Building water quality deterioration during water supply restoration after interruption
Influences of premise plumbing configuration

Yao, Mingchen; Zhang, Yue; Dai, Zihan; Ren, Anran; Fang, Jiaxing; Li, Xiaoming; van der Meer, Walter; Medema, Gertjan; Rose, Joan B.; Liu, Gang

DOI
10.1016/j.watres.2023.120149

Publication date
2023

Document Version
Final published version

Published in
Water Research

Water Research 241 (2023) 120149

Contents lists available at ScienceDirect

Water Research

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

Building water quality deterioration during water supply restoration after interruption: Influences of premise plumbing configuration

Mingchen Yao [a,b,c], Yue Zhang [a,b], Zihan Dai [a,b], Anran Ren [a,b], Jiaxing Fang [a,d], Xiaoming Li [a,b], Walter van der Meer [d,e], Gertjan Medema [c,f,g], Joan B. Rose [g], Gang Liu [a,b,*]

[a] Key Laboratory of Drinking Water Science and Technology, Research Centre for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] University of Chinese Academy of Sciences, Beijing, China
[c] Sanitary engineering, Department of Water management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, Delft, GA 2600, the Netherlands
[d] Membrane Science and Technology, Faculty of Science and Technology, University of Twente, P.O. Box 217, Enschede 7500AE, the Netherlands
[e] Oasen Drinkwater, PO BOX 122, Gouda, AC 2800, the Netherlands
[f] KWR Watercycle Research Institute, P.O. Box 1072, Nieuwegein 3430 BB, the Netherlands
[g] Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI 48823, United States of America

ARTICLE INFO

Keywords:
Premise plumbing
Water supply restoration
Water quality deterioration
Discoloration
System configuration

ABSTRACT

Premise plumbing plays an essential role in determining the final quality of drinking water consumed by customers. However, little is known about the influences of plumbing configuration on water quality changes. This study selected parallel premise plumbing in the same building with different configurations, i.e., laboratory and toilet plumbing. Water quality deteriorations induced by premise plumbing under regular and interrupted water supply were investigated. The results showed that most of the water quality parameters did not vary under regular supply, except Zn, which was significantly increased by laboratory plumbing (78.2 to 260.7 μg/l). For the bacterial community, the Chao1 index was significantly increased by both plumbing types to a similar level (52 to 104). Laboratory plumbing significantly changed the bacterial community, but toilet plumbing did not. Remarkably, water supply interruption/restoration led to serious water quality deterioration in both plumbing types but resulted in different changes. Physiochemically, discoloration was observed only in laboratory plumbing, along with sharp increases in Mn and Zn. Microbiologically, the increase in ATP was sharper in toilet plumbing than in laboratory plumbing. Some opportunistic pathogen-containing genera, e.g., *Legionella* spp. and *Pseudomonas* spp., were present in both plumbing types but only in disturbed samples. This study highlighted the esthetic, chemical, and microbiological risks associated with premise plumbing, for which system configuration plays an important role. Attention should be given to optimizing premise plumbing design for managing building water quality.

1. Introduction

Premise plumbing is the portion of the drinking water distribution system beyond household connections (pipes connecting building to water main) and inside buildings (e.g., schools, hospitals, public and private housing), the key characteristics of which include low disinfectant residual (if applied), small pipe diameter, high surface/volume ratio, long stagnation/retention time, and warm temperature (National Research Council, 2007; Wang et al., 2013). Depending on the building type, premise plumbing ranges in length from tens to several thousand meters, e.g., a German hospital has 2 km of warm water plumbing and 1 km of cold water plumbing (Schmidt et al., 2019). In total, there are over 9.7 million kilometers of premise plumbing in the U.S. connected to 1.6 million kilometers of distribution mains (Collier et al., 2021; National Academies of Sciences and Medicine, 2020; National Research Council, 2007). In many countries, management actions for premise plumbing may fall outside the responsibility of the drinking-water supplier. Property owners, managers or maintenance personnel are responsible for managing building water supplies, but awareness and application of drinking-water guidelines is often limited and water safety in buildings is often overlooked (World Health Organization, 2011). However, as the front line directly facing customers, premise plumbing plays an essential

* Corresponding author.
E-mail addresses: gliu@rcees.ac.cn, g.liu-1@tudelft.nl (G. Liu).

https://doi.org/10.1016/j.watres.2023.120149
Received 26 January 2023; Received in revised form 26 May 2023; Accepted 28 May 2023
Available online 30 May 2023

role in determining the final quality of water consumed by end users.

The unique characteristics of premise plumbing make it an ideal niche for the proliferation of opportunistic pathogens and other microbes (Feazel et al., 2009). Improper design and management of building water systems may cause outbreaks of disease (World Health Organization, 2011). The occurrence of opportunistic pathogens in premise plumbing has been well documented, especially *Legionella* and *Mycobacterium* (Dowdell et al., 2019; Falkinham et al., 2015; Shen et al., 2022). Studies have been conducted on the influences of pipe material, disinfectants, water age, and temperature on plumbing microbes (Buse et al., 2014; Neu and Hammes, 2020; Proctor et al., 2017, 2016; Wang et al., 2012). In addition, previous studies have found that stagnation in premise plumbing significantly decreased residual disinfectant, increased cell number, promoted opportunistic pathogen growth, and changed the bacterial community (Lautenschlager et al., 2010; Ling et al., 2018; Montagnino et al., 2022). This is especially true during the lock down period of pandemic. The U.S. Centers for Disease Control and Prevention recommended checking for microbial risks and heavy metal contamination before reopening after a prolonged period of building inactivity (US Centers for Disease Control and Prevention, 2021). However, the influences of premise plumbing configurations on water microbiology and its deterioration in buildings are still unknown.

Another point of concern is discoloration at customer taps, which is the main reason for customer complaints worldwide (Vreeburg and Boxall, 2007). The problems associated with discoloration are mostly attributed to the local distribution main. It has been proposed that the discoloration risks can be managed by further removing particles to avoid material accumulation and local cleaning activity targeting problematic distribution mains (Boxall et al., 2003; Vreeburg et al., 2008). Through spatial and temporal clustering, it was found that 50% of the discoloration events originated upstream, e.g., from trunk mains (Husband et al., 2010; Sunny et al., 2020). Surprisingly, no studies have linked discoloration events to premise plumbing, despite its special proximity to customer taps. Whether and to what extent premise plumbing may contribute to discoloration remain unclear.

Moreover, the premise plumbing is characterized by start-stop flow patterns with highly variable velocities, which may be subjected to additional/extended periods of stagnation during technical maintenance, long vacations, and pandemic lockdown (National Research Council, 2007; Viglione, 2020). This makes premise plumbing more susceptible to biofilm detachment, loose deposit resuspension and the associated negative effects on water quality and human health than other parts of drinking water distribution systems, especially during water supply restoration after interruptions. However, to the best of our knowledge, there is no available knowledge regarding the contribution of premise plumbing to water quality changes during water supply restoration. Therefore, the objective of this study is to investigate water quality deterioration caused by premise plumbing during the restoration of the water supply, with a special focus on the influences of system configuration on the esthetic (discoloration), chemical (heavy metal),

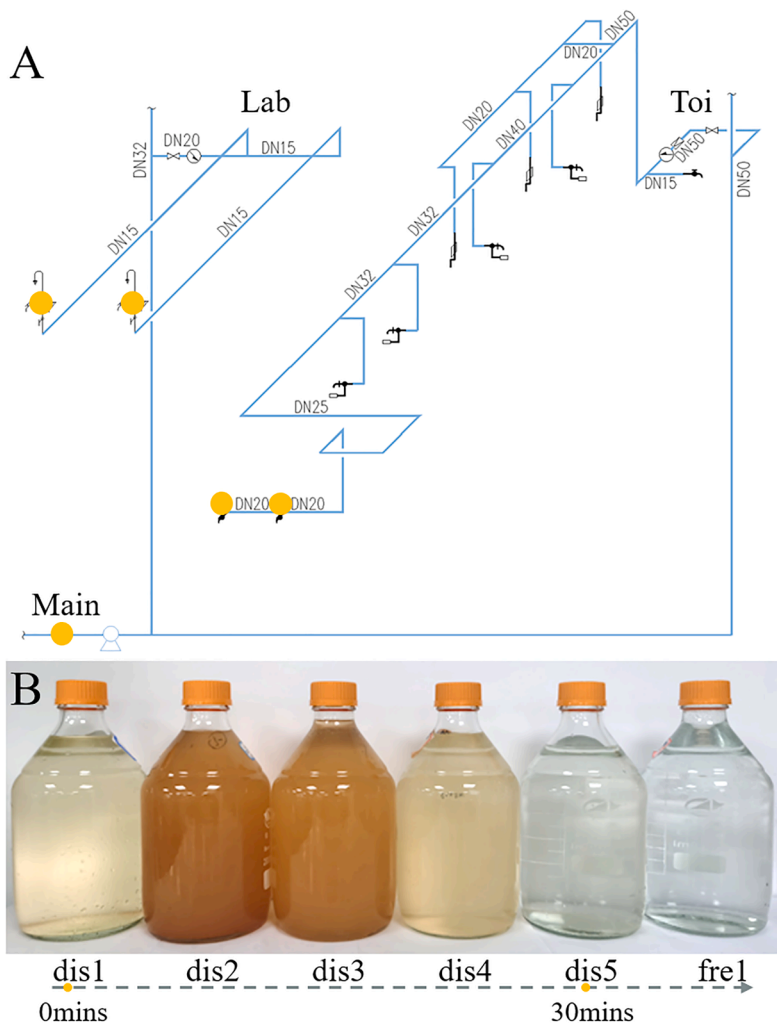

Fig. 1. A) Detailed configuration of the laboratory and toilet plumbing. Sampling points marked in Yellow. The pipe length, velocity, Reynolds number, and shear stress are given in Table 1; B) picture of disturbed samples from laboratory plumbing during restoration of the water supply condition (Lab-dis, heavy discoloration).

and microbiological (quantity, community, and potential pathogens) risks. The obtained results are valuable for plumbing engineers, water utilities, building owners and health authorities to optimize premise plumbing design and develop proper guidance and regulation on monitoring and managing water quality in buildings.

2. Materials and methods

2.1. Studied premise plumbing and detail configurations

The study was conducted in an office building on the campus of the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. It is an 8-floor building of 10,000 m^2 with office and laboratory rooms. The premise plumbing components that distribute water to laboratories and toilets are connected to the water main separately with parallel vertical pipes (Fig. 1A). The configurations of laboratory and toilet plumbing are different, both of which have a vertical plastic-lined galvanized steel pipe and horizontal branch polypropylene-random (PPR) pipes. There are two regular taps for the laboratory plumbing and seven flushing toilets and two taps for the toilet plumbing. The water usage in the laboratory and toilets are also different, which leads to significant differences in hydraulic conditions in the two piping systems (e.g., velocity, Reynolds number, and shear stress, Table 1).

2.2. Sampling during regular and disturbed water supply

The laboratory and toilet of the middle floor (5/8) were selected for sampling during regular water supply and the restoration of water supply after interruption (technical pump maintenance, 2 days). The two taps in the laboratory and toilet were used to take duplicate samples from each premise plumbing type. During the restoration of the water supply after 2 days of interruption, 5 bottles of water were taken from each tap within the first 30 min, referred to as Lab-dis ($n = 5 \times 2$) and Toi-dis ($n = 5 \times 2$) for laboratory and toilet plumbing, respectively. Forty-eight hours after restoring the water supply, fresh samples were collected in duplicate, representing regular water supply conditions, referred to as Lab-fre ($n = 2$) and Toi-fre ($n = 2$). A picture of discolored samples from the laboratory (Lab-dis, Tap 1, $n = 5$) is shown in Fig. 1B. As controls, three fresh samples were taken from the main pipe before, during and 48 h after the water supply interruption and restoration (referred to as Main-fre, $n = 3$). In total, 27 samples were taken, including 12 samples taken from the laboratory, 12 samples taken from the toilet, and 3 samples taken from the main pipe. During the sampling, heavy discoloration was continuously observed at the taps in the laboratory (~ 30 mins) during the restoration of the water supply but did not occur in the toilet at all. The containers and tools used in the study were sterile and carbon-free. All samples were immediately stored at 4 °C and processed within 24 h.

2.3. Water quality analysis

Turbidity was measured in situ using a turbidity meter (HACH, USA). The total organic carbon (TOC) concentration was analyzed by a TOC analyzer (Shimadzu, Japan). The concentrations of iron (Fe), manganese (Mn), and zinc (Zn) were detected by inductively coupled plasma–mass spectrometry (ICP–MS, Thermo Fisher Scientific, America), while the concentrations of calcium (Ca) and magnesium (Mg) were analyzed with inductively coupled plasma optical emission spectroscopy (ICP–OES, Shimadzu, Japan). All measurements were carried out in triplicate ($n = 3$).

2.4. ATP analysis

Total ATP contents were measured to examine the active biomass. GloMax® Navigator Microplate Luminometer (Promega, USA) was used in conjunction with Water-Glo™ reagent (Promega, USA) for ATP measurements as described previously (Abushaban et al., 2017; Javed et al., 2022). In short, 800 μL of sample was mixed with 200 μL of Water-Glo lysis reagent in a sterile Eppendorf tube and incubated for two hours at room temperature. 125 μL of each sample was added to a 96-well plate, 125 μL of Water-Glo detection reagent was automatically added to each well by the luminometer injector. Afterward, the luminescence was measured according to the manufacturer's instructions. The results in relative light units (RLU) were transformed into the ATP contents using the obtained calibration curve. Each sample was measured in triplicate ($n = 3$), and the standard deviation was always below 4%.

2.5. DNA extraction, sequencing and bioinformatic analysis

The collected water samples were filtered through 0.2 μm polycarbonate membrane filters (Whatman, UK) and stored at −20 °C before DNA extraction. DNA was extracted using the FastDNA SPIN Kit for Soil (MP Biomedicals, Santa Ana, California, USA) following the manufacturer's protocol. Then, the V3-V4 regions of bacterial 16S rRNA genes were amplified with a primer set (341F: 5′-CCTACGGGNGGCWGCAG-3′ and 785R: 5′-GACTACHVGGGTATCTAATCC-3′). PCR products were purified and prepared for paired-end sequencing (2 × 300 bp) on the Illumina MiSeq platform at Majorbio (Shanghai, China). The generated raw sequences were removed with primers and trimmed to 272 bp using cutadapt 3.1 (Martin, 2011). The trimming parameters of reads were determined by figaro v1.1.2 (Sasada et al., 2020). DADA2 v1.21.0 was used for quality filtering, error rate learning, sample inference, redundancy removal (duplicate sequences), paired read merging, amplicon sequence variant (ASV) table construction, and chimera removal, and finally, an ASV table was obtained (Callahan et al., 2016). Taxonomic classification based on SILVA138.1 and phylogenetic reconstruction were conducted using QIIME2 2020.11 (Bolyen et al., 2019). The sequencing data have been deposited in the NCBI database, with reference code PRJNA922072.

Table 1
Detailed configurations of the premise plumbing of the laboratory and toilet.

Premise plumbing		Diameter (mm)	Length (m)	Velocity (m/s)	Reynolds number	Shear stress (Pa)	Water consumption (m^3/d)
Laboratory (two taps)	Vertical	32	3.60	0.24	7546	0.09	0.25
	Horizontal	20	2.60	0.53	10,522	0.48	
		15	10.40	0.99	14,921	1.84	
Toilet (two taps)	Vertical	50	3.60	0.84	42,010	0.97	2.5
	Horizontal	50	2.20	0.72	35,955	0.71	
		50	2.70	0.70	34,820	0.67	
		40	0.75	1.04	41,400	1.56	
		40	1.45	1.00	40,196	1.47	
		32	1.80	1.59	50,931	3.89	
		32	1.00	1.54	49,357	3.66	
		25	5.60	0.30	7570	0.15	
		20	3.00	0.53	10,522	0.48	

2.6. Statistical analyses

The Mantel test was used to link turbidity with other environmental parameters. Relationships between environmental variables were tested based on Person's correlation. The alpha diversity was calculated using the Chao1 and Simpson diversity indices. Principal coordinates analysis (PCoA) was performed based on the Bray–Curtis dissimilarity metric via the vegan package (Dixon, 2003). The significance ($p < 0.05$) was determined by permutational multivariate analysis of variance (PERMANOVA). Adonis analysis was performed to partition the total variance and analyze the explanatory degree of different grouping factors to sample differences. Compositional dissimilarities among samples (beta-diversity) were partitioned into turnover and nestedness-resultant components (Baselga family, Jaccard-based indices) using the adespatial R package (Baselga, 2012). Microbial community composition was linked to water chemistry parameters by constructing a distance-based redundancy model (db-RDA). Variation partitioning analyses (VPA) were performed to evaluate the relative contribution of significant factors ($p < 0.05$) to the bacterial community by the vegan package. The linear discriminant analysis effect size (LEfSe) was applied to determine the key sensitive ASVs that were significantly influenced by selected factors (significance threshold > 3) (Segata et al., 2011).

3. Results

3.1. Physicochemical and microbiological water quality parameters

Generally, the esthetic, chemical and microbiological water qualities were negatively affected during the restoration of the water supply after the technical interruption, and the different plumbing system configurations in the laboratory and toilet showed clearly different impacts. Based on visual inspection, discoloration was observed in laboratory samples collected during the restoration of the water supply (Lab-dis, 53.2 NTU on average), which quickly disappeared within 30 mins (Fig. 1B). In contrast, there was no esthetic issue associated with water samples collected from the toilet during the same period (Toi-dis, ≤7.6 NTU). Within 48 h, there were no observed differences regarding turbidity among the water samples collected from the laboratory (Lab-fre), toilet (Toi-fre), and water main (Main-fre).

According to the chemical analysis, the contents of Zn and Mn were much higher in the samples collected during the restoration of the water supply (Fig. 2A). The concentrations of both Zn and Mn were significantly higher in the water samples from the laboratory than in those from the toilet. This may be due to the smaller diameter and flow in the laboratory, which offered a higher surface-to-volume ratio and longer retention time. Zn might have been released from vertical galvanized pipes, while Mn would have accumulated in the pipes during regular water supply and been released during restoration of the water supply. Interestingly, it was observed that the Zn in the fresh samples from the laboratory was clearly higher than that from the toilet and main, indicating the considerable contributions from laboratory plumbing but not toilet plumbing to the sharp increase in Zn (78.2 to 260.7 μg/l) during regular water supply.

The peak ATP concentrations were approximately 43 (Toi-dis) and 34 (Lab-dis) times higher in the water samples during the restoration of water supply than in fresh sample groups (Main-fre, Toi-fre and Lab-fre), indicating considerable release of active biomass during the restoration of water supply, especially in toilet plumbing (Fig. S1). However, regardless of sampling groups and periods, no clear differences were observed for the contents of Ca (33.7–40.5 mg/l), Mg (7.2–13.8 mg/l), and TOC (1.4–1.7 mg/l).

The correlation analysis revealed that turbidity is strongly correlated with Zn and Mn but not with TOC, ATP, and other elements, suggesting that the discoloration may be caused by the release of Zn- and Mn-containing material during the restoration of the water supply (Fig. 2B). The pairwise comparison showed that all metal elements had significant correlations ($p \leq 0.05$, $0.43 \leq r \leq 0.78$), except Mn and Mg ($p > 0.05$, $r = 0.33$). In addition, ATP and TOC were significantly correlated with each other but not with other metals.

3.2. Bacterial community diversity and composition

3.2.1. Bacterial community diversity

In total, 829,766 sequences with an average length of 402 bp were obtained from 27 samples, which were assigned to 950 ASVs. The rarefaction curves plateaued after 10,000 reads, signifying that sufficient sample coverage was obtained in this study (Fig. S2). As shown by Chao1, the species richness obviously increased after flowing through premise plumbing in both the laboratory and toilet under regular water supply (Main-fre vs. Lab/Toi-fre: 52 vs. 104; Fig. 3A). During the restoration of the water supply, the average Chao1 slightly increased in both the laboratory and toilet samples, while the laboratory samples

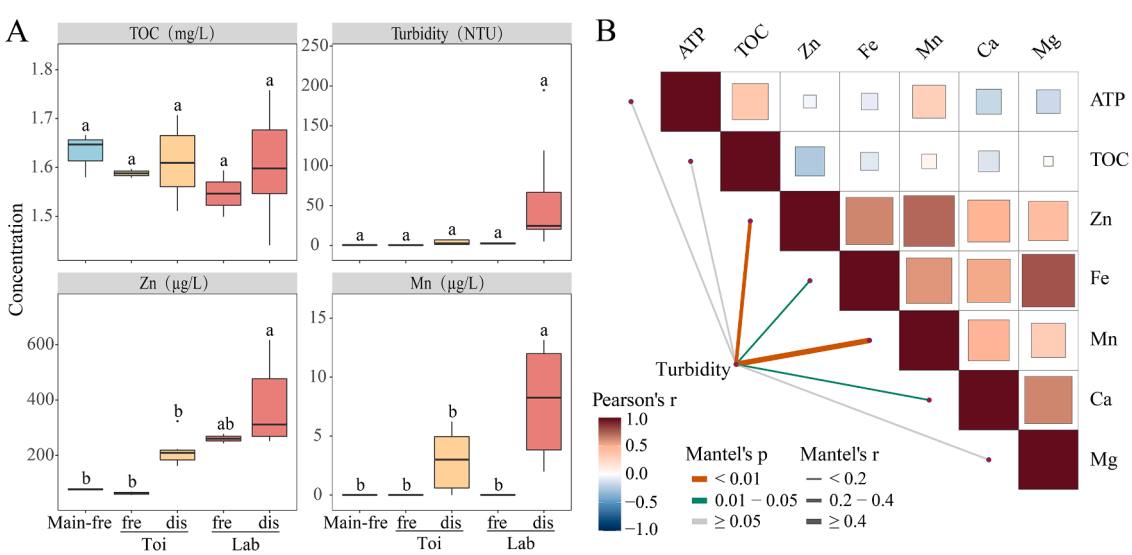

Fig. 2. Comparison and correlation analysis of water quality parameters: A) Boxplots showing the results of total organic carbon (TOC), turbidity, Zn and Mn in different sampling groups. Different lowercase letters on the boxes represent significant differences assessed using ANOVA; B) pairwise comparison among water quality parameters, the color gradient denotes Pearson's correlation coefficients. The correlations of turbidity with other parameters were assessed by Mantel tests. Edge color represents the statistical significance, and edge width corresponds to Mantel's r statistic.

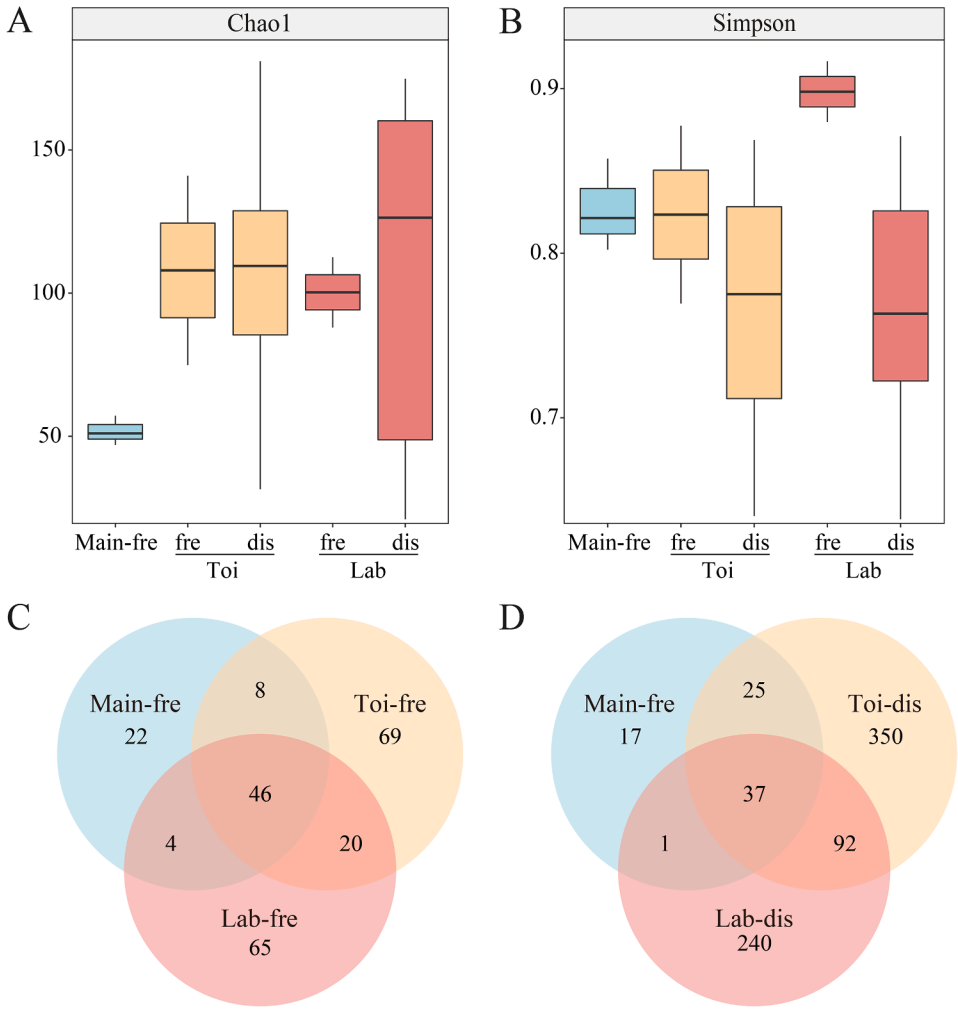

Fig. 3. A) Chao 1 indices of different sampling groups; B) Simpson diversity of different sampling groups; C) Venn diagram among fresh samples; D) Venn diagram among disturbed samples.

showed higher values and larger variations than the toilet samples. The higher species richness in disturbed samples during water supply restoration was better revealed by the Venn diagram in Fig. 3C and 3D. The number of ASVs sharply increased from 135 to 370 ASVs in the laboratory samples and from 143 to 504 ASVs in the toilet samples, most of which were unique in each group and were not present in fresh

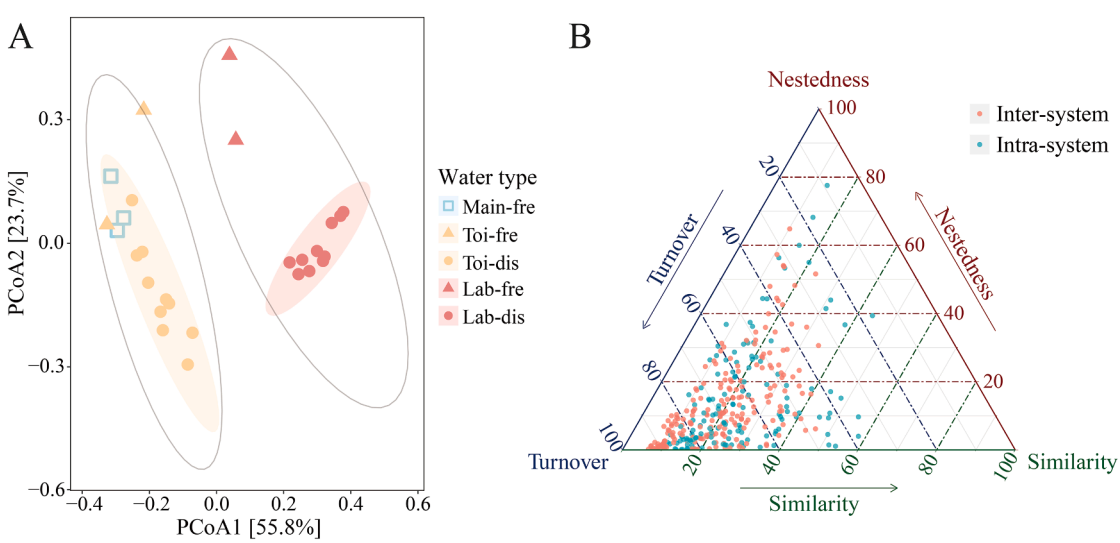

Fig. 4. A) PCoA plot based on Bray–Curtis dissimilarity; B) triangular plots of beta-diversity partitioning (using Jaccard dissimilarity index) comparisons for bacterial communities. Each point represents a pair of samples.

samples. Therefore, it is reasonable to hypothesize that the emerging ASVs were microbes released from biofilm and loose deposits accumulated in the premise plumbing, while the observed differences between laboratory and toilet systems were because of their different configurations, such as diameters, shear stress, and retention times.

Interestingly, although the species richness was higher in Lab-dis and Toi-dis, their Simpson diversities were much lower than those in Lab-fre and Toi-fre (Fig. 3B), indicating that the relative abundances of community members in fresh samples were more evenly distributed, while the community of planktonic bacteria during water supply restoration was possibly predominated by a few species. This is directly confirmed by the bacterial community composition results in the following section. Moreover, during regular water supply, toilet plumbing did not influence Simpson diversity, whereas laboratory plumbing clearly increased the Simpson diversity of the bacterial community (Fig. 3B).

The PCoA plot showed clear clusters of sample groups, indicating the dissimilarity among their bacterial communities (Fig. 4A). According to statistical tests, both plumbing configurations and water supply interruption/restoration significantly influenced the planktonic bacterial community (PERMANOVA, $P < 0.05$, Table S1), while the variances were mostly explained by the former ($R^2 = 0.537$, Table S1). Comparing the fresh samples, the bacterial community of Main-fre is similar to that of Toi-fre (overlapping) but different from that of Lab-fre (different clusters), confirming the significant influences of the plumbing configuration. During the restoration of the water supply, Lab-dis clustered closely together and completely separated from Lab-fre, while Toi-dis is more dispersed and separated from Toi-fre samples. The differences between Lab-dis and Lab-fre are sharper than that of Toi system. This means sharper changes may occur in laboratory plumbing during water supply restoration, which complied with the visually observed discoloration in Lab-dis samples, as mentioned above.

To reveal the underlying mechanisms of variation in microbial assembly, the beta diversity was further partitioned into species turnover and nestedness (Fig. 4B). The average Jaccard pairwise dissimilarity index was 0.794, which was predominantly governed by strong species turnover processes (82.5%) rather than nestedness-resultant dissimilarity (17.5%). Intersystem sample pairs (Lab vs. Toi) were less similar, and species turnover contributed more to their community dissimilarity than intrasystem (Lab vs. Lab; Toi vs. Toi) sample pairs, which confirmed that, as mentioned above, system configuration contributed more to the variations. Moreover, for intrasystem comparison, species turnover had a greater impact on the bacterial community in toilet plumbing than in laboratory plumbing (Fig. S3).

3.2.2. Bacterial community composition

At the phylum level, the bacterial community of all water samples was dominated by Proteobacteria (80.2–99.9%) and Cyanobacteria (0.1–15.3%) (Fig. S4). Under regular water supply, both laboratory and toilet plumbing decreased the relative abundances of Proteobacteria (93.3% to 84.3%) while increasing the relative abundances of Cyanobacteria (5.2% to 11.9%), Planctomycetota (1.1% to 2.2%), and Actinobacteriota (0.1% to 1.0%), suggesting a significant influence of plumbing on the bacterial community. Interestingly, during the restoration of the water supply, the relative abundance of Proteobacteria increased to 96.1%, while that of Cyanobacteria decreased to 1.6%, for which the observed changes were sharper in the laboratory than in the toilet system.

At the genus level, the top 30 abundant bacterial genera across all samples are shown as a heatmap in Fig. 5A (normalized relative abundance) and a bubble plot in Fig. 5B (relative abundance). During regular water supply, both laboratory and toilet plumbing promoted community members, such as *Mycobacterium* spp. (0.1% to 1.0%) and *Gemmata* spp. (0.9% to 1.3%), and prohibited community members, such as *DSSF69* spp. (16.7% to 9.9%) and *Hyphomicrobium* spp. (0.4% to 0.1%). In contrast, laboratory plumbing promoted *Sphingomonas* spp. (0.1% to 6.8%), while prohibited *Phreatobacter* spp. (28.1% to 21.9%), but toilet plumbing did not. During the restoration of the water supply, it is remarkable to observe that a few genera were not present in fresh

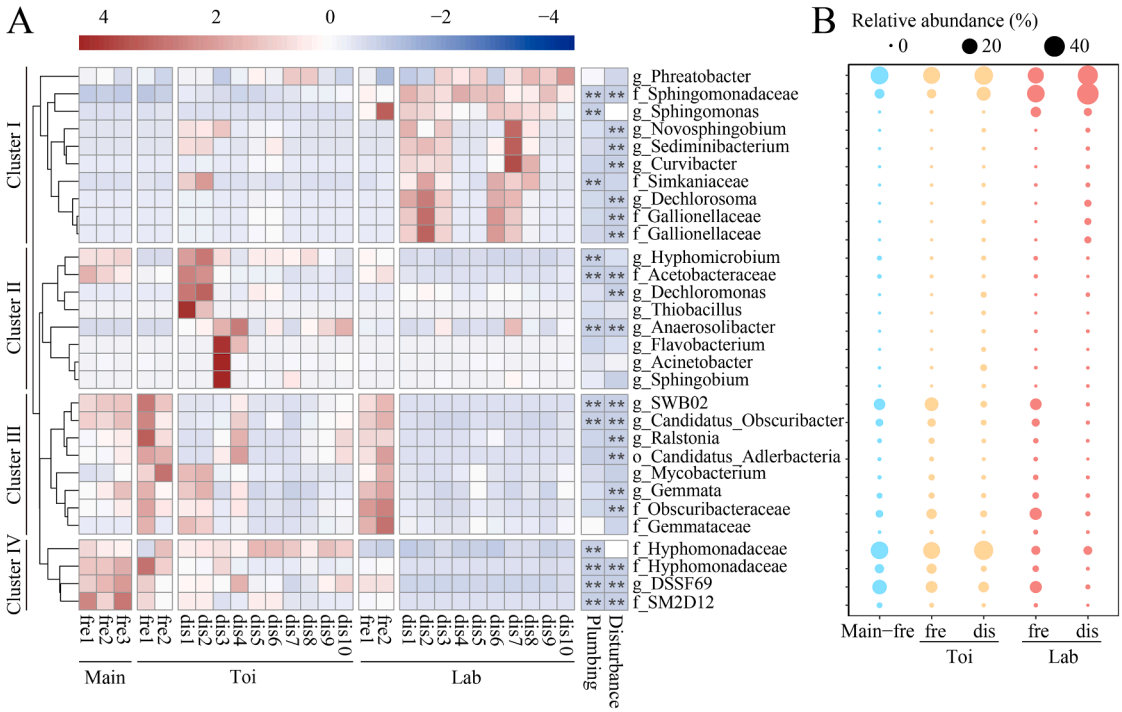

Fig. 5. Relative abundances of the top 30 genera: A) Distribution of the normalized relative abundance of the genera in different samples. Colors from blue to red denote an increase in normalized relative abundance. The significant difference between groups was calculated by Kruskal−Wallis tests (P values: ** < 0.05); B) Relative abundances of the genera in different sampling groups. The genera were classified into two types and four clusters: affected by disturbance (Clusters I and III) or by both disturbance and plumbing system configuration (Clusters II and IV). The genera of Cluster IV were only less abundant in the Lab-dis group. The genera of Cluster II were mainly found in the Toi-dis group.

samples but were detected in Lab-dis, such as *Dechlorosoma* spp. (2.0%), *Novosphingobium* spp. (0.4%), *Sediminibacterium* spp. (0.2%), and *Curivbacter* spp. (0.2%), while other genera in Toi-dis, such as *Acinetobacter* spp. (1.6%), *Dechloromonas* spp. (1.0%), *Hyphomicrobium* spp. (0.4%), *Thiobacillus* spp. (0.3%), *Anaerosolibacter* spp. (0.2%), and *Sphingobium* spp. (0.2%). There were genera that decreased sharply during water supply restoration, such as *SWB02* spp. (11.8% to 0.8%), *DSSF69* spp. (9.9% to 3.8%), *Gemmata* spp. (1.3% to 0.4%), and *Ralstonia* spp. (0.9% to 0.1%). Interestingly, the significantly increased members in Lab-dis corresponded well to the samples with high turbidity, indicating that those components were possibly associated with released particulate matter during water supply restoration. Moreover, it is also important to note that there were genera containing (opportunistic) pathogens, such as *Legionella* spp., *Pseudomonas* spp., and *Aeromonas* spp., that were detected only in samples collected during water supply restoration, indicating that water supply interruption and restoration might be associated with microbial risks (Fig. S5). Differently, the *Mycobacterium* spp. were less frequently and less abundantly detected in disturbed samples than in the fresh samples, indicating *Mycobacterium* spp. prefers bulk water but does not proliferate in biofilm or loose deposits within the studied system.

3.3. Influences of water quality parameters on the bacterial community

The LEfSe analysis identified ASVs significantly enriched by regular and interrupted water supply (Fig. 6A) and by premise plumbing with different configurations (Fig. 6B). The taxonomy information of these ASVs is given in Table S3. Remarkably, 3/5 of the ASVs enriched during water supply restoration were assigned as f_Gallionellaceae, the group of which is commonly called iron bacteria. This complies with, presented below, that iron drove bacterial community changes during the restoration of water supply (Fig. 6C, 6D). In addition, all ASVs enriched in laboratory plumbing belonged to f_Sphingomonadaceae, and the key sensitive ASVs in toilet and laboratory plumbing were strongly correlated with Ca and Mg.

The db-RDA plot showed that the first two axes cumulatively explained 84.6% of the total variance (Fig. 6C, 6D). The bacterial community of Lab-dis was mainly driven by metal elements (e.g., Mn), while the bacterial community of Toi-dis was mostly driven by TOC. This was directly confirmed by Mantel tests (Table S4). More specifically, the variations in species between the laboratory and toilet were more related to Ca, Mg, Fe and Zn, whereas the bacterial community changes induced by the disturbance during water supply restoration

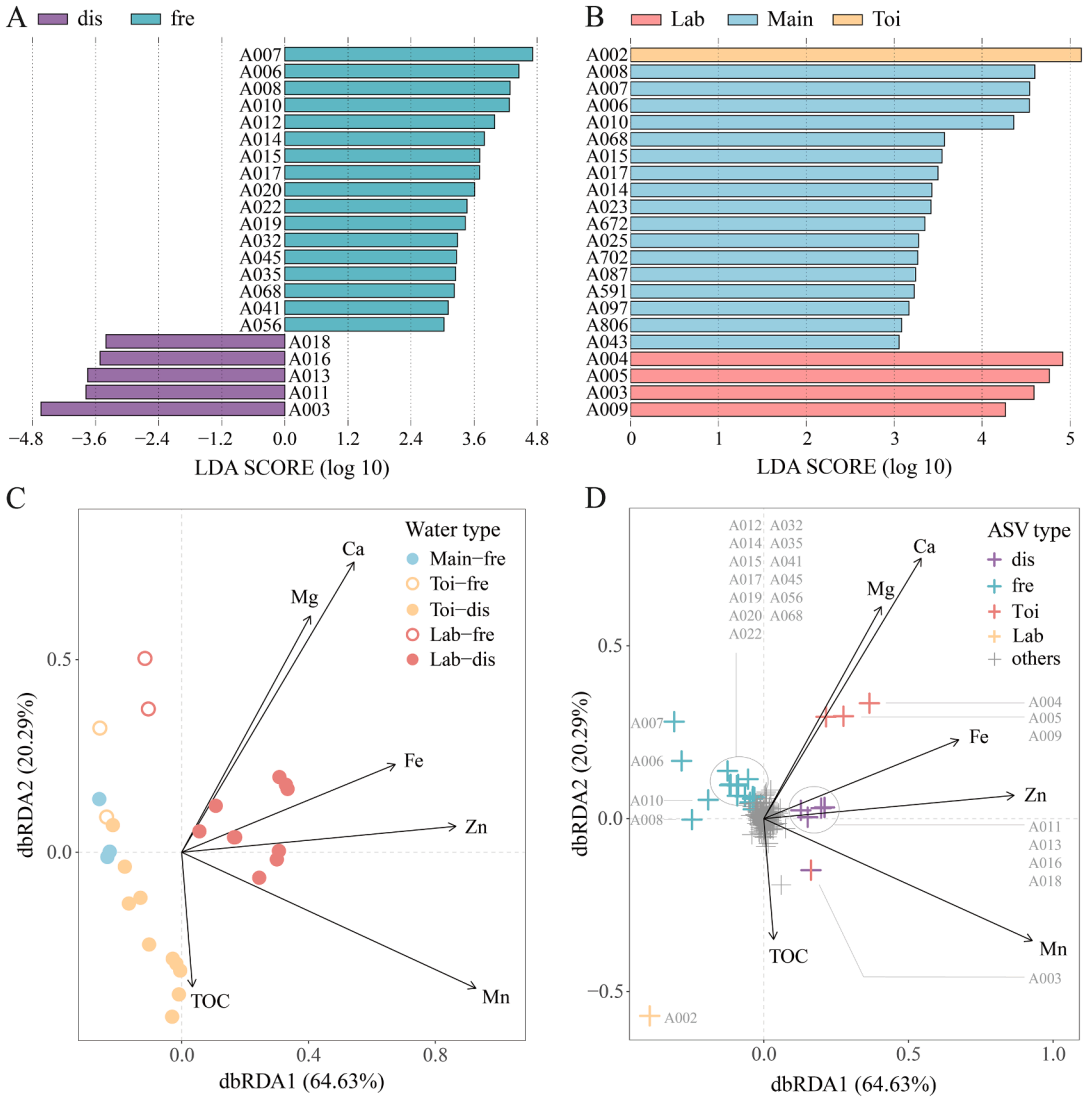

Fig. 6. A) LEfSe analysis selected significantly enriched ASVs during regular water supply (fre) and restoration of water supply (dis); B) LEfSe analysis selected significantly enriched ASVs in water main (Main), toilet (Toi) and laboratory plumbing (Lab); C) distance-based redundancy analysis (db-RDA) of the relationship between the bacterial community and environmental variables; D) db-RDA of the relationship between ASVs and environmental variables.

were positively correlated with Fe, Mn (Lab-dis), and TOC (Toi-dis). The variance partitioning analysis showed that the combination of water quality parameters explained 45.5% of the bacterial community changes. The specific contributions in descending order were Zn (31.8%), Mn (26.3%), Ca (20.2%), Fe (14.7%) and Mg (9.8%) (Table S4).

4. Discussion

In this study, water quality deterioration during restoration of the water supply was studied in premise plumbing with different configurations in an office building. The influences of water service disturbances and system configurations on physiochemical and microbiological water quality parameters were assessed, with a special focus on variations in the bacterial community. The observed differences between laboratory and toilet plumbing during regular and restoration of water service offered novel insights into the design and operation of premise plumbing from the perspective of managing water quality.

4.1. Extreme water quality deterioration during water supply restoration

For both laboratory and toilet plumbing, clear water quality deterioration was observed during water supply restoration as a sharp increase in turbidity (e.g., discoloration in laboratory plumbing), metal elements (e.g., Mn, Zn), ATP, and number of ASVs, and clear shifts in dominant ASVs driven by inorganic elements and organic carbon (Figs. 5 and 6). This might be caused by either long stagnation during the water supply interruption or the sudden hydraulic disturbances induced by water supply interruption and restoration that destabilized biofilms, pipe scales and loose deposits formed in premise plumbing under regular water supply. Heavy metal leaching and microbe growth during stagnation in premise plumbing have been widely reported (Ling et al., 2018; Montagnino et al., 2022; Zlatanović et al., 2017). However, the latter is likely the case for the present study because weekend stagnation (the same period of 2 days) did not lead to the observed extreme water quality deterioration either before or after the technical interruption.

Hydraulic disturbance-induced particle load variations were observed in distribution systems by online sampling and monitoring devices (Chen et al., 2022; Prest et al., 2021), the extreme cases of which were observed as discoloration combined with bacterial and chemical contamination (Husband et al., 2008; Liu et al., 2017; Vreeburg and Boxall, 2007). Such water quality deterioration is often attributed to local distribution network effects or originates from upstream areas (e.g., trunk mains) (Husband et al., 2010). There has been hardly any concern for discoloration risks in premise plumbing. Instead, most of the premise plumbing studies focused on microbiological aspects under regular water supply, particularly the proliferation of opportunistic pathogens (Ji et al., 2015; Julien et al., 2020; Lautenschlager et al., 2010; Ling et al., 2018). This study highlighted the esthetic, chemical and microbiological risks of premise plumbing in buildings. For example, *Mycobacterium* spp. was promoted in both laboratory and toilet plumbing during regular water supply (Fig. 5). Remarkably, it should be noted that the restoration of water supply significantly changed physiochemical water quality parameters and the dominant ASVs (Fig. 6). Considering that some of the opportunistic pathogen-containing genera, such as *Pseudomonas* spp., *Legionella* spp., and *Aeromonas* spp., were only present during the disturbances, special attention should be given to the influence of premise plumbing after water service interruptions.

4.2. Influence of premise plumbing configurations

Although water quality deteriorations were observed in both the laboratory and toilet plumbing after the water supply interruption (Lab-dis, Toi-dis), the system configurations showed significant influences. Interestingly, discoloration was observed only in laboratory plumbing but not in toilet plumbing. In line with the observation of turbidity, the concentrations of Zn, Mn and Fe were much higher in the Lab-dis samples than in the Toi-dis samples. These differences between laboratory and toilet plumbing might be because toilet plumbing has a larger diameter, higher flow, and larger water demand than laboratory plumbing, which favors flow conditioning, reduces chronic material load and therefore avoids discoloration during water supply restoration (Sunny et al., 2020). This also agrees with the velocity-based self-cleaning principle and technique (Jenks et al., 2023; Vreeburg et al., 2009).

In contrast, the peak and average ATP concentrations in the Lab-dis samples (16.4 ng/l; 6.0 ± 6.0 ng/l) were lower than those in the Toi-dis samples (23.6 ng/l; 7.7 ± 9.0 ng/l), both of which were higher than those in undisturbed fresh water samples from the laboratory, toilet and main (0.2 ± 0.1 ng/l). The greatly increased ATP concentrations in disturbed samples can be attributed to the detachment/release of biofilm from premise plumbing induced by the disturbances during water supply interruption and restoration (Choi and Morgenroth, 2003; Lehtola et al., 2006; Liu et al., 2017). Remarkably, the ATP was obviously higher in Toi-dis than in Lab-dis, indicating that the higher flow and larger water demand in toilet plumbing did not limit but promoted the active biomass loads. This can be explained by the growth of biofilm being mass-transfer limited, and the higher turbulence in toilet plumbing may increase nutrient consumption and biofilm growth during regular water supply (Fish et al., 2017; Lehtola et al., 2006; Paris et al., 2007; Percival et al., 1999; Rochex et al., 2008; Torvinen et al., 2007). Moreover, previous studies found that hydraulic regimes influenced the species richness, diversity, and composition of the bacterial community in biofilms, which could explain the observed significant differences in the bacterial community between Lab-dis and Toi-dis in the present study (Cowle et al., 2020; Douterelo et al., 2013; Rochex et al., 2008).

It is important to note that laboratory plumbing significantly increased the Zn concentration and Simpson diversity of the planktonic bacterial community during regular water supply (Lab-fre vs. Main-fre, Figs. 2A and 3B), while toilet plumbing did not. Although the number of observed ASVs increased in both Lab-fre and Main-fre to a similar level (Fig. 3C), the bacterial communities of Lab-fre were significantly different from those of Main-fre, but the bacterial communities of Toi-fre were clustered closely together with those of Main-fre (Fig. 4A). In other words, significant changes were observed in laboratory plumbing but not toilet plumbing during regular water supply, which may be because the small water demand and flow velocity in laboratory plumbing resulted in a longer stagnation time than that in toilet plumbing (Montagnino et al., 2022; Proctor et al., 2020; Zlatanović et al., 2017). During the restoration of water supply, the laboratory plumbing lead to significant changes in elemental composition, while the toilet plumbing lead to significant changes in ATP and clearly differences in dominant ASVs (Figs. 5 and 6). This highlights the importance of premise plumbing configurations. It poses significant influences during both regular and interruption of the water supply.

4.3. Practical implications

This study clearly illustrated that premise plumbing poses potential esthetic, chemical and microbiological risks to drinking water from taps, especially when the system is subjected to water supply interruption and restoration. The plumbing configuration plays an important role; for example, laboratory plumbing showed higher discoloration potential and heavy metals concentrations, while toilet plumbing showed higher amount of active biomass. In other words, the small pipe and low velocity accelerate the accumulation of particles and metals. Larger pipes and higher velocity limit the chronic accumulation of particles and metals but promote biofilm growth. The conflicts between physiochemical and microbiological risk management could possibly be solved by optimizing the premise plumbing configuration. For example, by proactively increasing flow velocity on a managed and regular base (e.g., once per week) to achieve hydraulic conditioning or so-called self-

cleaning effects (Jenks et al., 2023; Sunny et al., 2020; Vreeburg et al., 2009). Another possible solution would be further increasing the flow velocity for biofilm reduction, as intermediate velocity (0.5–1.0 m/s) promotes biofilm growth, but excessive shear forces (1.5–2.0 m/s) retard bacterial activity and favor biofilm detachment (Liu et al., 2020; Raya et al., 2010). The former would be a more sustainable option considering energy consumption.

Moreover, this study highlighted the importance of managing building water quality. Water utilities issue drinking water advisories when the water supply is interrupted or water quality is compromised, including informational, boil water, do not drink, and do not use advisories (Blake et al., 2016; Vedachalam et al., 2016). However, water utilities are only responsible for the water quality until the service line or meter, after which it is the property owner's responsibility (National Research Council, 2007; Ragain et al., 2019). For this reason, most water quality management strategies target either treatment plants or distribution systems but do not premise plumbing. Meanwhile, premise plumbing is frequently subjected to water supply/usage interruptions, such as holidays (lockdown), power failure, and technical maintenance (Viglione, 2020). Therefore, proper guidance and regulations are urgently needed for notifying and managing building water quality. For example, protocols for issuing official advisory and for properly flushing premise plumbing. Combined with the development of the internet of things (IoT), it may be possible to install wireless sensors and remote controllable devices with preprogramed flushing settings (Bouneb and Saidouni, 2022; Martinez Paz et al., 2022).

5. Conclusion

In summary, this study investigated the water quality changes caused by premise plumbing, with a special focus on the influences of the water supply interruption and plumbing configurations. It is found that premise plumbing played an important role in determining tap water quality in both regular and interrupted water supply conditions, while the interruption and restoration of water supply induced significant water quality deterioration in both laboratory and toilet plumbing.

- Under a regular water supply, most of the water quality parameters were not influenced by either laboratory or toilet plumbing, except Zn, which was significantly increased by laboratory plumbing (78.2 to 260.7 μg/l). Regarding the bacterial community, the Chao1 index significantly increased by both plumbing to a similar level (52 to 104). Toilet plumbing had a minor effect, but laboratory plumbing significantly changed the bacterial community.
- Water supply interruption and restoration lead to significant water quality deterioration in both laboratory and toilet plumbing but result in different changes. Physiochemically, heavy discoloration was observed only in the laboratory but not in the toilet, which was associated with sharper increases in Mn and Zn in the Lab-dis samples.
- Microbiologically, the increase in active biomass (ATP) during restoration of the water supply was sharper in toilet than in laboratory plumbing. Some opportunistic pathogen-containing genera, such as *Pseudomonas* spp. and *Legionella* spp., were present in both laboratory and toilet plumbing but only in disturbed samples.
- This study highlighted the esthetic, chemical, and microbiological risks associated with premise plumbing, for which system configuration plays an important role. Low turbulence and demand plumbing increased discoloration (heavy metal) risk, while high turbulence and demand plumbing promoted bacterial growth and microbiological risk. Attention should be given to optimizing the design of premise plumbing for managing building water quality, for example, incorporating hydraulic conditioning and/or velocity-based self-cleaning design.

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

The present work has been financially supported by the National Key R&D program (2018YFE0204100) and National Natural Science Foundation of China (52022103, 51820105011).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2023.120149.

References

Abushaban, A., Mangal, M.N., Salinas-Rodriguez, S.G., Nnebuo, C., Mondal, S., Goueli, S. A., Schippers, J.C., Kennedy, M.D., 2017. Direct measurement of ATP in seawater and application of ATP to monitor bacterial growth potential in SWRO pre-treatment systems. Desalination Water Treat. 99, 91–101.

Baselga, A., 2012. The relationship between species replacement, dissimilarity derived from nestedness, and nestedness. Global Ecol. Biogeogr. 21 (12), 1223–1232.

Blake, R.G.M.P.H.R., Yoder, J.M.P.H., Kou, J., 2016. Updated drinking water advisory communication toolkit. J. Environ. Health 79 (3), 40–41.

Bolyen, E., Rideout, J.R., Dillon, M.R., Bokulich, N.A., Abnet, C.C., Al-Ghalith, G.A., Alexander, H., Alm, E.J., Arumugam, M., Asnicar, F., Bai, Y., Bisanz, J.E., Bittinger, K., Brejnrod, A., Brislawn, C.J., Brown, C.T., Callahan, B.J., Caraballo-Rodríguez, A.M., Chase, J., Cope, E.K., Da Silva, R., Diener, C., Dorrestein, P.C., Douglas, G.M., Durall, D.M., Duvallet, C., Edwardson, C.F., Ernst, M., Estaki, M., Fouquier, J., Gauglitz, J.M., Gibbons, S.M., Gibson, D.L., Gonzalez, A., Gorlick, K., Guo, J., Hillmann, B., Holmes, S., Holste, H., Huttenhower, C., Huttley, G.A., Janssen, S., Jarmusch, A.K., Jiang, L., Kaehler, B.D., Kang, K.B., Keefe, C.R., Keim, P., Kelley, S.T., Knights, D., Koester, I., Kosciolek, T., Kreps, J., Langille, M.G.I., Lee, J., Ley, R., Liu, Y.-X., Loftfield, E., Lozupone, C., Maher, M., Marotz, C., Martin, B.D., McDonald, D., McIver, L.J., Melnik, A.V., Metcalf, J.L., Morgan, S.C., Morton, J.T., Naimey, A.T., Navas-Molina, J.A., Nothias, L.F., Orchanian, S.B., Pearson, T., Peoples, S.L., Petras, D., Preuss, M.L., Pruesse, E., Rasmussen, L.B., Rivers, A., Robeson, M.S., Rosenthal, P., Segata, N., Shaffer, M., Shiffer, A., Sinha, R., Song, S.J., Spear, J.R., Swafford, A.D., Thompson, L.R., Torres, P.J., Trinh, P., Tripathi, A., Turnbaugh, P.J., Ul-Hasan, S., van der Hooft, J.J.J., Vargas, F., Vázquez-Baeza, Y., Vogtmann, E., von Hippel, M., Walters, W., Wan, Y., Wang, M., Warren, J., Weber, K. C., Williamson, C.H.D., Willis, A.D., Xu, Z.Z., Zaneveld, J.R., Zhang, Y., Zhu, Q., Knight, R., Caporaso, J.G., 2019. Reproducible, interactive, scalable and extensible microbiome data science using QIIME 2. Nat. Biotechnol. 37 (8), 852–857.

Bouneb, Z.E.A., Saidouni, D.E., 2022. Toward an IoT-based software-defined plumbing network system with fault tolerance. IJHIoT 6 (1), 1–18.

Boxall, J.B., Skipworth, P.J., Saul, A.J., 2003. Aggressive flushing for discolouration event mitigation in water distribution networks. Water Supply 3 (1–2), 179–186.

Buse, H.Y., Lu, J., Lu, X., Mou, X., Ashbolt, N.J., 2014. 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. 88 (2), 280–295.

Callahan, B.J., McMurdie, P.J., Rosen, M.J., Han, A.W., Johnson, A.J.A., Holmes, S.P., 2016. DADA2: high-resolution sample inference from Illumina amplicon data. Nat. Methods 13 (7), 581.

Chen, L., Li, X., van der Meer, W., Medema, G., Liu, G., 2022. Capturing and tracing the spatiotemporal variations of planktonic and particle-associated bacteria in an unchlorinated drinking water distribution system. Water Res. 219, 118589.

Choi, Y.C., Morgenroth, E., 2003. Monitoring biofilm detachment under dynamic changes in shear stress using laser-based particle size analysis and mass fractionation. Water Sci. Technol. 47 (5), 69–76.

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., 2021. Estimate of burden and direct healthcare cost of infectious waterborne disease in the United States. Emerging Infect. Dis. 27 (1), 140.

Cowle, M.W., Webster, G., Babatunde, A.O., Bockelmann-Evans, B.N., Weightman, A.J., 2020. Impact of flow hydrodynamics and pipe material properties on biofilm development within drinking water systems. Environ. Technol. 41 (28), 3732–3744.

Dixon, P., 2003. VEGAN, a package of R functions for community ecology. J. Vegetation Sci. 14 (6), 927–930.

Douterelo, I., Sharpe, R., Boxall, J., 2013. Influence of hydraulic regimes on bacterial community structure and composition in an experimental drinking water distribution system. Water Res. 47 (2), 503–516.
Dowdell, K., Haig, S.-.J., Caverly, L.J., Shen, Y., LiPuma, J.J., Raskin, L., 2019. Nontuberculous mycobacteria in drinking water systems – the challenges of characterization and risk mitigation. Curr. Opin. Biotechnol. 57, 127–136.
Falkinham, J.O., Pruden, A., Edwards, M., 2015. Opportunistic premise plumbing pathogens: increasingly important pathogens in drinking water. Pathogens 4 (2), 373–386.
Feazel, L.M., Baumgartner, L.K., Peterson, K.L., Frank, D.N., Harris, J.K., Pace, N.R., 2009. Opportunistic pathogens enriched in showerhead biofilms. Proc. Natl. Acad. Sci. U.S.A. 106 (38), 16393–16398.
Fish, K., Osborn, A.M., Boxall, J.B., 2017. Biofilm structures (EPS and bacterial communities) in drinking water distribution systems are conditioned by hydraulics and influence discolouration. Sci. Total Environ. 593-594, 571–580.
Husband, P.S., Boxall, J.B., Saul, A.J., 2008. Laboratory studies investigating the processes leading to discolouration in water distribution networks. Water Res. 42 (16), 4309–4318.
Husband, P.S., Whitehead, J., Boxall, J.B., 2010. The role of trunk mains in discolouration. Proc. Inst. Civil Eng. Water Manage. 163 (8), 397–406.
Javed, M.A., Zafar, A.M., Al-Zuhair, S., El Badawy, A., Aly Hassan, A., 2022. Exogenous carbon substrates for biohydrogen production and organics removal using microalgal-bacterial co-culture. ACS Sustain. Chem. Eng. 10 (47), 15490–15500.
Jenks, B., Pecci, F., Stoianov, I., 2023. Optimal design-for-control of self-cleaning water distribution networks using a convex multi-start algorithm. Water Res., 119602
Ji, P., Parks, J., Edwards, M.A., Pruden, A., 2015. Impact of water chemistry, pipe material and stagnation on the building plumbing microbiome. PLoS One 10 (10), e0141087.
Julien, R., Dreelin, E., Whelton, A.J., Lee, J., Aw, T.G., Dean, K., Mitchell, J., 2020. Knowledge gaps and risks associated with premise plumbing drinking water quality. AWWA Water Sci. 2 (3), e1177.
Lautenschlager, K., Boon, N., Wang, Y., Egli, T., Hammes, F., 2010. Overnight stagnation of drinking water in household taps induces microbial growth and changes in community composition. Water Res. 44 (17), 4868–4877.
Lehtola, M.J., Laxander, M., Miettinen, I.T., Hirvonen, A., Vartiainen, T., Martikainen, P. J., 2006. The effects of changing water flow velocity on the formation of biofilms and water quality in pilot distribution system consisting of copper or polyethylene pipes. Water Res. 40 (11), 2151–2160.
Ling, F., Whitaker, R., LeChevallier, M.W., Liu, W.-.T., 2018. Drinking water microbiome assembly induced by water stagnation. ISME J. 12 (6), 1520–1531.
Liu, G., Zhang, Y., Knibbe, W.-.J., Feng, C., Liu, W., Medema, G., van der Meer, W., 2017. Potential impacts of changing supply-water quality on drinking water distribution: a review. Water Res. 116, 135–148.
Liu, Y., Shan, R., Chen, G., Liu, L., 2020. Linking flow velocity-regulated EPS production with early-stage biofilm formation in drinking water distribution systems. Water Supply 20 (4), 1253–1263.
Martin, M., 2011. Cutadapt removes adapter sequences from high-throughput sequencing reads. EMBnet J. 17 (1), 3.
Martinez Paz, E.F., Tobias, M., Escobar, E., Raskin, L., Roberts, E.F.S., Wigginton, K.R., Kerkez, B., 2022. Wireless sensors for measuring drinking water quality in building plumbing: deployments and insights from continuous and intermittent water supply systems. ACS ES&T Eng. 2 (3), 423–433.
Montagnino, E., Proctor, C.R., Ra, K., Ley, C., Noh, Y., Vigil, K., Aw, T.G., Dasika, S., Whelton, A.J., 2022. Over the weekend: water stagnation and contaminant exceedances in a green office building. PLOS Water 1 (3), e0000006.
National Academies of Sciences, E. and Medicine, 2020. Management of Legionella in Water Systems. National Academies Press.
National Research Council, N., 2007. Drinking Water Distribution systems: Assessing and Reducing Risks. National Academies Press.
Neu, L. and Hammes, F. 2020 Feeding the Building Plumbing Microbiome: the Importance of Synthetic Polymeric Materials for Biofilm Formation and Management.
Paris, T., Skali-Lami, S., Block, J.-.C., 2007. Effect of wall shear rate on biofilm deposition and grazing in drinking water flow chambers. Biotechnol. Bioeng. 97 (6), 1550–1561.
Percival, S.L., Knapp, J.S., Wales, D.S., Edyvean, R.G.J., 1999. The effect of turbulent flow and surface roughness on biofilm formation in drinking water. J. Ind. Microbiol. Biotechnol. 22 (3), 152–159.
Prest, E.I., Schaap, P.G., Besmer, M.D., Hammes, F., 2021. Dynamic hydraulics in a drinking water distribution system influence suspended particles and turbidity. But Not Microbiology. Water 13 (1), 109.
Proctor, C.R., Dai, D., Edwards, M.A., Pruden, A., 2017. Interactive effects of temperature, organic carbon, and pipe material on microbiota composition and Legionella pneumophila in hot water plumbing systems. Microbiome 5 (1), 130.
Proctor, C.R., Gächter, M., Kötzsch, S., Rölli, F., Sigrist, R., Walser, J.-.C., Hammes, F., 2016. Biofilms in shower hoses – choice of pipe material influences bacterial growth and communities. Environ. Sci. 2 (4), 670–682.
Proctor, C.R., Rhoads, W.J., Keane, T., Salehi, M., Hamilton, K., Pieper, K.J., Cwiertny, D. M., Prévost, M., Whelton, A.J.J.A.w.s, 2020. Considerations for large building water quality after extended stagnation. AWWA Water Sci. 2 (4), e1186.
Ragain, L., Masters, S., Bartrand, T.A., Clancy, J.L., Whelton, A.J., 2019. Analysis of building plumbing system flushing practices and communications. J. Water Health 17 (2), 196–203.
Raya, A., Sodagari, M., Pinzon, N.M., He, X., Zhang Newby, B.-m, Ju, L.-.K., 2010. Effects of rhamnolipids and shear on initial attachment of Pseudomonas aeruginosa PAO1 in glass flow chambers. Environ. Sci. Pollut. Res. 17 (9), 1529–1538.
Rochex, A., Godon, J.-.J., Bernet, N., Escudié, R., 2008. Role of shear stress on composition, diversity and dynamics of biofilm bacterial communities. Water Res. 42 (20), 4915–4922.
Sasada, R., Weinstein, M., Prem, A., Jin, M., Bhasin, J., 2020. FIGARO: an efficient and objective tool for optimizing microbiome rRNA gene trimming parameters. J. Biomol. Tech. 31 (Suppl), S2. -S2.
Schmidt, I., Rickert, B., Schmoll, O., Rapp, T., 2019. Implementation and evaluation of the water safety plan approach for buildings. J. Water Health 17 (6), 870–883.
Segata, N., Izard, J., Waldron, L., Gevers, D., Miropolsky, L., Garrett, W.S., Huttenhower, C., 2011. Metagenomic biomarker discovery and explanation. Genome Biol. 12 (6), R60.
II Shen, Y., Haig, S.-.J., Prussin, A.J., LiPuma, J.J., Marr, L.C., Raskin, L, 2022. Shower water contributes viable nontuberculous mycobacteria to indoor air. PNAS Nexus 1 (5).
Sunny, I., Husband, P.S., Boxall, J.B., 2020. Impact of hydraulic interventions on chronic and acute material loading and discolouration risk in drinking water distribution systems. Water Res. 169, 115224.
Torvinen, E., Lehtola, M.J., Martikainen, P.J., Miettinen, I.T., 2007. Survival of mycobacterium avium in drinking water biofilms as affected by water flow velocity, availability of phosphorus, and temperature. Appl. Environ. Microbiol. 73 (19), 6201–6207.
US Centers for Disease Control and Prevention, 2021. Reopening Buildings After Prolonged Shutdown Or Reduced Operation. US Centers for Disease Control and Prevention. https://www.cdc.gov/nceh/ehs/water/legionella/building-water-system.html.
Vedachalam, S., Spotte-Smith, K.T., Riha, S.J., 2016. A meta-analysis of public compliance to boil water advisories. Water Res. 94, 136–145.
Viglione, G., 2020. As lockdowns lift, new hazards lurk in the water. Nature.
Vreeburg, J.H.G., Blokker, E.J.M., Horst, P. and Van Dijk, J.C. 2009. Velocity-based self-cleaning residential drinking water distribution systems. water science and technology: water supply 9, 635–641.
Vreeburg, J.H.G., Boxall, D.J.B., 2007. Discolouration in potable water distribution systems: a review. Water Res. 41 (3), 519–529.
Vreeburg, J.H.G., Schippers, D., Verberk, J.Q.J.C., van Dijk, J.C., 2008. Impact of particles on sediment accumulation in a drinking water distribution system. Water Res. 42 (16), 4233–4242.
Wang, H., Edwards, M.A., Falkinham, III, J.O., Pruden, A, 2013. Probiotic approach to pathogen control in premise plumbing systems? A review. Environ. Sci. Technol. 47 (18), 10117–10128.
Wang, H., Masters, S., Hong, Y., Stallings, J., Falkinham, J.O., Edwards, M.A., Pruden, A., 2012. Effect of disinfectant, water age, and pipe material on occurrence and persistence of legionella, mycobacteria, pseudomonas aeruginosa, and two amoebas. Environ. Sci. Technol. 46 (21), 11566–11574.
World Health Organization, 2011. Water Safety in Buildings. World Health Organization. https://apps.who.int/iris/handle/10665/76145.
Zlatanović, L., van der Hoek, J.P., Vreeburg, J.H.G., 2017. An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system. Water Res. 123, 761–772.