

Review

Feeding the Building Plumbing Microbiome: The Importance of Synthetic Polymeric Materials for Biofilm Formation and Management

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Abstract: The environmental conditions in building plumbing systems differ considerably from the larger distribution system and, as a consequence, uncontrolled changes in the drinking water microbiome through selective growth can occur. In this regard, synthetic polymeric plumbing materials are of particular relevance, since they leach assimilable organic carbon that can be utilized for bacterial growth. Here, we discuss the complexity of building plumbing in relation to microbial ecology, especially in the context of low-quality synthetic polymeric materials (i.e., plastics) and highlight the major knowledge gaps in the field. We furthermore show how knowledge on the interaction between material properties (e.g., carbon migration) and microbiology (e.g., growth rate) allows for the quantification of initial biofilm development in buildings. Hence, research towards a comprehensive understanding of these processes and interactions will enable the implementation of knowledge-based management strategies. We argue that the exclusive use of high-quality materials in new building plumbing systems poses a straightforward strategy towards managing the building plumbing microbiome. This can be achieved through comprehensive material testing and knowledge sharing between all stakeholders including architects, planners, plumbers, material producers, home owners, and scientists.

Keywords: building plumbing systems; synthetic polymeric material; microbiome; management

1. Drinking Water Microbiology from Source to Tap

1.1. Bacteria Are Omnipresent in Drinking Water Treatment and Distribution Systems

Bacteria inhabit nearly every part of drinking water systems [1]. Complex microbial communities, comprising thousands of unique taxa, are found at various concentrations (10^3 – 10^6 cells/mL) [2–4] from the source water [5–7], through different treatment stages [8–10], through the drinking water distribution system (DWDS) [11–13] and building plumbing system right up to the tap [14–16] (Figure 1). Along the DWDS (i.e., from post-treatment until the property line), the majority of bacteria (~98%) is present in the form of biofilms and/or attached to particles, while only ~2% are present as planktonic cells in the water phase [17]. Here, typical pipe surface biofilm concentrations range between 10^5 – 10^7 cells/cm² [18,19]. The DWDS of the City of Zurich (Switzerland) comprises 1100 km of main and distribution pipes [20]. Calculating with an average inner pipe diameter of 100 mm, this translates to 3×10^5 m² pipe surface and 9×10^3 m³ of water.

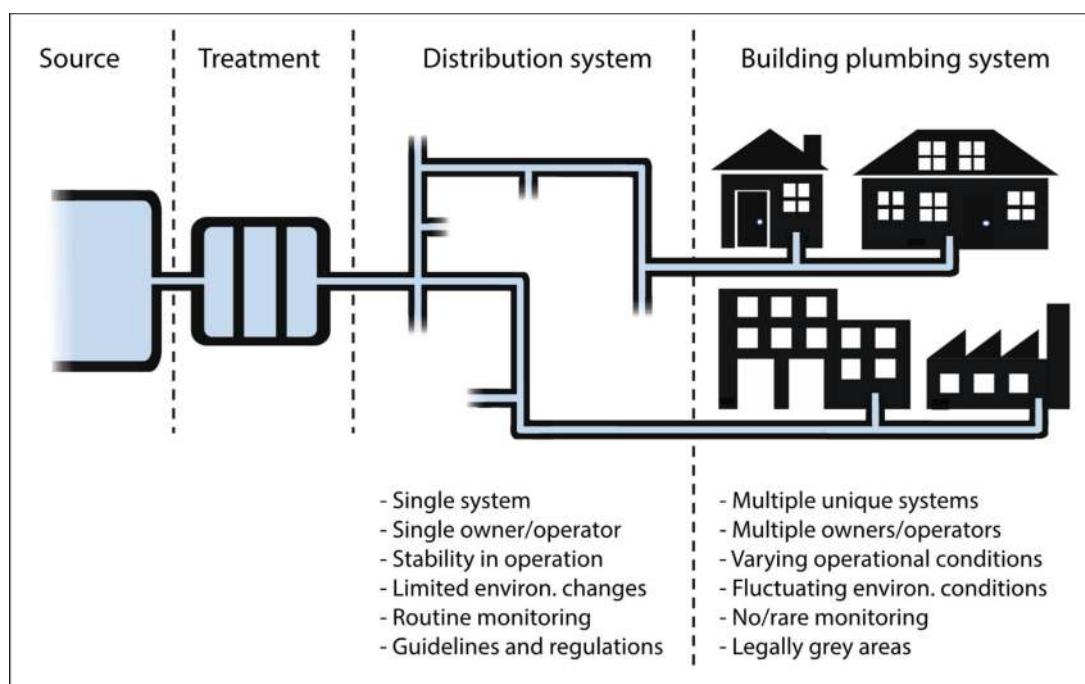


Figure 1. Drinking water from source to tap, highlighting key differences between the main distribution system and building plumbing systems.

Considering a planktonic bacterial concentration of up to $\sim 1 \times 10^5$ cells/mL after treatment [2] and a biofilm-to-water distribution of 98:2 (above), this means an estimated total of 4×10^{16} attached cells and 0.1×10^{16} planktonic cells for the entire DWDS; spectacular numbers indeed.

1.2. The Microbiology of DWDS Is Studied, Monitored, and Regulated

The microbiology of DWDS has been studied intensively (e.g., [17,21]) and is routinely monitored by utilities, following defined regulations. Here, several aspects allow for a comparatively controlled, and thus manageable, environment. First, a DWDS is often operated by a single “owner” (i.e., water utility), which allows for structured planning, operation, management, and monitoring. Second, legal guidelines and regulations are in place and areas of responsibilities are defined, e.g., which pipe materials to use or which water quality variables to monitor (e.g., EU guideline: DWD 98/83/EC [22]; USA (EPA) Safe Drinking Water Act [23]). Third, DWDS have relatively limited fluctuations in operating conditions. For example, the water in DWDS mains is essentially flowing continuously, resulting in (comparatively) limited changes in flow dynamics and water age at any given point in the system.

1.3. The Microbiology of DWDS Is Prone to (Environmental) Temporal and Spatial Changes

An ideal DWDS is microbiologically stable, meaning the water quality does not change during distribution (e.g., [24]). However, and despite comparatively limited fluctuations, temporal and spatial changes have still been documented. This includes short-term changes in planktonic cell concentrations, which can be attributed to fluctuations in flow velocity, following trends in water consumption throughout the day [25], and seasonal changes in both cell concentrations [26] and microbiome composition [27], presumably linked to changes in environmental conditions. In similar vein, spatial variations in bacterial concentration and composition resulted for example from increased water age and the depletion of disinfectant residuals throughout the DWDS [28,29].

1.4. Changes in Microbiological Quality Are Problematic

From an ecological perspective, understanding the link between changes in environmental conditions and changes in the drinking water microbiome is interesting. Unfortunately, changes such as these may also have profoundly adverse consequences for the drinking water quality. For example, the increased detection of *Mycobacterium avium* in a DWDS was linked to water age and the depletion of chlorine during distribution [30], and seasonal temperature changes within several DWDS were correlated with the growth of coliforms [31]. The most dramatic, least understood, and usually uncontrolled changes in environmental conditions occur when water from the DWDS enters building plumbing systems (also referred to as “premise(s) plumbing” [32,33] or “domestic plumbing” [34,35]). As discussed below, the environmental conditions between and within building plumbing systems change dramatically relative to the DWDS and relative to each other (Figure 1), and consequently so does the microbiology.

The purpose of this review was (1) to emphasize the complexity of building plumbing in relation to microbial ecology, especially in the context of low-quality synthetic polymeric materials (i.e., plastics) and (2) to highlight major knowledge gaps in the field. This should ultimately (3) highlight the need for more research on the fundamental aspects of biofilm growth in building plumbing systems, (4) allowing for both a better understanding and better options of proactive management of the microbiology in the built environment.

2. Building Plumbing Systems Change the Microbiology

2.1. The Microbiological Black Box Between the Water Meter and the Tap

A number of studies on building plumbing microbiology emerged during the past decade, for example investigating the impact of temperature on community composition [15], refining adequate building sampling strategies [36], monitoring biofilm formation in a new building [16], or evaluating the impact of stagnation on microbiome assemblages [14]. Despite this increase in knowledge, building plumbing microbiology still remains considerably less studied than DWDS microbiology, insufficiently monitored, and consequently, poorly understood. The two main reasons for this are (1) the severe challenges in sampling and monitoring buildings due to legal restrictions and (2) the constructional complexity of building plumbing systems.

Legal guidelines in most developed countries cover drinking water safety until the point of use (e.g., Drinking Water Directive, EU [22]; TrinkwV, Germany [37]). While this in theory also renders water utilities responsible for safe water within both private and public buildings, additional interpretations of the legislation allow for the transfer of legal obligations to building owners (e.g., AVBWasserV, Germany [38]). The consequence is that most buildings, and particularly private homes, are not controlled from a microbiological perspective on a regular basis, if at all.

Apart from legal aspects, additional challenges stem from the complexity of building plumbing systems. Not only are there thousands of unique buildings connected to each DWDS (e.g., >20,000 single-family houses in the City of Zurich (data 2010 [39])), but each building plumbing system also consists of multiple, different sub-units such as boilers, rising mains, and ring mains. In addition, each system typically has warm and cold water outlets (Figure 2), with hoses, taps, and various connected home appliances (e.g., a washing machine), all of which will potentially create unique and very different environments. From a microbiological point of view, bacteria that enter a building plumbing system from the DWDS experience an immediate and considerable change in environmental conditions, and it is common knowledge that a change in environmental conditions will often result in a change in bacterial numbers [40], viability [41], activity [42], and composition [43].

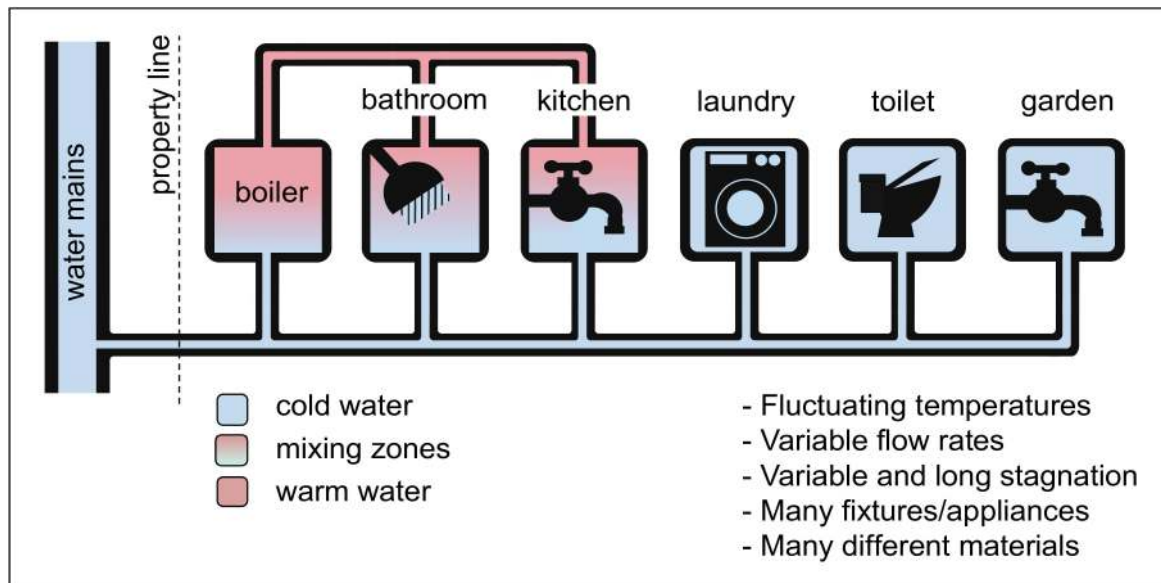


Figure 2. The complexity of building plumbing systems affects environmental conditions and ultimately alters the drinking water microbial composition and quality.

2.2. Specific Building Plumbing System Conditions Alter Microbiological Water Quality

Pipe diameters: Building plumbing pipes have small diameters, ranging between 1–2 cm (DN12–DN20), compared to diameters of 10–200 cm (DN100–DN2000) in the DWDS. This implies that the surface area within building plumbing systems is high compared to the corresponding water volume. For example, DN12 pipes have a surface area to volume (SA/V) ratio of ~3:1, meaning for every 3 cm² of pipe surface, there is approximately 1 mL of water (as opposed to the DWDS where 2 mL of water is in contact with 1 cm² of pipe surface). This is particularly relevant, as an increasing SA/V ratio (e.g., from 1:2 in the DWDS to 3:1 in building plumbing systems) translates to a much higher potential impact of the biofilm on the water phase (e.g., due to detachment dynamics). Moreover, pipe diameters directly impact flow velocity and thus shear stress, with both increasing due to decreasing pipe diameters [44]. This is microbiologically relevant, as water dynamics impact both the dominance of specific bacteria [45] as well as biofilm structure and overall community compositions [46,47].

Temperature: Upon entering a building, temperature changes considerably as the water from the DWDS diverges into cold and warm water lines (Figure 2). After entering a building, cold water is subject to gradual warming (e.g., fluctuating between 8–20 °C) [48,49], potentially favoring increased bacterial growth. Water in the warm water line is subject to a heat shock in the boiler (e.g., 60–63 °C) [48] and to severe temperature gradients along the building plumbing system, e.g., decreasing to below 30 °C within 1–3 h of stagnation [36]. One study showed that bacterial concentrations can be 20% higher in the cold water compared to the warm water [48]. Additionally, dissimilar community compositions have been found in warm and cold water, showing higher diversities at low temperatures and differences in abundant taxa between cold and warm water [15], [50]. Comparing the microbiology of associated cold and warm water in the same system highlights the impact that is introduced by installation design (e.g., pipe isolation) and the choice of operational settings (e.g., boiler temperature).

Stagnation time: In contrast to the DWDS, water stagnates for a significant amount of time in buildings. Here, user habits play an important role. Even though a building usually has a single owner, multiple inhabitants are using the installation, often in a variety of different and uncontrollable ways. For example, in a single family house, multiple people (a) use water for different purposes (e.g., showering, toilet flushing, laundry), (b) at different time points and in different frequencies, and (c) at different spatial locations in the building (e.g., tap in the bathroom on the upper floor vs. toilet in the basement) (e.g., [51]). These variations in operation result in highly irregular and uncontrollable water dynamics within a single building plumbing system and are, without the user's knowledge,

inevitably impacting the microbiology thereof. Studies showed that stagnation results in an increase in bacterial cell concentrations in the water phase (e.g., from $\sim 6 \times 10^4$ to $\sim 1 \times 10^5$ cells/mL during overnight stagnation [49]) as well as in community compositional changes, e.g., decreasing richness [14]. For some cases, the depletion of disinfectant residuals during stagnation was identified to be a reason for microbial changes [52], which ultimately resulted in drinking water deterioration [53].

Materials: Building plumbing systems consist of numerous types of very different materials. Here, not solely pipes but also components such as sealing rings, hoses, or fixtures are produced from a variety of metals as well as hard and flexible synthetic polymeric materials (Table 1). While this will be discussed in detail in Section 3, it is already important to notice that materials significantly impact the microbiology of building plumbing systems, e.g., due to different microbial colonization dynamics, based on surface properties [54] and nutrient migration [55,56].

Table 1. Materials used in building plumbing systems and their applications.

Material	Application
Metals	
Copper and copper alloys	Pipes and fittings
Brass (copper alloy)	Taps, valves, pipes, and fittings
Galvanized steel (GI)	Pipes and taps
Stainless steel	Fittings
Ductile iron	Pipes and fittings
Malleable iron	Nipples
Galvanized iron	Pipes and fittings
Synthetic materials	
Ethylene propylene diene monomer (EPDM)	O-rings, seals
Polyvinyl chloride (PVC)	
PVC-U (unplasticized)	Pipes and fittings
PVC-C (chlorinated)	Pipes and fittings
PVC-P (plasticized)	(Shower) hoses
Polyethylene (PE)	
PE-X (crosslinked; a, b, c)	Pipes (hot water pipes) Multilayer pipes
PE-RT (raised temperature resistant)	Pipes (hot water pipes) Multilayer pipes
Polybutylene (PB)	Pipes and fittings
Polypropylene (PP)	
PP-R (random Co-polymer)	Tubes and fittings
PP-C (Copolymer)	Tubes and fittings
PP-H (Hopolymer)	Tubes and fittings
Polyphenylsulfone (PPSU)	Fittings
Polyoxymethylen (POM)	Valve elements
Polyvinylidene fluoride (PVDF)	Fittings
Polytetrafluorethylen (PTFE; Teflon)	Valve elements, seals
Silicone rubber	Seals
Epoxy resin	Inline coating

Importantly, all of the conditions above can be altered/managed either by operational adaptations (e.g., temperature, circulation) or design (e.g., materials, isolation), providing the opportunity to manage building plumbing microbiology proactively. Here, interventions will inevitably bring their own challenges and will need to be evaluated separately (e.g., increased operational costs due to higher water temperatures). In this review, we argue that the selection of good plumbing materials is one of the most straightforward starting points for a good building plumbing management.

3. Synthetic Polymeric Materials in Building Plumbing Systems

3.1. The Variety of Materials Used in Building Plumbing Systems Creates Numerous Ecological Niches

Building plumbing originally consisted almost exclusively of metal-based products (copper, galvanized steel, etc.). However, during the last half-century, synthetic polymeric products were increasingly implemented (Figure 3A). The benefits of the latter are (1) the low cost, (2) an easier installation compared to rigid pipes, (3) high heat resistance, (4) long life-times, (5) corrosion resistance, and (6) better energy conservation due to reduced heat transfer and loss. A large variety of synthetic polymeric materials is used for both pipes and non-pipe components (Table 1). For example, cross-linked polyethylene (PE-X) and unplasticized polyvinyl chloride (PVC-U) are used for pipes. Fittings are often made from polybutylene (PB) and polypropylene (PP). Hoses are made from plasticized PVC (PVC-P), whereas ethylene propylene diene monomer (EPDM) and silicone rubber are typically used for the production of sealing materials. Importantly, there is not only substantially different material types within plumbing systems overall, but also within individual fixtures. For example, one single kitchen tap can comprise numerous different materials in contact with the water (e.g., galvanized steel, copper, PE-X, EPDM, and PVC-P; Figure 3B,C). It is important to realize that every single material potentially poses a unique environment and consequently creates a different niche for bacteria to grow.

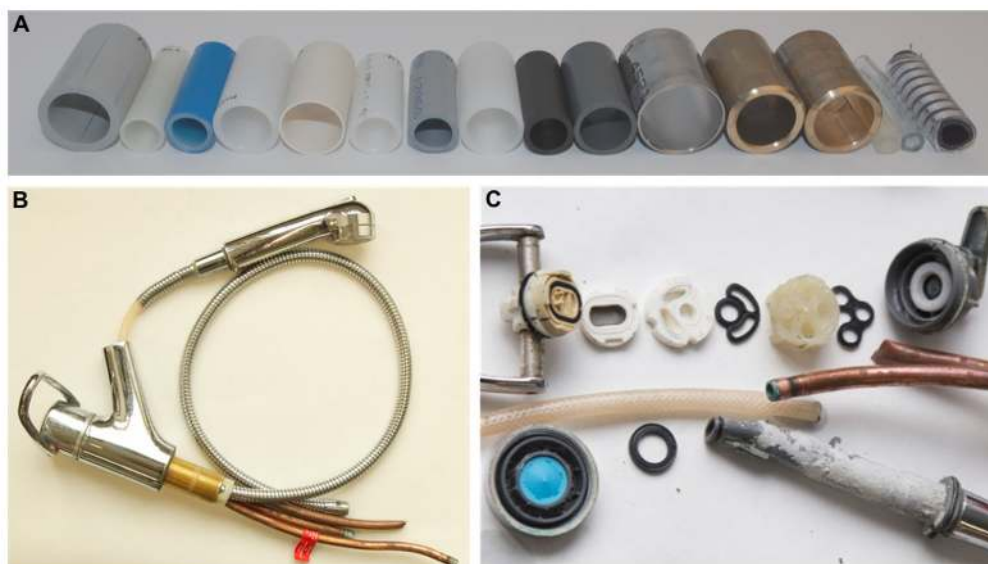


Figure 3. Variety of materials used within building plumbing systems and fixtures. (A) Different pipes and hoses from metals and both hard and flexible synthetic polymeric materials. (B,C) Materials used in a single kitchen tap.

3.2. Carbon Migrates from Synthetic Polymeric Materials

Organic carbon migration (or leaching) from the material into the water is a main reason why synthetic polymeric materials are relevant for microbial growth in buildings. Drinking water is typically carbon-limited with low concentrations of bioavailable organic carbon [57,58]. As a result, migrating carbon compounds increase the growth potential of a system. In most cases, the migrating substrates are not the polymers themselves, but rather the so-called additives (i.e., flexibilizers, plasticizers, stabilizers), which are added during production to improve or adapt specific properties of the material [59]. Stabilizers include antioxidants that protect the material against thermally introduced oxidation, i.e., increasing heat tolerance [60]. For example, Skjevraak et al. detected 2,4-di-tert-butyl-phenol (2,4-DTBP) in water running through HDPE pipes [60].

This compound was previously identified as a degradation by-product of Irgafos 168[®] (BASF, Switzerland [61]), an antioxidant used as an additive in PP pipes [62]. Plasticizers are added to

polymeric materials to increase flexibility [63]. Here, the most commonly used plasticizers are phthalates, such as di-(2-ethylhexyl) phthalate (DEHP [64]). Due to its structure and polarity, PVC is particularly susceptible to the incorporation of plasticizers. Hence, many flexible hoses such as shower hoses are made from PVC with additional plasticizers. Importantly, these additives are usually low molecular-weight compounds, thus prone to leaching from the material into the water phase. Some of these compounds can serve as primary growth-supporting nutrient sources for bacteria [65] as they are easily biodegradable [66], leading to growth, biofilm formation, and ultimately affecting the microbial water quality.

Therefore, European Standards on the “influence of materials on water for human consumption” [67] include material testing with respect to both migration potential assays (e.g., KTW guideline, Germany [68]) as well as bacterial growth potential assays. For the latter, three different test methods are recognized [69], where microbial growth is measured by the mean dissolved oxygen demand (MDOD), volumetric measurements of total biofilm growth, or the determination of the biomass production potential (BPP) based on metabolic activity (i.e., ATP). An alternative method is the Swiss BioMig assay, introduced by Bucheli-Witschel et al. [56], which combines both migration and growth potential assays in a single test. This assay was, for example, used to evaluate and classify a range of different building plumbing materials [65], but also to study the impact of chlorination on the migration potential of biodegradable carbon [70]. Importantly, disinfectants such as chlorine were shown to impact plumbing materials and migration dynamics [71]. Then again, different materials affect the decay of disinfectant residuals to different extents [58]. Mao et al. [70] investigated the decay of chlorine when exposed to different synthetic polymeric materials. They found that chlorine concentrations were decreasing considerably; however, with rather low decay rate constants compared to non-flexible materials (e.g., EPDM 0.12/h versus copper 1.2/h [72]).

3.3. Migrating Organic Carbon Compounds Drive Biofilm Formation and Selection

Materials differ considerably in the quantity, composition, and dynamics of carbon migration [56]. For example, a study by Wen et al. [65] found that high-quality PE-X pipe material leaches less (0.3 mg TOC/L/d) total organic carbon (TOC) than flexibilized EPDM (0.7 mg TOC/L/d) or flexible PVC-P (40 mg TOC/L/d) within the first 24 h of exposure. This study emphasizes the need for quality control of migrating carbon substances from plumbing materials. Especially shower hose materials are mainly made of flexible synthetic polymers (e.g., PVC-P), of which the exact chemical composition is normally not disclosed to the buyer and often not properly regulated by law. Consequently, shower hoses can be purchased in the whole spectrum of qualities: either high-quality and certified for drinking water use or low-quality and thus potentially leaching high carbon concentrations (see e.g., [73]). Proctor et al. [73] investigated the growth potential of migrating carbon compounds from five different flexible hose materials (1 × PE-X, 2 × PVC-P, 1 × silicone, and 1 × unknown). All materials showed different degrees of carbon migration that (mostly) correlated with the actual growth within the corresponding hose. Carbon migration during material testing varied between 0.4–10.4 $\mu\text{g C}/\text{cm}^2/\text{day}$ and supported growth in a range of 0.5–4.8 $\times 10^7$ cells/cm² in the same assay. Moreover, the diversity in the hose biofilm communities was shown to be at least 10-fold lower than in the corresponding water [73], highlighting the selectiveness of biofilm growth on flexible synthetic polymeric materials. While several studies observed such selective growth (e.g., [73,74]), it has barely (if at all) been explained on the basis of fundamental ecology. Studies from other research fields showed, however, that a change in the available carbon does alter microbial community composition [75], that this change is potentially due to differences in metabolic activities within the community [76], and that the one(s) that perform(s) best (growth rate and yield) will succeed and establish within the community [77]. Selective growth on different materials potentially impacts water quality. For example, several authors showed correlations between carbon migration of different materials, subsequent differences in bacterial growth, and differences in the establishment of *Legionella pneumophila* on those materials [74,78].

Importantly, the quantity of migrating carbon was shown to decrease considerably within days (to weeks). For example, Zhang and Liu [66] measured a decrease in migration from 0.25 to <0.1 $\mu\text{g TOC/d/cm}^2$ already within the first 10 days of operation. This suggests that the impact of migrating carbon is the greatest in the early stages of biofilm development. This does not necessarily exclude carbon migration from having long-term impacts. Despite the fast decrease in migrating carbon concentrations early on, Lund et al. [71] showed that the migration can stay on a constant level for at least up to 12 months (with 0.2 $\text{mg/m}^2/\text{d}$). This suggests that, in addition to the highest impact right in the beginning, there might be a potential long-term influence on biofilm growth at least on a minor level. Consequently, we propose that the understanding of nutrient-based selection is essential for understanding and managing biofilm formation in building plumbing systems, particularly during the initial stages (e.g., during the commissioning of a new building).

4. Quantifying Initial Biofilm Formation on Flexible Synthetic Polymeric Materials

4.1. Dispersal and Selection as Main Parameters for Initial Biofilm Formation

Similar to other ecosystems, biofilm formation in building plumbing systems follows known ecological principles such as dispersal, selection, drift, and diversification [79,80]. This allows the quantification of biofilm formation processes to better understand growth dynamics. In this section, we specifically explore the importance of (1) water-to-surface dispersal and (2) nutrient-based selection through basic quantification of initial biofilm formation processes. For a theoretical example, we focus on the dynamics that follow the installation of a new shower hose—a common plumbing-maintenance action undertaken by most home owners at some point in time. The purpose of this example is to show that engineering information (e.g., material quality and system operation) can be combined with microbiological knowledge (e.g., attachment and growth data) to develop a quantitative understanding of biofilm formation in buildings. A typical shower hose ($L = 180 \text{ cm}$, $d_i = 0.8 \text{ cm}$) is made from flexible PVC-P and has an inner surface area of $\sim 450 \text{ cm}^2$ and a volume of $\sim 90 \text{ mL}$. Five parameters that will govern the initial biofilm formation are: (1) The inorganic nutrients introduced daily with the drinking water, (2) the organic nutrients that migrate from the shower hose material into the water phase (see Section 3), (3) the ability and rate of bacteria to attach to the hose surface (water-to-surface dispersal), (4) the metabolic capability of bacteria to utilize the available nutrients and the rate at which they will grow, and (5) selection that occurs within the community due to the specific growth dynamics (nutrient-based selection). These parameters are not detached from each other but will, for the sake of clarity, be dealt with separately below.

1. Inorganic nutrients from the water: The tap water in this example is typical for Zurich (CH), meaning non-chlorinated, biologically stable (i.e., assimilable organic carbon (AOC) < 10 $\mu\text{g/L}$, [81]), oligotrophic water with approximately 1 mg/L dissolved organic carbon (DOC), 3 mg/L total nitrogen (TN), and 5 $\mu\text{g/L}$ total phosphorous (TP) [82]. This converts to 0.1 mg-TN/hose and 0.5 $\mu\text{g-TP/hose}$.
2. Organics from the material: Flexible PVC-P leaches up to 4 $\mu\text{g-TOC/cm}^2/\text{day}$, of which $\sim 50\%$ is AOC (i.e., 2 $\mu\text{g-AOC/cm}^2/\text{day}$) [65,73]. This converts to $\sim 900 \mu\text{g-AOC/hose/day}$.
3. Water-to-surface dispersal: Zurich tap water comprises $\sim 5 \times 10^4 \text{ cells/mL}$ (i.e., $4.5 \times 10^6 \text{ cells/hose}$) and >5000 different bacterial taxa [50]. Water-to-surface dispersal rates for initial colonization remain poorly characterized for drinking water systems, but it is known that bacterial attachment starts within seconds to minutes of the first exposure [83,84]. Here, we assume an attachment of 1% of the total cell concentration (TCC) from the water phase during 1 h of stagnation, which means $\sim 1.1 \times 10^6 \text{ cells/hose/day}$ in the absence of any growth.
4. Bacterial growth: Based on a conversion factor of $10^7 \text{ cells}/\mu\text{g-AOC}$ [85,86] and following the rule-of-thumb for growth requirements of bacteria (i.e., a C:N:P ratio of 100:10:1 [85]), bacterial growth in the water would be carbon-limited (allowing for the growth of $\sim 9 \times 10^6 \text{ cells/hose/day}$). However, this is reversed due to the excessive AOC that migrates continuously from the material,

rendering the shower-hose environment phosphorous-limited. Ultimately, the maximum growth potential of the combined system (i.e., water and hose) is $\sim 1 \times 10^8$ cells/hose/day, assuming that 100% of the phosphorous is biologically available.

5. Nutrient-based selection: The composition and biodiversity of biofilm communities is influenced by the type of material they grow on [87]. Based on the selection observed in previous studies, we assume for our example that only 10% of the bacteria present in the water phase and of those dispersing to the material's surface can actually utilize the migrated organic carbon and grow (i.e., 4.5×10^5 cells/hose/day).

4.2. Initial Colonization, Growth, and Biofilm Formation

In Figure 4, we demonstrate the calculated dynamics of initial biofilm formation on a new material, based on the example discussed above.

We calculated planktonic and biofilm growth during the first 72 h of operation with intermittent flushing events occurring every 24 h (Figure 4A). The calculation is based on (1) TP from the water being replenished with every 24-hour flushing event and (2) continuous carbon migration from the material with unutilized compounds being removed with every flushing event (Figure 4B). Within each 24 h-cycle, (3) a fraction of the planktonic cells will attach to the material's surface (water-to-surface dispersal) and (4) some will grow in both the planktonic and biofilm phase. This will (5) benefit growing taxa over others, resulting in a nutrient-based selection within the community.

For the calculation of planktonic growth, we used the following equation (Equation 1):

$$pTCC_t = ((pTCC_0 \cdot (1 - r)) + ((pTCC_0 \cdot r) \cdot (1 + \mu)^t)) - (((pTCC_0 \cdot r) \cdot (1 + \mu)^t) \cdot k_a) \quad (1)$$

with $pTCC_t$ representing the number of planktonic bacteria in the water phase at a certain time-point t , based on a fraction of growing cells $r = 0.1$ (i.e., 10% grow) for the originally (i.e., with each flushing event) introduced cells ($pTCC_0$), with a constant growth rate of $\mu = 0.125/h$ and taking a constant attachment into consideration, with the attachment rate coefficient $k_a = 0.01/h$.

For calculating biofilm growth, an adapted equation was used (Equation (2)):

$$sTCC_t = (sTCC_{t-1} \cdot (1 + \mu)) + (((pTCC_0 \cdot r) \cdot (1 + \mu)^t) \cdot k_a) \quad (2)$$

with $sTCC_t$ representing the number of bacteria in the biofilm phase at a certain time-point t , based on a fraction of growing cells $r = 0.1$ for the originally introduced cells ($pTCC_0$), with a constant growth rate of $\mu = 0.125/h$ and taking a constant attachment into consideration, with $k_a = 0.01/h$.

Applying this to input variables shows the following (Figure 4C):

1. During the first stagnation period, i.e., within the first 24 h of stagnation, planktonic growth dominates the shower hose system, with 1.2×10^7 planktonic (86%) and 1.8×10^6 attached (14%) cells/hose. However, in the subsequent day(s) (with daily shower/flushing events), the water phase is exchanged every 24 h, meaning a replacement of the grown planktonic cells by the source water community, and a replenishment of inorganic nutrients in the otherwise carbon-rich environment. Sessile cells remain in the biofilm and therefore continue growing at the concentration of $sTCC_{24}$ after the first flushing event, subsequently rendering the system biofilm dominated; with 1×10^7 $pTCC$ /hose (26%) versus 3×10^7 $sTCC$ /hose (74%) after 48 h.
2. Assuming continuous growth in the biofilm, the shower hose system will reach phosphorous-limitation after approximately 70 h (Figure 4B), limiting further growth until a replenishment of inorganic nutrients.
3. During the initial stagnation period, the biofilm community is dominated by the initial water-to-surface dispersal-driven colonization. However, the continuous growth of adapted cells in the biofilm results in a highly selective growth and biofilm development. More precisely, the original drinking water community in our example comprised around 5000 different species.

Due to the ability of (initially) only 10% to grow (i.e., 500 species), species heterogeneity in the biofilm inevitably declines. As a result, we can state that nutrient-based selection is important for the subsequent development of the biofilm and its microbial community composition.

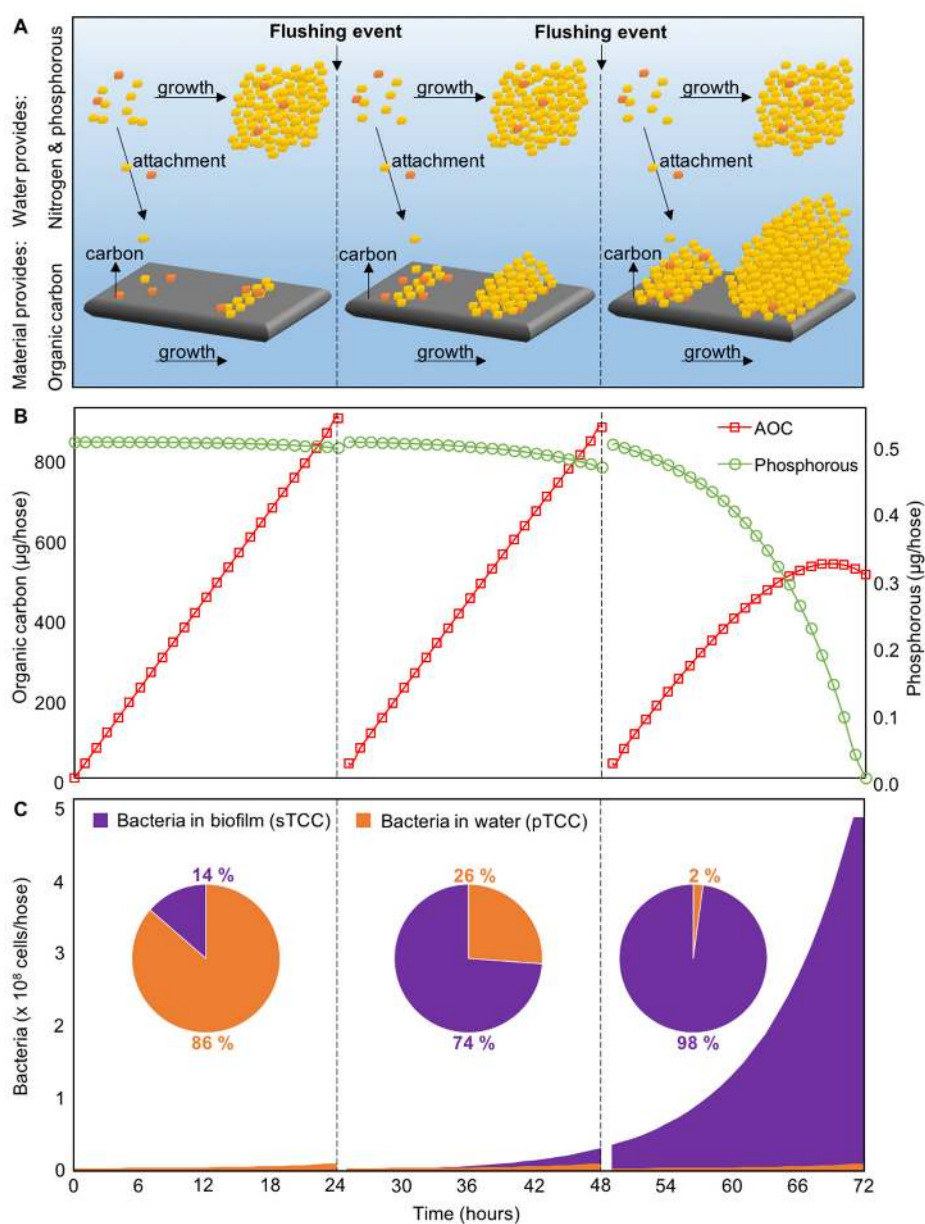


Figure 4. Theoretical example of initial biofilm formation on a new flexible synthetic polymeric material (e.g., PVC-P shower hose). (A) Visualization of the initial stages of biofilm formation, driven by attachment (water-to-surface dispersal) and (nutrient-based selective) growth. (B) Nutrient concentrations with phosphorous deriving from the water and assimilable organic carbon (AOC) migrating from the material. (C) Quantification of bacterial growth, showing rapid domination of the biofilm in the overall distribution of bacteria.

Details and absolute values of this initial biofilm formation “model” will certainly vary between locations. However, we argue that the basic concept will be the same. Consequently, these quantitative considerations are important as (1) bacterial/biofilm growth within building plumbing systems (and here especially on low-quality flexible materials) is relevant regarding drinking water quality and (2) knowledge on such ecological factors opens management options.

5. The Relevance and Management of Building Plumbing Biofilms

To be able to ensure high-quality drinking water until the point of consumption requires the understanding of basic principles of microbial ecology, as well as the collaboration and interplay between various disciplines and stakeholders (e.g., material producers, plumbers, planners, architects, home owners, and scientists).

5.1. Why Should We Care?

A lack in understanding bacterial growth in building plumbing systems equals a lack of control and can result in aesthetic, operational, and/or hygienic problems. Aesthetic and operational problems often manifest in customer dissatisfaction involving taste, odor, color, particles, or water pressure; all of which potentially indicate water quality deterioration [88]. Hygienic problems are particularly relevant, as the number of building plumbing related waterborne disease incidents increased over the last decades. A good example is the worldwide increase in Legionnaires' disease incidents, for example in the US (4.5-fold between 2000–2015 [89]) and Switzerland (four-fold between 2000–2015 [90]). The causative organism, *Legionella pneumophila*, is thriving in building plumbing systems, especially in biofilms [91]. Additionally, opportunistic pathogens such as *Pseudomonas aeruginosa* and *Mycobacterium avium* were shown to grow preferably in building plumbing systems [92]. For example, a nation-wide German study in 2010 detected *Pseudomonas* sp. above the legal limit (0 CFU/100 mL) in approximately 3% of all drinking water samples taken (n = 3468) [93]. The relevance of increasing *Pseudomonas aeruginosa* appearances has been discussed by Bédard et al. [94], highlighting not only their capability of incorporation in building plumbing biofilms but also the emerging health risk for susceptible people, e.g., cystic fibrosis patients. *M. avium* has, for example, been found to colonize shower heads, with 20% positive samples in a survey study by Feazel et al. [95] (n = 52 samples from 42 different sampling sites). This is critical as *M. avium* is an agent of pulmonary disease, leaving the inhalation of shower water droplets and aerosols as a major transfer route and risk area [96,97].

To emphasize this point, all of the opportunistic pathogens mentioned above are commonly detected in building plumbing biofilms [33]. However, to date, a connection between properties of materials and pathogenic growth is only done sporadically. One example by Wen et al. [65] used a pathogen growth potential assay [98], which illustrated the ability of selected pathogens to grow on migrated compounds as sole carbon sources. Additionally, previous studies showed: (1) that the number of growing bacteria increases with decreasing material quality (e.g., PEX_c < EPDC_{certified} < EPDM_{non-certified}) and (2) that an increase in bacterial numbers correlates with a higher concentrations of *L. pneumophila* [74,78]. However, to date, no clear correlations between specific materials and specific pathogens have been established.

5.2. What Can We Do?

One straightforward microbial management strategy for new building plumbing systems is to limit the overall use components that are made by default from lower quality materials (e.g., hoses, sealing rings) and only use the highest quality materials for specific applications (Table 1). This strategy depends on (1) proper microbial quality control for all materials in contact with drinking water, (2) knowledge exchange between all stakeholders to raise awareness of microbiological relevance and hygienic issues in building plumbing, and (3) further research to develop a better understanding of the microbial ecology of building plumbing systems.

1. A quality label for good materials: Important for the widespread use of high-quality materials are sensible and standardized quality control procedures. Irrespective of legal guidelines, assays for the assessment of carbon migration and growth potential exist (Section 3 [69]) and can be used by both material producers and policy makers. The result would be a material-grading system that is ideally freely available to all stakeholders, including plumbers, planners, and architects. This material grading system can, for example, be in form of a quality label, which enables

easy identification of high-quality materials for both professional and private costumers. Here, the incentive for producers would be the competitive advantage gained over lower quality products from competitors.

2. Information sharing: To address microbiological challenges requires extensive information sharing between the diverse stakeholders in building plumbing systems. Here, scientists have an opportunity to contribute knowledge on how the basic principles in microbial ecology relates to different plumbing materials and ultimately water quality. One example can be to incorporate microbiology courses in basic training and teaching modules for plumbers and architects. On a different level, opportunities exist to collaborate with producers of plumbing materials and fixtures on applied research projects focusing on the evaluation of (existing) material properties, their interaction with microorganisms, and their dependency on environmental conditions in buildings. Finally, it is important to engage the public as the end-users who are operating the building plumbing systems and therefore create the conditions that influence material behavior and microbiological growth potential. Elucidating the impact of low-quality materials on drinking water microbial quality will incentivize users to invest in high-quality materials, for example, when purchasing a new shower hose or fixture.
3. Further research: Considerable knowledge gaps exist in our understanding of the microbial ecology of building plumbing systems. There is a clear need for additional pilot- and full-scale experiments dealing with the interplay between existing materials, the developing microbial community, and water quality. More precisely, a better understanding is needed of a materials' behavior in the context of complex building plumbing systems (e.g., fluctuating water temperatures, stagnation, disinfectant residuals, different materials in concert, etc.). Additionally, it is still completely unclear whether material-specific microbial communities establish when similar plumbing materials are used in different locations, or what exactly the impact of source water differences (e.g., community composition) are on the microbiome development. In a similar vein, research is needed on whether specific materials (additives) favor the establishment of specific opportunistic pathogens. Finally, with respect to building plumbing, there are clear research opportunities in the field of new material design/development. On the one hand, there is interest in developing anti-microbial strategies focusing on surface-coatings (e.g., copper or silver [99]). Similarly, there is ongoing research on materials with anti-adhesive properties to combat fouling [100]. On the other hand, we propose that material design might also move towards exploring the management of a "good," stable microbial community composition. In this regard, Wang et al. [65] proposed a probiotic approach in which they would introduce specific bacteria into the building plumbing system, potentially coupled with a prebiotic approach of creating favorable conditions for such organisms in building plumbing systems. With respect to the latter, one option would be to tailor the leaching properties of a specific material (nutrient type, rate) to selected probiotic microorganisms in order to sustain their presence/dominance in a plumbing system.

6. Conclusions

- Conditions within building plumbing systems impact and change the microbial community composition of the water, potentially resulting in quality deterioration.
- Flexible synthetic materials leach organic carbon, which not only increases the potential for bacterial growth but also drives selection within the establishing biofilm community.
- Ecological principles can be used to understand and quantify microbial growth dynamics and their dependency on engineered components of plumbing systems.
- Gaining and sharing knowledge on the interaction between material properties and microbiology provides stakeholders with the possibility to actively manage building plumbing microbiology through material design, material selection, and operation.

- The exclusive use of high-quality materials in new building plumbing systems poses a straightforward strategy towards managing the building plumbing microbiome.

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