Antimicrobial Technologies for Built Environment

Subjects: Construction & Building Technology
Contributor: Ling Xin Yong, John Kaiser Calautit

Every year, more than 4 million people are at risk of dying due to acquiring a microbial infection. As per the 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 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 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

1. Introduction

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 [1][2][3], copper [4][5], and quaternary ammonium compounds [6][7]. Another mechanism focuses on repelling microbes inherently with antimicrobial polymer [8][9], thus preventing microbial attachment [10]. 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 [11].

2. Ceramics

Ceramics include a wide range of materials that are inorganic and nonmetallic and are known for their hardness, density, and durability [12]. 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 [12]. The base material of porcelain is strong, and glazing provides waterproof properties and facilitates easy cleaning [13]. 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 [14]. Studies have found that this worsens with poorly ventilated restrooms [15] and the emission of the airborne pathogen during flushing [16]. Hence, bathrooms are one of the most frequently sanitized public spaces. Additionally, sanitary ware already has several commercialized products incorporating antimicrobial technologies [17][18], and many of these were mentioned in a recent review, "The challenge of antimicrobial glazed ceramic surfaces" [13].

Another application of ceramics would be for wall and flooring tiles, chosen for their lasting properties and aesthetics [19]. In one particular work by Golshan et al., the research explored the possibility of modifying industrial floor tiles to achieve antibacterial activity [3]. The sol–gel method was used to prepare both titanium dioxide (TiO_2) solution and silver-titanium dioxide ($Ag\text{-}TiO_2$) 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%. 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)* [20]. 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 [11]. 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 [21].

Many studies on glass surfaces evaluate the use of oxides and/or metals such as silver [1][2][4][22][23][24] 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 [2]. 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 [22].

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 [4]. 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. [1]. 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.

Quaternized polydopamine coatings with magnetite nanoparticles attaching silver salts could offer an alternative strategy for good dispersion of silver ion [25]. 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, 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.

Photodynamic inactivation (PDI) of microbes in the presence of reactive oxygen species [26] and polycationic polymer for cell wall disruption [27] 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 [28]. 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) [27]. 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 [29], Azure A and 5-(4-aminophenyl)-10,15,20-(triphenyl)porhyrin (APTPP) [30], and TiO_2 nanocoated glass [23].

3. Textile

Textiles are cloth or woven fabric that can be found as curtains, carpets, tablecloths, cushions/sofa/seat covers, and blankets/bedsheet in hospitals [31]. Textiles frequently affect the comfort of people [32], and hence, the material requires a vastly different set of properties compared to other materials such as glass, discussed Section 2. Common properties considered are flexibility, durability, weight, tactility, water absorption, and mechanical properties of the textile [33][34]. In many of their applications, textiles should provide insulation (e.g., carpet), visual privacy (e.g., curtains), and comfort (e.g., bedding) as well [32]. 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 [35].

Again, the incorporation of metal/metal compound nanoparticles is one of the main strategies studied for antimicrobial textiles or yarn [36][37][38][39][40][41][42][43]. 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 [44]. 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 [45], cuprose oxide and titanium dioxide [46], and silver and titanium oxide [47] 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 [7]. 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) [48]. 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 [49][50][51][52][53] for hospital garments and personal protection equipment (PPE).

Cationic antimicrobial polymers have also been explored for application on textiles; polyionenes were functionalized with silane to aid bonding to cotton fabric [9]. The silane-functionalized polyionenes were effective 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.

A handful of works focus on evaluating antimicrobial properties, but not all studies suggested to work on textiles were evaluated for their suitability [54][55]. 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 [55].

Lastly, the work by Mirzaei et al. [56] 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 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.

4. 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 [57]. The majority of HVAC filters in air-conditioning are made of either fiberglass [58], cotton, or polymeric materials such as polypropylene [59]. Despite the strong emphasis and importance of ventilation [60][61][62] 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 [58]. 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 [63][64].

Out of four articles found, two of them discuss the application of their antimicrobial work for personal-use masks [65][66], while the others discuss air filters for use in air-conditioning or air purifiers [63][64]. 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. PP-GO-PD was evaluated for its antimicrobial property with *E. coli*, and the bacterial cell viability was 72.5%. Kasbe et al. [64] then added cationic poly[(2-(methacryloyloxy) ethyl) trimethylammonium chloride] (PMETAC) polymer grafting on GO to further reduce *E. coli* cell viability to 42.2%.

In another work by Park et al. [63], 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. [57] 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 2×10^6 CFU of microbes.

5. Polymer

Plastics or polymers needs no introduction, and they are everywhere around people. 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 [67]. 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 [68]. 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 [69]. 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 [70].

Antimicrobial coatings using silver (Ag) nanoparticles were again studied for application in a biopolymer blend [71]. 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.

Finally, a work by Francone et al. utilized a different approach that looks at preventing microbial attachment by engineering the surface of polypropylene film [72]. Nanoimprint lithography was used to create texture, 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.

6. 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 [73][74]. 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 [74].

One study introduced the use of core-shell-incorporated coating for multifunction purposes [75]; 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 was validated by Wang et al. [76] 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 [77]. Santos et al. demonstrated copper incorporation into plasma electrolytic oxidation, which produces a high-adherence ceramic coating [78] 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 [79]. 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 [80]. 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 [6]. 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 [81], 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. [82]. 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.

7. 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 [83][84][85], leather [86][87], and wood [82][88]. 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 [89][90] and metal-based antimicrobials that utilize zinc [5][91][92][93], copper [5][94], and silver [95][96][97][98][99][100] metal or metal compounds on their own or combined for synergistic effect [96][101][102][103][104]. Titanium dioxide (TiO_2) was also widely studied, as it can generate reactive oxygen species under UV radiation [105][106][107]. With the recent pandemic, a few of these works were also investigated for COVID-19 antiviral performance [91][108][109].

On top of that, some works developed less prevalent antimicrobial approaches, such as enzyme lysozyme grafting [110], guanidinium-containing polyoxometalate-ionic liquids integrated into poly (methyl methacrylate) [111], and visible light irradiated boron dipyrromethenes-containing copolymer [112]. Other studies also investigated conductive polymer poly 3,4-ethylenedioxythiophene (PEDOT) with carbon nanomaterial fullerene C60, covalently linked, which allows for photodynamic antimicrobial activity [113]. 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 [114]. The use of vertically aligned, layered double hydroxide (V-LDH) also leverages its structure to rupture bacteria [115]. 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 [110], diamond nanospike [114], and V-LDH [115] can be beneficial in the long run in preventing the evolution of microbials exposed to antimicrobials [116].

8. Sustainability Considerations

Some studies also explored the incorporation of organic and nature-derived compounds, including castor seed oil [117] and tea [118], 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 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 [71].

In one work, curcumin, a natural ingredient derived from turmeric, was mixed with TiO_2 and ZnO to prepare a potentially antimicrobial film [119]. 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 [120]. Another work that leverages natural ingredients combines antimicrobial cinnamon bark oil into polydopamine, a biodegradable coating investigated by Cox et al.

References

1. Hosseini, M.; Chin, A.W.H.; Williams, M.D.; Behzadinasab, S.; Falkinham, J.O.; Poon, L.L.M.; Ducker, W.A. Transparent Anti-SARS-CoV-2 and Antibacterial Silver Oxide Coatings. ACS Appl. Mater. Interfaces 2022, 14, 8718–8727.
2. Khan, G.R.; Malik, S.I. Ag-enriched TiO2 nanocoating apposite for self-sanitizing/self-sterilizing/self-disinfecting of glass surfaces. Mater. Chem. Phys. 2022, 282, 125803.
3. Golshan, V.; Mirjalili, F.; Fakharpour, M. Self-Cleaning Surfaces with Superhydrophobicity of Ag–TiO2 Nanofilms on the Floor Ceramic Tiles. Glass Phys. Chem. 2022, 48, 35–42.
4. Delumeau, L.V.; Asgarimoghaddam, H.; Alkie, T.; Jones, A.J.B.; Lum, S.; Mistry, K.; Aucoin, M.G.; Dewitte-Orr, S.; Musselman, K.P. Effectiveness of antiviral metal and metal oxide thin-film coatings against human coronavirus 229E. APL Mater. 2021, 9, 111114.
5. Pan, C.; Phadke, K.S.; Li, Z.; Ouyang, G.; Kim, T.H.; Zhou, L.; Slaughter, J.; Bellaire, B.; Ren, S.; Cui, J. Sprayable copper and copper-zinc nanowires inks for antiviral surface coating. RSC Adv. 2022, 12, 6093–6098.
6. Ikner, L.A.; Torrey, J.R.; Gundy, P.M.; Gerba, C.P. Efficacy of an antimicrobial surface coating against human coronavirus 229E and SARS-CoV-2. Am. J. Infect. Control 2021, 49, 1569–1571.
7. Phutthatham, L.; Ngernchuklin, P.; Kaewpa, D.; Chaiyasat, P.; Chaiyasat, A. UV-activated coating polymer particle containing quaternary ammonium for antimicrobial fabrics. Colloid Polym. Sci. 2022, 300, 351–364.
8. Ghosh, S.; Haldar, J. Cationic polymer À based antibacterial smart coatings. In Advances in Smart Coatings and Thin Films for Future Industrial and Biomedical Engineering Applications; Elsevier, Inc.: Amsterdam, The Netherlands, 2020; ISBN 9780128498705.
9. Qiu, Q.; Yang, C.; Wang, Y.; Alexander, C.A.; Yi, G.; Zhang, Y.; Qin, X.; Yang, Y.Y. Silane-functionalized polyionenes-coated cotton fabrics with potent antimicrobial and antiviral activities. Biomaterials 2022, 284, 121470.
10. Jampílek, J.; Král'ová, K. Nanoantimicrobials: Activity, Benefits, and Weaknesses. In Nanostructures for Antimicrobial Therapy; Nanostructures in Therapeutic Medicine Series; Elsevier: Amsterdam, The Netherlands, 2017; ISBN 9780323461511.
11. Ziff, M. The Role of Glass in Interior Architecture: Aesthetics, Community, and Privacy. J. Aesthetic Educ. 2004, 38, 10–21.
12. Bechthold, M.; Kane, A.; King, N. Ceramic Material Systems: In Architecture and Interior Design; Birkhäuser: Basel, Switzerland, 2015.
13. Reinosa, J.J.; Enríquez, E.; Fuertes, V.; Liu, S.; Menéndez, J.; Fernández, J.F. The challenge of antimicrobial glazed ceramic surfaces. Ceram. Int. 2022, 48, 7393–7404.
14. Matini, E.; Shayeghi, F.; Vaghar, M.; Nematian, J.; Hosseini, S.S.; Mojri, N.; Taherabadi, N.T.; Hakimi, R.; Ahmadi, N.; Badkoubeh, N.; et al. A survey of public restrooms microbial contamination in Tehran city, capital of Iran, during 2019. J. Fam. Med. Prim. Care 2020, 9, 3132–3135.
15. Lee, M.C.J.; Tham, K.W. Public toilets with insufficient ventilation present high cross infection risk. Sci. Rep. 2021, 11, 20623.
16. Lai, A.C.K.; Tan, T.F.; Li, W.S.; Ip, D.K.M. Emission strength of airborne pathogens during toilet flushing. Indoor Air 2018, 28, 73–79.
17. Microban Products Company. Antimicrobial Ceramic Glaze; Microban Products Company: Hong Kong, China, 2005.
18. Microban Products Company. Method for Applying a Ceramic Glaze Layer having Antimicrobial Property; Microban Products Company: Hong Kong, China, 2012.
19. Monfort, E.; Mezquita, A.; Vaquer, E.; Celades, I.; Sanfelix, V.; Escrig, A. Ceramic Manufacturing Processes: Energy, Environmental, and Occupational Health Issues; Elsevier: Amsterdam, The Netherlands, 2014; Volume 8, ISBN 9780080965338.
20. Kim, J.; Kim, U.; Han, K.; Choi, J. Antibacterial persistence of hydrophobically glazed ceramic tiles. J. Korean Ceram. Soc. 2022, 59, 920–928.
21. National Environmental Agency (NEA). General Sanitation and Hygiene Advisory for Premises Owners and Operators. 2020. Available online: https://www.nea.gov.sg/our-services/public-cleanliness/environmental-cleaning-guidelines/advis

ories/general-sanitation-and-hygiene-advisory-for-premises-owners-and-operators (accessed on 11 April 2022).

22. Prawira, R.A.; Ariyanti, D. TiO2-M self-cleaning coating with antimicrobial and superhydrophilic properties. Mater. Today Proc. 2022, 63, S214–S221.
23. Álvarez, Á.L.; Dalton, K.P.; Nicieza, I.; Abade Dos Santos, F.A.; de la Peña, P.; Domínguez, P.; Martin-Alonso, J.M.; Parra, F. Virucidal Properties of Photocatalytic Coating on Glass against a Model Human Coronavirus. Microbiol. Spectr. 2022, 10, e00269-22.
24. Vitelaru, C.; Parau, A.C.; Kiss, A.E.; Pana, I.; Dinu, M.; Constantin, L.R.; Vladescu, A.; Tonofrei, L.E.; Adochite, C.S.; Costinas, S.; et al. Silver-Containing Thin Films on Transparent Polymer Foils for Antimicrobial Applications. Coatings 2022, 12, 170.
25. Mude, H.; Maroju, P.A.; Balapure, A.; Ganesan, R.; Ray Dutta, J. Quaternized Polydopamine Coatings for Anchoring Molecularly Dispersed Broad-Spectrum Antimicrobial Silver Salts. ACS Appl. Bio Mater. 2021, 4, 8396–8406.
26. Pucelik, B.; Dąbrowski, J.M. Photodynamic inactivation (PDI) as a promising alternative to current pharmaceuticals for the treatment of resistant microorganisms. Adv. Inorg. Chem. 2022, 79, 65–103.
27. Pigareva, V.A.; Senchikhin, I.N.; Bolshakova, A.V.; Sybachin, A.V. Modification of Polydiallyldimethylammonium Chloride with Sodium Polystyrenesulfonate Dramatically Changes the Resistance of Polymer-Based Coatings towards Wash-Off from Both Hydrophilic and Hydrophobic Surfaces. Polymers 2022, 14, 1247.
28. Baigorria, E.; Durantini, J.E.; Martínez, S.R.; Milanesio, M.E.; Palacios, Y.B.; Durantini, A.M. Potentiation Effect of Iodine Species on the Antimicrobial Capability of Surfaces Coated with Electroactive Phthalocyanines. ACS Appl. Bio Mater. 2021, 4, 8559–8570.
29. Pigareva, V.A.; Stepanova, D.A.; Bolshakova, A.V.; Marina, V.I.; Osterman, I.A.; Sybachin, A.V. Hyperbranched Kaustamin as an antibacterial for surface treatment. Mendeleev Commun. 2022, 32, 561–563.
30. Nyga, A.; Czerwińska-Główka, D.; Krzywiecki, M.; Przystaś, W.; Zabłocka-Godlewska, E.; Student, S.; Kwoka, M.; Data, P.; Blacha-Grzechnik, A. Covalent immobilization of organic photosensitizers on the glass surface: Toward the formation of the light-activated antimicrobial nanocoating. Materials 2021, 14, 3093.
31. Mogensen, J.E.; Poulsen, B.; Fisker, A.M. Interior Textiles and the Concept of Atmospheres—A Case Study on the Architectural Potential of Textiles in Danish Hospitals Interiors. In Textile Society of America Symposium Proceedings; Textile Society of America: Baltimore, MD, USA, 2014.
32. Angelova, R.A. Non-Woven Textiles in the Indoor Environment. In Non-Woven Fabrics; InTech: Rijeka, Crotia, 2016.
33. Andreucci, M.B.; Marvuglia, A.; Baltov, M.; Hansen, P. Future City 15 Rethinking Sustainability Towards a Regenerative Economy; Springer: Berlin/Heidelberg, Germany, 2021; ISBN 9783030718183.
34. Grishanov, S. Structure and properties of textile materials. In Handbook of Textile and Industrial Dyeing: Principles, Processes and Types of Dyes; Woodhead Publishing Limited: Cambridge, UK, 2011; Volume 1, ISBN 9780857093974.
35. Joly, S.B. Architecture Fabric: The New Use of Textiles as A Building Material. 2021. Available online: https://www.fashionnovation.com/architecture-fabric-the-new-use-of-textiles-as-a-building-material/ (accessed on 17 April 2022).
36. Tania, I.S.; Ali, M. Coating of ZnO nanoparticle on cotton fabric to create a functional textile with enhanced mechanical properties. Polymers 2021, 13, 2701.
37. Munir, M.U.; Ashraf, M.; Abid, H.A.; Javid, A.; Riaz, S.; Khanzada, H.; Rehman, A.; Iqbal, K. Coating of modified ZnO nanoparticles on cotton fabrics for enhanced functional characteristics. J. Coat. Technol. Res. 2022, 19, 467–475.
38. Prorokova, N.; Vavilova, S. Properties of polypropylene yarns with a polytetrafluoroethylene coating containing stabilized magnetite particles. Coatings 2021, 11, 830.
39. El-Naggar, M.E.; Khattab, T.A.; Abdelrahman, M.S.; Aldalbahi, A.; Hatshan, M.R. Development of antimicrobial, UV blocked and photocatalytic self-cleanable cotton fibers decorated with silver nanoparticles using silver carbamate and plasma activation. Cellulose 2021, 28, 1105–1121.
40. Feng, J.; Feng, L.; Xu, S.; Zhu, C.; Pan, G.; Yao, L. Universal Preparation Strategy for Ultradurable Antibacterial Fabrics through Coating an Adhesive Nanosilver Glue. Nanomaterials 2022, 12, 2429.
41. Shahid, M.; Ali, A.; Khaleeq, H.; Farrukh Tahir, M.; Militky, J.; Wiener, J. Development of Antimicrobial Multifunctional Textiles to Avoid from Hospital-Acquired Infections. Fibers Polym. 2021, 22, 3055–3067.
42. Islam, M.T.; Mamun, M.A.A.; Hasan, M.T.; Shahariar, H. Scalable coating process of AgNPs-silicone on cotton fabric for developing hydrophobic and antimicrobial properties. J. Coatings Technol. Res. 2021, 18, 887–898.
43. Andra, S.; Balu, S.K.; Jeevanandam, J.; Muthalagu, M.; Danquah, M.K. Surface cationization of cellulose to enhance durable antibacterial finish in phytosynthesized silver nanoparticle treated cotton fabric. Cellulose 2021, 28, 5895–5910.

44. Rezić, I.; Škoc, M.S.; Majdak, M.; Jurić, S.; Stracenski, K.S.; Vinceković, M. Functionalization of Polymer Surface with Antimicrobial Microcapsules. Polymers 2022, 14, 1961.
45. Hu, J.; Zhao, Y.; Meng, Y.; Su, J.; Han, J. Long-lasting antimicrobial activity achieved through the synergy of graphene oxide and cuprous oxide coating on PET fabrics. Synth. Met. 2022, 286, 117033.
46. Yuzer, B.; Iberia, M.; Hilmi, A.; Inan, H.; Can, S.; Selcuk, H.; Kadmi, Y. Photocatalytic, self-cleaning and antibacterial pr operties of Cu (II) doped TiO2. J. Environ. Manag. 2022, 302, 114023.
47. Abualnaja, K.M.; ElAassar, M.R.; Ghareeb, R.Y.; Ibrahim, A.A.; Abdelsalam, N.R. Development of photo-induced Ag0/Ti O2 nanocomposite coating for photocatalysis, self-cleaning and antimicrobial polyester fabric. J. Mater. Res. Technol. 2 021, 15, 1513–1523.
48. Wang, P.; Zhang, M.Y.; Qu, J.H.; Wang, L.J.; Geng, J.Z.; Fu, F.Y.; Liu, X.D. Antibacterial cotton fabric prepared by a "gr afting to" strategy using a QAC copolymer. Cellulose 2022, 29, 3569–3581.
49. Hongrattanavichit, I.; Aht-Ong, D. Antibacterial and water-repellent cotton fabric coated with organosilane-modified cellu lose nanofibers. Ind. Crops Prod. 2021, 171, 113858.
50. Hou, J.; Yang, Y.; Yu, D.G.; Chen, Z.; Wang, K.; Liu, Y.; Williams, G.R. Multifunctional fabrics finished using electrospra yed hybrid Janus particles containing nanocatalysts. Chem. Eng. J. 2021, 411, 128474.
51. Wang, D.; Li, K.; Zhou, C.; Lei, L.; de Mimérand, Y.d.R.; Jin, X.; Guo, J. Bi2MoO6 and Ag nanoparticles immobilized on textile by plasma-derived innovative techniques to generate antimicrobial activity. Appl. Surf. Sci. 2022, 585, 152591.
52. Ye, Z.; Li, S.; Zhao, S.; Deng, L.; Zhang, J.; Dong, A. Textile coatings configured by double-nanoparticles to optimally c ouple superhydrophobic and antibacterial properties. Chem. Eng. J. 2021, 420, 127680.
53. Alzahrani, H.K.; Munshi, A.M.; Aldawsari, A.M.; Keshk, A.A.; Asghar, B.H.; Osman, H.E.; Khalifa, M.E.; El-Metwaly, N. M. Development of photoluminescent, superhydrophobic, and electrically conductive cotton fibres. Luminescence 202 1, 36, 964–976.
54. Ali, D.; Butt, M.Z.; Muneer, I.; Bashir, F.; Hanif, M.; Khan, T.M.; Abbasi, S.A. Synthesis, characterization and antibacteria l performance of transparent c-axis oriented Al doped ZnO thin films. Surf. Interfaces 2021, 27, 101452.
55. Ayon, S.A.; Jamal, M.; Billah, M.M.; Neaz, S. Augmentation of magnetic properties and antimicrobial activities of band g ap modified Ho3+ and Sm3+ doped ZnO nanoparticles: A comparative experimental study. J. Alloys Compd. 2022, 897, 163179.
56. Mirzaei, M.; Furxhi, I.; Murphy, F.; Mullins, M. A supervised machine-learning prediction of textile's antimicrobial capacit y coated with nanomaterials. Coatings 2021, 11, 1532.
57. Watson, R.; Oldfield, M.; Bryant, J.A.; Riordan, L.; Hill, H.J.; Watts, J.A.; Alexander, M.R.; Cox, M.J.; Stamataki, Z.; Scu rr, D.J.; et al. Efficacy of antimicrobial and anti-viral coated air filters to prevent the spread of airborne pathogens. Sci. R ep. 2022, 12, 2803.
58. Hassan Al-abdalall, A.; Abdullah Al-dakheel, S.; Abdulhadi Al-Abkari, H. Impact of Air-Conditioning Filters on Microbial Growth and Indoor Air Pollution. In Low-Temperature Technologies; IntechOpen: London, UK, 2020; pp. 1–27.
59. Chen, Y.; Li, X.; Zhang, X.; Zhang, Y.; Gao, W.; Wang, R.; He, D. Air conditioner filters become sinks and sources of ind oor microplastics fibers. Environ. Pollut. 2022, 292, 118465.
60. Morawska, L.; Tang, J.W.; Bahnfleth, W.; Bluyssen, P.M.; Boerstra, A.; Buonanno, G.; Cao, J.; Dancer, S.; Floto, A.; Fra nchimon, F.; et al. How can airborne transmission of COVID-19 indoors be minimised? Environ. Int. 2020, 142, 105832.
61. Senatore, V.; Zarra, T.; Buonerba, A.; Choo, K.-H.; Hasan, S.W.; Korshin, G.; Li, C.-W.; Ksibi, M.; Belgiorno, V.; Nadde o, V. Indoor versus outdoor transmission of SARS-COV-2: Environmental factors in virus spread and underestimated s ources of risk. Euro-Mediterr. J. Environ. Integr. 2021, 6, 30.
62. Burridge, H.C.; Bhagat, R.K.; Stettler, M.E.J.; Kumar, P.; De Mel, I.; Demis, P.; Hart, A.; Johnson-Llambias, Y.; King, M. F.; Klymenko, O.; et al. The ventilation of buildings and other mitigating measures for COVID-19: A focus on wintertime. Proc. R. Soc. A 2021, 477, 20200855.
63. Park, K.; Kang, S.; Park, J.W.; Hwang, J. Fabrication of silver nanowire coated fibrous air filter medium via a two-step p rocess of electrospinning and electrospray for anti-bioaerosol treatment. J. Hazard. Mater. 2021, 411, 125043.
64. Kasbe, P.S.; Gade, H.; Liu, S.; Chase, G.G.; Xu, W. Ultrathin Polydopamine-Graphene Oxide Hybrid Coatings on Poly mer Filters with Improved Filtration Performance and Functionalities. ACS Appl. Bio Mater. 2021, 4, 5180–5188.
65. Tsutsumi-Arai, C.; Iwamiya, Y.; Hoshino, R.; Terada-Ito, C.; Sejima, S.; Akutsu-Suyama, K.; Shibayama, M.; Hiroi, Z.; To kuyama-Toda, R.; Iwamiya, R.; et al. Surface Functionalization of Non-Woven Fabrics Using a Novel Silica-Resin Coati ng Technology: Antiviral Treatment of Non-Woven Fabric Filters in Surgical Masks. Int. J. Environ. Res. Public Health 2 022, 19, 3639.

66. Goswami, M.; Yadav, A.K.; Chauhan, V.; Singh, N.; Kumar, S.; Das, A.; Yadav, V.; Mandal, A.; Tiwari, J.K.; Siddiqui, H.; et al. Facile development of graphene-based air filters mounted on a 3D printed mask for COVID-19. J. Sci. Adv. Mater. Devices 2021, 6, 407–414.

67. Sadiklar, Z.; Tavsan, F. A study on selection of polymer based surface materials in interior design. Glob. J. Humanit. So c. Sci. 2016, 3, 387–396.

68. Fischer, T.; Suttor, S.; Mansi, S.; Osthues, L.; Mela, P. Antimicrobial silicone rubbers based on photocatalytically active additives. J. Appl. Polym. Sci. 2021, 138, 51352.

69. Duvanova, E.; Krasnou, I.; Krumme, A.; Mikli, V.; Radio, S.; Rozantsev, G.M.; Karpichev, Y. Development of Functional Composite Cu(II)-Polyoxometalate/PLA with Antimicrobial Properties. Molecules 2022, 27, 2510.

70. Bedard, J.; Caschera, A.; Foucher, D.A. Access to thermally robust and abrasion resistant antimicrobial plastics: Synthe sis of UV-curable phosphonium small molecule coatings and extrudable additives. RSC Adv. 2021, 11, 5548–5555.

71. Motas, J.G.; Gorji, N.E.; Nedelcu, D.; Brabazon, D.; Quadrini, F. Xps, sem, dsc and nanoindentation characterization of silver nanoparticle-coated biopolymer pellets. Appl. Sci. 2021, 11, 7706.

72. Francone, A.; Merino, S.; Retolaza, A.; Ramiro, J.; Alves, S.A.; de Castro, J.V.; Neves, N.M.; Arana, A.; Marimon, J.M.; Torres, C.M.S.; et al. Impact of surface topography on the bacterial attachment to micro- and nano-patterned polymer fil ms. Surfaces Interfaces 2021, 27, 101494.

73. Colin, M.; Klingelschmitt, F.; Charpentier, E.; Josse, J.; Kanagaratnam, L.; De Champs, C.; Gangloff, S.C. Copper alloy touch surfaces in healthcare facilities: An effective solution to prevent bacterial spreading. Materials 2018, 11, 2479.

74. Birkett, M.; Dover, L.; Cherian Lukose, C.; Wasy Zia, A.; Tambuwala, M.M.; Serrano-Aroca, Á. Recent Advances in Met al-Based Antimicrobial Coatings for High-Touch Surfaces. Int. J. Mol. Sci. 2022, 23, 1162.

75. Verma, J.; Gupta, A.; Kumar, D. Progress in Organic Coatings Steel protection by SiO2/TiO2 core-shell based hybrid n anocoating. Prog. Org. Coat. 2022, 163, 106661.

76. Wang, X.; Ye, X.; Zhang, L.; Shao, Y.; Zhou, X.; Lu, M.; Chu, C.; Xue, F.; Bai, J. Corrosion and antimicrobial behavior of stainless steel prepared by one-step electrodeposition of silver at the grain boundaries. Surf. Coat. Technol. 2022, 439, 128428.

77. Da Silva, F.S.; de Paula e Silva, A.C.A.; Barbugli, P.A.; Cinca, N.; Dosta, S.; Cano, I.G.; Guilemany, J.M.; Vergani, C.E.; Benedetti, A.V. Anti-biofilm activity and in vitro biocompatibility of copper surface prepared by cold gas spray. Surf. Coa t. Technol. 2021, 411, 126981.

78. Santos, J.S.; Márquez, V.; Buijnsters, J.G.; Praserthdam, S.; Praserthdam, P. Antimicrobial properties dependence on t he composition and architecture of copper-alumina coatings prepared by plasma electrolytic oxidation (PEO). Appl. Sur f. Sci. 2023, 607, 155072.

79. Nie, Y.; Ma, S.; Tian, M.; Zhang, Q.; Huang, J.; Cao, M.; Li, Y.; Sun, L.; Pan, J.; Wang, Y.; et al. Superhydrophobic silan e-based surface coatings on metal surface with nanoparticles hybridization to enhance anticorrosion efficiency, wearing resistance and antimicrobial ability. Surf. Coat. Technol. 2021, 410, 126966.

80. Mandal, P.; Ghosh, S.K.; Grewal, H.S. Graphene oxide coated aluminium as an efficient antibacterial surface. Environ. Technol. Innov. 2022, 28, 102591.

81. Calfee, M.W.; Ryan, S.P.; Abdel-Hady, A.; Monge, M.; Aslett, D.; Touati, A.; Stewart, M.; Lawrence, S.; Willis, K. Virucid al efficacy of antimicrobial surface coatings against the enveloped bacteriophage Φ6. J. Appl. Microbiol. 2022, 132, 181 3–1824.

82. Eliwa, E.M.; Elgammal, W.E.; Sharaf, M.H.; Elsawy, M.M.; Kalaba, M.H.; El-Fakharany, E.M.; Owda, M.E.; Abd El-Wah ab, H. New Gd(I)/Cs(III) complexes of benzil-based thiocarbohydrazone macrocyclic ligand: Chemical synthesis, chara cterization, and study their biological effectiveness as antibacterial, antioxidant, and antiviral additives for polyurethane surface coating. Appl. Organomet. Chem. 2022, 36, e6689.

83. Faheim, A.A.; Elsawy, M.M.; Salem, S.S.; Abd El-Wahab, H. Novel antimicrobial paint based on binary and ternary diox ouranium (VI) complexes for surface coating applications. Prog. Org. Coat. 2021, 151, 106027.

84. Machado Querido, M.; Paulo, I.; Hariharakrishnan, S.; Rocha, D.; Pereira, C.C.; Barbosa, N.; Bordado, J.M.; Teixeira, J.P.; Galhano Dos Santos, R. Auto-disinfectant acrylic paints functionalised with triclosan and isoborneol—Antibacterial assessment. Polymers 2021, 13, 2197.

85. Qu, M.; Pang, Y.; Xue, M.; Ma, L.; Peng, L.; Liu, X.; Xiong, S.; He, J. Colorful superhydrophobic materials with durability and chemical stability based on kaolin. Surf. Interface Anal. 2021, 53, 365–373.

86. Freitas, D.S.; Teixeira, P.; Pinheiro, B.; Castanheira, E.M.S. Chitosan Nano/Microformulations for Antimicrobial Protecti on of Leather with a Potential Impact in Tanning Industry. Materials 2022, 15, 1750.

87. Ma, J.; Liu, C.; Yan, K. CQDs-MoS2 QDs loaded on Dendritic fibrous Nanosilica/Hydrophobic waterborne polyurethane acrylate for antibacterial coatings. Chem. Eng. J. 2022, 429, 132170.

88. Wu, X.; Yang, F.; Gan, J.; Kong, Z.; Wu, Y. A superhydrophobic, antibacterial, and durable surface of poplar wood. Nanomaterials 2021, 11, 1885.

89. Kim, M.J.; Linstadt, R.T.H.; Ahn Ando, K.; Ahn, J. Gemini-Mediated Self-Disinfecting Surfaces to Address the Contact Transmission of Infectious Diseases. Langmuir 2022, 38, 2162–2173.

90. Druvari, D.; Antonopoulou, A.; Lainioti, G.C.; Vlamis-gardikas, A.; Bokias, G.; Kallitsis, J.K. Preparation of antimicrobial coatings from cross-linked copolymers containing quaternary dodecyl-ammonium compounds. Int. J. Mol. Sci. 2021, 22, 13236.

91. Hosseini, M.; Behzadinasab, S.; Chin, A.W.H.; Poon, L.L.M.; Ducker, W.A. Reduction of Infectivity of SARS-CoV-2 by Zinc Oxide Coatings. ACS Biomater. Sci. Eng. 2021, 7, 5022–5027.

92. Sportelli, M.C.; Izzi, M.; Loconsole, D.; Sallustio, A.; Picca, R.A.; Felici, R.; Chironna, M.; Cioffi, N. On the Efficacy of ZnO Nanostructures against SARS-CoV-2. Int. J. Mol. Sci. 2022, 23, 3040.

93. Li, Y.; Liu, Y.; Yao, B.; Narasimalu, S.; Dong, Z.L. Rapid preparation and antimicrobial activity of polyurea coatings with RE-Doped nano-ZnO. Microb. Biotechnol. 2022, 15, 548–560.

94. Hutasoit, N.; Topa, S.H.; Javed, M.A.; Rahman Rashid, R.A.; Palombo, E.; Palanisamy, S. Antibacterial efficacy of cold-sprayed copper coatings against gram-positive staphylococcus aureus and gram-negative escherichia coli. Materials 2021, 14, 6744.

95. Cui, J.; Shao, Y.; Zhang, H.; Zhang, H.; Zhu, J. Development of a novel silver ions-nanosilver complementary composite as antimicrobial additive for powder coating. Chem. Eng. J. 2021, 420, 127633.

96. Padmanabhan, N.T.; Thomas, R.M.; John, H. Antibacterial self-cleaning binary and ternary hybrid photocatalysts of titanium dioxide with silver and graphene. J. Environ. Chem. Eng. 2022, 10, 107275.

97. Linzner, N.; Antelmann, H. The Antimicrobial Activity of the AGXX® Surface Coating Requires a Small Particle Size to Efficiently Kill Staphylococcus aureus. Front. Microbiol. 2021, 12, 731564.

98. Blomberg, E.; Herting, G.; Rajarao, G.K.; Mehtiö, T.; Uusinoka, M.; Ahonen, M.; Mäkinen, R.; Mäkitalo, T.; Odnevall, I. Weathering and Antimicrobial Properties of Laminate and Powder Coatings Containing Silver Phosphate Glass Used as High-Touch Surfaces. Sustainability 2022, 14, 7102.

99. Lam, W.T.; Babra, T.S.; Smith, J.H.D.; Bagley, M.C.; Spencer, J.; Wright, E.; Greenland, B.W. Synthesis and Evaluation of a Silver Nanoparticle/Polyurethane Composite That Exhibits Antiviral Activity against SARS-CoV-2. Polymers 2022, 14, 4172.

100. Pulit-Prociak, J.; Staroń, A.; Staroń, P.; Chwastowski, J.; Kosiec, A.; Porębska, H.; Sikora, E.; Banach, M. Functional antimicrobial coatings for application on microbiologically contaminated surfaces. Mater. Technol. 2021, 36, 11–25.

101. Valenzuela, L.; Faraldos, M.; Bahamonde, A.; Rosal, R. High performance of electrosprayed graphene oxide/TiO2/Ce-TiO2 photoanodes for photoelectrocatalytic inactivation of S. aureus. Electrochim. Acta 2021, 395, 139203.

102. Walji, S.D.; Bruder, M.R.; Aucoin, M.G. Virus matrix interference on assessment of virucidal activity of high-touch surfaces designed to prevent hospital-acquired infections. Antimicrob. Resist. Infect. Control 2021, 10, 133.

103. Pulit-Prociak, J.; Staroń, A.; Prokopowicz, M.; Magielska, K.; Banach, M. Analysis of Antimicrobial Properties of PVA-Based Coatings with Silver and Zinc Oxide Nanoparticles. J. Inorg. Organomet. Polym. Mater. 2021, 31, 2306–2318.

104. Singhal, A.V.; Malwal, D.; Thiyagarajan, S.; Lahiri, I. Antimicrobial and antibiofilm activity of GNP-Tannic Acid-Ag nanocomposite and their epoxy-based coatings. Prog. Org. Coat. 2021, 159, 106421.

105. Marín-Caba, L.; Bodelón, G.; Negrín-Montecelo, Y.; Correa-Duarte, M.A. Sunlight-Sensitive Plasmonic Nanostructured Composites as Photocatalytic Coating with Antibacterial Properties. Adv. Funct. Mater. 2021, 31, 2105807.

106. Bucuresteanu, R.; Ionita, M.; Chihaia, V.; Ficai, A.; Trusca, R.D.; Ilie, C.I.; Kuncser, A.; Holban, A.M.; Mihaescu, G.; Petcu, G.; et al. Antimicrobial Properties of TiO2 Microparticles Coated with Ca- and Cu-Based Composite Layers. Int. J. Mol. Sci. 2022, 23, 6888.

107. Gorthy, R.; Wasa, A.; Land, J.G.; Yang, Z.; Heinemann, J.A.; Bishop, C.M.; Krumdieck, S.P. Effects of post-deposition heat treatment on nanostructured TiO2-C composite structure and antimicrobial properties. Surf. Coat. Technol. 2021, 409, 126857.

108. Ghosh, S.; Jolly, L.; Haldar, J. Polymeric paint coated common-touch surfaces that can kill bacteria, fungi and influenza virus. MRS Commun. 2021, 11, 610–618.

109. Gentili, V.; Pazzi, D.; Rizzo, S.; Schiuma, G.; Marchini, E.; Papadia, S.; Sartorel, A.; Di Luca, D.; Caccuri, F.; Bignozzi, C.A.; et al. Transparent Polymeric Formulations Effective against SARS-CoV-2 Infection. ACS Appl. Mater. Interfaces 2

021, 13, 54648–54655.

110. Beaussart, A.; Retourney, C.; Quilès, F.; Dos Santos Morais, R.; Gaiani, C.; Fiérobe, H.P.; El-Kirat-Chatel, S. Supported lysozyme for improved antimicrobial surface protection. J. Colloid Interface Sci. 2021, 582, 764–772.
111. Enderle, A.G.; Franco-Castillo, I.; Atrián-Blasco, E.; Martín-Rapún, R.; Lizarraga, L.; Culzoni, M.J.; Bollini, M.; De La Fuente, J.M.; Silva, F.; Streb, C.; et al. Hybrid Antimicrobial Films Containing a Polyoxometalate-Ionic Liquid. ACS Appl. Polym. Mater. 2022, 4, 4144–4153.
112. Cullen, A.A.; Rajagopal, A.; Heintz, K.; Heise, A.; Murphy, R.; Sazanovich, I.V.; Greetham, G.M.; Towrie, M.; Long, C.; Fitzgerald-Hughes, D.; et al. Exploiting a neutral BODIPY copolymer as an effective agent for photodynamic antimicrobial inactivation. J. Phys. Chem. B 2021, 125, 1550–1557.
113. Reynoso, E.; Durantini, A.M.; Solis, C.A.; Macor, L.P.; Otero, L.A.; Gervaldo, M.A.; Durantini, E.N.; Heredia, D.A. Photoactive antimicrobial coating based on a PEDOT-fullerene C60polymeric dyad. RSC Adv. 2021, 11, 23519–23532.
114. Paxton, W.F.; Rozsa, J.L.; Brooks, M.M.; Running, M.P.; Schultz, D.J.; Jasinski, J.B.; Jung, H.J.; Akram, M.Z. A scalable approach to topographically mediated antimicrobial surfaces based on diamond. J. Nanobiotechnol. 2021, 19, 458.
115. Yi, G.; Gao, S.; Lu, H.; Khoo, W.Z.; Liu, S.; Chng, S.; Yang, Y.Y.; Ying, J.Y.; Zhang, Y. Surface Antimicrobial Treatment by Biocompatible, Vertically Aligned Layered Double Hydroxide Array. Adv. Mater. Interfaces 2022, 9, 2101872.
116. Wasa, A.; Aitken, J.; Jun, H.; Bishop, C.; Krumdieck, S.; Godsoe, W.; Heinemann, J.A. Copper and nanostructured anatase rutile and carbon coatings induce adaptive antibiotic resistance. AMB Express 2022, 12, 117.
117. Siyanbola, T.O.; Ajayi, A.A.; Vinukonda, S.; Jena, K.K.; Alhassan, S.M.; Basak, P.; Akintayo, E.T.; Narayan, R.; Raju, K.V.S.N. Surface modification of TiO2 nanoparticles with 1,1,1-Tris(hydroxymethyl)propane and its coating application effects on castor seed oil-PECH blend based urethane systems. Prog. Org. Coat. 2021, 161, 106469.
118. Cox, H.J.; Sharples, G.J.; Badyal, J.P.S. Tea-Essential Oil-Metal Hybrid Nanocoatings for Bacterial and Viral Inactivation. ACS Appl. Nano Mater. 2021, 4, 12619–12628.
119. Philip, A.; Ghiyasi, R.; Karppinen, M. Photoactive Thin-Film Structures of Curcumin, TiO2 and ZnO. Molecules 2021, 26, 3214.
120. Branco, R.; Sousa, R.; Dias, C.; Serra, C.; Morais, P.V.; Coelho, J.F.J.; Fernandes, J.R. Light-Activated Antimicrobial Surfaces Using Industrial Varnish Formulations to Mitigate the Incidence of Nosocomial Infections. ACS Appl. Mater. Interfaces 2021, 13, 7567–7579.