
(60) Haig, S.-J.; Kotlarz, N.; LiPuma, J. J.; Raskin, L. A High-Throughput Approach for Identification of Nontuberculous Mycobacteria in Drinking Water Reveals Relationship between Water Age and Mycobacterium Avium. *mBio* **2018**, *9* (1), e02354-17 DOI: 10.1128/mBio.02354-17.

(61) Hayes-Phillips, D.; Bentham, R.; Ross, K.; Whiley, H. Factors Influencing Legionella Contamination of Domestic Household Showers. *Pathogens* **2019**, *8* (1), 27.
(62) Tolofari, D. L.; Bartrand, T.; Masters, S. V.; Duarte Batista, M.; Haas, C. N.; Olson, M.; Gurian, P. L. Influence of Hot Water Temperature and Use Patterns on Microbial Water Quality in Building Plumbing Systems. *Environmental Engineering Science* **2022**, 309−319.
(63) Deem, S. Preparing for COVID-19's Effect on *Legionella* and Building Water Systems. *J. Am. Water Works Assoc* **2020**, *112* (9), 60−62.
(64) De Giglio, O.; Diella, G.; Lopuzzo, M.; Triggiano, F.; Calia, C.; Pousis, C.; Fasano, F.; Caggiano, G.; Calabrese, G.; Rafaschieri, V.; Carpagnano, F.; Carlucci, M.; Gesualdo, L.; Ricci, M. L.; Scaturro, M.; Rota, M. C.; Bonadonna, L.; Lucentini, L.; Montagna, M. T. Impact of Lockdown on the Microbiological Status of the Hospital Water Network during COVID-19 Pandemic. *Environmental Research* **2020**, *191*, 110231.
(65) Hozalski, R. M.; LaPara, T. M.; Zhao, X.; Kim, T.; Waak, M. B.; Burch, T.; McCarty, M. Flushing of Stagnant Premise Water Systems after the COVID-19 Shutdown Can Reduce Infection Risk by *Legionella* and *Mycobacterium* Spp. *Environ. Sci. Technol.* **2020**, *54* (24), 15914−15924.
(66) Smith, K. L.; Shuman, H. A.; Findeisen, D. Evaluation of the Microbial Community Structure of Potable Water Samples from Occupied and Unoccupied Buildings Using16S RRNA Amplicon Sequencing. *bioRxiv* **2020**, DOI: 10.1101/2020.07.17.209346, (accessed 2021-11-23).
(67) Rhoads, W. J.; Hammes, F. Growth of *Legionella* during COVID-19 Lockdown Stagnation. *Environ. Sci.: Water Res. Technol.* **2021**, *7* (1), 10−15.
(68) Richard, R.; Boyer, T. H. Pre- and Post-flushing of Three Schools in Arizona Due to COVID −19 Shutdown. *AWWA Water Science* **2021**, *3* (5), e1239 DOI: 10.1002/aws2.1239.
(69) Ye, C.; Xian, X.; Bao, R.; Zhang, Y.; Feng, M.; Lin, W.; Yu, X. Recovery of Microbiological Quality of Long-Term Stagnant Tap Water in University Buildings during the COVID-19 Pandemic. *Science of The Total Environment* **2022**, *806*, 150616.
(70) Rhoads, W. J.; Sindelar, M.; Margot, C.; Graf, N.; Hammes, F. Variable Legionella Response to Building Occupancy Patterns and Precautionary Flushing. *Microorganisms* **2022**, *10* (3), 555.
(71) United States Department of Energy (DOE). *Energy Star Water Heater Market Profile*. Energy.gov. https://www.energy.gov/energysaver/water-heating/reduce-hot-water-use-energy-savings (accessed 2021-07-01).
(72) Maguire, J.; Fang, X.; Wilson, E. *Comparison of Advanced Residential Water Heating Technologies in the United States* **2013**, 129.
(73) Rakić, A.; Perić, J.; Foglar, L. Influence of Temperature, Chlorine Residual and Heavy Metals on the Presence of Legionella Pneumophila in Hot Water Distribution Systems. *Ann. Agric Environ. Med.* **2012**, *19* (3), 431−436.
(74) Joly, J. Legionella and Domestic Water Heaters in the Quebec City Area. *Can. Med. Assoc J.* **1985**, *132* (2), 160.
(75) Dewailly, E.; Joly, J. R. Contamination of Domestic Water Heaters WithLegionella Pneumophila: Impact of Water Temperature on Growth and Dissemination of the Bacterium. *Environ. Toxicol. Water Qual.* **1991**, *6* (2), 249−257.
(76) Mathys, W.; Stanke, J.; Harmuth, M.; Junge-Mathys, E. Occurrence of Legionella in Hot Water Systems of Single-Family Residences in Suburbs of Two German Cities with Special Reference to Solar and District Heating. *Int. J. Hyg Environ. Health* **2008**, *211* (1−2), 179−185.
(77) Wang, H.; Masters, S.; Falkinham, J. O.; Edwards, M. A.; Pruden, A. Distribution System Water Quality Affects Responses of Opportunistic Pathogen Gene Markers in Household Water Heaters. *Environ. Sci. Technol.* **2015**, *49* (14), 8416−8424.
(78) Proctor, C. R.; Dai, D.; Edwards, M. A.; Pruden, A. Interactive Effects of Temperature, Organic Carbon, and Pipe Material on Microbiota Composition and Legionella Pneumophila in Hot Water Plumbing Systems. *Microbiome* **2017**, *5* (1), 130.
(79) Dai, D.; Rhoads, W. J.; Edwards, M. A.; Pruden, A. Shotgun Metagenomics Reveals Taxonomic and Functional Shifts in Hot Water Microbiome Due to Temperature Setting and Stagnation. *Front. Microbiol.* **2018**, *9*, 2695 DOI: 10.3389/fmicb.2018.02695.
(80) Rhoads, W. J.; Pruden, A.; Edwards, M. A. Convective Mixing in Distal Pipes Exacerbates Legionella Pneumophila Growth in Hot Water Plumbing. *Pathogens* **2016**, *5* (1), No. 29.
(81) Williams, K.; Pruden, A.; Falkinham, J. O.; Edwards, M. Relationship between Organic Carbon and Opportunistic Pathogens in Simulated Glass Water Heaters. *Pathogens* **2015**, *4* (2), 355−372.
(82) Ji, P.; Rhoads, W. J.; Edwards, M. A.; Pruden, A. Impact of Water Heater Temperature Setting and Water Use Frequency on the Building Plumbing Microbiome. *ISME J.* **2017**, *11* (6), 1318−1330.
(83) Spencer, M. S.; Cullom, A. C.; Rhoads, W. J.; Pruden, A.; Edwards, M. A. Replicable Simulation of Distal Hot Water Premise Plumbing Using Convectively-Mixed Pipe Reactors. *PLoS One* **2020**, *15* (9), e0238385.
(84) Rhoads, W. J.; Pruden, A.; Edwards, M. A. Survey of Green Building Water Systems Reveals Elevated Water Age and Water Quality Concerns. *Environ. Sci.: Water Res. Technol.* **2016**, *2* (1), 164−173.
(85) Katz, S. M.; Hammel, J. M. The Effect of Drying, Heat, and PH on the Survival of Legionella Pneumophila. *Ann. Clin Lab Sci.* **1987**, *17* (3), 150−156.
(86) *Legionella Growth and Spread: For Healthcare Facilities | CDC*. https://www.cdc.gov/legionella/wmp/overview/growth-and-spread.html (accessed 2022-10-27).
(87) Consumer Product Safety Commission. *CPSC Safety Alert: Avoiding Tap Water Scalds*, 2012. https://www.cpsc.gov/safety-education/safety-guides/kids-and-babies-home/avoiding-tap-water-scalds. (accessed 2021-07−27).
(88) Centers for Disease Control and Prevention (CDC). *Monitoring Your Building Water*. https://www.cdc.gov/legionella/wmp/monitor-water.html#monitoring-water (accessed 2021-08−12).
(89) *Legionella and the Prevention of Legionellosis*; World Health Organization (WHO), Ed.; World Health Organization: Geneva, 2007.
(90) Lasheras, A.; Boulestreau, H.; Rogues, A.-M.; Ohayon-Courtes, C.; Labadie, J.-C.; Gachie, J.-P. Influence of Amoebae and Physical and Chemical Characteristics of Water on Presence and Proliferation of Legionella Species in Hospital Water Systems. *Am. J. Infect Control* **2006**, *34* (8), 520−525.
(91) Flannery, B.; Gelling, L. B.; Vugia, D. J.; Weintraub, J. M.; Salerno, J. J.; Conroy, M. J.; Stevens, V. A.; Rose, C. E.; Moore, M. R.; Fields, B. S.; Besser, R. E. Reducing *Legionella* Colonization of Water Systems with Monochloramine. *Emerg. Infect. Dis.* **2006**, *12* (4), 588−596.
(92) Bagh, L. K.; Albrechtsen, H. J.; Arvin, E.; Ovesen, K. Distribution of Bacteria in a Domestic Hot Water System in a Danish Apartment Building. *Water Res.* **2004**, *38* (1), 225−235.
(93) Proctor, C. R.; Hammes, F. Drinking Water Microbiology—from Measurement to Management. *Curr. Opin. Biotechnol.* **2015**, *33*, 87−94.
(94) Neu, L.; Hammes, F. Feeding the Building Plumbing Microbiome: The Importance of Synthetic Polymeric Materials for Biofilm Formation and Management. *Water* **2020**, *12* (6), 1774.
(95) Yu, J.; Kim, D.; Lee, T. Microbial Diversity in Biofilms on Water Distribution Pipes of Different Materials. *Water Sci. Technol.* **2010**, *61* (1), 163−171.
(96) Lehtola, M. J.; Miettinen, I. T.; Keinänen, M. M.; Kekki, T. K.; Laine, O.; Hirvonen, A.; Vartiainen, T.; Martikainen, P. J. Microbiology, Chemistry and Biofilm Development in a Pilot Drinking Water Distribution System with Copper and Plastic Pipes. *Water Res.* **2004**, *38* (17), 3769−3779.
(97) Niquette, P.; Servais, P.; Savoir, R. Impacts of Pipe Materials on Densities of Fixed Bacterial Biomass in a Drinking Water Distribution System. *Water Res.* **2000**, *34* (6), 1952−1956.

(98) Jang, H.-J.; Choi, Y.-J.; Ka, J.-O. Effects of Diverse Water Pipe Materials on Bacterial Communities and Water Quality in the Annular Reactor. *J. Microbiol Biotechnol* **2011**, *21* (2), 115−123.

(99) Tiefenbrunner, F.; Arnold, A.; Dierich, K. D. *Current Status and Emerging Perspectives*; American Society for Microbiology: Washington, DC, 1993; pp 235−238.

(100) Borella, P.; Montagna, M. T.; Romano-Spica, V.; Stampi, S.; Stancanelli, G.; Triassi, M.; Neglia, R.; Marchesi, I.; Fantuzzi, G.; Tatò, D.; Napoli, C.; Quaranta, G.; Laurenti, P.; Leoni, E.; De Luca, G.; Ossi, C.; Moro, M.; D'Alcalà, G. R. Legionella Infection Risk from Domestic Hot Water. *Emerg Infect Dis* **2004**, *10* (3), 457−464.

(101) Buse, H. Y.; Lu, J.; Lu, X.; Mou, X.; Ashbolt, N. J. Microbial Diversities (16S and 18S RRNA Gene Pyrosequencing) and Environmental Pathogens within Drinking Water Biofilms Grown on the Common Premise Plumbing Materials Unplasticized Polyvinylchloride and Copper. *FEMS Microbiol Ecol* **2014**, *88* (2), 280−295.

(102) van der Kooij, D.; Veenendaal, H. R.; Scheffer, W. J. H. Biofilm Formation and Multiplication of Legionella in a Model Warm Water System with Pipes of Copper, Stainless Steel and Cross-Linked Polyethylene. *Water Res.* **2005**, *39* (13), 2789−2798.

(103) Rhoads, W. J.; Pruden, A.; Edwards, M. A. Interactive Effects of Corrosion, Copper, and Chloramines on Legionella and Mycobacteria in Hot Water Plumbing. *Environ. Sci. Technol.* **2017**, *51* (12), 7065−7075.

(104) Liu, R.; Zhu, J.; Yu, Z.; Joshi, D.; Zhang, H.; Lin, W.; Yang, M. Molecular Analysis of Long-Term Biofilm Formation on PVC and Cast Iron Surfaces in Drinking Water Distribution System. *J. Environ. Sci. (China)* **2014**, *26* (4), 865−874.

(105) van der Kooij, D.; Veenendaal, H. R.; Italiaander, R. Corroding Copper and Steel Exposed to Intermittently Flowing Tap Water Promote Biofilm Formation and Growth of Legionella Pneumophila. *Water Res.* **2020**, *183*, 115951.

(106) Wang, H.; Masters, S.; Hong, Y.; Stallings, J.; Falkinham, J. O.; Edwards, M. A.; Pruden, A. Effect of Disinfectant, Water Age, and Pipe Material on Occurrence and Persistence of *Legionella*, *Mycobacteria*, *Pseudomonas Aeruginosa*, and Two Amoebas. *Environ. Sci. Technol.* **2012**, *46* (21), 11566−11574.

(107) Zhang, L.; Liu, S. Investigation of Organic Compounds Migration from Polymeric Pipes into Drinking Water under Long Retention Times. *Procedia Engineering* **2014**, *70*, 1753−1761.

(108) Garner, E.; Inyang, M.; Garvey, E.; Parks, J.; Glover, C.; Grimaldi, A.; Dickenson, E.; Sutherland, J.; Salveson, A.; Edwards, M. A.; Pruden, A. Impact of Blending for Direct Potable Reuse on Premise Plumbing Microbial Ecology and Regrowth of Opportunistic Pathogens and Antibiotic Resistant Bacteria. *Water Res.* **2019**, *151*, 75−86.

(109) Inkinen, J.; Kaunisto, T.; Pursiainen, A.; Miettinen, I. T.; Kusnetsov, J.; Riihinen, K.; Keinänen-Toivola, M. M. Drinking Water Quality and Formation of Biofilms in an Office Building during Its First Year of Operation, a Full Scale Study. *Water Res.* **2014**, *49*, 83−91.

(110) Hallam, N. B.; West, J. R.; Forster, C. F.; Simms, J. The Potential for Biofilm Growth in Water Distribution Systems. *Water Res.* **2001**, *35* (17), 4063−4071.

(111) Pedersen, K. Biofilm Development on Stainless Steel and Pvc Surfaces in Drinking Water. *Water Res.* **1990**, *24* (2), 239−243.

(112) Connell, M.; Stenson, A.; Weinrich, L.; LeChevallier, M.; Boyd, S. L.; Ghosal, R. R.; Dey, R.; Whelton, A. J. PEX and PP Water Pipes: Assimilable Carbon, Chemicals, and Odors. *Journal AWWA* **2016**, *108* (4), No. E192-E204.

(113) Salehi, M.; Odimayomi, T.; Ra, K.; Ley, C.; Julien, R.; Nejadhashemi, A. P.; Hernandez-Suarez, J. S.; Mitchell, J.; Shah, A. D.; Whelton, A. An Investigation of Spatial and Temporal Drinking Water Quality Variation in Green Residential Plumbing. *Building and Environment* **2020**, *169*, 106566.

(114) Moritz, M. M.; Flemming, H.-C.; Wingender, J. Integration of Pseudomonas Aeruginosa and Legionella Pneumophila in Drinking Water Biofilms Grown on Domestic Plumbing Materials. *International Journal of Hygiene and Environmental Health* **2010**, *213* (3), 190−197.

(115) Mullis, S. N.; Falkinham, J. O. Adherence and Biofilm Formation of Mycobacterium Avium, Mycobacterium Intracellulare and Mycobacterium Abscessus to Household Plumbing Materials. *J. Appl. Microbiol.* **2013**, *115* (3), 908−914.

(116) Buse, H. Y.; Morris, B. J.; Struewing, I. T.; Szabo, J. G. Chlorine and Monochloramine Disinfection of Legionella Pneumophila Colonizing Copper and Polyvinyl Chloride Drinking Water Biofilms. *Appl. Environ. Microbiol.* **2019**, *85* (7), e02956-18.

(117) Learbuch, K. L. G.; Lut, M. C.; Liu, G.; Smidt, H.; van der Wielen, P. W. J. J. Legionella Growth Potential of Drinking Water Produced by a Reverse Osmosis Pilot Plant. *Water Res.* **2019**, *157*, 55−63.

(118) Thomson, R. M.; Carter, R.; Tolson, C.; Coulter, C.; Huygens, F.; Hargreaves, M. Factors Associated with the Isolation of Nontuberculous Mycobacteria (NTM) from a Large Municipal Water System in Brisbane, Australia. *BMC Microbiology* **2013**, *13* (1), 89.

(119) Norton, C. D.; LeChevallier, M. W.; Falkinham, J. O. Survival of Mycobacterium Avium in a Model Distribution System. *Water Res.* **2004**, *38* (6), 1457−1466.

(120) Soothill, J. S. Carbapenemase-Bearing Klebsiella Spp. in Sink Drains: Investigation into the Potential Advantage of Copper Pipes. *Journal of Hospital Infection* **2016**, *93* (2), 152−154.

(121) Proctor, C. R.; Gächter, M.; Kötzsch, S.; Rölli, F.; Sigrist, R.; Walser, J.-C.; Hammes, F. Biofilms in Shower Hoses - Choice of Pipe Material Influences Bacterial Growth and Communities. *Environ. Sci.: Water Res. Technol.* **2016**, *2* (4), 670−682.

(122) Cao, G.; Huang, K.; Whelton, A. J.; Shah, A. D. Formation and Sorption of Trihalomethanes from Cross-Linked Polyethylene Pipes Following Chlorinated Water Exposure. *Environmental Science: Water Research & Technology* **2020**, *6* (9), 2479−2491.

(123) DeOreo, W. B.; Mayer, P.; Dziegielewski, B.; Kiefer, J. *Residential End Uses of Water, Version 2*; 4309B; Water Research Foundation, 2016.

(124) American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Chapter 50: Service Water Heating. In *ASHRAE Handbook of HVAC Applications*; ASHRAE: Atlanta, GA, 2015.

(125) United States Environmental Protection Agency (EPA). *WaterSense*. https://www.epa.gov/watersense (accessed 2021-10-14).

(126) Feazel, L. M.; Baumgartner, L. K.; Peterson, K. L.; Frank, D. N.; Harris, J. K.; Pace, N. R. Opportunistic Pathogens Enriched in Showerhead Biofilms. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106* (38), 16393−16399.

(127) Kuroki, T.; Watanabe, Y.; Teranishi, H.; Izumiyama, S.; Amemura-Maekawa, J.; Kura, F. *Legionella* Prevalence and Risk of Legionellosis in Japanese Households. *Epidemiol. Infect.* **2017**, *145* (7), 1398−1408.

(128) Proctor, C. R.; Reimann, M.; Vriens, B.; Hammes, F. Biofilms in Shower Hoses. *Water Res.* **2018**, *131*, 274−286.

(129) Hamilton, K. A.; Hamilton, M. T.; Johnson, W.; Jjemba, P.; Bukhari, Z.; LeChevallier, M.; Haas, C. N.; Gurian, P. L. Risk-Based Critical Concentrations of *Legionella Pneumophila* for Indoor Residential Water Uses. *Environ. Sci. Technol.* **2019**, *53* (8), 4528−4541.

(130) Estrada-Perez, C. E.; Kinney, K. A.; Maestre, J. P.; Hassan, Y. A.; King, M. D. Droplet Distribution and Airborne Bacteria in an Experimental Shower Unit. *Water Res.* **2018**, *130*, 47−57.

(131) Health and Safety Executive (HSE). Part 2: The Control of Legionella Bacteria in Hot and Cold Water Systems. In *Legionnaires' disease: Technical guidance*; HSE Books: United Kingdom, 2014. https://www.hse.gov.uk/pubns/books/hsg274.htm (accessed 2023-02-07).

(132) Singh, R.; Hamilton, K. A.; Rasheduzzaman, M.; Yang, Z.; Kar, S.; Fasnacht, A.; Masters, S. V.; Gurian, P. L. Managing Water Quality in Premise Plumbing: Subject Matter Experts' Perspectives and a Systematic Review of Guidance Documents. *Water* **2020**, *12* (2), 347.

(133) Rhoads, W. J.; Pruden, A.; Edwards, M. A. Anticipating Challenges with In-Building Disinfection for Control of Opportunistic Pathogens. *water environ res* **2014**, *86* (6), 540−549.
(134) International Code Council (ICC). *2021 International Residential Code for One- and Two- Family Dwellings (IRC)*, 2021.
(135) Peck, M.; Chang Brewer, A.; Pressman, M.; Blank, E.; Mickalide, A. Hot Tap Water Legislation in the United States. *Journal of Burn Care & Research* **2010**, *31* (6), 918−925.
(136) Persily, A.; Yashar, D.; Milesi Ferretti, N.; Ullah, T.; Healy, W. *Measurement Science Research Needs for Premise Plumbing Systems*; NIST TN 2088; National Institute of Standards and Technology: Gaithersburg, MD, 2020; NIST TN 2088. DOI: 10.6028/NIST.TN.2088.
(137) Bédard, E.; Fey, S.; Charron, D.; Lalancette, C.; Cantin, P.; Dolcé, P.; Laferrière, C.; Déziel, E.; Prévost, M. Temperature Diagnostic to Identify High Risk Areas and Optimize Legionella Pneumophila Surveillance in Hot Water Distribution Systems. *Water Res.* **2015**, *71*, 244−256.
(138) American National Standards Institute (ANSI); American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *ANSI/ASHRAE Standard 188-2018, Legionellosis: Risk Management for Building Water Systems*; 2018.
(139) American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *Guideline 12-2020 Managing the Risk of Legionellosis Associated with Building Water Systems*; 2020.
(140) *Recirculation Systems*. RL Deppmann. https://www.deppmann.com/products/recirculation-systems/ (accessed 2022-10-28).
(141) *Demand Hot Water Recirculating System*. https://www.energystar.gov/products/water_heaters/demand_hot_water_recirculating_system (accessed 2022-10-28).
(142) Julien, R.; Dreelin, E.; Whelton, A. J.; Lee, J.; Aw, T. G.; Dean, K.; Mitchell, J. Knowledge Gaps and Risks Associated with Premise Plumbing Drinking Water Quality. *AWWA Water Science* **2020**, *2* (3), No. e1177.
(143) Lee, Y. An Evaluation of Microbial and Chemical Contamination Sources Related to the Deterioration of Tap Water Quality in the Household Water Supply System. *Int. J. Environ. Res. Public Health* **2013**, *10* (9), 4143−4160.
(144) Bartrand, T. A.; Causey, J. J.; Clancy, J. L. Naegleria Fowleri: An Emerging Drinking Water Pathogen. *Journal AWWA* **2014**, *106* (10), E418−E432.

https://doi.org/10.1021/acs.est.2c04277
Environ. Sci. Technol. 2023, 57, 6360−6372