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TOPICAL REVIEWS

Advances in Nanoarchitectonics of Antimicrobial Tiles and a Quest for Anti-SARS-CoV-2 Tiles

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Abstract

Design of antimicrobial tiles seems necessary to combat against contagious diseases, especially COVID-19. In addition to personal hygiene, this technology facilitates public hygiene as antimicrobial tiles can be installed at hospitals, schools, banks, offices, lobbies, railway stations, etc. This review is primarily focused on preparing antimicrobial tiles using an antimicrobial layer or coatings that fight against germs. The salient features and working mechanisms of antimicrobial tiles are highlighted. This challenge is a component of the exploratory nature of nanoarchitectonics, that also extends farther than the realm of nanotechnology. This nanoarchitectonics has been successful at the laboratory scale as antimicrobial metal nanoparticles are mainly used as additives in preparing tiles. A detailed description of various materials for developing unique antimicrobial tiles is reported here. Pure metal (Ag, Zn) nanoparticles and a mixture of nanoparticles with other inorganic materials (SiO_2, TiO_2, anatase, nepheline) have been predominantly used to combat microbes. The developed antimicrobial tiles have shown excellent activity against a wide range of Gram-positive and Gram-negative bacteria. The last section discussed a hypothetical overview of utilizing the antimicrobial tiles against SARS-CoV-2. Overall, this review gives descriptive knowledge about the importance of antimicrobial tiles to create a clean and sustainable environment.

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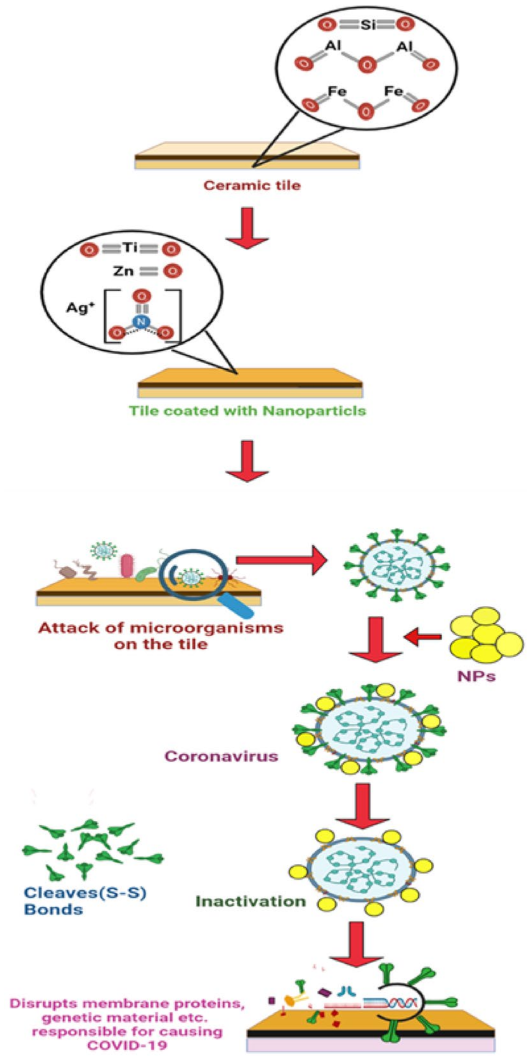
Graphical Abstract



Keywords Antimicrobial tiles · Ceramic tiles · Anatase · Glaze · Nanoparticles · SARS-CoV-2 · COVID-19

1 Introduction

As we explore, science attempts to answer how nature has been working. Nature is always dynamic, as all organisms are interdependent and perform various activities for being part of the ecosystem [1–3]. Nowadays, microbial research has become fundamental in many areas, specifically, medicine, environmental science, food science, agriculture, genetics, etc. [4–7]. Amongst all, microorganisms have noticeable features of having extraordinary diversity in structure, function, habitat, and applications [8–10].

Being nostalgic since the beginning days of microbe's discovery, we all learned about their harmful effects. Since childhood, we all learned to keep our surroundings clean and thus maintain a hygienic environment. In reality, pathogens dominate our overview of the microbial world, and hence, it became necessary to maintain the cleanliness in our habitat [11–13]. Though we are habituating, nature is throwing new challenges with the evolution of several disease-causing organisms. The most recent is the pandemic explosion of COVID-19 (CoronaVirus Disease-2019) in December 2019 in China [14, 15]. COVID-19 is a viral disease caused by SARS-CoV-2 (severe acute respiratory syndrome coronavirus-2) (here onwards, it will be mentioned as coronavirus) [16, 17], which belongs to *Coronaviridae* [18, 19]. The current pandemic has drastically changed our perception ofhygiene and cleanliness [20, 21]. WHO (World Health Organization) declared that the coronavirus spreads primarily from the infected person's aerosols or droplets containing the virus. When these droplets contact the healthy person's eyes and/or nose, they can cause COVID-19 [22]. This virus also spreads through poorly ventilated or crowded indoor settings [23, 24].

Current researchers aware of the fact that the tasks of bio-systems are ultimately based on configurations of nano-sized synthetic manifestations like biochemical accolades, transfer of energy, and self-assembly, owing to swift scientific advances. As a result, attempts to control nano-sized processes and their arrangements will indeed pave the way for our aspirations to come true [25]. Nanotechnology, which includes multiple techniques for fabricating nano-sized frameworks, is playing vital role in regulating nano-worlds. This functionality is very distinct from what is seen in bio-systems, where numerous factors perform in perfect harmony [26]. As a result, paradigms to living-creature-like fully efficient processes include more optimization techniques beyond innovation. Nanoarchitectonics is a novel phenomenon for making innovative smart materials by integrating different deeds such as atomic/molecular modification, chemical reactions, self-assembly and self-organization, and their activation by artificial fields/stimuli [27]. At the 1st Global Conference on Nanoarchitectonics Using Suprainteractions in 2000, Masakazu Aono described for the first time about "nanoarchitectonics" [28]. This fundamental precept is identical to that for biosystems, wherein every facet of natural systems is highly reliant on physicochemical instances at the nano–micro scale length. This notion is being applied to various scientific disciplines, ranging from basic raw material manufacturing [29] to sophisticated technologies such as bio-related domains [30].

Unfortunately, cleaning or disinfection using strong chemicals at regular intervals is not possible and viable [31–33]. Moreover, it is essential to protect the surfaces from pathogen contact and recognize their infection pathway to human beings [34, 35]. Thus, the design of antimicrobial tiles plays an indispensable role in a cleaner, greener and healthier environment [36]. These tiles inhibit microbial growth and thus reduce the possibility of contamination to create healthier and hygienic surroundings. The present review focuses on the development of unique antimicrobial tiles which prevent microbial growth and keep our surroundings clean. An overview and a possible mechanism of microbial disinfection by antimicrobial tiles is shown in Fig. 1. Keeping the current scenario of COVID-19 in mind, this article gives a hypothetical review about the resistivity against corona virus from antimicrobial tiles. Considering the microbes and microbe-free surroundings, this review provides a descriptive knowledge of antimicrobial tiles, the best innovative development to control the ongoing pandemic [37]. Management and preventive strategies with a way forward for possible applicability in various places are discussed. Further, the current scenario and future perspective have also been highlighted.

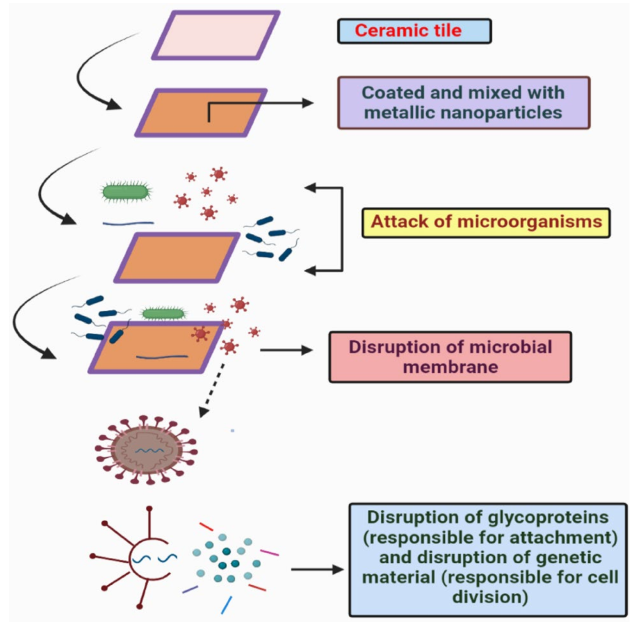


Fig. 1 Mechanism of disinfecting microbes using antibacterial tiles

2 Salient Features and Working Mechanism of Antimicrobial Tiles

Many investigations have suggested the utilization of antimicrobial tiles for hygienic surroundings. Various metals like zinc, mercury, silver, lead, bismuth, tin, cadmium, thallium and chromium possess antimicrobial properties and have been tested for the design of antimicrobial tiles [38–40].

Biocompatibility and non-toxicity are the highest qualities of these products compared to the others. Experts have carried out several studies to validate the exchange of metals that impart antimicrobial activities with inorganics such as zeolites. Uzguret al. [41] have suspended antibacterial metal cations in a carrier system composed of calcium silicate and calcium phosphate. Another study by De Niederhãusern et al. [38] revealed that silver is supposedly the best antimicrobial agent because of its strong cytotoxicity effect against a broad range of pathogens. In addition, silver causes minimal toxicity to humans compared to other heavy metal ions. Atay [42] identified that silver posess antimicrobial properties and provides good mechanical behavior at the juncture of ceramic tiles. A more recent investigation by Ozcan et al. [39] showed that zinc oxide nanoparticles exhibited antibacterial activities when ceramic tiles were coated with industrially applicable glazes modified with metallic Zn powder. Varghese et al. [40] evaluated the antimicrobial nature of novel surface coatings that include silver and silica and prepared both glass and ceramic tiles using the flame-assisted chemical-vapour deposition methods. Do Evangelho et al. [43] highlighted the antimicrobial coatings that might have applications in healthcare for the standard cleaning and disinfecting regime. NPs attack bacteria cells through multiple mechanisms: formation of ROS (Reactive Oxygen Species) to damage membrane, protein, and DNA, direct interaction between NPs and cell membrane via dissolved metal ions, for example, inhibition of electron transport chain, and the regulation of bacterial metabolic processes as shown in Fig. 2.

3 Raw Materials Used for the Development of Unique Antimicrobial Tiles

The development of antimicrobial tiles depends on the unique properties of raw materials while processing the tiles. Globally, various researchers have used different raw materials for developing unique antimicrobial tiles [44]. The best-suited raw materials that showed high microbicidal properties are titanium and silver. However, these two materials are used as either mineral or combined state (mixture of two elements). Some of the raw materials include anatase (the mineral form of TiO_2), TiO_2–$AgNO_3$ (titanium oxide, silver nitrate), Ag/SiO_2 (silver, silicon dioxide), Ag/nepheline (silver, nepheline), Zinc metal, etc. [45–53]. Many researchers have been working on these raw materials to develop antimicrobial tiles, and the research that showed successful results is described here.

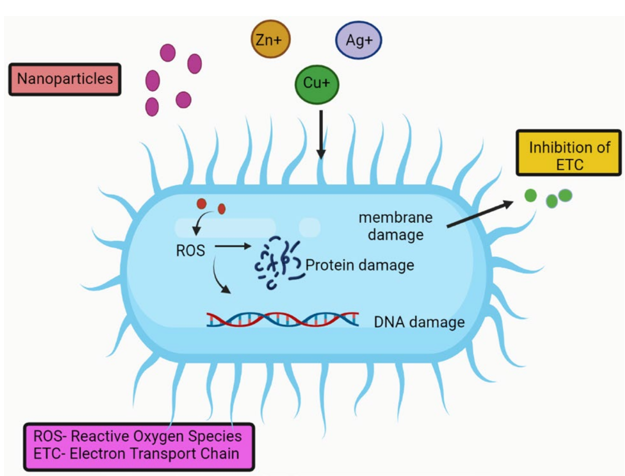


Fig. 2 Schematic sketch of the antimicrobial activity of metal nanoparticles

3.1 *Anatase (Mineral Form of TiO_2)*

Anatase is a meta-stable, natural crystalline mineral that shows photocatalytic activity. It is extensively used as a sterilizing agent that disinfects the surface coatings, especially for medical applications [54]. Anatase is the mineral form of titanium dioxide (TiO_2), a stable (both biologically and chemically) and inexpensive semiconductor that posess photocatalytic and self-cleaning activity. To enhance the surface stability, TiO_2 is cast off. Metal oxide nanoparticles are well known for their microbicidal effects that include silver, iron oxide, and titanium dioxide [55, 56]. Hence, due to the unique features and excellent functional performances against microbes, anatase is one of the most common and favorable manufacturing materials. Several techniques have also prepared anatase coatings, such as sputtering, dip-coating, and sol–gel technology. Anatase glazed ceramic tiles are used in organizations like healthcare centers to create a healthier environment by killing pathogens.

One such research was carried out by [57], where they performed a dip-coating method in which anatase was mixed with the glaze and coated on the surface of ceramic tiles. Their work focused on bacteria, and they used *Escherichia coli* for antibacterial testing. For coating, anatase powder was used in two forms, i.e. micron and nano-size, to examine the differences in the performance of antibacterial materials. Different micron-sized anatase powders were used, i.e. 5 wt%, 10 wt% and 15 wt%, although the concentration of nano-sized anatase was fixed at 10 wt%. They reported that the increase in the composition of anatase enhanced the antibacterial activity. Their approach concluded that nano-sized anatase showed better antibacterial activity than micron-sized because of the large surface area of the antibacterial agent on the tiles.

3.2 *Titanium dioxide (TiO_2)*

TiO_2exhibits good photocatalytic properties, it has been used as an antiseptic and antimicrobial agent. TiO_2 is the most accepted, inexpensive, safe to use, and chemically stable raw material. It can act under mild solar irradiation in an open/outdoor environment. Thus photocatalytic and super hydrophilic properties play a crucial role in designing TiO_2-based antimicrobial tiles. Experimentation was carried out to fabricate self-cleaning surfaces using TiO_2 on ceramic tiles [58]. The ceramic tiles coated with photoactive TiO_2 have been self-cleaning, showing bactericidal action. Da Silvaa et al. [59] evaluated that self-cleaning can be achieved by two super hydrophobicity and photocatalytic degradation. Several factors like Ti-crystal phase, thickness, roughness, firing temperature, deposition method, and specific surface area are responsible for the photocatalytic action of TiO_2 on ceramic surfaces. Thus, this material kills or prevents the growth of bacteria and fungi from creating a self-sterile ceramic tile. The coated surface of the tile shows re-usable photocatalytic activities. Photocatalytic tiles can be used again after cleaning the tiles thoroughly with water without affecting the photocatalytic activity. Moreover, TiO_2 coated ceramic tiles are also used for the photo-degradation of pharmaceutical compounds, such as paracetamol and aspirin [60].

Nakano et al. [61] demonstrated the photocatalytic properties of TiO_2 nanoparticles by immobilizing them on glass plates and successfully inactivating the influenza virus. UV-rays do not limit these excellent antibacterial and antiviral activities. The sample product with the antibacterial coating has been used as smart glass, exterior tiles, paving blocks, PVC fabric, and cultural heritage surfaces. This product with an antibacterial coating was manufactured for interior and exterior applications in the buildings as cement mortar. Many practical applications such as air and water purification, self-cleaning, and antimicrobial effect can be obtained.

TiO_2 is frequently used to manufacture glazes to anticipate color and make it opaque. Many studies revealed the microbicidal features of TiO_2. In an experimental study by Maryani et al. [62], TiO_2 was used as the active material to acquire an antimicrobial glaze**.** According to the study, the basic materials are silica, sand, commercial glaze 107, and TiO_2 powder of weight 0–5% (Fig. 3a). To the glazed mixture, distilled water was added, and then the mixture was grinded for 24 h in an alumina pot mill. The result concluded that the addition of TiO_2 to the glaze showed antimicrobial activities against *E. coli* and *S. aureus,* (Fig. 3b). They reported that TiO_2 glaze showed high antibacterial activity against *S. aureus* than *E. coli* (Fig. 3b). The results suggested that glaze samples and glazed tiles were shown to have antibacterial properties characterized by clear zones until inhibition diameter values were obtained. The microbicidal action of TiO_2 compounds against *S. aureus* was higher than *E. coli* for all glaze samples.

3.3 Silver (Ag)

In general, the antimicrobial activity of silver (Ag) is due to the affinity of monovalent or ionic Ag (Ag with + 1 charge) for hydrogen ions. Joining with the sulfhydryl groups present in microbes, Ag ions disrupt electron transfer and respiration in bacteria and other microbes [63]. The antimicrobial mechanism of Ag is linked via its interaction with thiol group compounds found in the respiratory enzymes of bacterial cells. Ag binds to the bacterial cell wall and cell membrane

a

b

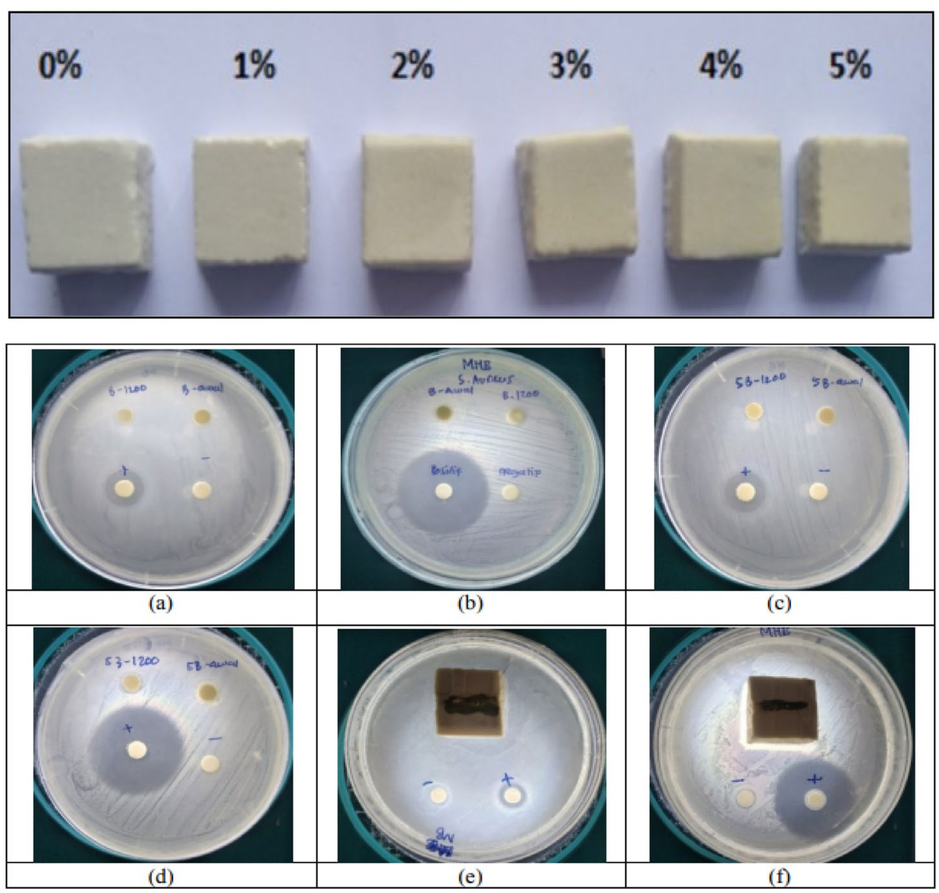


Fig. 3 Glaze tiles resulted from the combustion with different TiO_2, from 0 to 5% (Adapted under creative common attribution 3.0 from [62]. **b** (a) 1% TiO_2glaze against *E. coli*; (b) 1% TiO_2 glaze against *S. aureus*; (c) 5% TiO_2 glaze against*E.coli*; (d) 5% TiO_2 glaze against *S. aureus*; (e) 1% TiO_2 glazed tile against *E. coli*; (f) 1% TiO_2 glazed tile against *S. aureus*(Adapted under creative common attribution 3.0 from [62]

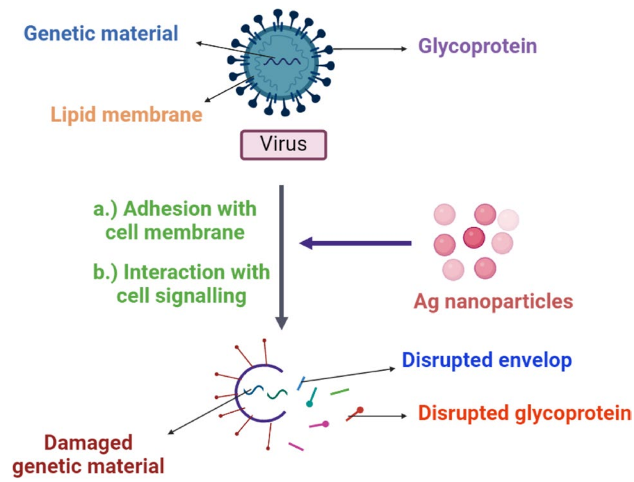


Fig. 4 Damage of viral components by Ag nanoparticles. Upon contact with the virus, they adhere to the cell membrane and disrupt the glycoprotein layer. After this, Ag nanoparticles undergo a cell signaling pathway and interact with the cell. Once interacted, Ag nanoparticles destroy the virus's envelope, glycoprotein, and genetic material [109]

and inhibits the respiration process. In addition, Ag ions and Ag nanoparticles can generate morphological and structural changes in the bacterial cells as shown in Fig. 4 [64].

Atay [42] reported the synthesis of Ag nanoparticles for reinforced ceramic joints. Ag nanoparticles were synthesized from $AgNO_3$, $C_6H_{12}O_6$ and distilled water. With a ratio of about 2:1 by weight, $AgNO_3$ and $C_6H_{12}O_6$ were dissolved using distilled water in an ultrasonic bath. This accelerated the reaction process, and then transparent solutions were prepared. Ag nanoparticles were chemically balanced in the mixture and used as a joint sealant. Silver reinforced joints were organized by mixing Ag nanoparticles at several ratios in the joint matrix. It has been concluded that increasing Ag nanoparticles concentration has decreased the antibacterial effect; this may be due to the agglomeration, as the antibacterial mechanism works with the ionization of Ag nanoparticles.

In the development of antimicrobial materials, silver plays a significant role. Antibacterial materials are manufactured to avert the growth and spread of harmful viruses and bacteria, and disrupt them [65]. Silver nanoparticles are active against viruses like hepatitis B virus, monkeypox virus, herpes simplex virus, human immune-deficiency virus (HIV) and respiratory syncytial virus by disrupting the glycoproteins and several proteins present in spikes and envelop of the virus [42]. Suitable environment is essential to protect against disease-causing bacteria and necessary to keep hygiene in our utilities. The joint ceramic tiles are manufactured to maintain hygiene in toilets and sanitary wares by adding silver nanoparticles and glass spheres, as shown in Fig. 5. Silver can disrupt bacteria and

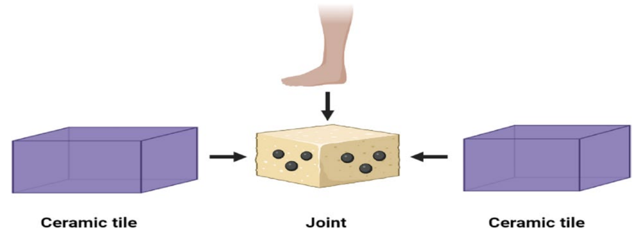


Fig. 5 Silver nanoparticles and glass spheres to the joint matrix (Modified from [42])

harmful micro-organisms activity. Glass spheres were used for mechanical improvement.

3.4 Silver Photo Deposited Nepheline (Ag/Nepheline)

Nepheline is an igneous-rock forming mineral that belongs to the feldspathoid group (Na,K) $AlSiO_4$ and forms small grains [66]. It shows similarities with granite and silica. Due to the high alumina content, iron-free nepheline is used for manufacturing glasses. The analysis evaluated that the Ag/nepheline composite of the thin film is a suitable coating for producing antimicrobial results. The raw materials used for the experimented work were $AgNO_3$, PVP, TiO_2, and SiO_2.

Another study was carried out by Ghaffari-Nazriya et al. [67], where antibacterial activity was investigated by preparing silver-coated thin films. For this, $AgNO_3$ (Silver nitrate, 99%), PVP (polyvinyl pyrrolidone, 98%), TiO_2, SiO_2 and nepheline were taken. H_2O, $AgNO_3$, and PVP (5 wt%) were mixed in a container. 5 wt% was set as the limit for the composite film of silver. After mixing for 2 h, SiO_2, TiO_2, and nepheline were added. Afterwards, a thin film of monolithic silver was amalgamated into the mixture. The experiment was carried out in the presence of UV lamp. After the synthesizing process, color of the solution was balanced. With the help of a spray gun, the solution containing H_2O (weight ratio of 1:10) was sprayed on the ceramic tiles, which were then heated. The result showed that the nepheline has high antibacterial activity among the three oxides. Ag/nepheline composite (around 99%) antibacterial tiles produced 99.9% bactericidal activity (Fig. 6). They reported the higher blending and microbicidal activity of Ag/nepheline than Ag/TiO_2 and Ag/SiO_2. According to the results, the hypothesis of standardization and higher antimicrobial property of Ag/nepheline tiles also proved high compared to other samples.

3.5 Silver with Titanium Oxide

Machida et al. [68] investigated Ag and its combination with titanium oxide (Ag + TiO_2) thin film on the glaze of sanitary wares. The thin films of titanium oxide deposited

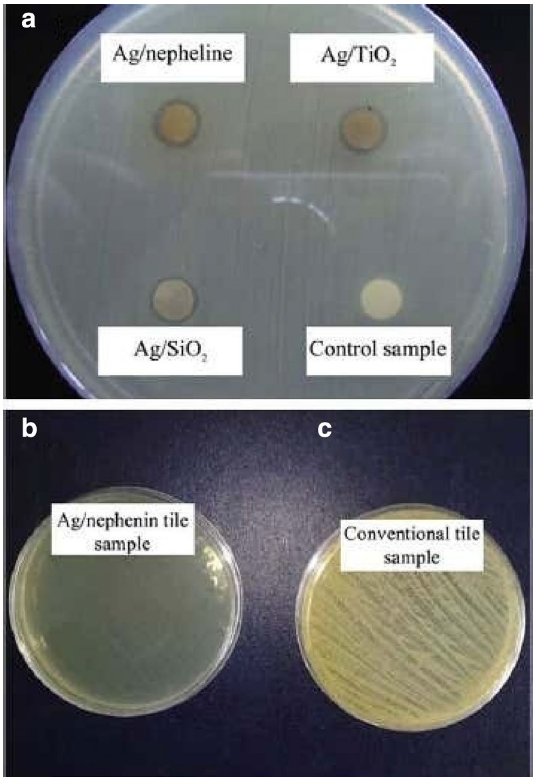


Fig. 6 (**a**) Clear zones represent the antibacterial activity of silver composites disks against *S.aureus* (control is water sample). (**b**) The bacteriostatic activity of the tile coated with silver/nepheline composite (**c**) sample of conventional tile (Retrieved from [67])

with silver on the sanitary surfaces developed microbicidal properties and produced sterilizing effects under UV irradiation. Metal ions displayed their antibacterial properties under dark environment as well. Titanium oxide solution was mixed while preparing the samples. This solution was sprayed on the sample tile, calcined at 880–980 °C and then photo-deposited with the silver ions on the glazy layer of the sanitary wares. After that, the coated tiles were thoroughly washed (twice) ultrasonically in de-ionized water to obtain sample tiles. The result concluded that increased film thickness and increased photo-deposited silver showed improved antibacterial activities. Moreover, an increase in calcination temperature showed less antimicrobial potentiality.

3.6 Zinc

Zinc oxide nanoparticles are well-known to exhibit broad-spectrum antimicrobial properties, especially antibacterial and antifungal activities. The work by Ozcan et al. [39] showed that zinc can induce hydrophobic and antimicrobial properties. They prepared a glaze composed of china clay 5%, 30% frit and metallic Zn powder 65%. The modified glaze was developed in ceramic mills loaded with 35% water, 65% dry matter, and alumina balls. Afterwards, metallic zinc powder was added to prepare the glaze. 30% frit was prepared using the modified glaze of 5% china clay and 65% metallic Zn powder, which were kept in ceramic jar jet mills. Then the glazed slurry was sieved. After sieving, the coated tiles were heated at the appropriate temperature. With the help of the spray coating method, few coated tiles were cured at 120 °C for 10 min to remove moisture, which in turn enhanced the hydrophobicity. The results concluded that the inclusion of metallic Zn powder in industrially applicable glaze resulted in nano-crystalline-ZnO granules when applied at the peak of heat treatment temperature. The topography of the micro-patterned nanocrystalline ZnO particles also possess microbicidal features to ceramic tile surfaces, which correlate with the hydrophobic characters. Augmentation of microbes on the tiles was restricted up to 99% with zinc modified glaze.

3.7 Silica

Studies revealed -many applications for silica-coated products in health care industry. Silica nanoparticles have become essential for the coating because of their antibacterial properties [69]. Silica nanoparticles have unique chemical and physical stability and possess antibacterial activity against significant number of disease-causing bacteria. Silver is doped to the silica films; as the combination gives excellent results of antibacterial activity when mixed [70]. Silica nanoparticles provide a good option to dope with silver due to their high thermal and chemical stability, high surface area, and biocompatibility. For coating, silica is essential as it has low toxicity and long durability. Varghese et al. [40] introduced antimicrobial coatings with silver and silica using flame-assisted chemical vapor deposition technique. Cations were deposited on ceramic and glass tiles using flame-assisted vapor deposition method. At the end of the study, the concentration of silver content varied by interchanging the precursor concentration in the film and changing the coating head rate. The film produced a slightly dark pale brown tinge with high silver content. The results concluded that Ag–SiO_2 coatings showed good antibacterial activity against tested bacteria like *E. coli*, *S. aureus*, *E. faecalis,* etc. Thus, the result assured the safety from infection and diseases.

Baheiraei et al. [71] carried out a work on silver doped silica films in which the sol–gel technique was used for the synthesis. The solution was prepared from HNO_3 (nitric acid, 2 M), H_2O (distilled water), C_2H_5OH (ethanol 99.9%) and $AgNO_3$ (silver nitrate > 99%). First, the tetraethylortho silicate, distilled water, and ethanol were mixed as a precursor. Then, nitric acid was added drop by drop to the mixture by maintaining the pH at 1.5. After few hours, the coating was applied using the dip-coating method. All the films were dried out at a specific temperature for an hour in the oven, followed by the thermal treatment. It was concluded that the glazed coated tiles have the antimicrobial potential to decrease air pollution and improve hygiene. Results suggested that the coated films exhibit an excellent antimicrobial performance against *S. aureus* and *E. coli*. In addition, ceramics doped with silver are chemically durable and release silver ions, thus having a tremendous antimicrobial activity.

4 Antimicrobial Tiles from Waste Materials

Scientific and technological inventions have led to various advanced materials using raw materials, including pure chemicals and waste materials. Also, recycling waste materials has become a priority to protect the environment from harmful effects [72]. As waste material consist of various chemical constituents and mineral phases, it becomes easier to convert it into useful material [73]. Antibacterial tiles can thus be obtained from the waste by suitable treatment using appropriate process parameters. Before the pandemic, various types of plastic wastes like PP (Polypropylene), HDPE (High-Density Polyethylene), LDPE (Low-Density Polyethylene), water sachets, bags, polyethylene, etc. were significant threats to the environment. During this COVID-19 pandemic, another new type of waste has been added along with the various kinds of plastic waste, i.e., PPE waste like surgical masks, N95 masks, gowns, nitrile gloves, goggles, etc., as depicted in Fig. 7 [74, 75].

Hardikar et al. [76] concluded that replacing ceramic tiles with LDPE provides similar strength compared to the typical ceramic tiles; moreover, the product is fully recycled at a low cost. Dhawan et al. [77] used plastic waste bags from households and industrial wastes from thermal power stations and recycled them into tiles. These were proven to be environmentally and economically friendly with resistance to corrosion and different chemicals. Similarly, Temitope et al. [78] carried out the research work using plastic water bottles and sachets for the composition of the tiles. The research work explains that their non-biodegradable properties and lightweight nature require less time for manufacturing than regular ceramic tiles. Hamid et al. [79] suggested that the use of plastics for the preparation of tiles would be useful as they possess mechanical properties such as high tensile strength, compressibility, low water absorption, and firing shrinkages.

Moreover, plastics in tile manufacturing can reduce harmful gases like CO_2, CO, NO, etc. Therefore, to remove waste from the environment and bring a variety of recycled tiles, we can manufacture tiles using plastic wastes like PPE kits, surgical masks etc. [80]. Apart from this, combining the plastic-based tiles with antimicrobial agents (TiO_2, Silver, copper, enzyme-based coatings, bio-based antimicrobial coatings, etc.) is the unique approach to enhance the antimicrobial activities and manage waste utilization [81].

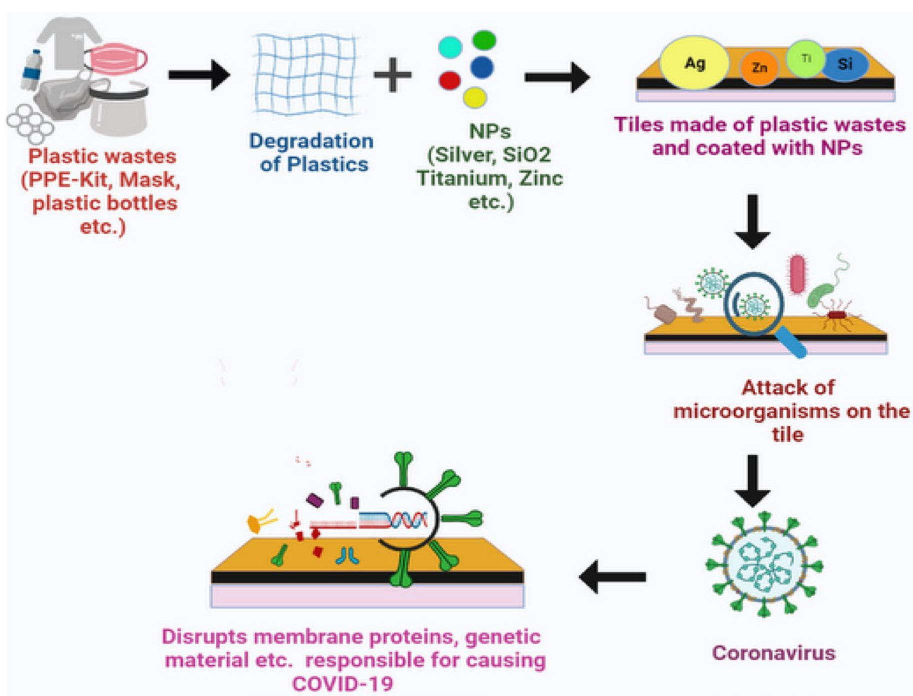


Fig. 7 Development of antimicrobial tiles from plastic waste

5 Advantages of Antimicrobial Tiles

Growing worldwide population indicates more infection due to the difficulty to maintain sanitization, and thus focus is more on infection control. As the world population becomes dense, frequent contact between people leads to the spread of infection. The infection significantly increases from prominent areas like restaurants, public transport, hospitals, and other public places [82]. The importance of cleaning and bringing a pathogen-free environment cannot be underestimated, and to ensure this, highest standards in prevention are critical. As the population grows, the demand for healthy surroundings and the materials that reduce the spread of infection also rise. In this regard, the use of antimicrobial ceramic tiles would be effective.

As the demand grows for materials that reduce the spread of infection, ceramic tiles are embedded with additives to deliver continuous surface protection against microbial growth and their ability to cause infection. The tiles embedded with active substances enhance the antibacterial, antiviral and antifungal properties and protects against diseases by controlling the growth of microorganisms [75]. The acquired antimicrobial properties of tiles display bactericidal activity for a probable long duration as long as the treated glaze remains intact. Moreover, substituting the standard surfaces with antimicrobial tiles will support the hygienic environment as cleaning in common spaces is more often impossible [83].

However, the need for antimicrobial products has gained much interest because of the current COVID-19 outbreak. Keeping the present scenario in mind, it became essential to maintain a hygienic environment since the disease is contagious and fatal. Hence, the use of antimicrobial tiles is appropriate for a healthy environment because these can be applied in every public place. Applying antimicrobial surfaces in such sites give best results in creating a pathogen-free environment. Maintaining cleanliness in public areas via this advanced antimicrobial technology would yield significant implications in the health sector.

6 Current Scenario and Future Perspective

While exploring the popular perception about the microbial world, general health and hygiene have become the topmost concern [84, 85]. As antimicrobial tile is an important innovation to the construction and logistics industry, it provides an efficient first line of defense against disease-causing microorganisms [86]. In addition, antimicrobial tiles contribute tremendous benefits to the environment too. They reduce harsh chemical treatment while cleaning. It helps to maintain air and sewage quality and hygienic surfaces for a prolonged period of time [87, 88]. The rise in demand for antimicrobial tiles can be predicted after the current COVID-19 outbreak [89].

Metal nanoparticles showed broad-spectrum antimicrobial activities [90, 91]. Incorporating nanoparticles or plant extracts into the tiles increases the reduction potential against microorganisms [92–94]. In general, the activity of disinfecting agents tends to decay after using for few times, especially in submerged areas, crowded areas and the surfaces exposed to air. Instead of using disinfecting agents with strong acids or chemicals at regular intervals, tiles with additional antimicrobial activity can be used. Moreover, these tiles are non-hazardous, safe, and easy to prepare [95, 96].

Comparatively, photo-catalytic and non-photocatalytic techniques are the two primary kinds of advancements capable of effectively monitoring and removing the microbial population infecting surfaces. They are nanostructured coverings that use TiO_2 or Ag^+ as antimicrobial compounds. Both of these nanomaterials are well recognized for their toxic effect on various microbial species, resulting in microbial growth inhibition [97]. Overall, TiO_2-based photo-catalytic technique is constrained by illumination conditions (necessitate UV luminance); however, in ceramic tiles' particular instance, special consideration should be given to the manufacturing process. Anatase is identified to have the ideal photo-catalytic efficiency of any TiO_2 copolymers, accompanied by rutile [98]. Silver-based solubilized substances can be used in non-photocatalytic systems, benefiting silver's beneficial environmental versatility, which does not involve excitation situations. Specific physical contact with microbes initiates anti-bacterial property, which is performed via bioactive Ag^+ ions transfer. This liability assures the resilience of silver-based new technology to diverse application methodologies, like the manufacture of ceramic tiles, adhesives, protective coating, or substances introduced to the ceramic-body-glaze framework [99].

According to the deliverables by worldwide scientists, it was seen that titanium and silver have gained much attention with regards to antimicrobial tiles. However, not much research has been carried on using zinc and silica to produce antimicrobial tiles. This is because, despite being an antimicrobial agent, durability and strength were comparatively less than TiO_2 and Ag^+ [100], and resistivity to pathogens are comparatively less than titanium and silver. However, they are still under consideration [101]. Nevertheless, research should be carried out by using zinc and silica to produce antimicrobial tiles for future prospects.

7 Hypothetical Overview of Utilization of Antimicrobial Tiles Against SARS-CoV-2

COVID-19, causative agent of SARS-CoV-2 has become a global pandemic**.** Both theoretically and experimentally, research has been carried out to generate effective treatments to suppress the virus growth and spread by accounting current global safety concerns and burden on global economies [102, 103]. It spreads through contaminated surfaces in public places like banks, schools, offices, shops, hospitals etc. [104]. Depending on the type of surface, this virus remains alive for nearly 15 days without replicating [23, 105]. Once entered the host body, it starts replicating and causes the disease [106]. Thus, the application of antimicrobial technologies on surfaces, i.e. walls, floors, schools, railings of hospitals, residential areas, industrial and institutional countertops [107, 108] would prevent the virus transmission and curtail the spread of disease. Thus, developing innovative tiles by adding antimicrobial materials is essential to stop the spread or transmission of the pathogen into the host body. Based on the similarity in the structure of viruses, a hypothetical overview has been given in this review. Different experiments proved that metallic elements developing against SARS-CoV-2 are useful. Tiles can be prepared with plastic wastes and additional antimicrobial agents to heal our environment from pollution. In achieved aa hygienic environment, this innovative approach facilitates pollution reduction and global economy growth [38]. Henceforth, development of advanced designs and technologies is necessary to create the next-generation antiviral surfaces to combat COVID-19.

8 Conclusion

The existing COVID-19 pandemic has significant effect on a range of facets of life. Due to the COVID-19 pandemic, maintaining hygiene and keeping our surroundings clean has become the new normal for every wellbeing. The drastic changes with the COVID-19 pandemic have literally changed public health and hygiene perceptions. Thus, the innovative approach for antimicrobial tiles is gaining a lot of interest across the world. Antimicrobial tiles are perfect for living spaces at domestic, public and industrial locations. They are manufactured using microbial technology via antimicrobial coating, which eradicate pathogens and provide a pathogen-free environment. Antimicrobial tiles provide excellent hygiene and have a tremendous global utility. As a result, nanoarchitectonics can act as a guide for transforming composite methods into life-like elevated functionalities. It will be a central aspect in the forthcoming years in which ne discoveries of composite advancement will be seen.

Pure metal nanoparticles (Ag, Zn) and in combination with other inorganic compounds (SiO_2) have been used as antimicrobial agents while preparing glaze for tile surface coatings. These additives have shown activity against a wide range of Gram positive and Gram negative bacteria. Researchers are still working upon this technology to correlate with the global pandemic COVID-19. As this pandemic caused drastic changes, efforts are needed to develop unique antimicrobial tiles that combat against microbes, ultimately initiating sustainable development. This review also gives a hypothetical overview regarding how antimicrobial tiles can act upon many microbes, including SARS-CoV-2.

Owing to the existing scenario of the COVID-19 pandemic, it has become mandatory to produce such products which can inhibit microbial resistance. Moreover, the concept of antimicrobial tile plays a pivotal role in the pandemic era, which is beneficial for the welfare of society. Additionally, the COVID-19 pandemic has changed the overview of the people's perception regarding maintenance of hygiene. Hence, antimicrobial tile is a scientific gift that prevents from microbial infection.

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Declarations

Conflict of interest There are no conflicts to declare.

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