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REVIEW

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Antimicrobial nanocoatings: A breakthrough in healthcare and industrial hygiene

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ABSTRACT

Antimicrobial nano coatings represent a significant advancement in materials science, offering innovative solutions for healthcare and industrial hygiene. These coatings utilize nanoscale materials, such as silver, copper, zinc oxide, and graphene, to inhibit microbial growth and prevent the spread of infections. In healthcare, antimicrobial nano coatings have shown potential in reducing hospital-acquired infections, improving the hygiene of medical devices, and enhancing surface hygiene in high-contact areas. In industrial applications, they contribute to food safety, water treatment, and the maintenance of cleanliness in public spaces. Despite the promising applications, the development and scaling of antimicrobial nano coatings face challenges such as safety concerns, toxicity, environmental impact, and high production costs. The review also highlights the growing interest in smart, responsive coatings and their integration with other technologies like UV and heat treatments to enhance effectiveness. Looking forward, future research is focused on improving the sustainability and biocompatibility of these coatings, developing regulatory frameworks, and addressing barriers to large-scale production. The future of antimicrobial nano coatings holds great promise for improving both healthcare and industrial hygiene.

KEYWORDS

Antimicrobial nano coatings; Nanomaterials; Silver nanoparticles; Smart coatings

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Introduction

Antimicrobial nanocoatings represent a groundbreaking development in surface engineering, utilizing nanoscale materials to provide protective, antimicrobial features to different surfaces. These coatings aim to inhibit microbial growth and spread by harnessing the distinct characteristics of nanoparticles, including expanded surface area and elevated reactivity. Due to their capacity to prevent the dissemination of bacteria, fungi, and viruses, antimicrobial nanocoatings have become vital resources in the healthcare and industrial fields. The application of these coatings plays a major role in lowering hospital-acquired infections (HAIs) and enhancing overall hygiene levels in high-traffic environments such as public areas, transport, and production sites. In the healthcare industry, antimicrobial nanocoatings are mainly used to protect medical instruments, hospital surfaces, and personal protective gear (PPE). Applying these coatings to surfaces like surgical instruments, catheters, and bed rails has demonstrated a decrease in infection rates, which can otherwise result in extended hospitalizations, higher medical expenses, and potential patient fatalities [1,2].

The increasing worry about HAIs, particularly due to worldwide pandemics, has highlighted the necessity for novel approaches like antimicrobial nanocoatings to foster safer hospital settings. In the industrial sector, antimicrobial coatings are progressing notably in improving hygiene in food packaging, water filtration systems, and public areas. These coatings inhibit the accumulation of harmful microorganisms on surfaces that frequently interact with individuals and goods, guaranteeing both safety and effectiveness. The growing need for cleaner, safer environments across different industries has resulted in the extensive use of nanotechnology in coating solutions. These coatings not only inhibit microbial contamination but also prolong the lifespan of the materials they safeguard, providing both practical and financial advantages [3].

This review seeks to offer an in-depth examination of antimicrobial nanocoatings, emphasizing their essential characteristics, production techniques, uses in medical care and industrial sanitation, as well as the obstacles and future opportunities in this area. The goal is to provide perspectives on the present condition of antimicrobial nanocoatings and their ability to transform our methods of infection management and surface cleanliness [4,5].

Fundamentals of Antimicrobial Nanocoatings

Antimicrobial nanocoatings are thin layers or films of substances crafted at the nanoscale (usually under 100 nm) that exhibit antimicrobial characteristics, aimed at hindering the proliferation or expansion of microorganisms. These coatings are utilized on different surfaces to establish sanitary surroundings by decreasing microbial contamination. They can generally be divided into two primary types according to their mechanism of action: contact-killing and release-based nanocoatings [6].

Contact-killing coatings engage directly with microorganisms to prevent their growth upon physical contact, leading to cell damage or death via mechanisms like membrane disruption. Coatings based on release gradually release antimicrobial agents (such as metal ions or biocides) to produce a prolonged antimicrobial effect over a period. Each category has distinct uses in healthcare, food processing, and public health [7].

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Mechanisms of action

The effectiveness of antimicrobial nanocoatings is attributed to several mechanisms that inhibit microbial growth, including:

Physical Damage: Some nanocoatings, such as those containing silver or copper nanoparticles, physically disrupt the cell membranes of bacteria, causing cell lysis and death. The sharp edges of nanoparticles can puncture microbial cell walls [6].

Release of Active Agents: Coatings may slowly release antimicrobial agents, such as silver or copper ions, which penetrate bacterial cells, interfering with their metabolic processes and ultimately leading to cell death. This mechanism is commonly used in medical devices, where continuous antimicrobial activity is necessary [3].

Electrostatic Interactions: Nanocoatings can exert electrostatic forces that attract microorganisms, enhancing their interaction with the coating and facilitating antimicrobial activity [7].

Reactive Oxygen Species (ROS) Generation: Certain nanocoatings, like those incorporating zinc oxide or titanium dioxide, generate reactive oxygen species when exposed to UV light. ROS damage bacterial cell structures, including membranes and DNA, leading to microbial inactivation [7].

Synthesis and Fabrication Techniques

The synthesis and fabrication of antimicrobial nanocoatings are essential in ensuring their efficacy and applicability across various industries. These coatings are typically fabricated using a combination of chemical and physical deposition methods, each offering unique advantages for different applications [8].

Chemical deposition methods

Sol-Gel Process: This wet chemical technique involves the transition of a solution into a solid gel phase. It is widely used for producing thin coatings with controlled thickness and porosity. The sol-gel process allows for incorporating antimicrobial agents like silver or copper nanoparticles into the coating matrix, ensuring that the antimicrobial properties are effectively embedded within the material. This method offers ease of scalability and cost-efficiency, making it suitable for large-scale applications. [9]

Chemical Vapor Deposition (CVD): CVD is a versatile method for depositing thin material films onto substrates. In this process, gaseous precursors react on the substrate surface, forming a solid coating. CVD allows for the creation of high-purity antimicrobial coatings with excellent adhesion and uniformity. This method is ideal for fabricating coatings on complex surfaces such as medical implants or intricate industrial components [8,9].

Physical deposition methods

Electrospinning: Electrospinning is a process used to produce nanofibers from polymer solutions, often incorporating antimicrobial agents within the fibers. These nanofibers can be deposited onto various substrates, creating a high surface area that enhances the antimicrobial properties. Electrospinning is particularly useful for applications requiring flexible or porous coatings, such as wound dressings or filtration systems [10].

Sputtering: Sputtering is a physical vapor deposition technique in which atoms or molecules are ejected from a target material and deposited onto a substrate. This method can create thin, durable antimicrobial coatings on a wide range of surfaces. It is particularly effective for creating uniform coatings with minimal contamination, making it ideal for use in medical devices and food packaging [11].

Surface modification

Surface treatments such as plasma treatment, UV irradiation, and surface functionalization can enhance the antimicrobial properties of coatings. Plasma treatment alters the surface characteristics of materials, improving their adhesion and introducing functional groups that promote antimicrobial activity. Surface functionalization with antimicrobial agents or peptides further boosts the effectiveness of the coating in preventing microbial colonization [11]

Scalability and manufacturing challenges

Scaling up the production of antimicrobial nanocoatings faces several challenges. The transition from laboratory-scale synthesis to large-scale manufacturing requires maintaining consistency in coating quality and ensuring cost-effectiveness. Some methods, such as CVD and electrospinning, may face limitations in throughput and scalability. Additionally, the cost of raw materials and the complexity of the manufacturing process can pose significant barriers to widespread commercial adoption. Overcoming these challenges requires advancements in fabrication techniques and the development of more efficient production processes [12].

Applications in Healthcare

Hospital-acquired infections (HAI)

Infections acquired in hospitals (HAIs) continue to pose a major issue in healthcare, leading to prolonged patient admissions, elevated treatment expenses, and greater rates of illness and death. Antimicrobial nanocoatings have demonstrated significant potential in lowering the occurrence of HAIs by inhibiting microbial contamination on frequently touched surfaces and medical equipment. These coatings are used on surfaces like bed rails, patient monitoring devices, and different hospital furniture, where they consistently lower microbial load, reducing the chance of infection spread. Incorporating nanomaterials such as silver and copper into healthcare settings can offer a preventive strategy for infection management, particularly in intensive care units, where patients face the highest risk [3,11].

Medical devices

Medical instruments, such as implants, catheters, and surgical equipment, are highly susceptible to microbial contamination, frequently resulting in infections that hinder recovery. Antimicrobial nanocoatings can improve the biocompatibility and safety of these devices by inhibiting bacterial adherence and biofilm development. For instance, coatings that include silver nanoparticles on implants, like orthopedic or dental implants, have shown a marked decrease in microbial colonization. Likewise, antimicrobial nanocoatings applied to catheters inhibit the proliferation of bacteria such as E. coli and Staphylococcus aureus, which frequently lead to catheter-associated urinary tract infections (CAUTIs). These

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coatings serve to prevent infections while also aiding in quicker healing by minimizing the inflammatory response to infections [4,12].

Antimicrobial surfaces in healthcare facilities

High-contact surfaces in healthcare facilities, including door knobs, light switches, and elevator controls, act as hotspots for spreading pathogens. Nanocoatings with antimicrobial properties applied to these surfaces can greatly lower the microbial load and enhance a cleaner, safer environment. For example, copper-based nanocoatings have effectively been used on door handles and bed rails, demonstrating a decrease in bacterial counts by as much as 90% over prolonged durations. Antimicrobial coatings applied to frequently touched surfaces assist in minimizing the transmission of infections among patients, healthcare staff, and visitors, especially in environments such as emergency rooms and operating theatres [13,14].

Case studies

Recent research has emphasized the efficacy of antimicrobial nanocoatings in medical environments. A study assessed the effectiveness of surfaces coated with silver nanoparticles in a hospital setting and discovered a noticeable decrease in bacterial contamination, resulting in fewer HAIs in areas that received these treatments. Likewise, clinical trials with antimicrobial-coated catheters showed a lower risk of catheter-associated infections in patients, significantly reducing bacterial adhesion and biofilm development. Additionally, the application of graphene oxide-based coatings in medical equipment has demonstrated potential in enhancing the antimicrobial features of surgical tools and implants, rendering them more resistant to infections while preserving their mechanical strength [15,16].

These case studies highlight the increasing significance of antimicrobial nanocoatings in preventing infections and maintaining hygiene in healthcare. As an increasing number of hospitals implement these technologies, the opportunity to alleviate the impact of HAIs and enhance patient outcomes keeps growing [17].

Applications in Industrial Hygiene

Antimicrobial nanocoatings are revolutionizing industrial cleanliness by providing cutting-edge solutions to reduce microbial contamination across different industries, thus improving public safety and the quality of products. A key application lies in food packaging and processing. The food sector continually encounters difficulties in ensuring cleanliness and extending the longevity of perishable products. By incorporating antimicrobial nanocoatings into packaging materials—like films, containers, and coatings on processing equipment—producers can greatly decrease the likelihood of foodborne pathogens. Nanomaterials such as silver, copper, and zinc oxide are frequently incorporated into packaging layers to prevent microbial proliferation. These coatings function by either releasing antimicrobial ions or disrupting microbial cell membranes upon contact, which helps prevent spoilage and prolongs the freshness of food items. Consequently, these coatings play a crucial role in minimizing food waste and safeguarding consumer safety [14,18].

Besides food packaging, antimicrobial nanocoatings are more frequently utilized in water treatment and filtration systems. The quality of water is a crucial public health issue, and microbial contamination within water systems can result in serious health problems. Coatings applied to filtration membranes and pipes provide a preventive strategy to hinder the development of bacterial biofilms and blockages, which frequently undermine filtration efficiency. For example, coatings of silver nanoparticles have been applied to membranes to continuously emit ions that prevent the buildup of bacteria and other pathogens. This ongoing antimicrobial effect improves the efficiency and durability of filtration systems while lowering maintenance needs. In addition, comparable coatings on water supply pipes inhibit the growth of harmful bacteria, guaranteeing that water stays safe for drinking and industrial applications [18,20].

Antimicrobial coatings are also crucial for safeguarding frequently touched surfaces in public areas, where the risk of pathogen transmission is always present. Public transit systems, workplaces, retail centers, and other bustling locations possess surfaces that often interact with various people. Utilizing antimicrobial nanocoatings on surfaces like handrails, door knobs, elevator buttons, and seating areas can significantly decrease the transmission of infectious agents. For instance, nanocoatings made of copper on public transport fixtures have shown a significant reduction in microbial levels, thus decreasing the likelihood of disease spread in densely populated areas. These applications enhance hygiene and also increase public trust in the safety of communal areas [19,21].

Recent developments and case studies underscore the efficacy of antimicrobial nanocoatings in industrial environments. In the food sector, a preliminary study with packaging infused with silver nanoparticles showed an enhancement in shelf life by as much as 30% when compared to conventional packaging techniques. Likewise, water treatment facilities utilizing silver-coated membranes indicate reduced maintenance expenses and enhanced filtration performance, showing significant decreases in biofouling. Moreover, a number of municipalities have launched initiatives to cover high-touch surfaces in public areas, indicating a notable reduction in microbial loads on these surfaces, which has helped lower community-acquired infections [22,23].

These effective applications highlight the ability of antimicrobial nanocoatings to boost industrial hygiene by enhancing food safety, water quality, and public health in busy areas, while also providing economic and operational advantages across various sectors [24].

Environmental and Toxicological Considerations

Biocompatibility and safety

The safety of antimicrobial nanocoatings, particularly those designed for medical and food-related uses, is essential. Toxicological evaluations are crucial for identifying possible harmful impacts on human cells and tissues. For example, research has investigated the cytotoxic effects of titanium dioxide (TiO_2) nanocoatings, showing that although TiO_2 is commonly used as a food additive (E171), its nanosized variant might present varying safety profiles. Additional studies are

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needed to completely comprehend the effects of TiO_2 nanocoatings in medical and dental applications. Likewise, the biocompatibility of different nanomaterials, including silver and copper nanoparticles, necessitates careful assessment. Although these nanoparticles demonstrate significant antimicrobial characteristics, it is essential to thoroughly evaluate their possible cytotoxic effects to ensure they do not damage human cells upon exposure. Thorough in vitro and in vivo investigations are crucial to determine safety profiles for these nanocoatings [20,25].

Ecotoxicity and environmental impact

The ecological effect of antimicrobial nanocoatings is a major issue, especially concerning the release of nanoparticles into natural environments. Research has pointed out the possible ecotoxicological impacts of these coatings, stressing the importance of thoroughly assessing their environmental hazards. For instance, the introduction of nanoparticles into water environments may result in bioaccumulation and harmful effects on aquatic species, disturbing ecosystems. To address these risks, it is essential to evaluate both the toxicity of antimicrobial substances and their levels in the environment. Adopting measures to reduce nanoparticle emissions and confirming that coatings break down into harmless byproducts are crucial actions for lessening environmental effects [26 27].

Regulatory challenges

The authorization and oversight of antimicrobial nanocoatings pose intricate difficulties because of the distinct characteristics of nanomaterials. Regulatory authorities demand comprehensive information regarding the safety, effectiveness, and ecological effects of these coatings. Producers must comply with strict regulations to guarantee that nanocoatings are safe, biocompatible, and eco-friendly. This procedure typically includes extensive testing and certification, which may be both time-consuming and expensive. The absence of standardized testing protocols for nanomaterials adds to the complexity of the regulatory framework. Creating widely recognized guidelines is crucial to simplify the approval process and guarantee uniform safety standards across various applications [27,28].

Sustainable solutions

Tackling environmental and health issues has led to the creation of sustainable and biodegradable antimicrobial nanocoatings. Scientists are investigating natural substances that possess antimicrobial characteristics as substitutes for traditional chemical agents. For example, green synthesis techniques using plant extracts have been suggested to generate environmentally friendly nanoparticles that are effective and non-harmful [28,29].

Furthermore, progress in coating technologies seeks to lower energy usage and remove volatile organic compounds (VOCs). Coatings like Parylene, plasma, and atomic layer deposition (ALD) are recognized for their eco-friendly characteristics, including reduced carbon footprints and adherence to environmental regulations such as RoHS and REACH. The creation of biodegradable nanocoatings, especially for uses such as food packaging, represents a hopeful field of study. These coatings are designed to offer antimicrobial features while ensuring they decompose into harmless substances, thus minimizing environmental pollution [29,30].

Future Perspectives and Challenges

Smart and responsive nanocoatings

The potential of antimicrobial nanocoatings is in creating intelligent, stimuli-reactive materials that adjust to changes in the environment. These coatings can emit antimicrobial substances when exposed to certain stimuli, like changes in pH, variations in temperature, or the detection of pathogens. For example, studies have investigated coatings that emit metal ions during infection, delivering focused antimicrobial effects as required [31,32].

Moreover, research is being conducted on bioinspired methods to develop coatings that show self-defensive characteristics, triggering antimicrobial actions in response to bacterial presence. These smart coatings are designed to inhibit bacterial adhesion and biofilm development, improving the durability and efficiency of medical devices [33].

Integration with other technologies

Integrating antimicrobial nanocoatings with additional technologies like ultraviolet (UV) light or heat treatments can improve their effectiveness. For instance, UV exposure can trigger specific nanocoatings, enhancing their antimicrobial features. Nonetheless, the efficacy of this combination may differ, and elements like the photocatalytic activity of the nanocoating and the existence of impurities can affect results. Combining nanocoatings with other technologies necessitates thoughtful evaluation of compatibility and efficiency. Although integrating UV or heat treatments with nanocoatings can yield synergistic benefits, it is crucial to confirm that the combined method does not jeopardize the material's integrity or safety [34,35].

Conclusions

Antimicrobial nanocoatings have shown considerable promise in enhancing healthcare and industrial cleanliness by offering ongoing defense against microbial proliferation. The review underscored significant progress in the design, synthesis, and use of these coatings, stressing their efficacy in minimizing hospital-acquired infections, improving food safety, and safeguarding public areas.

The integration of nanomaterials like silver, copper, and graphene has transformed antimicrobial surfaces, providing extensive effectiveness and lasting strength. Although antimicrobial coatings demonstrate encouraging outcomes, the review also addressed important environmental and safety factors, such as biocompatibility, toxicity, and the hazards associated with nanoparticle leaching. Looking forward, the outlook for antimicrobial nanocoatings is promising, featuring new developments like intelligent, adaptive coatings and the combination of nanotechnology with other methods such as UV and thermal treatments. Nonetheless, issues like expenses, safety, and large-scale manufacturing still need to be tackled.

Disclosure statement

No potential conflict of interest was reported by the authors.

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