frontiers | Frontiers in Built Environment

TYPE Mini Review
PUBLISHED 07 June 2023
DOI 10.3389/fbuil.2023.1212920

Methods for infection prevention in the built environment—a mini-review

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RECEIVED 27 April 2023
ACCEPTED 30 May 2023
PUBLISHED 07 June 2023

CITATION
Salonen N, Ahonen M, Sirén K, Mäkinen R, Anttila V-J, Kivisaari M, Salonen K, Pelto-Huikko A and Latva M (2023), Methods for infection prevention in the built environment—a mini-review. *Front. Built Environ.* 9:1212920. doi: 10.3389/fbuil.2023.1212920

The COVID-19 pandemic has shown that infection prevention actions need to be more efficient in public indoor environments. In addition to SARS-CoV-2, the cause of COVID-19, many pathogens, including other infectious viruses, antibiotic-resistant bacteria, and premise plumbing pathogens, are an invisible threat, especially in public indoor spaces. The indoor hygiene concept for comprehensive infection prevention in built environments highlights that the indoor environment should be considered as a whole when aiming to create buildings with increased infection prevention capacity. Within indoor environments, infections can indirectly spread through surfaces, air, and water systems. Many methods, such as antimicrobial technologies and engineering solutions, targeting these indoor elements are available, which aim to increase the hygiene level in indoor environments. The architectural design itself lays a foundation for more efficient infection prevention in public buildings. Touchless solutions and antimicrobial coatings can be applied to frequently touched surfaces to prevent indirect contact infection. Special ventilation solutions and air purification systems should be considered to prevent airborne infection transmissions. Proper design and use of water supply systems combined with water treatment devices, if necessary, are important in controlling premise plumbing pathogens. This article gives a concise review of the functional and available hygiene-increasing methods—concentrating on indoor surfaces, indoor air, and water systems—to help the professionals, such as designers, engineers, and maintenance personnel, involved in the different stages of a building's lifecycle, to increase the infection prevention capacity of public buildings.

KEYWORDS

indoor environment, infection prevention, healthy buildings, antimicrobial surfaces, indoor air, premise plumbing

Introduction

Despite the development of medicine, humankind still suffers from numerous infectious diseases. Emerging zoonotic viruses, drug-resistant bacteria and fungi, as well as well-known older pathogens, such as *Legionella pneumophila* and influenza viruses, are a concern (Kanarek et al., 2022; Mohapatra and Menon, 2022; Rehman, 2023). As attempts to treat infections have often turned out to be expensive and insufficient, more attention should be paid, in advance, to preventing infections.

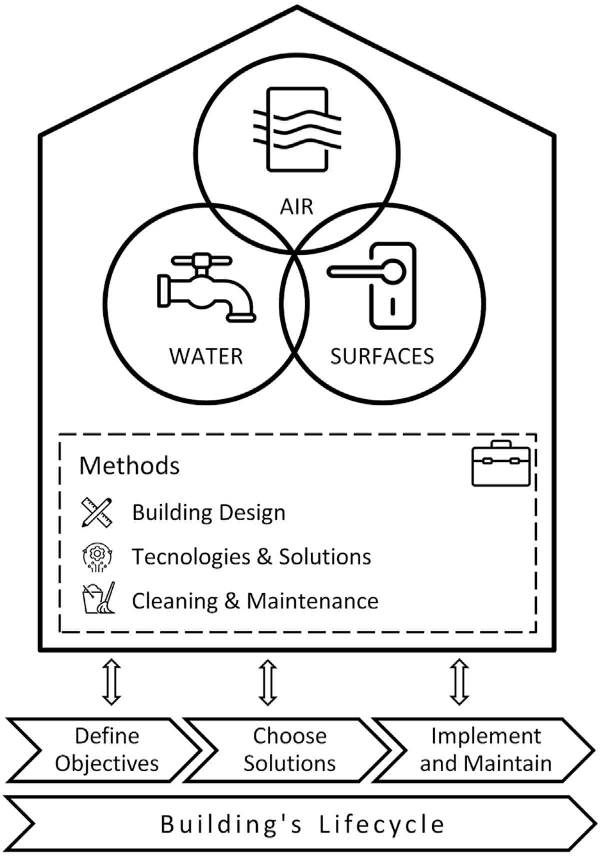

FIGURE 1
Simplified presentation of the indoor hygiene concept for creating hygienic indoor environments. All the elements of the indoor environment—surfaces, air, and water system—should be considered for infection prevention because of the different habitats of micro-organisms and different routes of infection transmission. Efficient infection prevention in built environments includes appropriate infection prevention methods targeted at all these elements. A hygienic indoor environment is created throughout a building's lifecycle, starting from defining the hygiene objectives at an early stage, continuing to choose suitable solutions, and then implementing and maintaining them. A building's lifecycle starts from the needs assessment and design stages and continues to construction, commissioning, and use (Salonen et al., 2022). The icons in the figure are downloaded from Icons8 (Icons8, 2023).

The indoor environment plays an important role in mediating infections because people generally spend a lot of time indoors. Many infections can be transmitted through indoor environments, and the possible transmission routes are fomite transmission caused by touching contaminated surfaces, airborne transmission caused by breathing contaminated air, and waterborne transmission caused by being exposed to contaminated water (Dai et al., 2017).

Green building has gained much attention to achieve energy efficiency and low greenhouse gas emissions in construction (Doan et al., 2017; Udomiaye et al., 2022). However, few design and engineering-based measures have been employed to limit infection transmissions in public buildings, excluding healthcare facilities (Morawska et al., 2021). Thus, there is a need for designing, constructing, and renovating healthier buildings that can limit infection transmissions within built environments. Public buildings where many people pass through, such as public transport terminals and shopping centers, and buildings accommodating people with low immunity, such as nurseries and rest homes, should be the focus. Implementing solutions for infection prevention in indoor environments, such as antimicrobial materials, increases building costs, but it will also prevent economic losses in the form of medical treatment and sick leaves (Cutler and Summers, 2020; Falkinham, 2020; Abraham et al., 2021; Morawska et al., 2021).

We have previously introduced the indoor hygiene concept, summarized in Figure 1, which establishes a comprehensive infection prevention framework for built environments (Salonen et al., 2022). Creating healthy and hygienic buildings requires technical knowledge from the professionals, involved in different phases of the building's lifecycle, on how to improve the infection-prevention capacity of indoor environments. To meet this challenge, the current review summarizes the available methods, which have capacity to decrease the spread of infections in indoor environments, concentrating on antimicrobial technologies and solutions targeted to indoor surfaces, indoor air, and water systems.

Infection-preventing building design

Construction engineering decisions influence the building's infection-prevention capacity throughout its lifecycle. Health-related choices are made in the architectural, spatial, internal facilities, premise plumbing system, and HVAC (heating, ventilating, and air-conditioning) design.

The architectural design can support infection prevention by prioritizing compact, clear, and easy-to-clean structures and flexible design solutions to cope with changing demands. Adequate spacing is required to support social distancing when needed. Decreasing opportunities for close social interactions, for example, by designing private offices instead of densely populated open offices, lessens the probability of infection transmissions (Dietz et al., 2020; Udomiaye et al., 2020; Shepley et al., 2021). Building design can be utilized to control the flow of people and supply traffic. Separating dirty areas from clean ones should be carefully designed to prevent cross-contamination. Cleaning and maintenance rooms should be centrally located and easily accessible.

Spatial planning can support adequate ventilation, especially when utilizing natural ventilation, by avoiding closed-end corridors, lobbies, and waiting areas. In areas of abundant sunlight, adequate windows can allow daylight to reach the indoor space decreasing the spread of pathogens (Udomiaye et al., 2022).

High hygiene in furnishing and equipment can be pursued, for example, by choosing antimicrobial and antifouling materials and utilizing touchless technologies. When installing any product, the accumulation of dirt on the product's surface should be minimal, and the product and its surroundings should be easily cleanable. Maintaining hand hygiene should be made easy, such as by appropriately locating hand sanitizer dispensers and hand washing points (Stiller et al., 2016; Clancy et al., 2021).

The next sections will discuss how to improve the infection prevention capacity of indoor surfaces, ventilation, and water systems. The available and functional infection-preventing technologies and solutions are summarized in Table 1.

TABLE 1 The available and functional antimicrobial technologies and solutions for indoor surfaces, HVAC, and water systems for establishing hygienic indoor environments with increased infection-prevention capacity. Determining the hygiene requirements for the indoor environment in question helps to select the appropriate solutions. The list of references is not fully comprehensive.

Antimicrobial technology or solution	Description	Advantages	Disadvantages	References
Surfaces				
Release active surfaces	Surfaces are preloaded with biocides that need to be released to destroy micro-organisms. Surface-released biocides can damage different components in microorganisms, such as outer membranes, proteins, and nucleic acids. In addition, they can generate ROS that kill microbes. For example, copper, silver, and zinc-containing coatings, fabrics, and paints are available	+The oldest and most studied group of antimicrobial surface materials +Many applications available	-Effectiveness can depend on environmental factors (e.g., humidity) -Possible release of antimicrobial agents to the environment -Possible increase of microbial resistance or tolerance to metals or co-selection of antibiotic resistance	Taylor et al., 2009; Verbič et al., 2019; Mitra et al., 2020; Pietsch et al., 2020; Lara et al., 2020; Abraham et al., 2021; Blomberg et al., 2022
Contact active surfaces	Biocides are permanently bound to surfaces and destroy micro-organisms when they meet the surface. For example, a strong positive charge attracts microorganisms and interferes with their genomic content or structural units causing disintegration. Polycations, such as polyethyleneimines, can be applied, for example, through painting. Specific antimicrobial surface nanopatterns have also been shown to damage microbes	+No release of biocides to surroundings +Antimicrobial properties are permanent +Development of resistance is unlikely	-Novel approach, not yet many applications available for indoor surfaces	Kaur and Liu, 2016; Zubris et al., 2017; Modaresifar et al., 2019; Imani et al., 2020
Anti-adhesive surfaces	Anti-adhesive or antifouling surfaces reject the adhesion of microorganisms. They are often based on superhydrophilic or superhydrophobic surfaces or specific surface topography. For example, hydrophilic polyethylene glycol (PEG) attached to the surface prevents the adhesion of microorganisms	+No risk of increase in resistance or microbial imbalance +Surfaces are typically also easy to clean because they repel organic dirt	-Do not kill microbes and they may end up on other surfaces	Dancer, 2014; Encinas et al., 2020; Olmos and González-Benito, 2021; Zou et al., 2021
Light-activated antimicrobial surfaces	Light-activated antimicrobial surfaces can excite electrons under a specific light, which results in the production of ROS on the surface from H_2O and O_2. The highly reactive ROS degrades organic contaminants, including microbes on the surface. The most used photocatalyst is TiO_2 (also, e.g., ZnO). Coatings can be applied to surfaces, for example, by spraying or within paints	+Can be applied to old or new surfaces and on different materials +Photo-oxidation of cell debris and organic matter results in a self-cleaning surface +Low risk of an increase in microbial resistance	- Specific light sources are often required to gain full activity (e.g., ultraviolet (UV) or blue light, which is switched on when the space is not occupied) -Not all surfaces in the indoor environment are reachable by light	Walker et al., 2017; Mathew et al., 2018; Bishweshwar et al., 2019; Meng et al., 2019; Hwang et al., 2020; Schutte-Smith et al., 2023
Touch-free solutions	Replacing touch surfaces with touchless options decreases opportunities for infection transmissions via surfaces. For example, touch-free faucets, soap dispensers, lights, and doors are available	+Easy and practical alternative without the use of antimicrobial materials	-Require typically more technology than non-touchless solutions	Dancer et al., 2021; Salonen et al., 2022; Navaratnam et al., 2022
Antimicrobial light	UV-C radiation can be used to control the number of harmful microorganisms on indoor surfaces. UV-C damages the DNA of microbes. Lamps can be installed on walls or ceilings and automated to switch off when the room is	+Automatic +Simultaneous disinfection of surfaces and air +The antimicrobial effect can be enhanced by using photocatalytic coatings on surfaces	-Not all surfaces in the indoor environment are reachable by light - UV can be utilized when the room is not occupied, or the occupants are protected -UV can harm materials	Wang et al., 2017; Inagaki et al., 2020; Füszl et al., 2021; Demeersseman et al., 2023; Graeffe et al., 2023

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TABLE 1 (*Continued*) The available and functional antimicrobial technologies and solutions for indoor surfaces, HVAC, and water systems for establishing hygienic indoor environments with increased infection-prevention capacity. Determining the hygiene requirements for the indoor environment in question helps to select the appropriate solutions. The list of references is not fully comprehensive.

Antimicrobial technology or solution	Description	Advantages	Disadvantages	References
	occupied. UV robots and UV disinfection chambers for small objects are available. In addition, blue light in the spectrum of 400–470 nm has antimicrobial properties based on exciting endogenous photosensitizers leading to ROS production		-UV can produce ozone or other harmful compounds in the air	
HVAC				
Increased ventilation rate	Higher air exchange rates in buildings help to dilute indoor air contaminants, including pathogen-containing aerosols, thus decreasing the probability of airborne infection transmission. This is applicable for mechanical ventilation when the ventilation rate is adjustable. In some cases, the ventilation rate can be increased by opening windows	+Easy and simple way to decrease the probability of airborne transmission	-Increases energy demand -Does not guarantee protection if the airflow patterns, inlet and outlet locations, and supplied air velocity are not properly designed	Pantelic and Tham, 2013; Dietz et al., 2020; Izadyar and Miller, 2022
Displacement ventilation	Cool fresh air is supplied near the floor level and moves upward vertically to the exhaust. Contaminated air is displaced with the fresh air. Polluted air is not mixed with fresh air, as with the mixing ventilation. This is suitable for high rooms with no fans or other sources causing air mixing	+Not mixing the fresh and polluted air, thus, decreasing the risk of infection transmission	-Sufficient room height required -Heating is often required -Airflows caused by the movement of people and unexpected sources of heat can send the polluted air back to the occupant level -Risk for draught at the floor level	Cao et al., 2014b; Bhagat and Linden, 2020; Izadyar and Miller, 2022
Personalized ventilation	Fresh air is supplied directly to the breathing zones, such as to workstations or patient beds. It can be combined with the existing ventilation strategy. Local exhaust, in addition to air inlet, can improve performance	+Reduces energy use and clean air demand	-Airflows caused by the movement of people can disturb the protected zones -Fixed locations for occupants need to be known	Cao et al., 2014a; Izadyar and Miller, 2022
Protected occupied zone ventilation	Indoor space is separated into a few subzones protected from one another using a low turbulence plane jet diffuser	+Can be used to protect chosen areas in the indoor space from infective particles	- Airflows caused by the movement of people can disturb the protected zones -Always leaks, no full separation	Cao et al., 2014a; Cao et al., 2014b; Cao et al., 2017; Izadyar and Miller, 2022
Pressure differentials	With pressure differentials, airflows can be controlled to flow from areas of high cleanliness to areas of lower cleanliness, from personal use areas to public areas. Positive pressure is created in the spaces where people need to be protected. Negative pressure is recommended, such as for toilets and other areas with lower hygienic levels	+Can be used to protect chosen rooms or separate spaces from infective particles	-Opening doors can enable the infective particles to escape -Doors need to be closed or preferably a specific anteroom placed between the clean and polluted rooms	Offermann et al., 2016; Guo et al., 2021; Izadyar and Miller, 2022
Physical barriers	Physical barriers can be used to prevent the spread of virus-containing airborne particles. For example, plexiglass barriers can be installed to protect workstations in open spaces. The height of the barriers and their locations in relation to the air outlets and infection sources are important parameters	+Easy way to mitigate the spread of infective particles +Can be installed also in old buildings	-The level of protection depends on, for example, the location of the infection source and the airflow patterns in the space	Ren et al., 2021; Izadyar and Miller, 2022

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Antimicrobial technology or solution	Description	Advantages	Disadvantages	References
Mechanical filters	Indoor air can be purified using filters capable of removing particles containing microorganisms. High-efficiency MERV filters (MERV 13–16) or more efficient HEPA (high-efficiency particulate air) filters are suitable for microbial decontamination. HEPA filters can remove at least 99.97% of particles of 0.3 µm (MERV 17–20). Filters can be centralized or portable	+No production of harmful by-products + High-efficiency MERV filters can decrease contamination at a reasonable price +Can be combined with UV disinfection	-Require fan energy (especially HEPA filters) - Require maintenance (replacing filters) -Do not destroy the microbes causing risk of secondary pollution	Azimi and Stephens, 2013; Zhang et al., 2020b; Guo et al., 2021; Izadyar and Miller, 2022; Szczotko et al., 2022
Electrostatic precipitators (ESP)	Electrostatic precipitators use static electricity to charge impurities in the air, which are then collected on charged plates inside the purifier. Microbes are inactivated. Portable disinfectors can be installed in different spaces	+Remove particles in the nanometer scale +Can be combined with an activated carbon filter to remove volatile organic compounds (VOCs)	-Require energy -Generate waste -May generate ozone	Feng et al. (2021)
Non-thermal plasma air purifiers	Non-thermal plasma air purifiers release bipolar ions that stick to airborne impurities (e.g., viruses, bacteria, VOCs) and destroy them via generated free radicals. They can be combined with other air-cleaning technologies to improve performance and minimize by-product formation	+Remove microbes, particles, and VOCs	-Generate ozone and other by-products -Require energy	Bahri and Haghighat, 2013; Hernandez-Díaz et al., 2021; Szczotko et al., 2022
Photocatalytic oxidation air purifiers (PCO)	The photocatalytic oxidation system uses UV light and (usually) a TiO_2 catalyst to produce radicals. Airborne pollutants, including microorganisms, are oxidized and degraded. PCO units can be mounted to an existing forced-air HVAC system	+Degradation of toxic compounds into non-toxic ones +Low energy consumption	-Generate by-products -Require maintenance (catalyst replacement) -Increased humidity inhibits PCO	Zhong and Haghighat, 2015; Binas et al., 2017; Ahmadi et al., 2021; Szczotko et al., 2022
Air disinfection with UV	Airborne microorganisms are killed by the absorption of UV-C light causing DNA damage. UV lamps can be installed in the upper part of a room limiting the exposure in the occupied zone and/or switched on when the room is unoccupied. Installation within air-conditioning systems and ventilation ducts can be used to disinfect circulated air	+Low energy consumption +Simultaneous disinfection of air and surfaces	-Possible harm to materials -Can generate by-products -Does not remove particles -Only partial disinfection - Maintenance required - Restricted use when the space is occupied	Kowalski, 2009; Morawska et al., 2020; Szczotko et al., 2022
Water systems				
Temperature adjustments	Keeping cold water <20°C and hot water >55°C will restrain microbial growth in water systems because optimal growth temperatures for many microbess it between those temperatures. Flushing with hot (70°C) water from time to time can be used for thermal disinfection of pipes and taps. Avoiding recirculation of hot water decreases the possibility of maintaining optimal growth temperature for opportunistic pathogens	+ Easily applied, also to older buildings + Efficient way to decrease the growth of certain pathogens	-Higher hot water temperature increases energy consumption -Flushing to keep cold water cold, increases water consumption -High hot water temperatures pose a risk of burns	Gavalda et al., 2019; Falkinham, 2020; Leslie et al., 2021

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Antimicrobial technology or solution	Description	Advantages	Disadvantages	References
Flow control	Regular flushing of rarely used pipelines increases the microbiological quality of tap water. Increased water age and stagnation of water in rarely used pipelines allow harmful micro-organisms to proliferate and accumulate	+ Easily applied, also to older buildings +Efficient way to decrease microbial counts	-Increases water consumption -Work required if automatic flushing is not available	Singh et al., 2020; Leslie et al., 2021; Julien et al., 2022; Rahmatika et al., 2022
Pipeline design and configuration and the materials used in contact with water	Correct sizing of the premise plumbing system, based on demand, decreases water age. Eliminating dead-ends helps to avoid stagnation. Copper as a plumbing material does not encourage microbial growth. Some rubber and plastic materials may enhance growth by releasing organic nutrients.	+Decrease the demand for other measures of microbiological control +Decrease pressure build-ups +Decrease energy and water requirements	-Applicable mostly to new construction	Inkinen et al., 2017b Julien et al., 2020; Leslie et al., 2021; Logan-Jackson et al., 2023
Control of scaling	Magnetic water treatment removes scaling and precipitates inside pipes by introducing an alternative magnetic field in the flowing water and causing the formation of nanobubbles. Ultrasound cleaning can be utilized to dislodge solid residues and remove biological and other fouling. The disinfection effects result from acoustic cavitation, which leads to chemical, mechanical, and heat effects.	+Improved quality of water and pipes + Makes the conditions less favorable for microbes +Decreases corrosion and increases the effect of thermal or chemical disinfection +Applicable also to older buildings	-Removal of biofilms and scales decreases the water quality temporarily after (the start of) the treatment	Latva et al., 2016; Pečnik et al., 2016; Al-Juboori and Bowtell, 2019; Zou and Tang, 2019; Quach et al., 2020
Filtration	Point-of-use filtration removes harmful microorganisms from drinking water before consumption, which is useful especially for buildings accommodating high-risk people. Filtration devices can be installed on faucets and shower heads or under a kitchen counter or bathroom sink.	+Easily applied in the case of contamination or preventively +Applicable also to older buildings	-Requires maintenance of filters	Molloy et al., 2008; Cervia et al., 2010; Leslie et al., 2021
Disinfection	On-site disinfection of water can be achieved, for example, by chlorine-based chemicals, UV light, ozone (produced on-site), and copper-silver ionization. Water disinfection is useful in epidemic situations but also preventing installations can be done. In addition, regular disinfection of showerheads is sometimes recommended.	+Quick help in the case of contamination	-May cause harmful by-products in the water -May change the smell and taste of the water -Microbes, especially in biofilms, can resist disinfection	Lin et al., 2011; Falkinham, 2020; Leslie et al., 2021; Buse et al., 2022; LeChevallier, 2023
Choice of water outlets	Aerosol-generating devices should be avoided (hot tubs, fountains, “ultrasonic” humidifiers, etc.) because pathogen-containing aerosols are an important source of infection. Installation of showerheads with large holes helps to avoid the formation of aerosols.	+Cheap and easy to apply	-User experience can be less pleasant	Falkinham (2020)

Indoor surfaces

Microbial contamination on indoor surfaces often originates from people touching the surfaces with contaminated hands or causing airborne contamination settling on surfaces (Dai et al., 2017). Many harmful micro-organisms can stay viable on dry inanimate surfaces from hours to several months, thus increasing the likelihood of onward transmission via touching surfaces (Otter et al., 2013; Cook et al., 2016; Cassidy et al., 2020; Kampf et al., 2020; Riddell et al., 2020).

Frequent cleaning and disinfection are important when controlling the microbial load on surfaces. However, they are often not sufficient to fully eliminate harmful micro-organisms because of poor cleaning practices, overwhelming bioburden, and disinfectant tolerance (Dancer, 2014; Meyer et al., 2021). Cleaning is often not performed immediately after contamination, and, thus, there is time for infection transmission before cleaning. Replacing as many touch surfaces as possible with touchless options, such as touchless faucets, soap containers, and automatic doors and lights, helps to decrease human contact with surfaces (Dancer et al., 2021; Navaratnam et al., 2022).

Using antimicrobial materials that repel or kill microbes can also improve surface hygiene. Antimicrobial materials typically offer a continuous and nonspecific intervention targeting a wide spectrum of microbes, including bacteria, viruses, and fungi. Inactivation can occur even minutes after contamination depending on the used technology, the microbes present, and environmental conditions. Using antimicrobial materials on critical surfaces, such as door handles, handrails, and toilet flush buttons, would stop these surfaces from functioning as microbial reservoirs, thus reducing the risk of indirect contact infections. Antimicrobial material can be used as the surface itself, such as copper, or can be incorporated into a bulk material to be used, for example, as a paint, coating, or fabric.

Antimicrobial surfaces can be classified by their functional principle (Ahonen et al., 2017), but several mechanisms may also act in parallel (Adlhart et al., 2018). Different antimicrobial solutions for indoor surfaces are summarized in Table 1. Light-activated antimicrobial surfaces can excite electrons under a specific light, producing the reactive oxygen species (ROS) on the surface that degrade organic contaminants, including microbes. Titanium dioxide (TiO_2) is probably the best-known light-activated antimicrobial material and is widely used in antimicrobial coatings (Shang et al., 2022). For better stability and action under visible light, TiO_2 has been morphologically modified and doped with metal and non-metal elements (Nigussie et al., 2018; Schutte-Smith et al., 2023). For example, Ag-doped TiO_2 caused the decomposition of *Escherichia coli* cells in 3 h under visible light (Endo et al., 2018).

Silver and copper are classified as release killing because the release of the ionic species is required for the antimicrobial effect (Ahonen et al., 2017). Copper and some copper alloys can destroy even over 99% of bacteria within 2 hours after contamination even after repeated contamination (Abraham et al., 2021). SARS-CoV-2 was inactivated in 4 h, coronavirus 229E in a couple of minutes, and norovirus in 5–30 min on copper surfaces (Warnes and Keevil, 2013; Warnes et al., 2015; van Doremalen et al., 2020). In real-life studies, copper surfaces have been shown to harbor 33%–90% fewer bacteria than conventional touch surfaces (Inkinen et al., 2017a; Colin et al., 2018). Hard surfaces and linens containing copper have been associated with fewer healthcare-associated infections (von Dessauer et al., 2016; Lazary et al., 2014; Marcus et al., 2017; Salgado et al., 2013; Sifri et al., 2016; Zerbib et al., 2020). Unlike copper, silver is more effective in moist surroundings or as silver compounds or nanoparticles, because silver is less susceptible to the surface oxidation required to produce the ionic species (Pietsch et al., 2020). When several fittings in a hospital setting were replaced with silver-incorporated replicates, the average microbial contamination was reduced by 96% (Taylor et al., 2009). However, studies on the effects of silver-containing surfaces on preventing infections are scarce.

When comparing antimicrobial coatings, the time required for the elimination of microbes is an important factor. The standards used for evaluating the efficacy of antimicrobial coatings often have a testing time of 24 h (ISO 22196:2011, 2011; ISO 21702:2019, 2019). However, a significant level of elimination should be more quickly reached for the coating to fulfill its purpose. Before installing antimicrobial coating, it is also important to consider that the possible release of antimicrobial agents from the coating may affect its shelf life and lead to environmental contamination (Rosenberg et al., 2019). The potential effects of antimicrobial surfaces on microbial communities and resistance need further study (Mäki, et al., 2023). Until then, the application of antimicrobial surfaces should be limited to frequently touched locations in public indoor environments (Dunne et al., 2018).

Regular cleaning maintains a hygienic indoor environment. Antimicrobial surfaces also need cleaning because dirtiness may hinder their function. The cleaning method should be suitable for the material in question to retain its desired function (Dunne et al., 2018). The cleanliness of surfaces can be verified, for example, by ATP or optical measurements (Inkinen et al., 2019; Kwan et al., 2019).

Indoor air

Harmful micro-organisms in indoor air typically originate when human carriers cough, sneeze, talk, or simply exhale. These actions spread microbes in droplets and aerosols to the surroundings. Droplets usually settle close to their origin, while aerosols can travel a longer distance and be inhaled, causing airborne transmission. For example, SARS-CoV-2 can remain infectious in aerosols for several hours, making airborne transmission a risk even when the source is not present anymore (van Doremalen et al., 2020). Although many viral diseases, such as chicken pox and measles, are well-known for airborne transmission, airborne bacteria, such as *Mycobacterium tuberculosis*, also cause infections (Fujiyoshi et al., 2017; Swaminathan et al., 2021).

HVAC systems have received attention because of the airborne spread of COVID-19 (Zhang et al., 2020a). Poor ventilation allows contagious aerosols to stay longer in indoor air and is thus associated with increased transmission of airborne infections (Guo et al., 2021). In general, higher outside air fractions and higher air exchange rates in buildings help to dilute indoor air contaminants, including pathogen-containing aerosols, thus decreasing the probability of infection transmission (Dietz et al., 2020). Demand-controlled, flexible ventilation can be adjusted to control energy use (Morawska et al., 2021). Different infection transmission-decreasing solutions for ventilation and air purification are summarized in Table 1.

In mechanical ventilation, air distribution should be designed to deliver external air to each part of the space to efficiently remove airborne pollutants. Exhaled aerosols can be transmitted both directly and via the room air distribution method. Mixing air ventilation—that is, mixing fresh air with polluted air—is not always the best choice. Displacement ventilation, which pushes pollutants upwards from the lower part of the room without mixing the polluted and fresh air, has shown better performance in contaminant removal efficiency. However, when the distance between two people is short, exposure to contaminants seems to be higher with displacement ventilation than with mixing ventilation (Olmedo et al., 2012; Cao et al., 2014a), probably because of the direct connection. Thus, choosing an optimal air distribution system is not straightforward and should be based on the dimensions, the heating strategy, and the planned use of the space. In a warm atmosphere, natural ventilation can sometimes provide a higher ventilation rate in an energy-efficient manner. In a hybrid approach, mechanical ventilation is available if necessary (Udomiaye et al., 2020).

Special ventilation solutions include personalized ventilation installed to workstations, and protective occupied zone ventilation, which separates the indoor area into a few subzones protected from one another (Cao et al., 2014a; Cao et al., 2014b; Cao et al., 2017). Pressure differentials between zones in the building should be controlled so that air flows from less contaminated to more contaminated areas (Guo et al., 2021). Physical barriers placed, for instance, to open offices, can mitigate the spread of aerosols, lowering the risk of infection transmission (Ren et al., 2021).

Air-conditioning systems in large buildings often require circulation of indoor air, especially when a larger cooling capacity is needed. Circulating indoor air creates a certain risk of airborne infection transmission. Air-conditioning systems have been associated with the transmission of SARS-CoV-2 and *L. pneumophila* (Hamilton et al., 2018; Lu et al., 2020; Elsaid and Ahmed, 2021). It is sometimes not possible to increase the ventilation rate enough to lower the risk of infection to an acceptable level (Blocken et al., 2021). These spaces can benefit from air filtration and disinfection strategies (Brągoszewska and Biedroń, 2021; Alvarenga et al., 2023). For example, SARS-CoV-2 was detected in the hospital ward air before the activation of HEPA air filtration and after its deactivation but not during the filter operation (Morris et al., 2022). In an intervention study implementation of an air purifier significantly decreased the number of microbes detected in the air and on surfaces. In addition, the number of hospital-acquired infections was lower when compared to the control space (Arikan et al., 2022). Special air purifiers can be portable or incorporated into a building's HVAC system (Cheek et al., 2021). The air purifier should be selected carefully based on the required capacity and safe performance (Blocken et al., 2021).

For desired performance, the building's HVAC system requires regular maintenance, such as replacing the filters and cleaning the air terminal units and ventilation ducts. The performance of the ventilation system can be monitored by certain parameters, such as temperature, carbon dioxide, humidity, and particle content.

Building water systems

In moist surroundings, many bacteria form biofilms with increased tolerance to biocides and other environmental factors. Building water systems are prone to develop microbiological problems because of high surface area-to-volume ratios, stagnation periods, diverse materials, and low disinfectant levels (McCoy and Rosenblatt, 2015). Biofilms in premise plumbing can form a reservoir for harmful micro-organisms that is difficult to destroy. Starting and stopping pumps as well as opening and closing valves create pressure shocks that may release biofilms into the drinking water. In addition, favorable conditions make biofilm microbes proliferate in water. Waterborne infections can be transmitted when exposed to contaminated water through the gastrointestinal tract, skin, or mucous membranes. In addition, the building's water system, such as toilets and showers, generates aerosols that may cause infection transmissions via the respiratory tract (Dai et al., 2017). Water systems are an important source of *L. pneumophila* and *Pseudomonas aeruginosa*, both of which cause mild to severe infections (Moriz et al., 2010). Biofilms in handwashing sinks can also play a role in outbreaks (Breathnach et al., 2012; Roux et al., 2013; Franco et al., 2020).

The water treatment plants and distribution systems have limited potential to control opportunistic pathogens in a building's plumbing systems. Thus, to reduce the risk of water-borne infection transmission, it is necessary to decrease microbial concentrations in premise plumbing. Implementing a water safety plan for public buildings is recommended (McCoy and Rosenblatt., 2015; Schmidt et al., 2019). Strategies to control premise plumbing pathogens are summarized in Table 1.

Water temperature is an important factor when preventing microbial growth in premise plumbing. Cold water should be kept below 20°C and warm water over 55°C, preferably 60°C at the outlets, to avoid temperatures favorable to micro-organisms. Energy saving often results in too low warm water temperatures, which encourages the growth of *Legionella* (Falkinham, 2020). In a 2-year study, the renovation of a hospital's hot water pipelines and keeping the hot water temperatures around 60°C throughout the whole circuit led to the disappearance of *Legionella* from water samples (Quero et al., 2021). In this context, it is also important to adequately insulate water pipes. Premise hot water systems can be frequently decontaminated by raising the hot water temperature to around 70°C for a certain time and flushing the outlets with hot water (Gavalda et al., 2019). Despite decontamination, biofilms can protect the pathogens, and regrowth can happen within weeks or months (Cazals et al., 2022; Molina et al., 2022). Maintaining regular flow is also important to ensure that the cold water does not increase in temperature, which would enable colonization (Leslie et al., 2021).

Extended water retention time in pipelines and water stagnation in dead-ends or rarely used pipelines result in the loss of residual disinfectant and the proliferation of micro-organisms (Singh et al., 2020; Julien et al., 2022; Rahmatika et al., 2022). Water-efficient fixtures both increase water age and can cause aerosolization, increasing the risk of infection transmission (Leslie et al., 2021). Regular flushing, avoiding dead-ends, and correct sizing of a premise plumbing system help to decrease stagnation.

Copper-silver ionization has been successfully used to control *Legionella* and other opportunistic pathogens in public buildings, however, it must be properly designed, operated, and maintained to be effective. In a hospital case study, copper-silver ionization was installed in two hospital buildings where *Legionella* samples were regularly positive. After installation, the *Legionella* concentrations started to decline and were no more detected after 3 months (LeChevallier, 2023). In the case of disease outbreak or the detection of opportunistic pathogens in building water samples, on-site chemical disinfection can be useful, especially in facilities accommodating at-risk populations. However, biofilms can be 100 to 1,000 times less susceptible than planktonic bacteria to different disinfectants. Even prolonged treatment with chlorine-based disinfectants usually fails to remove all adherent biofilm (Zubris et al., 2017). Thus, reliable control of biofilms requires stringent and repeated cleaning strategies, aimed at physically disrupting them. Magnetic water treatment devices installed to premise plumbing have been shown to remove scales, hence limiting biofilm formation (Latva et al., 2016). In addition, generated nanobubbles may decrease biofilm formation (Xiao et al., 2020). Total eradication of opportunistic pathogens is still difficult to achieve. Instead, limiting their growth and human exposure should be pursued (Dancer, 2014; Julien et al., 2022).

Maintaining a building's drinking water system requires verifying that the water temperatures remain within the required thresholds. The flow must be steady, without harmful pressure buildups. If automatic flushing is used, its function should be regularly checked. In spaces where the quality of water is critical, various parameters, such as water temperatures, disinfectant residuals, and bacterial counts, need to be monitored (Falkinham, 2020; Nakade et al., 2023).

Discussion

COVID-19 has shown that more attention should be paid to the role of indoor environments in infection prevention, especially in public buildings. Being a current topic, infection prevention in indoor environments has been approached in some recent reports discussing healthy architecture, antimicrobial surfaces, and air purification strategies (Dietz et al., 2020; Udomiaye et al., 2020; Shepley et al., 2021; Alhusban and Alhusban, 2022; Amran et al., 2022; Navaratnam et al., 2022; Tokazhanov et al., 2022; Udomiaye et al., 2022; Yong and Calautit, 2023). The articles provide useful recommendations on how to prevent the spread of infections, in particular COVID-19, through air and contact surfaces.

To broaden the perspective to an even more comprehensive approach, the indoor environment should be considered as whole to establish buildings with increased infection prevention capacity. Indoor environments can mediate infections via air, surfaces, and the building's water system. For example, antibiotic-resistant bacteria spread through contaminated indoor surfaces, and premise plumbing pathogens cause a threat via building water systems, especially to people with low immunity. The methods available for increasing indoor hygiene in these areas include building design, antimicrobial technologies and solutions, and cleaning and maintenance. These methods should be implemented already during the design and construction phases and throughout the building's lifecycle. For this purpose, building design and engineering professionals involved in the early stage of the construction or renovation process need to be aware of the opportunities to limit infection transmissions via the indoor environment. Nominating a hygiene-dedicated expert for each construction or renovation project to help set the hygiene targets and monitor their fulfillment throughout the project might be useful (Salonen et al., 2022). Moreover, guidelines for constructing hygienic indoor environments, set by authorities or certificates, would be necessary when integrating the described methods throughout the building's lifecycle.

The goal of infection prevention may sometimes conflict with other objectives, such as sustainability. Energy and water conservation strategies can enable pathogens to proliferate in a building's water system. Thus, it is important to design and operate a building according to its purpose to keep the infection risk at an acceptable level. For example, hospitals have different requirements for indoor hygiene than museums or swimming halls. Flexible and demand-controlled design solutions help to adapt to changing situations.

Plenty of antimicrobial technologies and solutions for indoor surfaces, ventilation, and water systems are available and more are under research. It is not always easy to evaluate which of these are effective. More real-life studies are required to clarify the impacts of antimicrobial technologies and engineering solutions on the viability and spread of pathogens. However, no standard protocols are available, for example, for testing the antimicrobial efficacy of antimicrobial coatings in real-life settings. More research is also required to determine the effects of antimicrobial technologies and solutions, or more generally, hygienic indoor environments, on morbidity to infectious diseases, and demonstrate their cost-effectiveness.

Author contributions

NS prepared the manuscript. MA contributed to supervising the writing process, editing the text, and administering the project. KS contributed to supervising and editing the indoor air section. RM contributed to editing the text and acquiring funding. V-JA contributed to editing the text concerning clinical aspects. MK contributed to editing the indoor surfaces section. KS contributed to creating Figure 1. AP-H contributed to editing the building water systems section. ML contributed to supervising the writing process, editing the text, and acquiring funding. All authors contributed to the article and approved the submitted version.

Funding

This study was funded by the Ministry of Education and Culture in Finland and Satakunta University of Applied Sciences. It is a part of the project HEAL: healthier life with the comprehensive indoor hygiene concept. The grant number for the HEAL project is OKM/119/523/2021.

Acknowledgments

We thank the funders and all participants of the following project: HEAL: healthier life with the comprehensive indoor hygiene concept, 1/2022 onwards, the Ministry of Education and Culture, Finland.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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