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# A Comprehensive Review on the Integration of Antimicrobial Technologies onto Various Surfaces of the Built Environment

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**Abstract:** With the recent surge in interest in microbial prevention, this review paper looks at the different antimicrobial technologies for surfaces in the built environment. Every year, more than 4 million people are at risk of dying due to acquiring a microbial infection. As per the recent COVID-19 pandemic, such infections alone increase the cost and burden to the healthcare system. Therefore, mitigating the risk of microbial infection in the built environment is one of the essential considerations in our preparedness for future pandemic situations. This is especially important for a dense population within urban cities and for indoor environments with higher concentrations of indoor contaminants due to poorer ventilation. The review assesses antimicrobial technologies developed in the last two years and their potential and suitability for implementation on surfaces within a building, and it also suggests key considerations when developing these technologies for a built environment. The keywords in the main search include "antimicrobial", "coating", and "surfaces". The work found various studies describing the potential use of antimicrobial technologies for different material surfaces. Still, a more thorough investigation and upscaling of work are required to assess their suitability for built environment applications. The widely diverse types of built environments in public areas with their varying purpose, design, and surfaces also mean that there is no "one-size-fits-all" solution for every space. In order to improve the adoption and consideration of antimicrobial surfaces, the built environment industry and stakeholders could benefit from more in-depth and long-term evaluation of these antimicrobial technologies, which demonstrate their real-time impact on various built environment spaces.

**Keywords:** antimicrobial; buildings; coating; COVID-19; surface; materials

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## 1. Introduction, Gaps, and Method

Antimicrobials contain chemical substances that could kill or inhibit the growth of microorganisms [1]. In a built environment, antimicrobial technologies mostly come in the form of a formulated coating, which can be applied with different methods. They can either be used to reduce mold growth in a building or to prevent the transmission of harmful microorganisms [2]. This review's objective is to focus on the latter concerning pathogen and disease transmissions.

Microbial infections are global health challenges that have caused a significant burden on the healthcare system, even more so than cancer or cardiovascular disease [3]. According to World Health Organization (WHO), in developed countries, 7 out of 100 hospitalized patients, and in developing countries, 10 out of 100 hospitalized patients, will acquire at least one healthcare infection [4]. Following an earlier review on antimicrobial resistance [5], in 2019, the UN's ad hoc Interagency Coordinating Group on Antimicrobial Resistance released news that without further intervention, drug-resistant microbial triggered infections can take away the lives of 10 million people every year by 2050, paralyzing the economy [6].

The primary type of microorganisms common to spreading infections in the built environment are bacteria, fungi, and viruses [7,8]. Microbials that surround us in the built environment can vary depending on various factors [7,9,10], but common species that have been reported include staphylococcus, pseudomonas, candida, norovirus, and coronavirus [10,11]. Many of these studies show data of infections occurring in mainly healthcare settings due to the concentrated numbers of vulnerable patients [12,13]. However, microbial infections can happen in any built environment within the community [14]. The importance of reducing the risk of microbial infection was emphasized by figures provided by Smith et al. [15]. The work charted that infectious disease outbreaks have been rising progressively since 1980. In recent years, microbial studies in a wider variety and more areas of built environments have also increased, with several works being funded by the Alfred P. Sloan Foundation Microbiology of the Built Environment (MoBE) program [9,16,17].

With the increase in human lifespan, rapidly aging population, and, consequently, a more vulnerable population worldwide, it is essential to consider minimizing microbial infection both in and out of healthcare facilities to protect the wellbeing of our family and loved ones. Immunocompromised patients are much more likely to be severely infected and make up about 20% of the population [18]. This was also the case for COVID-19 pandemic. Belsky et al. reiterated this concern, describing patients with cancer or who are undergoing solid organ or hematopoietic cell transplants as having more severe symptoms when infected with the COVID-19 virus [19].

The built environment is defined as any man-made environment which provides a setting for human activities, including our homes, offices, parks, buildings, or neighborhoods. In Figure 1 the mechanisms and modes of transmission of the recent COVID-19 pandemic were used to demonstrate the potential ways that the virus can spread in an indoor office setting. Several factors such as building design, air circulation, air pollution, surface contamination, crowding, and socioeconomic factors can all impact on microbial infections [20,21]. These factors often have multiple overlapping variables, such as cities' accessibility to healthcare and government policies in place [22], more of these factors will be further discussed in Section 4. Generally, urban cities are more susceptible to COVID-19 transmission due to having better transport connectivity, which allows city dwellers to move around more frequently [23], and their high density [24–26] increases crowding tendencies.

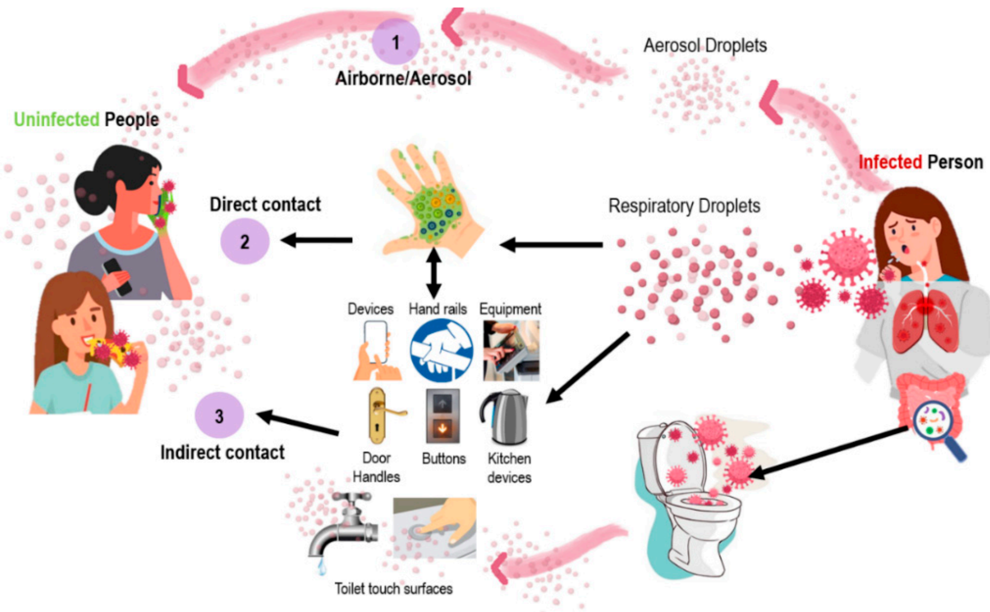


**Figure 1.** Mechanisms and modes of transmission of virus between humans in the built environment: an example showing the spread of COVID-19 in office buildings. This review will mainly focus on mitigating microbial transmission via (2) direct and (3) indirect contact.

Therefore, applying technical solutions to mitigate these concerns is one of the key strategies for reducing transmission risks within urban cities. After all, as mentioned by the US Centers for Disease Control and Prevention (CDC), eliminating these pathogens from our environment is the most effective approach compared to other strategies, such as separating humans and pathogens or instructing people on what to do. This is confirmed by research stating the importance of disinfection as COVID-19 contamination is detected in environmental fomites [27]. Yet, there is another twist to this complex problem when disinfecting the built environment: overusing broad spectrum biocides was found to increase microbial resistance in the community, and overusing them may cause environmental pollution [14,18,28].

### 1.1. Research Gaps, Aims, and Objectives

The concept of surface transmission became even more prominent after several research works discussed the extended survival of the COVID-19 virus on different surfaces [29–32]. Some perspectives dispute the exaggerated efforts to disinfect surfaces, stating that the risk of surface contamination is relatively low compared to airborne droplets [33,34]. Nevertheless, many reports could not dismiss the risk of surface transmission conclusively. Research works have also outlined the deadly risk of bacterial infection after patients were infected with COVID-19 [13,35–37]. Studies have suggested that the complications and detrimental impact of microbial infections on a long-term health basis should not be undermined. Hence, this review will summarize recent works that look at antimicrobial technologies suitable for different built environment surfaces, discuss their pros and cons, consider the factors that are crucial for such applications, and suggests the gaps in research studies in this area.

Unsurprisingly, experts and academics have claimed that the world was unprepared for the impact of a pandemic such as COVID-19 [38–40]. However, learning from the lessons and looking beyond COVID-19 will improve future preparedness to survive the next one better, be it an epidemic or a full-blown pandemic [41]. Microbial infection is an essential aspect of Sustainable Development Goals (SDG) 3, which addresses "good health and wellbeing". That said, microbial infections during an outbreak would cascade impacts on other SDGs such as SDG 9—"industry, innovation and infrastructure" and SDG 11—"sustainable cities and communities".

This work aims to systematically review how antimicrobial technologies can be considered and better applied to reduce environment fomites in various public spaces. While there are also other reviews written on antimicrobial works, they look at more specific technologies, such as nanoparticles, or target particular microbials such as the COVID-19 virus [42–45]. This review considers all antimicrobial technologies evaluated on different microbes which is also said to be suitable for the built environment, hence evaluating any research gaps in current technologies. It discusses newly developed antimicrobial technologies, categorizing them according to the built environment surfaces. The key studies are tabulated to summarize and compare the technologies in terms of their ease of application, durability, and long-term sustainability. The possible factors affecting microbes in an environment will also be discussed. The key considerations of antimicrobial technology for built environment surfaces will also be reviewed and summarized.

### 1.2. Method

During the last 30 years, studies related to "antimicrobial", technologies", and "buildings" have increased, especially after 2002 (see Figure 2 below). Although the literature on antimicrobial research is rich, and there is a significant number of review articles, what is lacking is a review that looks at an antimicrobial work with a focus on built environment applications. Therefore, research articles published from 2021 to 2022 from Scopus (734 document results) were considered for this review. In addition, focusing on studies from 2021 to 2022 is important because it was during this time period that the majority of new information and research about the virus and its impact was being conducted.

This was a crucial time in the ongoing global pandemic, as new variants emerged and the world continued to adapt to the effects of the virus. Understanding the developments, breakthroughs, and challenges from this time can help inform current and future efforts to address the pandemic and its aftermath. The keywords in the main search include "antimicrobial", "coating", and "surfaces".

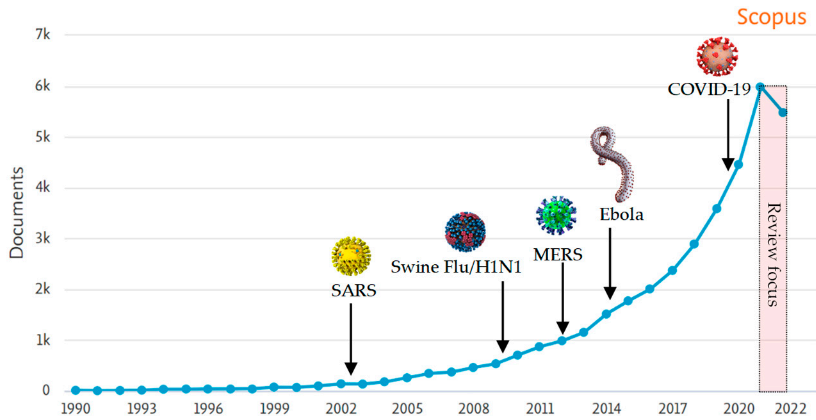


**Figure 2.** Number of studies related to "antimicrobial", "technologies", and "buildings" from 1990 to 2021 (data from Scopus, accessed on 15 October 2021).

Based on the searched keywords and bibliometric data (from Web of Science), a map was generated (see Figure 3) using VOSviewer to visualize the co-occurrence networks of important terms extracted from the selected literature. The co-occurrence networks map is fully interactive and can be explored in the VOSviewer Online https://tinyurl.com/2gvh9sbu (accessed on 2 October 2022).

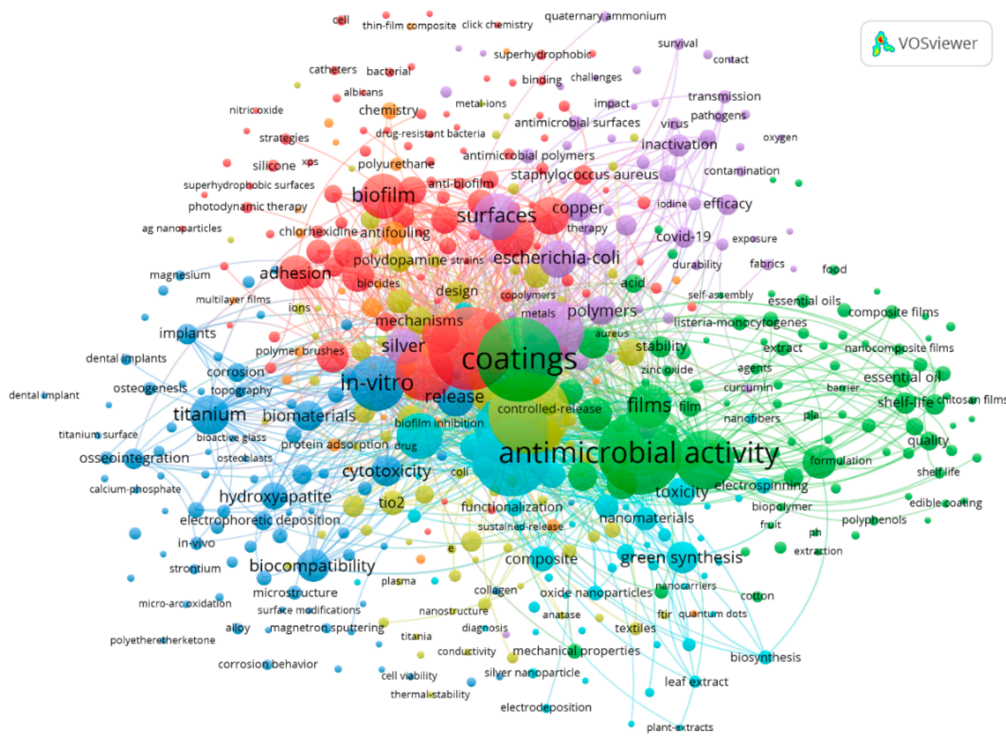


**Figure 3.** Co-occurrence networks of important terms extracted from the selected literature related to "antimicrobial", "coating", and "surfaces" from 2021 to 2022 (data from Web of Science, accessed on 15 October 2021). The co-occurrence networks map is fully interactive and available from VOSviewer Online https://tinyurl.com/2gvh9sbu (accessed on 2 October 2022).

The size and color (clusters) indicate the total strength of the co-occurrence links of the terms. The distance between two terms in the visualization indicates their relatedness regarding co-occurrence links. Related terms have strongly connected lines and are clustered together. As observed, there are no direct links with keywords such as "buildings" and "built environment"; hence, each identified full text article is further screened for eligibility. In the specific papers, the suitability of the papers for specific applications was sifted out with various keywords such as "public spaces", "public transport", "building", "built environment", and "touch surface". Research articles for other applications, i.e., food packaging and biomedical devices, were not included in this review.

In summary, this paper will review studies on antimicrobial technologies published from 2021 to 2022. The keywords in the main search include "antimicrobial", "coating", and "surfaces". The potential and suitability of antimicrobial technologies for implementation on surfaces within a building will be evaluated. Furthermore, the review will suggest key considerations when developing these technologies for a built environment.

## 2. Criteria of Antimicrobial Technology for the Built Environment

As discussed in the introduction, surface contamination is often not considered to be the primary transmission source compared to ventilation [46–50]. Therefore, antimicrobial technologies on surfaces should be implemented after comprehensive consideration of their potential impacts. Other benefits of incorporating antimicrobial coating and informing users of public spaces can include bringing about assurance to users in public spaces. This is especially true after the COVID-19 pandemic, where studies have since reported an increase in anxiety when in public spaces and in fear of touching surfaces [51]. Below are key factors to consider when installing antimicrobial coating in a built environment.

The antimicrobial coating can help reduce the need to incessantly disinfect surfaces, reducing the cost of chemical disinfection [52], decreasing manpower required, and minimizing the build-up of microbial resistance in the community by using broad-spectrum disinfecting agents [53]. On top of that, works have suggested that frequent cleaning cannot achieve thoroughly disinfected surfaces [54]. Similar to the properties of an ideal disinfectant described Guideline for Disinfection and Sterilization in Healthcare Facilities by the CDC [55], the criteria consideration of antimicrobial technology for the built environment will be discussed in this section. Below are some key considerations when using antimicrobial technologies for the built environment (not in order of importance).

- **Price:** Price point is crucial when applying an antimicrobial coating in different public areas, be it high-touched areas or large surface areas in public places such as lecture halls, playgrounds, supermarkets, and gyms. Affordability would encourage organizations to consider antimicrobial technologies without overspending.
- **Sustainability:** In order to ensure that our sustainable goals are within reach, the SDGs were set out by the United Nations (UN); it is important to consider SDGs when selecting antimicrobial technologies for the built environment. Antimicrobial products should be produced responsibly—the manufacturing process and materials used should consider their carbon footprint and minimize any forms of pollution whereas possible [28,56].
- **Ease of application:** Antimicrobial technologies should be easily applied via simple coating techniques such as easy-to-apply adhesive tapes and should not require an extremely tedious or lengthy process. Ease of application would therefore encourage the adoption of technology.
- **Mechanical properties:** Depending on the area of application, technology after application should retain good mechanical properties and effectiveness [57,58]. For example, suppose the antimicrobial coating is applied on an outdoor hand railing. In that case, the product should be able to resist different weathering conditions and not lose its antimicrobial properties upon exposure to rain, etc. The antimicrobial coating should also be able to withstand repetitive cleaning. Good mechanical and antimi-

crobial properties would result in long-term use of a coating, minimizing wastage of materials, meeting SDGs, and reducing the cost needed for coating replacement.

- **Toxicity:** Antimicrobial coatings should not be toxic to mammal cells in general. It should not release dangerous compounds and should not be able to cause any adverse health impact on humans [58,59].
- **Effectiveness on organisms:** Antimicrobial technology would benefit if it can reduce or resist as many microbial types as possible without using broad spectrum biocides that could lead to microbial resistance.
- **Authority:** Obtaining approval from a relevant authority such as the United States Environmental Protection Agency (EPA), which regulates the effectiveness of antimicrobial technology, would prove its effectiveness and increase user confidence.
- **Testing Standards:** While there is currently no single, standard test method developed for evaluating the efficacy of antimicrobial coating, several test methods were developed by organizations. These include the American Society of Testing and Material (ASTM), International Organization for Standardization (ISO), and the Japanese Industrial Standard (JIS). For example, the ISO 22196, Test for Antimicrobial Activity on Plastic Surfaces [60], ASTM E1428, Standard Test Method for Determining the Antimicrobial Activity of Immobilized Antimicrobial Agents Under Dynamic Contact Conditions [61], and JIS Z 2801, Test for Antimicrobial Activity and Efficacy [62].
- **Functionality, Aesthetic, and Tactility:** Lastly, functionality, aesthetic, and tactility are also important criteria to consider when designing antimicrobial technology [63,64] in the built environment. Antimicrobial technology, when used, should allow, e.g., doorknob and elevator buttons to retain their functionality even after application. When applied on a glass panel such as windows, it should not cause the window to lose its transparency or, when applied to a touchscreen, result in a loss of touchscreen sensitivity.

## 3. Antimicrobial Technologies for Built Environment

There are two fundamental mechanisms in antimicrobial technologies. Key mechanisms look at contact killing of microbial mechanisms by incorporating materials with biocide actives released to kill microbes. Common biocides are silver [65–67], copper [68,69], and quaternary ammonium compounds [70,71]. Another mechanism focuses on repelling microbes inherently with antimicrobial polymer [72,73], thus preventing microbial attachment [74]. On top of functionality and aesthetic purposes, in a built environment, materials are also considered for their ability to induce physical and psychological responses in the occupants [75]. Therefore, this section will discuss commonly found built environment materials and the antimicrobial technologies developed for these individual materials.

### *3.1. Ceramics*

Ceramics include a wide range of materials that are inorganic and nonmetallic and are known for their hardness, density, and durability [76]. Ceramic materials include clay, bricks, and glass. For example, glazed porcelain is frequently used for sanitary wares, such as basins and toilet bowls found in bathrooms [76]. The base material of porcelain is strong, and glazing provides waterproof properties and facilitates easy cleaning [77]. Since bathrooms are where users discharge their fecal and urine waste, it is not surprising that the space would be a breeding ground for pathogens [78]. Studies have found that this worsens with poorly ventilated restrooms [49] and the emission of the airborne pathogen during flushing [79]. Hence, bathrooms are one of the most frequently sanitized public spaces. Additionally, sanitary ware already has several commercialized products incorporating antimicrobial technologies [80,81], and many of these were mentioned in a recent review, "The challenge of antimicrobial glazed ceramic surfaces" [77].

Another application of ceramics would be for wall and flooring tiles, chosen for their lasting properties and aesthetics [82]. In one particular work by Golshan et al., the research explored the possibility of modifying industrial floor tiles to achieve antibacterial activity [67]. The sol–gel method was used to prepare both titanium dioxide ($TiO_2$) solution and silver-titanium dioxide ($Ag-TiO_2$) solution for dip-coating of the tiles. The solution prepared with 0.1% $TiO_2$ and 0.2% silver nitrate ($AgNO_3$) has the best effect, reducing *S. aureus* by 99% and *E. coli* by 95%. While the presence of coating was confirmed, the mechanical properties of this coating were not evaluated in this work of the literature. Another work evaluating tiles designed copper hydrophobic glazed ceramic tile. These copper glazed ceramic tiles were able to increase antibacterial properties against *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli (E. coli)* [83]. The tiles undergo real-life assessment in a public toilet, and consistent antibacterial efficiency of 99.9% was found even after two years when evaluated with the JIS Z 2081/ISO 22196 standard.

Glass

Glass is a type of ceramic that is commonly used in window panels, touch screens, doors, display shelves, and tabletops within the built environment. In many of these applications, transparency and aesthetic appeal are the main reasons for utilizing this material [75]. Additionally, the cleanliness of glass should be frequently maintained to ensure it retains its transparency; hence, any antimicrobial technology applied should be resistant to frequent cleaning. With the abundance of touch screens in this era, numerous works have demonstrated antimicrobial coatings specifically for their application on glass surfaces. In order to minimize COVID-19 transmission, touch screens were also listed as one of the most highly-touched surfaces that require frequent sanitation [84].

Many studies on glass surfaces evaluate the use of oxides and/or metals such as silver [65,66,68,85–87] for their antimicrobial effect. The use of nano titanium oxide coating doped with silver ($Ag-TiO_2$) was described in the work by Khan and Mailk [66]. The $Ag-TiO_2$ nanocoating was spin coated on glass substrates with different concentrations and underwent surface and optical analysis. Although the $Ag-TiO_2$ nanocoating was not evaluated for its antimicrobial properties, the work predicted that the smaller crystallite size, lower band gap energy, higher surface area, and more excellent light absorption would result in superior self-disinfecting properties. Another paper on metal oxide compares titanium dioxide incorporated with silver ($Ag-TiO_2$), graphene ($G-TiO_2$), and iron ($Fe-TiO_2$). These three materials, when tested against *E. coli*, found that 10% $Ag-TiO_2$ had the best ability to reduce bacteria growth with 5 mm of inhibition around the material. Additionally, $G-TiO_2$, at 10%, had the best self-cleaning properties when assessed for its photocatalytic ability to degrade methylene blue. The initial concentration of 4.99 mg/mL methylene blue was reduced to 0.55 mg/mL after 180 min [85].

Due to the COVID-19 pandemic, there were also works assessing antiviral properties. Delumeau et al. evaluated six different antiviral coatings (of about 50 nm thick): copper (Cu), copper oxide ($Cu_2O$), silver (Ag), zinc oxide (ZnO), zinc tin oxide (ZTO), and titanium oxide ($TiO_2$) on glass and polypropylene fabric surfaces against the virus [68]. The work found that Cu-containing coatings demonstrated the most robust virucidal properties but proposed that this could vary based on test conditions. It was hypothesized that the key mechanism of Cu ion release kills the COVID-19 virus. However, durability, coating strength, and detailed mechanism will need to be further investigated.

The use of micro-size silver oxide ($Ag_2O$) as antimicrobial coating prepared with a modified Stöber sol−gel process was reported by Hosseini et al. [65]. The work compares the effectiveness of a single layer (1.2 mm) and a double layer (2.4 mm) of $Ag_2O$ against the COVID-19 virus, *Pseudomonas aeruginosa (P. aeruginosa)*, and *S. aureus* bacteria. Both single- and double-layered $Ag_2O$ could inactivate at least 95% of the COVID-19 virus and kill at least 99% of all the bacteria tested. As shown in Figure 4, the UV/vis spectrometer measuring the light transmission through the coated material found that 60–75% transparency was retained even with $Ag_2O$ coating.

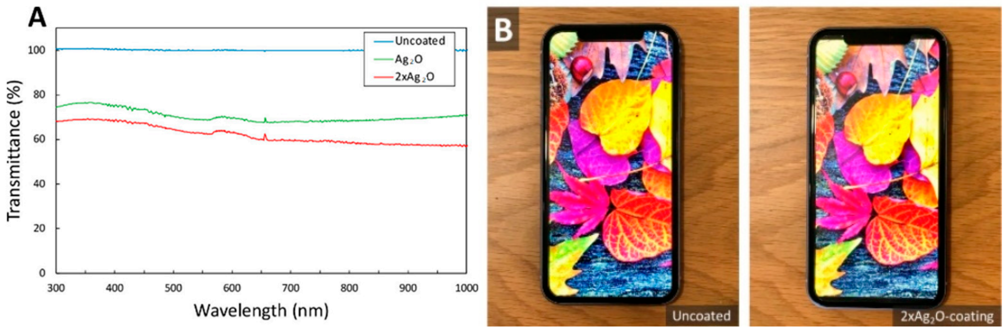


**Figure 4.** (**A**) UV/vis spectrometer measuring the light transmission through the coated material found that 60–75% transparency was retained even with $Ag_2O$ coating. (**B**) Visual comparison before and after use of $Ag_2O$ coating [65]. Adapted with permission from Hosseini, M. et al. Transparent Anti-SARS-CoV-2 and Antibacterial Silver Oxide Coatings. *ACS Appl. Mater. Interfaces* **14**, 8718–8727 (2022). Copyright 2023 American Chemical Society.

Several articles reviewed in this paper maximize the benefit of high surface area from nano silver. However, when the utility of micro-size $Ag_2O$ can achieve similar antimicrobial results, it could be a more favorable option, as it is more stable, easier to handle when scaling up, and has less toxicity risk than nano silver [58,88,89].

Quaternized polydopamine coatings with magnetite nanoparticles attaching silver salts could offer an alternative strategy for good dispersion of silver ion [90]. Mude et al. synthesized such coatings and evaluated them on both bacteria and fungi. Significant antibacterial properties (on *S. aureus* and *E. coli*) were witnessed after 20 min–40 min (as per Figure 5), and antifungal properties toward *Aspergillus nigger* (*A. nigger*) after 24 h. The antibacterial effect remains even after wiping artificial sweat over the glass slips up to 20 times.

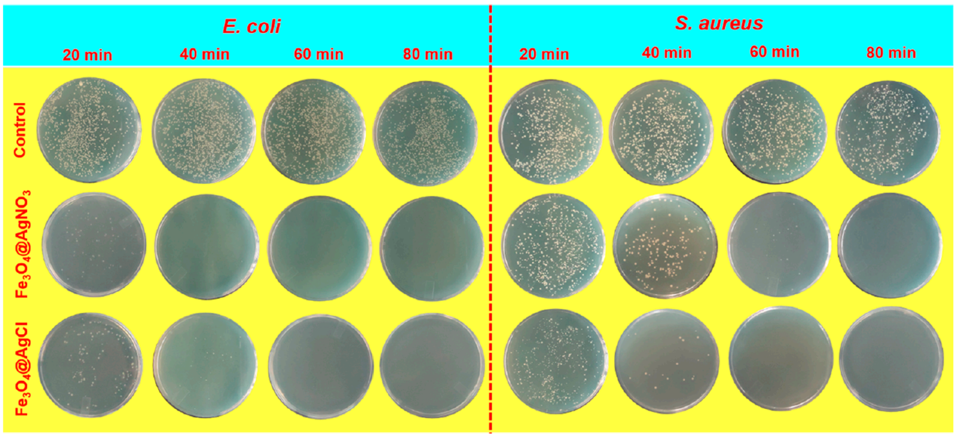


**Figure 5.** Reduction in *E. coli* and *S. aureus* was seen in quaternized polydopamine coatings over magnetite nanoparticles attaching silver salts—$Fe_3O_4$ @ $AgNO_3$ and $Fe_3O_4$ @ AgCl [90]. Adapted with permission from Mude, H., Maroju, P. A., Balapure, A., Ganesan, R., and Ray Dutta, J. Quaternized Polydopamine Coatings for Anchoring Molecularly Dispersed Broad-Spectrum Antimicrobial Silver Salts. *ACS Appl. Bio Mater.* **4**, 8396–8406 (2021). Copyright 2023 American Chemical Society.

Photodynamic inactivation (PDI) of microbes in the presence of reactive oxygen species [91] and polycationic polymer for cell wall disruption [92] were also considered to be antimicrobial technology for glass surfaces. Instead of using the commonly studied titanium dioxide, Baigorria et al. shared the potential of PDI of bacteria using electroactive metalated phthalocyanines added with potassium iodide (KI) to enhance PDI effect [93]. In another work, Pigareva et al. described the use of polycation polymer coating, polydiallyldimethylammonium chloride (PDADMAC), and water-soluble complex, sodium polystyrene sulfonate (PSS), to form an interpolyelectrolyte complex (IPEC) [92]. Glass or poly vinyl chloride (PVC) substrate that had been prepared was dip coated in the IPEC and PDADMAC. IPEC was found to have slightly better performance during wash-off evaluation, retaining 50% of IPEC after the first cycle of washing.

In comparison, 75% of PDADMAC polymer was washed off after the first cycle. Though the work demonstrated that IPEC could improve in washing resistance as a proof-of-concept data, evaluating its antimicrobial behavior toward specific microbe species would provide a better understanding of the benefit of such a polymer coating. The durability of IPEC would also require further improvement to be suitable for actual application. Commercially available materials have also been assessed in three separate works, this includeshyperbranched Kaustamin [94], Azure A and 5-(4-aminophenyl)-10,15,20-(triphenyl)porhyrin (APTPP) [95], and $TiO_2$ nanocoated glass [86]. The key antimicrobial studies on glass discussed above, including the three commercially available materials, can be found in Table 1, which summarizes its ease of application, durability, consideration of long-term sustainability, and the microbials that were tested in the individual work.

**Table 1.** Overview of studies evaluating coating on glass surfaces.

| Method [Ref.] | Ease of Application | Durability | Sustainability | Microbial Tested |
|---|---|---|---|---|
| Polycation polymer (PDADMAC) interpolyelectrolyte complex [92] | ++++ Dip Coating | + | ++ | N/A |
| Silver Oxide ($Ag_2O$) Coating [65] | ++++ Dip Coating | + | ++ | N/A |
| Silver-enriched $TiO_2$ Nanocoating [66] | ++ Spin Coating and Annealing | N/A | + | N/A |
| Iron, Graphene, Silver-infused $TiO_2$ Nanocoating [85] | ++++ Dip Coating | N/A | + | *E. coli* |
| Silver Nanoparticle embedded in $TiO_2/SiO_2$ [87] | +++ Sputtering | N/A | + | *E coli* |
| Nano Cu, $Cu_2O$, Ag, ZnO, ZTO and $TiO_2$ [68] | +++ Thermal Evaporation | Varying | + | SARS-CoV-2 |
| Quaternized Polydopamine-Ag Nanoparticle Complex [90] | N/A | +++ | ++ | *E. coli*, *S. aureus*, *A. nigger* |
| Metalated phthalocyanine (ZnPc-EDOT and CuPc-EDOT) with Potassium Iodide (KI) [96] | ++ Electro-polymerization | N/A | + | *E. coli*, *S. aureus* |
| Al-doped ZnO Nanorods [96] | ++ Spray Pyrolysis | N/A | + | *E. coli* |
| Hyperbranched Polymer Kaustamin [94] | ++++ Dip Coating | + | ++ | *B. subtilis*, *E. coli* |
| Azure A (AA) and 5-(4-aminophenyl)-10,15,20-(triphenyl)porhyrin (APTPP) [95] | + Chemical Grafting and Chemical Post modification | N/A | ++ | *E. coli* |

N/A = not available/tested; the number of **+** indicates the ease of application, durability, and sustainability of coating material. For example, a coating process with + involves various tedious processing steps (may require prolonged soaking and/or additional heating). At the same time, the ++++ is easier to apply, typically with a single-step process. The sustainability gauge indicates the sustainability of the material used and the lower impact on the environment.

### 3.2. Textile

Textiles are cloth or woven fabric that can be found as curtains, carpets, tablecloths, cushions/sofa/seat covers, and blankets/bedsheet in hospitals [97]. Textiles frequently affect the comfort of people [98], and hence, the material requires a vastly different set of properties compared to other materials such as glass, discussed Section 3.1. Common properties considered are flexibility, durability, weight, tactility, water absorption, and mechanical properties of the textile [99,100]. In many of their applications, textiles should provide insulation (e.g., carpet), visual privacy (e.g., curtains), and comfort (e.g., bedding) as well [98]. Certain textiles would benefit from their ability to block out ultraviolet light, and bedsheets, which are frequently changed, should also have antimicrobial technology applied that is highly resistant to continuous spinning in washing machine and heat resistant to the steaming/ironing process. Common textile materials usually found in the built environment include cotton, polyester, nylon, or a blend of these materials [101]. Table 2 below summarizes all the antimicrobial technologies that claimed suitability on textile materials and provides information on their durability, sustainability, application process, and the microbials tested.

Again, the incorporation of metal/metal compound nanoparticles is one of the main strategies studied for antimicrobial textiles or yarn [102–109]. In one such work, Tania and Ali presented a straightforward mechanical thermo-fixing method to prepare zinc oxide (ZnO)-coated textiles. Cotton was dipped into a ZnO nanoparticle solution, roller squeezed, and then dried at 90 °C before curing at 150 °C for 5 min. Three samples were prepared—ZnO only; ZnO and binder (OB-45, thermally cross-linkable acrylate dispersion); and ZnO, binder, and wax emulsion (Jinlub Eco NP-825N, a polyethylene wax emulsion). All the samples had antimicrobial ability against *E. Coli* and *S. aureus*; the sample with binder had the highest bacteria reduction, with 86.14% for *E. Coli* and 90.43% for *S. aureus* in the 1st hour of contact killing. The inclusion of binder was found to stabilize the coating during washing and has minimal impact on antimicrobial activity after 10 laundering cycles. Samples with wax emulsion created a flexible coating, improving mechanical properties such as tensile strength, bending length (a measure of stiffness), elongation, and tearing strength. Rezic et al. shared an investigation of dip-coating nanosilver that is encapsulated in alginate [110]. While the encapsulated silver is a different approach and can offer prolonged release of nanosilver, an extensive study on its durability and actual antimicrobial performance is required to understand its viability. Consideration of how to trigger the release of nanosilver in textile applications will also be crucial for real-life applications.

Several other metal/metal compound nanoparticle studies leverage dual materials/mechanisms to achieve a combinatorial effect by combining graphene and cuprose oxide [111], cuprose oxide and titanium dioxide [112], and silver and titanium oxide [113] to enhance antimicrobial properties. The usage of quaternary ammonium compounds was also considered for textile-type materials. However, it is a challenge to prepare durable coating on such materials. Phutthatham et al. applied quaternary ammonium for antimicrobial effects and benzophenone group to bond quaternary ammonium on the textile surface. The study used poly(2-methacryloyloxy dodecyl dimethyl ammonium chloride-4-allyloxy-2-hydroxybenzophenone)-iodide ((P($QAC_{12}$-BP)-I)) to prepare poly(styrene-butyl methacrylate) (P(S-BA)) particles via emulsion iodine transfer polymerization [71]. The work demonstrated the effectiveness of the particles against *E. Coli* and *S. aureus* and these spray dried and UV curedparticles, help to reduce loss of particles while washing the textile.

Another example of quaternary ammonium on fabric was developed by Wang et al., who prepared a copolymer, poly(DMD-co-MA) of [2-(methacryloyloxy) ethyl] trimethylammonium chloride (DMC) and methyl acrylate (MA) [114]. Cotton fabric was first treated with carboxymethyl chitosan (CMC), allowing an amidation reaction between amino groups and pendant ester from poly (DMD-co-MA). They thoroughly studied the antibacterial effect (for *E. coli* and *S. aureus*), and its tactile properties remained similar to uncoated cotton. The antibacterial effect of the coated cotton fabric remains above 98% even after 50 laundering cycles. While the work targets wearable textiles by evaluating their tactile properties, such cotton can also be considered in built environment applications such as bedsheets or cushion covers in hospitals. A few other studies look at differing technologies for antimicrobial textiles [115–119] for hospital garments and personal protection equipment (PPE). While they are not reviewed in this paper, they could also have similar requirements and find themselves suitable for textiles used within the built environment.

Cationic antimicrobial polymers have also been explored for application on textiles; polyionenes were functionalized with silane to aid bonding to cotton fabric [73]. The silane-functionalized polyionenes were effective (Figure 6) when tested against *E. coli*, *S. aureus*, and *Candida albicans* (*C. albicans*). In conjunction with the COVID-19 pandemic, Qiu et al. also applied the material to model the virus with p22 bacteriophage, and killing was evidenced by 7 log PFU (plaque-forming units). The materials were evaluated for skin irritation on mice with no erythema or edema observed. The cytotoxicity test found high L929 cells after 48 h, and antimicrobial activity was retained even with the laundering of up to 50 cycles.

| | Polymer | Silane coupling reagent | Tertiary amine | Fabrics |
|---|---|---|---|---|
| Nucleophilic Addition | P1 | GPTMS | 3,3-iminobis(*N*,*N*-dimethylpropylamine) | F1 |
| | P2 | GPTMS | 3,3-iminobis(*N*,*N*-dimethylpropylamine) | F2 |
| | P3 | IPTS | 3,3-iminobis(*N*,*N*-dimethylpropylamine) | F3 |
| Quaternization | P4 | TMSPrCl | TMEDA | F4 |
| | P5 | TMSPrBr | TMEDA | F5 |
| | P6 | TMSPrBr | PMDTA | F6 |

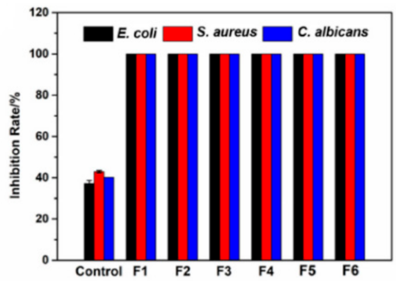


**Figure 6.** (**Left**) Summary of different chemicals and processes tested in the work (GPTMS: 3-glycidyloxypropyl)trimethoxysilane), IPTS: 3-(triethoxysilyl)propyl isocyanate, TMSPrCl: 3-trimethoxysilylpropyl chloride, TMSPrBr: 3-trimethoxysilylpropyl bromide, TMEDA: N,N,N′,N′-tetramethylethylenediamine, and PMDTA: N,N,N′,N′′,N′′-pentamethyldiethylenetriamine). (**Right**) Antimicrobial properties of the treated fabrics by plate counting method; raw cotton was used as control sample [73]. Reprinted/adapted with permission from Qiu et al. 2023, Elsevier.

A handful of works focus on evaluating antimicrobial properties, but not all studies suggested to work on textiles were evaluated for their suitability [96,120]. For example, in an interesting work that considers magneto-optical properties of ZnO nanoparticles doped with the rare-earth elements $Ho^{3+}$ and $Sm^{3+}$, the work mentioned their potential suitability for walls and fabrics utilizing antimicrobial activity of doped ZnO. However, the suitability was not evaluated in the paper. While the doped ZnO has better antimicrobial performance against ZnO when tested with *Staphylococcus epidermidis* (*S. epidermidis*), *Bacillus subtillis* (*B. subtillis*), *C. albicans*, and *A. niger*, the additional magnetic properties are not typical properties required for the built environment [120].

Lastly, the work by Mirzaei et al. [121] approached antimicrobial technologies on textiles from a refreshing perspective. Instead of developing a new way to prepare the antimicrobial coating, the group designed a regression model that can predict the antimicrobial ability of nanomaterials after several cycles of laundering, as many studies (also mentioned in this review paper) incorporate nanoparticles to achieve antimicrobial properties. To date, the model has an accuracy rate of 70%. In the future, researchers working on the incorporation of nanoparticles into textile materials for antimicrobial properties can consider using this machine learning model for prediction. This is especially helpful for long laundering cycles that can be incredibly time consuming.

**Table 2.** Summary of studies evaluating antimicrobial technologies on textiles.

| Method [Ref.] | Ease of Application | Durability | Sustainability | Microbial Tested |
|---|---|---|---|---|
| Plasma pretreated surface with Silver Nanoparticle [105] | +++ Plasma and Pad-Dry-Cure | + | + | *E. coli*, *C. albicans*, *S. aureus* |
| Adhesive Nanosilver Glue [106] | ++++ Pad-Dry-Cure | ++++ | + | *E. coli*, *S. aureus* |
| Pretreated with Citric Acid, then coated with $Cu_2O$ Nanoparticle [107] | +++ Pretreated and Dip Coating | ++ | + | *S. aureus*, *E. coli* |
| Silver Nanoparticle with Silicone Binder [108] | ++ Dip Coating and Reduction | N/A | + | *S. aureus*, *E. coli* |
| Nano Silver Particle Encapsulated in Alginate [110] | ++ Dip Coating and Drying | Varying | + | N/A |
| ZnO Nanoparticle with Binder and Wax Emulsion [102] | ++++ Pad-Dry-Cure | +++ | + | *E. coli*, *S. aureus* |
| ZnO Nanoparticles modified with Silanol and attached with Tertiary Amine-based Coupling Agent [103] | ++++ Dip Coating | ++ | + | *S. aureus* |
| Graphene Oxide and $Cu_2O$ anchored with Polydopamine [111] | ++ Dip Coating, Stirring 24H, and Drying | ++++ | + | *S. aureus*, *E. coli* |
| $Ag^0$ and $TiO_2$ Nanocoating [113] | ++++ Pad-Dry-Cure | + | + | *E. coli* |
| PTFE Coating with Magnetite Particle [104] | ++ Ultrasonic, Yarn-Spinning with PTFE Extruding | ++++ * | + | *C. albicans*, *S. aureus*, *E. coli* |
| Quaternary Ammonium and Benzophenone [71] | +++ Spray Coating, Drying, and UV Curing | ++ | ++ | *S aureus*, *E. coli* |
| Pretreated with Carboxymethyl Chitosan, then apply Quaternary Ammonium that was copolymerized with Methyl Acrylate [114] | +++ Surface Modification and grafting (Dip, Heat, and Dry) | ++++ | + | *S aureus*, *E. coli* |
| Silane-functionalized Polyionenes [73] | +++ Ultrasonic Incubation, Dry, and Cure | ++++ | ++ | *S. aureus*, *E. coli*, *P. aeruginosa*, *C. albicans* |
| $Ho^{3+}$ and $Sm^{3+}$ doped ZnO Nanoparticles [120] | N/A (Tested as particles only) | N/A | + | *S. epidermidis*, *B. subtilis*, *P. aeruginosa*, *E. coli* |
| Ag nanoparticle-coated Cationized Cotton | ++++ Pad-Dry-Cure | ++++ | ++ | *E. coli*, *S, aureus* |

N/A = not available/tested; the number of + provides an indication of the ease of application, durability, and sustainability of coating material. For example, a coating process with + involves various tedious steps of processing (may require long hours of soaking and/or additional heating), while the ++++ is easier to apply, typically with a standard industry process such as the pad-dry-cure. However, the durability gauge is based on the number of cycles evaluated; it is possible that not all materials were tested until their limit. The sustainability gauge indicates the sustainability of the material used and its impact on the environment. * Evaluated as yarn instead of fabric.

*3.3. Fibrous Material (Filter)*

Filter is one application that is especially important for indoor conditioned spaces. While high-efficiency particulate air (HEPA) filters are commonly used in air purifiers and are known to be efficient in removing airborne pathogens, significantly more energy is needed to have air pass through these filters as compared to typical heating, ventilation, and air-conditioning (HVAC) filters [122]. The majority of HVAC filters in air-conditioning are made of either fiberglass [123], cotton, or polymeric materials such as polypropylene [124]. Despite the strong emphasis and importance of ventilation [46,48,50] in infection spreading, relatively fewer research articles evaluating antimicrobials for air filters were found as compared to those for textile and glass material. Research has also shown that certain microbes can colonize filter surfaces, especially bacteria and fungal species [123]. Key factors when applying antimicrobial technology to filter are to ensure that the use of technology should minimize the need to increase energy output and coating should not leech out with pressure from the fan within HVAC [125,126].

Out of four articles found, two of them discuss the application of their antimicrobial work for personal-use masks [127,128], while the others discuss air filters for use in air-conditioning or air purifiers [125,126]. In one such work, which targets both medical and industrial filters made of nonwoven polypropylene (PP), graphene oxide (GO) and polydopamine (PD) were evaluated for their performance to achieve antimicrobial filters. PD as an adhesive and GO have high hydrophilicity and surface charge, which are qualities known to inhibit bacterial adhesion. The work offers a very scalable solution with spray drying; the coated filter also has improved efficiency and little change in pressure drop (as per Figure 7). PP-GO-PD was evaluated for its antimicrobial property with *E. coli*, and the bacterial cell viability was 72.5%. Kasbe et al. [126] then added cationic poly[(2-(methacryloyloxy) ethyl) trimethylammonium chloride] (PMETAC) polymer grafting on GO to further reduce *E. coli* cell viability to 42.2%.

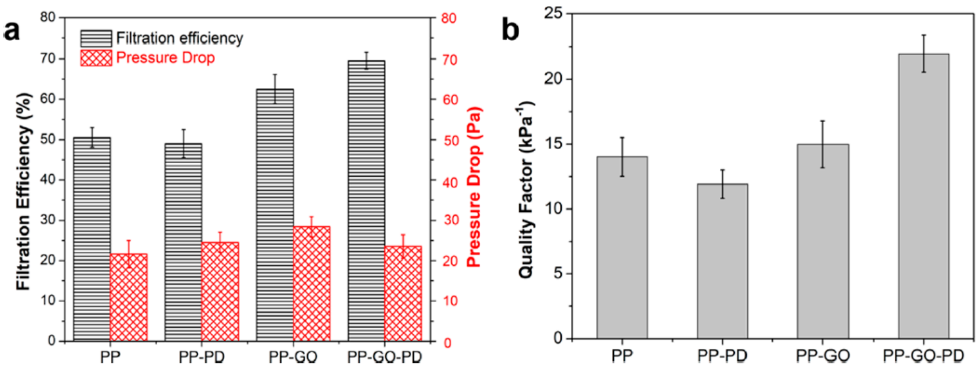


**Figure 7.** (**a**) PP-GO-PD has the highest filtration efficiency with minimal change in pressure drop. (**b**) Quality factor was highest in PP-GO PD [126]. Adapted with permission from Kasbe, P. S., Gade, H., Liu, S., Chase, G. G., and Xu, W. Ultrathin Polydopamine-Graphene Oxide Hybrid Coatings on Polymer Filters with Improved Filtration Performance and Functionalities. *ACS Appl. Bio Mater.* **4**, 5180–5188 (2021). Copyright 2023 American Chemical Society.

In another work by Park et al. [125], silver nanowire was electrosprayed on electrospun polyacrylonitrile (PAN) fibers. Again, filtration efficiency was improved without affecting the pressure drop. The material was then tested for its antimicrobial efficiency and was found to be 95.2% efficient toward *Bacillus cereus* (*B. cereus*), 93.7% efficient toward *Micrococcus luteus* (*M. luteus*), and 98% efficient toward *S. aureus*. The silver nanowire-coated fibers were also evaluated on bacteriophage MS2 as a model virus and were 72.5% efficient.

A quick scan in Google Scholar picked up another recent work by Watson et al. [122] that did not appear in the Scopus search. Watson et al. demonstrated the use of chlorhexidine digluconate (CHDG), a broad-spectrum biocide, on an air filter. It was then tested to be efficient in killing fungi *C. albicans*, bacteria *E. coli*, and Methicillin-resistant *S. aureus*

(MRSA). It was also effective in destroying the COVID-19 virus within 30 s. The group took the extra step to evaluate the durability of this air filter and measure the leaching of CHDG with continuous air flow. No CHDG was detected after 24 h. More interestingly, the air filter was evaluated on a field test in an actual train transport in the UK for 3 months. The CHDG-containing air filter found no detectable microbes, whereas the standard air filter had $2 \times 10^6$ CFU of microbes.

A summary of these three studies can be found in below Table 3. For more insights into antimicrobial air filter studies before 2021, a publication consolidating antimicrobial air filter technologies can be found in a review paper written by Mallakpour et al., "Fabrication of air filters with advanced filtration performance for removal of viral aerosols and control the spread of COVID-19" [129].

**Table 3.** Compilation of works evaluating antimicrobial technologies on fibrous material (air filter).

| Method [Ref.] | Ease of Application | Durability | Sustainability | Microbial Tested |
|---|---|---|---|---|
| Polydopamine-Graphene Oxide Hybrid Coating [126] | ++++ Spray Coating | N/A | ++ | *E. coli* |
| Pretreatment of Filter with Chlorhexidine Digluconate [122] | N/A | ++++ | ++ | *E. coli*, *C. albicans*, SARS-CoV-2 |
| Silver Nanowire coated Fibrous Air Filter [125] | ++++ Electrospraying | N/A | + | *S. aureus*, *E. coli* |

N/A = not available/tested; the number of + indicates the ease of application, durability, and sustainability of coating material.

### 3.4. Polymer

Plastics or polymers needs no introduction, and they are everywhere around us. In some cases, polymers can be a more affordable option, and yet, they have probably the widest range of form and properties, from insulation to strong chairs made of polymer composite [130]. Their applications are almost limitless, and there is no fixed set of properties, as the applications vary. Hence, the works performed on polymer cover a wide range of applications.

Fischer et al. presented work on the incorporation of titanium dioxide ($TiO_2$) or zinc oxide (ZnO) into silicone rubber matrix [131]. Compared to using coating mechanism as in most studies, blending these fillers into the matrix would ensure that the antimicrobial effect will not be lost from surface damage. One reported concern in mixing such particles into the matrix would be the reduction of tensile strength when the particles are poorly distributed. The composite materials were found to have an antibacterial effect against *E. coli*, *S. aureus*, and *Pseudomonas fluorescens* (*P. fluorescens*), with varying degrees depending on the additive amount and type. The inherent mechanical strength of silicone rubber enhanced with antimicrobial additives is especially useful in high-touch areas such as door handles and keypads. Another study of composites looked at the preparation of polylactic acid (PLA) filled with nanosized particles of polyoxometalates (POM); a double sodium–copper(II) paratungstate was processed by solvent casting and melt extrusion method [132]. The antimicrobial test here uses the agar diffusion test to evaluate the inhibition zone as a result of the antimicrobial PLA composite. PLA with POM $Na_2Cu_3(CuOH)_2[W_{12}O_{40}(OH)_2]\_32H_2O$ had the largest inhibition zone of 16 mm against *E. coli*. As PLA is a common material used for the three-dimensional (3D) printing processes, one other advantage of such PLA composite is its potential to be prepared into filament for 3D printing, which is becoming increasingly popular for the customization of parts. Additionally, UV-curable polymers have also been explored. Bedard et al. developed a phosphonium-containing benzophenone that can either be used as a coating or can be coextruded with polypropylene [133]. While the durability of the coating was not assessed in this work, coextruded material continued to withstand *E. coli* after 100 cycles of solvent rub, according to ASTM D540242 protocol.

Antimicrobial coatings using silver (Ag) nanoparticles were again studied for application in a biopolymer blend [134]. The work leverages Arboblend, which contains various biopolymers, lignin, and other naturally derived organics such as cellulose and oils. Ag nanoparticles were coated on the pellet and compared against noncoated pellet as injection molded parts. The work used sustainable and renewable biopolymers, which is often a neglected factor in several of the studies reviewed thus far. However, using an alternative of Ag nanoparticles as an antimicrobial can further improve sustainability of this material. Another work that considers sustainability when designing the material uses renewable source from nature rubber to synthesize cationic hydrophilic polyurethane. This helps to reduce the use of toxic chemicals for synthesis. Moreover, the addition of protonated chitosan (which can come from a sustainable source such as extraction from shellfish waste) further aids the inhibition of *E. coli* in this work [135]. Nevertheless, the authors did not mention specific usage of these materials, and hydrophilic material can pose a challenge in built environment applications.

Finally, a work by Francone et al. utilized a different approach that looks at preventing microbial attachment by engineering the surface of polypropylene film [136]. Nanoimprint lithography was used to create texture (as seen in Figure 8), with hierarchical samples showing good inhibition toward *E. coli* and *S. aureus*. The surfaces were also exposed to a wet scrub test with chemical agents for 810 cycles, were found to show resistance to cleaning protocol, and are potentially suitable to replace frequently cleaned surfaces in hospitals. A summary of all the studies evaluated on polymeric materials can be found in Table 4 below.

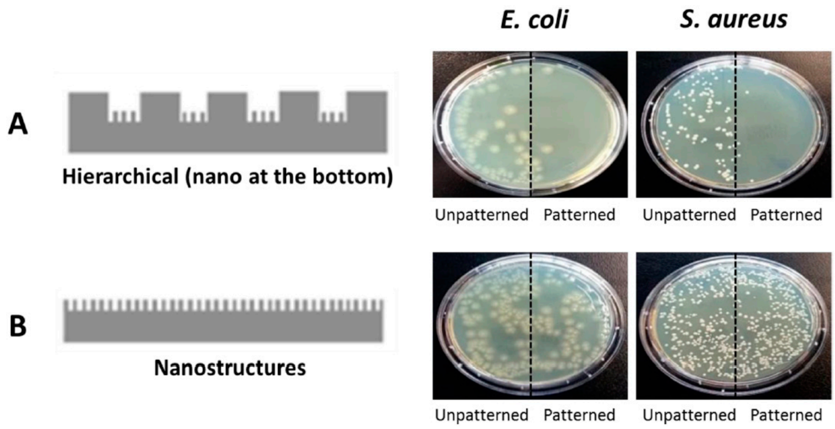


**Figure 8.** Hierarchical texture (in **A**) could reduce *E. coli* and *S. aureus* by 82% and 86%, respectively while nanostructure (in **B**) had no effect on bacterial reduction [136]. Reprinted/adapted with permission from Francone et al., 2023, Elsevier.

**Table 4.** Summary of work evaluating antimicrobial technologies on polymer.

| Method [Ref.] | Ease of Application | Durability | Sustainability | Microbial Tested |
|---|---|---|---|---|
| Silver-coated Sustainable Biopolymer Pellets for Injection Molding [134] | ++++ Sputtering | N/A | ++ | N/A |
| Polylactic Acid/Polyoxometalates with Double Sodium-copper(II) paratungstate B | ++++ Solvent Casting/Melt Extrusion | N/A | + | *E. coli* |
| Protonated chitosan mixed with Cationic Waterborne Polyurethane [135] | ++++ High Speed Mixing | N/A | +++ | *E. coli* |

**Table 4.** *Cont.*

| Method [Ref.] | Ease of Application | Durability | Sustainability | Microbial Tested |
| --- | --- | --- | --- | --- |
| Incorporation of $TiO_2$ and ZnO into Silicone Rubber [131] | ++++ Roller Mixing | N/A | + | *E. coli*, *S. aureus*, *P. fluorescens* |
| Sprayable Quaternary Small Molecule [137] | ++++ Spray Coating | ++++ | ++ | *C. albicans*, *S. aureus (MRSA)* |
| UV-curable Phosphonium with Benzophenone | +++ Electrospraying and UV Curing | ++++ (Coextruded material) | + | *Arthrobacter* sp., *E. coli* |

N/A = not available/tested; the number of + provides an indication of the ease of application, durability, and sustainability of coating material.

### 3.5. Metal

Metallic materials are sturdy and strong materials that are frequently found in public spaces and public transport. Handrails, lift buttons, doorknobs, and handles are some of the typical applications of metal surface/finishing found in a built environment [138,139]. Many of these applications are also known as high-touch surfaces (which will be discussed in detail in the following Section 4). Therefore, they are one of the areas that would benefit from antimicrobial technology. Common metallic materials that can be found on surfaces of the built environment are brass, stainless steel, and aluminum [139]. A summary of all the works published in the last two years on metal surfaces can be found in Table 5. It is important to note that studies where durability evaluation was performed on metals mainly look at the coating's resistance to abrasion, coating adhesion, and corrosion instead of its continuous antimicrobial performance.

One study introduced the use of core-shell-incorporated coating for multifunction purposes [140]; silica was used as the core material to improve mechanical properties and $TiO_2$ shell was used to achieve antimicrobial properties. Verma et al. fabricated such core-shell particles and included them in polyurethane coating. The coating was then evaluated on stainless steel coupons and tested on blue green algae, *Fusarium solani (F. solani)*, *Bacillus*, and *E. coli*. A total of 1% of core-shell particles were already sufficient to kill 100% of fungi growth; 4% was required for both bacteria and algae. The coating with 4% of these particles was also put through an antiscratch test and could withstand up to 20 N load.

Unlike the methods used to bond silver nanoparticles to textile and glass, it is possible to bind silver to metal surfaces with electrodeposition for a more durable layer by making use of grain boundaries of 304 stainless steel. This work was validated by Wang et al. [141] on the stainless steel surface and found to have increased resistance toward the bacteria species *E. coli* and *S. aureus*. Another common metal used for its antimicrobial properties, copper, was also investigated using cold gas spraying on a stainless steel 316 surface [142]. Santos et al. demonstrated copper incorporation into plasma electrolytic oxidation, which produces a high-adherence ceramic coating [143] on an aluminum surface.

In another work on the aluminum surface AA2024, Nie et al. developed a sandwich-like superhydrophobic coating with a silicon dioxide-hybridized silane layer that is superhydrophobic and, on top, a Mxene ($Ti_3C_2$)-hybridized silane layer. This sandwich-like coating was tested in various conditions and was found to have the best antimicrobial performance against *E. coli* when tested under light condition [144]. Several of the strategies mentioned here would provide very durable antimicrobial surfaces. However, they would be more suitable for greenfield projects, as the recommended processes require several pretreatment steps and coatings. It would be challenging to apply these technologies to existing infrastructure. Mandal et al. reported the use of a more scalable process that uses filter paper to transfer graphene oxide (GO) onto pretreated aluminum surfaces [145]. However, minor delamination was observed in 2.0 mg/mL of GO concentration coating after 5 min of sonication.

The use of quaternary ammonium on metal was investigated by Ikner et al., who reported spray coating of a quaternary ammonium polymer (Surfacewise2) on stainless steel coupon [70]. They then evaluated their work against coronavirus 229E and the COVID-19 virus. A reduction of 99.9% was observed after 2 h of exposure. The brief report, however, did not measure long-term effectiveness, durability, and mechanical properties, which will be insightful for built environment applications.

As shared by a work that investigated the use of more than 20 different antimicrobial commercial products [146], while many tested products did demonstrate initial antiviral behavior, several lost their efficiency after wet abrasion, hence emphasizing again the importance of durability studies for actual application. The products tested in that particular work contain quaternary ammonium using organosilane 3-(trimethoxysilyl)propyl-dimethyloctadecyl ammonium chloride or 3-(trihydroxysilyl) propyl-dimethyl octadecyl ammonium chloride) applied as a coating on both copper and steel surfaces via spray coating stick-on film on metal alloy. A more straightforward and quick way to coat metal would be to consider the use of varnish, as reported by Eliwa et al. [147]. Varnish made of polyurethane containing gadolinium (I)/cesium and CS (III) metal complexes (Gd(I)/Cs(III)) was tested on stainless steel and wood. Such a varnish may be easier to apply on existing infrastructure in a brownfield project, as it can be cured at room temperature. The bacterial inhibition zone studies on *B. cereus*, *S. aureus*, *E. coli*, and *P. aeruginosa* are shown in Figure 9.

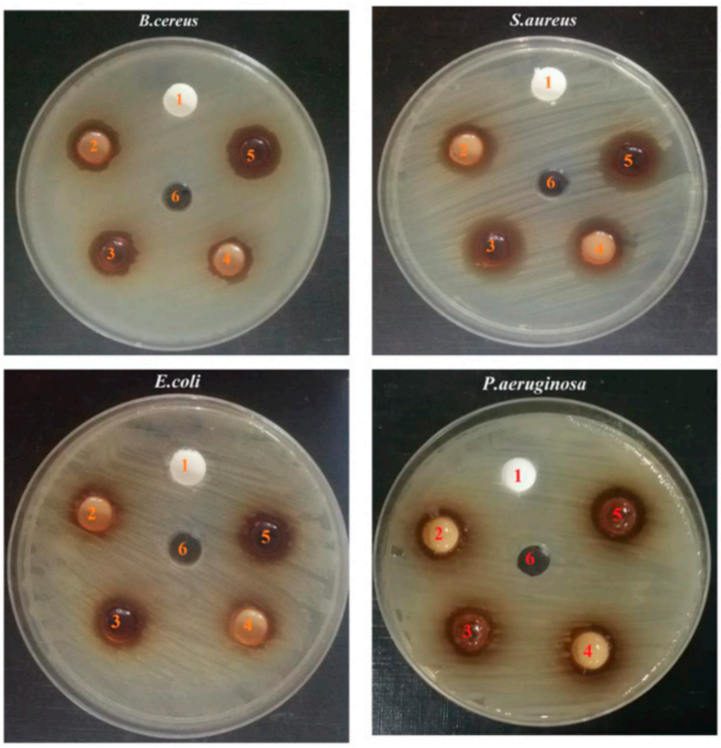


**Figure 9.** Antibacterial activity comparing inhibition zones; 1 = paint, 2 = gadolinium, 3 = paint + gadolinium, 4 = cesium, 5 = paint + cesium and 6 = control (solvent—dimethyl sulfoxide) [147]. Reprinted/adapted with permission from Eliwa et al., 2023, John Wiley and Sons.

**Table 5.** Overview of work antimicrobial development work on metal surfaces.

| Method [Ref.] | Ease of Application | Durability * | Sustainability | Microbial Tested |
|---|---|---|---|---|
| $SiO_2/TiO_2$ Core-Shell Polyurethane Nanocoating [140] | ++<br>Painting and Drying | ++++ | + | Cyanobacteria, *F. solani*, *E. coli*, *Bacillus* |
| Copper-Incorporated Alumina PEO Coating [143] | +<br>Plasma Electrolytic Oxidation | +++ | ++ | *E. coli*, *S. aureus* |
| Superhydrophobic Silane-Based Coating [144] | +<br>Spin Coating–Curing-Spray Coating–Curing | +++ | +++ | *E. coli* |
| Quaternary Ammonium Polymer Coating [70] | ++<br>Electrospraying | N/A | ++ | HCoV-229E, SARS-CoV-2 |
| Silver on Stainless Steel [141] | +<br>Electrochemical Polishing and Pulse-Reverse Electrodeposition | ++++ | +++ | *E. coli*, *S. aureus* |
| Graphene Oxide on Aluminum [145] | ++++<br>Simple Transfer Method (With Filter Paper) | +++ | + | *E. coli* |
| Copper Surface on Stainless Steel [142] | ++<br>Cold Gas Spray | N/A | ++ | *E. coli*, *S. aureus (MSSA)*, *C. albicans* |
| Polyurethane Varnish Containing Gd(I)/Cs(III) Metal Complexes [147] | +++<br>Paint and cure at room temperature for 24H | N/A | +++ | ADeno-7, HSV-1, CV-B4, *S. aureus*, *B. cereus*, *E. coli*, *P. aeruginosa* |

N/A = not available/tested; the number of + provides an indication of the ease of application, durability, and sustainability of coating material. * There was not a standard way of measuring, but durability on metal was mostly evaluated based on its mechanical properties and abrasion and corrosive evaluations, which differs from other materials such as textiles, which evaluates the antimicrobial performance of the materials over washing cycles/use.

### *3.6. Other Works and General Antimicrobial Applications (Nonsurface Specific)*

There are several different material surfaces in the built environment that may benefit from having an antimicrobial coating. However, there were only a handful of studies on these surfaces, such as walls [148–150], leather [151,152], and wood [147,153]. While these are also frequently used materials in common built environment spaces, there is significantly more work focusing on textiles and glass, as they are considered "high-touch places" in hospital ward facilities, personal protective equipment (PPE), and touch screens.

Numerous studies suggested their suitability for the built environment but were not tested for their application on specific surface materials. Many of them reported the use of similar or derivatives of technologies that were mentioned in earlier sections suggesting the use of quaternary compounds [154,155] and metal-based antimicrobials that utilize zinc [69,156–158], copper [69,159], and silver [160–165] metal or metal compounds on their own or combined for synergistic effect [161,166–169]. Titanium dioxide ($TiO_2$) was also widely studied, as it can generate reactive oxygen species under UV radiation [170–172].

With the recent pandemic, a few of these works were also investigated for COVID-19 antiviral performance [156,173,174].

On top of that, some works developed less prevalent antimicrobial approaches, such as enzyme lysozyme grafting [175], guanidinium-containing polyoxometalate-ionic liquids integrated into poly (methyl methacrylate) [176], and visible light irradiated boron dipyrromethenes-containing copolymer [177]. Other studies also investigated conductive polymer poly 3,4-ethylenedioxythiophene (PEDOT) with carbon nanomaterial fullerene C60, covalently linked, which allows for photodynamic antimicrobial activity [178]. The PEDOT-C60 resulted in >99.9% *S. aureus* reduction. Another fascinating way of destroying microbials is to use a mechanical approach. Paxton et al. demonstrated such an approach where a diamond nanospike can rupture and kill bacteria (Figure 10) [179]. The use of vertically aligned, layered double hydroxide (V-LDH) also leverages its structure to rupture bacteria [180]. The studies by Yi et al. investigated V-LDH on various substrate types, including glass and stainless steel. They concluded that calcination of V-LDH improves the hydrophilicity, and the sharper V-LDH resulted in improved antimicrobial properties against *E. coli*, *S. aureus*, and *C. albicans*. Many of these works present very attractive proof-of-concept data, which may require a more in-depth understanding of their scalability and long-term application to be considered in built environment surfaces. Works which are less likely to trigger microbial resistance, such as enzyme lysozyme grafting [175], diamond nanospike [179], and V-LDH [180] can be beneficial in the long run in preventing the evolution of microbials exposed to antimicrobials [181].

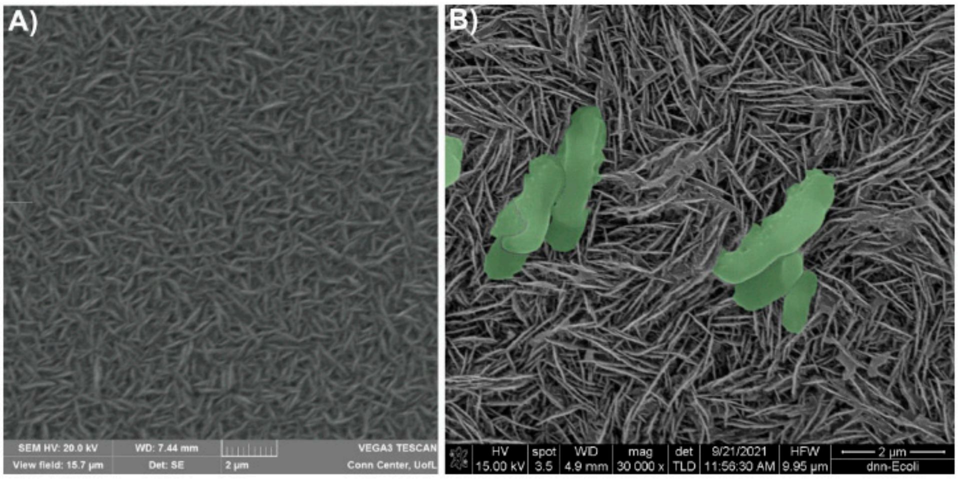


**Figure 10.** (**A**) SEM images of the diamond nanospikes, (**B**) *E. coli* cells being disrupted by the diamond nanospikes [179]. Reprinted/adapted with permission from Paxton et al., 2023, Springer Nature.

### *3.7. Sustainability Considerations*

Some studies also explored the incorporation of organic and nature-derived compounds, including castor seed oil [182] and tea [183], in the coating preparation process. Using such nature-derived and biodegradable material can be a sustainable option and reduce environmental impact. One of the works reviewed for polymers in Section 3.4 suggested coating of Arboblend pellets (contains various biopolymers, lignin, and other naturally derived organics) with silver (Ag) nanoparticles. Although the idea cleverly allows for the incorporation of Ag nanoparticles into injected molded parts, improper handling during degradation in landfill could lead to Ag nanoparticles leeching into soil and intoxicating living organisms [134].

In one work, curcumin, a natural ingredient derived from turmeric, was mixed with $TiO_2$ and ZnO to prepare a potentially antimicrobial film [184]. The usage of curcumin was also described in a work which combined it with cationic polymeric biocides to obtain a higher number of bacteria reduction [185]. Another work that leverages natural ingredients combines antimicrobial cinnamon bark oil into polydopamine, a biodegradable coating investigated by Cox et al. This work was one of the rare studies that consider sustainability meticulously in its material selection process without neglecting its durability. It also has a fuss-free and straightforward one-step fabrication process, which increases its potential as a sustainable technology [186].

While this review does not focus on the synthetic process of the biocides, another way to reduce the impact on the environment is to use environmentally friendly ingredients to prepare antimicrobial biocides. This helps to reduce the use of toxic chemicals during synthesis. Some works presented include using neem extract [187], sumac leaf extract [188], sand olive leaf extract [109], and soluble soybean polysaccharide [189]. For the synthesis of antimicrobial gold (Au) nanoparticles, lemon juice was also reported to catalyze synthetic process [190]. A review by Garg et al. that consolidates studies on greener ways to prepare many of such antimicrobial nanoparticles could shed more light on this topic [191]. Another helpful review that looks at biobased materials to mitigate the COVID-19 virus specifically, prepared by Usmani et al., would also be a valuable source on environmental-friendly antimicrobial agents [192].

### 3.8. Summary

This section reviewed several antimicrobial technologies developed in the last two years that suggested their potential use on different built environment surfaces. Ag and other metal nanoparticles were key technologies considered and studied for many of the different surfaces. However, it is also noteworthy to consider the longer-term risks these particles may have on ecosystems [193]. A study on silver ions and nanoparticles hypothesized that *E. coli* could gain resistance to silver nanoparticles after the authors found a permanent mutation in the bacteria after repeated exposure to silver nanoparticles [194]. Hence, when considering these materials, the advantages of their application and their impact on sustainability should be assessed thoroughly, especially in terms of the disposal management of nanoparticles to mitigate the risk of intoxicating other organisms.

Another crucial consideration would be the longevity and durability of the coating on targeted surfaces. Mechanical properties in dry and wet conditions are critical for the performance of the coating. A coating that does not last will lose its effect and cause a false sense of security. Moreover, frequent reapplication is not environmental-friendly and is expensive in the long run. Durability tests for the different materials were also evaluated differently. Metal material focuses on mechanical testing, while most textile studies look at postlaundering antimicrobial ability. As for glass materials, several works reported did not perform durability tests or did not last well beyond a few washes. Real-life evaluation, such as field testing, will also be very insightful. In this review thus far, only two works have been studied for their application in an actual setting—the toilet [83] and in train transport [122]. Unfortunately, the scalability of studies was frequently unavailable in most works, and consideration of scalability will be one of the essential considerations in real-life built environment applications. For example, many works presented several steps of surface pretreatment and metal coating techniques. These may be hard to achieve on existing infrastructure and may also be challenging to scale up.

The performance of an actual antimicrobial test was also missing in some works. In order to better compare the different technologies, antimicrobial test results would also give us better insights. Standardizing test protocols, be it for the durability or for antimicrobial studies, would also be beneficial for comparing the performance of different studies [195].

The price point of the technology is also an essential consideration, especially when built environment surfaces tend to cover a large surface. However, it is a complex process to provide direct analysis, as it depends on several factors, including material cost, the process of synthesizing antimicrobial agents/coating, the complexity of coating steps, and the number of antimicrobial agents required for technology to work. Raw materials consisting of Ag and Zn nanoparticles will unquestionably be costlier, and alternatives with lower-cost materials would be favored. While the synthetic process behind the antimicrobial agent and biocides are not the highlights of this paper, a tedious manufacturing process will be unfavorable to both its cost and adoption of technology. Lastly, the use of technologies repelling microbial attachment, such as the work by Jegel et al. [196] and Francone et al. [136] as compared to killing mechanisms (most works reviewed in this paper), would be beneficial in mitigating the risk of developing microbial resistance and could also be a more sustainable solution. The low-to-no leaching of chemicals or nanoparticles in these works is also highly favorable for the environment in the longer run.

## 4. Factors Affecting Microbes in Built Environment: Considerations and Potential Challenges

Section 3 discussed, in-depth, some of the available antimicrobial technologies studied in the last two years. In Section 4, the possible factors affecting microbes in an environment will be discussed. In developed countries, it is estimated that people spend 90% of their time indoors [197]. This increases people's exposure to indoor microorganisms, which can have an impact on human health and well-being. Since each building is designed, operated, and used differently, no "normal" or "typical" indoor microbiome is found in buildings [198]. Microbiomes can vary significantly in buildings with different functionalities, from residential, office, and hospital buildings to school and public buildings [199,200]. The indoor microbial communities also depend on factors, including the characteristics and operation of the building, the occupants and their behavior, and the external environment or conditions.

Figure 11 shows some of the environmental factors which shape the microbiome in an office environment. Within the building itself, the microbial communities could vary across the rooms or spaces with different functions. The bacterial communities in toilets will be significantly different from other rooms [201]. Consequently, understanding these factors associated with microbial transport and how interventions may affect it is necessary when developing methods for controlling or reducing microbial exposures in buildings [17]. For example (see Figure 11), the design and operation of an office building have a substantial part in shaping the microbiome of an indoor environment. The building design, such as the positioning and shape of the windows, can impact the sunlight transmission [2] and natural ventilation patterns [47], which in turn impacts the indoor environmental conditions. Furthermore, environmental factors, including air temperature, humidity, turbulence, and light, are also critical factors for the survival and transmission of the microbiomes indoors [202]. Another important design parameter is the material of the building and its components, which influences microbial growth. Certain building materials will be more susceptible to microbial colonization and growth [203]. The building design can also indirectly affect the indoor microbiome, such as the building layout, which influences how the occupants use or move around the space. A comprehensive review by Horve et al. also elaborated on many factors and their connectivity to microbial transmission between occupants [204].


**Figure 11.** Design, environmental and occupancy factors, and subsequent effects on built environment microorganisms. The office isometric image is adapted with permission from Freepik [205].

Occupants are major sources of indoor microorganisms, and their accumulation increases with occupancy level [206]. Furthermore, the skin, which acts as a barrier and protects us from pathogens, is a massive ecosystem with many bacteria and fungi [207]. Adams et al. [9] highlighted that humans are the key source of microbial input in buildings, predominately from their skin, which accounts for 5–40% of sequence reads.

The study by Cao et al. [208] confirms that occupancy-associated microbiota had a more significant influence on the indoor surface bacterial microbiomes in high-occupancy buildings/areas than in low-occupancy buildings/areas. This is especially significant in an older building (with occupancy of >5 years) than in a newly constructed one. These microbiomes are dispersed in buildings via direct/indirect contact with surfaces, emissions of particulates/bioaerosols from the occupants, and resuspension of settled particles which contain these microbiomes. They also found that human skin sources contributed between 6.2% (new building) and 13.4% (older building) on average to the indoor microbiome, while oral microbiota only contributed between 0.7–2.8%. Cao et al. [135] observed that human sources contributed higher in some areas, indicating variations across rooms within the same building. His work aligns with the findings of a study by Wang et al. [207], which found that even individuals of different nationalities living in the same environment can have different human skin microbiota. Studies highlighted that the health [209], age [210], and gender [211] of building occupants could influence the skin microorganisms, which subsequently affects the variability of the composition of the indoor microbiome.

Occupants can be exposed to these microorganisms when touching these microbe-covered surfaces or breathing in the particles with microbes (refer to Figure 1). While ventilation was frequently found to be the critical factor in reducing airborne transmission [46–48,50], it is often challenging to improve ventilation in certain climatic conditions, such as during winter or in countries with hot tropical or desert climates. Additionally, until now, available reports mainly consider either ventilation studies or surface transmission individually without considering the impact of surface transmission that may vary with its ventilation and other environmental factors. Therefore, studies in this area will be very informative in deciding the need for antimicrobial surfaces within a specific built environment. Indoor surfaces and building components such as HVAC and plumbing can also support microbial growth. Hence, identifying the surfaces of the most tremendous significance for improved design or maintenance practices to reduce bacterial and viral microbes is a significant challenge. In order to evaluate the risk associated with the contamination of building surfaces, one must consider the types of surfaces that are most likely to be contaminated during activities of daily living [18].

Of most significant concern are surfaces touched by multiple occupants, also known as **high-touch surfaces**. These surfaces represent an exceptionally high risk of transmission of infectious microorganisms indoors. Examples of high-touch surfaces in houses and hospitals are covered in the work of Smith et al. [212]. For this review, examples of high-touch surfaces in an office environment, as summarized in Table 6, were consolidated.

**Table 6.** Example of office building high-touch surfaces and bacterial reservoir.

| Office Zones | High-Touch Surfaces and Bacterial Reservoir |
| --- | --- |
| All rooms | Switches, door handles, floor/carpet, curtain/blinds, window handle, phones, dust, air, and HVAC filters |
| Office space | Keyboard, mouse, laptop, telephone, desks, chair, LCD screen, cabinet handle, printer interface, water fountain, and coffee machine |
| Meeting/conference rooms | Conference equipment, keyboard, mouse, laptop, telephone, desks, and chair |
| Restroom | Sink, faucet handles, toilet seat, toilet flush, hand towel dispenser, hand blower button, countertop, soap dispenser, stall door and handles, and water |
| Kitchen | Kettle, coffee machine, microwave oven buttons, refrigerator handle, countertop, sink, faucet handles, table, chair, water fountain, soap dispenser, and water |
| Lobby, reception, and front desk | Telephone, keyboard, mouse, desk, chair, sofa, coffee table, and coffee/snack machine |
| Hallway and corridors | Elevator switches and handrails |

Numerous other strategies can be applied to minimize the opportunity for infection through human contact with contaminated building surfaces. This includes hand washing, touchless controls, ultraviolet light, and surface sterilization. However, there are limited studies or evidence which show the efficacy and effectiveness of these approaches [15]. For example, the inability of existing disinfectants to disrupt biofilms has been reported [213]. The study showed that up to 30% of surfaces are contaminated. There are also concerns regarding the increased risk in microbial resistance and the prevalence of chemicals in buildings when using some of these approaches. Therefore, further research and experimentation are required to better understand the effectiveness of different cleaning and disinfection strategies.

The entire cycle of infection and reinfection as shown in Figure 1 must not be forgotten when applying these approaches. Timely and effective use of targeted approaches may help interrupt the cycle and eliminate the necessity for the continuous cleaning and decontamination of all building surfaces [214]. A recommendation by Scott et al. [18] states that the following points should be considered in the development and implementation of decontamination strategies for targeted surfaces:

1. Probability of contamination at the targeted surface;
2. The survivability of the pathogens on these surfaces;
3. Length of infectiousness, probability of the transfer of the infectious microorganism from the surfaces to humans and to other surfaces and host;
4. Susceptibility of the new hosts to acquire the infection and;
5. The personnel who will carry out the decontamination and factors such as training, equipment, and staff competencies.

As elaborated in this section, the indoor microbial communities in a building depend on many factors, including the characteristics and operation of the building, the occupants and their behavior, and the external environment or conditions. The relationships between these factors impact the transport and removal of microbes and the formation of their reservoirs. Consequently, understanding the different factors associated with microbial transport and how interventions may affect it are necessary when developing methods for controlling microbial exposures in buildings. Studies should focus on rigorously examining the efficacy and effectiveness of different interventions. Finally, more attention should be paid to studying surface contamination in different building spaces so that better guidelines can be developed for microbiologic assessment and implementation of decontamination strategies.

## 5. Research Gap and Conclusions

There have been numerous works on antimicrobial technologies for surfaces. This review highlights the work that were specifically studied on built environment surfaces such as ceramics, textiles, metals, etc. Such studies are important in understanding the ease of preparation and application, and they provide insights into the functionality and durability of the antimicrobial coating on the selected surfaces. Technologies such as the use of $TiO_2$, metal nanoparticles, and quaternary compounds/polymers are often considered to be strong contenders in the field of antimicrobial technologies. However, longer-term concerns such as cost effectiveness, durability, sustainability, scalability, and potential leaching of chemicals need to be thoroughly studied before the wide-reaching adoption of the technology in the built environment. In Section 2 of this review, criteria that are important when considering the integration of antimicrobial technologies were also summarized. Other important factors to consider are the ease of application, effectiveness on different types of microbials, approval from relevant authorities, standardized method for testing, functionality, and aesthetics.

While the risk of surface contamination is generally lower than that of poor indoor ventilation, it is still a mitigable cause of concern. Usage of an antimicrobial fibrous air filter in HVAC systems could be one way to minimize the number of microbes attached to the filter, minimizing the risk of spreading airborne pathogens. It is an area that is not widely investigated as compared to other built environment surfaces. Many of the works studying surface contamination investigated hospital environments, as they have higher risks and a higher number of vulnerable patients. Even so, works that evaluate other indoor built environment spaces would be beneficial for researchers to understand better and develop suitable antimicrobial technologies as required for different indoor environments. With the importance of ventilation, investigations that consider the dynamic of both surface contamination and the influence of ventilation would be highly insightful.

In terms of application, careful consideration should be taken for indoor spaces with a higher level of social interactions throughout the day and have occupants more susceptible to infections, such as residential homes [215], children's daycare centers [216], facilities supporting patients with intellectual disabilities [217], and schools [214]. In urban cities, public transportation can have a large number of passengers throughout the day, and high-touch areas on transportation sites would benefit from antimicrobial surfaces or installation of antimicrobial air filters to improve the air quality [122].

The widely diverse types of built environment in public areas with varying purposes, designs, and types of surfaces mean that there is no single strategy for every space. Some of the main challenges include the extensive interaction occurring among indoor air, water, and surfaces. This increases the challenges of designing and integrating antimicrobial technologies into a building. Additionally, indoor and outdoor conditions change continuously throughout the day and continuously affect the formation, transportation, and removal of microbiomes. Meticulous planning and considerations should also take place while designing the space to find an optimal solution.

In order to improve the adoption and consideration of antimicrobial surfaces, the built environment industry and stakeholders could benefit from more in-depth and long-term evaluation of these antimicrobial technologies, which demonstrate their real-time impact on various built environment spaces. Several public spaces have resorted to frequent sanitation to reduce pathogens, as this is easier to accomplish when compared to upgrading or repurposing a surface to have antimicrobial properties. Incorporating the right antimicrobial technology would combat the need to perform such repetitive cleaning.

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