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Review

Silver Nanoparticle-Based Antimicrobial Coatings: Sustainable Strategies for Microbial Contamination Control

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Abstract: Silver nanoparticles have gained significant attention due to their remarkable antimicrobial properties, making them ideal candidates for incorporation into various coatings. These coatings exhibit antimicrobial activity through multiple mechanisms, including the release of silver ions, the generation of reactive oxygen species, and the disruption of microbial cell membranes and intracellular metabolic pathways. The integration of silver nanoparticles into coating matrices through physical embedding, chemical bonding, or surface grafting not only influences the controlled release of antimicrobial agents but also affects the mechanical stability and longevity of the coatings. Several factors, including nanoparticle size, shape, surface chemistry, and functionalization, influence the antimicrobial efficiency of these nanoparticle-based coatings. As a result, silver nanoparticle coatings have been widely applied in medical devices, textiles, antifouling surfaces, and food packaging. This review discusses the advances in using silver nanoparticles in antimicrobial coatings, focusing on the mechanisms of action, fabrication methods, and diverse applications. The review also highlights the influence of nanoparticle characteristics on antimicrobial performance, providing insights into the future directions for smart coatings. Future research is expected to focus on optimizing the fabrication techniques, enhancing the stability of silver nanoparticle coatings, and exploring innovative applications in emerging fields.

Keywords: pathogen; antimicrobial; polymer; smart; antifouling; fabric; food packaging

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1. Introduction

Microbial contamination remains a persistent and significant challenge across multiple sectors, including healthcare, food production, and environmental systems [1,2]. Recent World Health Organization (WHO) data indicate that hospital-acquired infections affect approximately 7–15% of hospitalized patients globally, contributing to extended hospital stays, elevated healthcare costs, and increased mortality rates [3]. Beyond hospital settings, inadequate sanitation and hygiene practices in communities continue to fuel the spread of infectious diseases. For example, a study by Kerketta et al. documented an acute diarrheal disease outbreak in Rourkela, India, primarily caused by *Vibrio cholerae* and *Shigella flexneri*. The outbreak was strongly linked to poor sanitation, particularly the use of inadequate toilet facilities, emphasizing the urgent need to improve sanitation and hygiene infrastructure in vulnerable populations [4]. Similarly, in water systems, pathogens such as *Escherichia coli*, *Salmonella*, and *Cryptosporidium* have been detected in both treated and untreated water sources, contributing to gastrointestinal disease outbreaks and posing serious public health risks, especially in economically disadvantaged regions [5]. In the food industry,

microbial contamination remains a leading cause of spoilage and foodborne illnesses, with the WHO reporting that 1 in 10 (about 600 million) people worldwide fall ill annually due to contaminated food, resulting in 420,000 deaths [6].

The effects of microbial contamination extend beyond health impacts, causing substantial economic losses due to product spoilage, equipment biofouling, and increased maintenance requirements [7]. To address these challenges, effective infection control strategies are essential to reduce the transmission of pathogenic microorganisms, particularly in high-risk environments such as healthcare facilities, food processing plants, and municipal water systems.

A promising infection control strategy involves antimicrobial coatings, which form a continuous protective barrier that inhibits microbial adhesion, growth, and biofilm formation. These coatings can significantly reduce microbial load and the risk of cross-contamination, making them valuable in healthcare, textiles, and environmental sanitation applications [8–11]. Among the most effective agents incorporated in these coatings are silver nanoparticles (AgNPs), known for their exceptional antimicrobial properties. AgNPs have garnered significant attention due to their broad-spectrum activity against bacteria, fungi, and viruses [12,13]. When incorporated into coatings, AgNPs exert their antimicrobial effects through multiple, complementary mechanisms. These include the sustained release of silver ions (Ag^+), which penetrate microbial cell walls and bind to thiol groups in key enzymes, leading to metabolic disruption and cell death. AgNPs also catalyze the generation of reactive oxygen species (ROS), which cause oxidative stress and damage to DNA, proteins, and lipids [11–14]. Furthermore, the nanoparticles (NPs) themselves can interact directly with microbial membranes, increasing permeability and structural disintegration. These mechanisms are particularly effective when AgNPs are embedded or grafted into coating matrices, which facilitate controlled ion release and prolong antimicrobial action over time [15]. The efficiency of these coatings depends on critical parameters such as NP size, shape, surface chemistry, and method of integration, whether by physical embedding, chemical bonding, or surface grafting [16].

Incorporating AgNPs into coatings has significantly enhanced microbial control in several critical fields. In water purification, AgNP-coated membranes and filters effectively eliminate microbial contaminants [17], improving access to clean and safe drinking water, particularly in resource-limited settings. For surface sterilization, AgNP-based coatings applied to high-touch surfaces in hospitals, laboratories, and public spaces help inhibit microbial colonization and reduce the risk of cross-contamination [18]. In wound healing, AgNP-infused dressings offer antimicrobial protection that promotes faster recovery by preventing infections, reducing inflammation, and maintaining a sterile environment at the wound site [19].

This review highlights recent progress in AgNP-based antimicrobial coatings, emphasizing the influence of nanoparticle size, shape, and surface chemistry on antimicrobial activity. It also examines the mechanisms by which AgNPs exert their effects and highlights various fabrication methods for coating development. Emerging innovations—such as smart coatings that respond to environmental triggers or microbial presence to provide controlled, on-demand antimicrobial activity—are also discussed. Together, these developments highlight the transformative potential of AgNP coatings in enhancing modern infection prevention and control strategies.

2. Silver Nanoparticles in Antimicrobial Coatings: Effect of Size, Shape, and Surface Chemistry

Silver nanoparticles are effective antimicrobial agents used in coatings to inhibit pathogens and prevent biofilm formation. Their performance depends on factors such

as size, shape, and surface chemistry, which influence stability, bioavailability, and microbial interactions [20]. Researchers have enhanced their antimicrobial effectiveness by adjusting these properties and incorporating AgNPs into polymers, biopolymers, and hybrid materials.

This section examines how nanoparticle characteristics impact coating performance across applications in healthcare, water treatment, food preservation, and textiles. Table 1 summarizes AgNP formulations, including their sizes, shapes, coatings, and antimicrobial effects.

Table 1. Antimicrobial silver nanoparticles, their coatings, and efficacy.

NPs	Size (nm)	Shape	Coating	Effect	Ref
AgNPs	17.16 ± 1.94	Spherical	Polyurethane (PU) nanofiber	AgNPs concentrations of 0.5, 2, and 4 wt% were tested; 4 wt% PU/AgNPs nanofibers exhibited the most ZOI against *E. coli* (18.2 ± 0.9 mm) and *Staphylococcus aureus* (16.1 ± 0.7 mm).	[21]
	18 ± 4.32	Spherical	Polyhexamethylene biguanidine (PHMBG) embedded on chitosan thiourea/polyvinyl alcohol (PVA) nanofibers	Notable antimicrobial efficacy against *S. aureus* and *Pseudomonas aeruginosa* at 3 wt% Ag/PHMBG concentration, with animal studies showing faster wound healing.	[22]
	8 ± 2	Spherical	Oleylamine (OA) as NPs capping agent coated on textile of surgical masks	Ag@OA-coated textiles (2.9–47.1 µg) showed increasing anti-SARS-CoV-2 activity, reaching up to 100% inactivation after 10 min.	[23]
	15 to 118	Spherical	Polyvinyl butyral (PVB)	The nanocomposite coatings (AgNP-PVB with AgNP concentrations from 150 to 1000 ppm) were effective in reducing the activity of SARS-CoV-2 virus, with 1000 ppm coating showing the highest antiviral efficacy.	[24]
	123	Spherical, flake, triangle, wire, and rod-shaped	Cotton fabrics	Cotton fabric composites with AgNPs (250–2000 µg/mL) showed antimicrobial activity against *S. aureus* and *E. coli* at all concentrations.	[25]
	4.8 ± 2.4	Spherical	Chloroxylenol-carboxyethylchitosan (CECSX)	The resulting CECSX-AgNP-coated surgical suture surfaces demonstrated outstanding antimicrobial properties against *E. coli*, *S. aureus*, and *A. baumanii* with MIC values of 25, 12.5, and 1.56 mg/L, respectively.	[26]
	4	Spherical	Polylactic acid (PLA)	TiO_2 surfaces coated with AgNPs and PLA microfibers exhibited antimicrobial activity against *S. aureus*.	[27]
	20	Spherical	Urushiol-based polybenzoxazine (UOHP)	UOHP composite coatings with 0.05–1.0 wt% AgNPs showed antimicrobial activity against bacteria and marine microalgae, even at 0.05 wt%.	[28]
	194 ± 55	Spherical	Polydopamine on open-cell polyurethane foams	Complete microbicidal effect against *C. albicans* and *E. coli* after 3 h of contact time and after 24 h of contact time for *S. aureus*.	[29]
	-	Uniform shape	Acacia gum/chitosan nanogel	AgNPs@acacia gum/chitosan nanogel coatings achieved 6-log reduction in *E. coli*, *K. pneumoniae*, *E. faecalis*, and *B. subtilis* at 150–200 mg/L.	[30]
	-	-	Cotton fabric is treated with perfluorooctyltri-ethoxysilane	Superior antibacterial properties against *E. coli*.	[31]
	72.1 to 159.2	-	Kappa-carrageenan on cotton fabric	AgNPs/kappa-carrageenan coating significantly improved antibacterial activity against *S. aureus*.	[32]
	37.91 ± 2.35	Spherical	Sodium dodecyl sulfate (SDS)	SDS-coated AgNPs exhibit superior antibacterial activity against *S. aureus*, *Listeria monocytogenes*, *Salmonella Typhimurium*, *Yersinia enterocolitica*, *Enterococcus faecalis*, *E. faecium*, *E. coli*, and *Klebsiella pneumoniae* with the MIC of 78.125 µg/mL.	[33]
	85.37 to 117.51	Spherical	Calliandra surinamensis (Cs) leaf extract	Cs-AgNPs effectively inhibit biofilm formation on medical catheters at concentrations of 30 µM and 50 µM.	[34]

Table 1. *Cont.*

NPs	Size (nm)	Shape	Coating	Effect	Ref
	12.18	-	Polymethyl methacrylate (PMMA), an acrylic resin	Nystatin-coated AgNPs in PMMA effectively inhibited *C. albicans* growth and showed considerable antibacterial activity against *Streptococcus mutans*. The MIC of AgNPs/PMMA extracts ranged from 220 to 323 µL/mL, while the MBC ranged from 234 to 389 µL/mL against *S. mutans*.	[35]
	6.5	-	Dialdehyde-modified TEMPO-oxidized cellulose nanofibers	Paper sheets coated with nanocellulose/AgNPs suspensions containing 120 µg Ag/g effectively inhibited the growth of *B. subtilis* for at least one month.	[36]
	11 ± 3	-	Polyurethane (PU) nanofibers	PU embedded with 1–10% heparin-functionalized AgNPs (0.3–1.7% Ag) exhibited potent antibacterial activity against *S. aureus* and *Salmonella Typhimurium*.	[37]
	50–100	Spherical	Collagen-coated polycaprolactone (PCL) nanofiber	The AgNP-functionalized membranes significantly reduced biofilm formation in *P. aeruginosa* and *Vancomycin-resistant Enterococcus*. The MICs were 50 µg/mL for *P. aeruginosa*, 100 µg/mL for *vancomycin-resistant Enterococcus*, and above 400 µg/mL for *S. aureus*.	[38]
	10–30	Spherical	Mesoporous silica (MS) loaded with octadecylamine (ODA) and coated with polydopamine (PDA)	ODA/Ag-PDA@MS nanomaterial exhibited excellent bactericidal performance (against *P. aeruginosa* and *B. subtilis*), fully inhibiting growth at 6.3 mg/L within 72 h and effectively preventing biofouling.	[39]
	55 ± 5	Cube-shaped	Stearyl methacrylate (SM) and vinyl pyrrolidone	-	[40]
CaO_2@SiO_2/AgNPs	89 ± 9.6	Quasi-spherical	Silicon dioxide-coated calcium peroxide (CaO_2@SiO_2)	CaO_2@SiO_2/AgNPs hydrogels exhibited enhanced antibacterial activity against *S. aureus* and *E. coli*, with bactericidal efficiency of over 99% at a concentration of 40 µg/mL.	[41]
Alginate-Chitosan Loaded with AgNPs	between 30 and 50	Spherical	Eugenol/Quercetin	Antibacterial activity against *E. coli*, *B. subtilis*, *Klebsiella*, and *S. aureus*.	[42]
AgNPs coated with silicon dioxide (Ag@SiO_2 NPs)	Aggregates SiO_2 NPs 260, AgNPs 890 length	Spherical SiO_2NPs and rod-shaped AgNPs	Bisphenol A-glycidyl methacrylate (BisGMA) and Triethylene glycol dimethacrylate (TEGDMA)-based resin	3 wt% and 5 wt% Ag@SiO_2 NPs in a resinous matrix demonstrated a significant reduction in *S. mutans* biofilm.	[43]
SiO_2@AgNPs	-	Spherical	Steel	Antibacterial activity against *Bacillus subtilis* with an MIC of 250 µg/mL.	[44]
	28 with an SiO_2 shell of 16	Spherical	Polyurethane-doped films	Films containing AgNPs at concentrations of 4.0 and 8.0 µg/cm^2 exhibited a bactericidal effect against *E. coli* and *Salmonella enterica* subsp. *enterica* serovar Choleraesuis and *B. cereus*.	[45]
Mixed metal oxides (MMOs) of TiO_2, ZnO, SiO_2, and CuO with AgNPs (MMO–AgNPs)	-	Spherical	Fabric	Excellent antimicrobial properties against *E. coli* and *S. aureus* bacteria and bacteriophage viruses, with an MIC of 107 mg/mL. The minimum bactericidal concentration required to reduce 99.9% of *S. aureus* was 2.5 mg/mL.	[46]
Graphene oxide (GO)-AgNPs composite	-	Spherical	Surface	The 20 µg/cm^2 GO-AgNPs composite completely prevents *P. aeruginosa* biofilm formation.	[47]

Minimum inhibitory concentration = MIC.

Table 1 shows AgNPs with varying shapes, sizes, and surface coatings demonstrating a broad-spectrum antimicrobial activity against various pathogens. These physicochemical properties influence their effectiveness, with some morphologies exhibiting enhanced interactions with microbial cell membranes, leading to improved bactericidal and fungicidal outcomes.

2.1. Effect of Size on Silver Nanoparticles (AgNPs) Antimicrobial Activity

Size plays a crucial role in the antimicrobial efficacy of AgNPs, as smaller nanoparticles typically exhibit enhanced activity due to their larger surface area-to-volume ratio [48]. A study by Khan et al. demonstrated the size-dependent antibacterial efficacy of AgNPs against *S. aureus*. The study found that AgNPs within the 9–15 nm size range exhibited

the highest antimicrobial activity, outperforming larger nanoparticles measuring 15–25 nm and 30–40 nm. This trend was quantitatively reflected in the zone of inhibition (ZOI) measurements, where the 9–15 nm AgNPs produced a ZOI of 22.00 mm, compared to 20 mm for the 15–25 nm nanoparticles and 18 mm for the 30–40 nm nanoparticles [49]. These findings highlight the importance of nanoparticle size in determining antibacterial potency, as smaller AgNPs dissolve faster, facilitating greater silver ion release and stronger interactions with bacterial membranes, leading to improved antibacterial action [13,50]. Figure 1 illustrates the distinct behaviors of smaller (≤10 nm) versus larger (≥20 nm) nanoparticles, highlighting how their size influences interactions with cells.

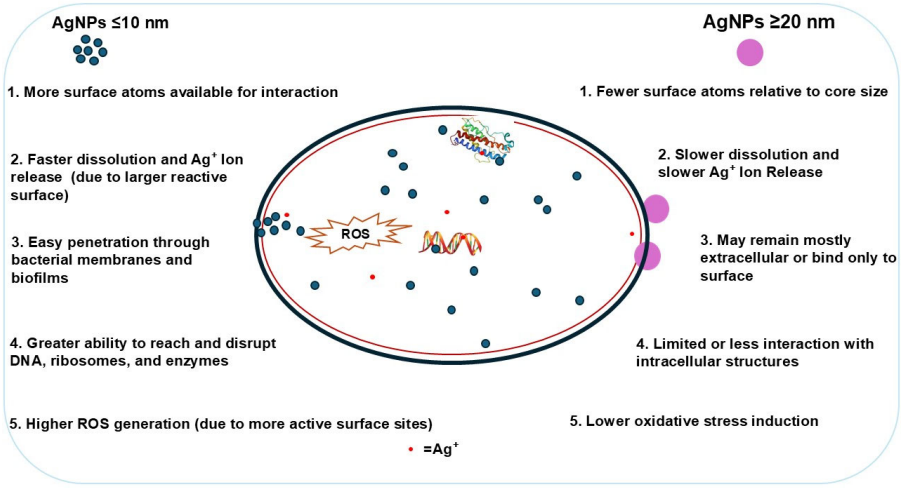


Figure 1. Size-dependent cellular interactions of nanoparticles: Comparison between smaller (≤10 nm) and larger (≥20 nm) nanoparticles.

In Table 1, several examples illustrate the enhanced antimicrobial effects of small AgNPs. For instance, 4 nm AgNPs coated with poly(lactic acid) exhibited significant antimicrobial activity against *S. aureus* on TiO_2 surfaces [27], showing the enhanced interaction between small nanoparticles and pathogens. Similarly, 4.8 ± 2.4 nm AgNPs coated with chloroxylenol-carboxyethylchitosan displayed potent antimicrobial properties against a range of pathogens, including *E. coli* and *S. aureus* [26]. Furthermore, 6.5 nm AgNPs incorporated into TEMPO-oxidized cellulose nanofibers for paper sheets effectively inhibited *Bacillus subtilis* growth for up to one month [36]. These enhanced antimicrobial effects are attributed to the high surface energy of smaller nanoparticles, which increases their likelihood of interacting with bacteria and fungi, preventing their growth or causing cell death.

In contrast, larger AgNPs exhibit reduced bioactivity due to slower ion release. However, they offer prolonged antimicrobial effects, making them suitable for sustained protection applications, such as wound dressings or antibacterial coatings [51,52]. As shown in Table 1, 123 nm AgNPs on cotton fabrics exhibited excellent antimicrobial performance against *S. aureus* and *E. coli* [25]. However, their larger size may limit their ability to penetrate bacterial cell walls compared to smaller AgNPs. Similarly, 194 ± 55 nm AgNPs on polydopamine-coated polyurethane foams demonstrated complete microbicidal effects against *C. albicans* and *E. coli* after longer contact times [29]. This indicates that larger AgNPs may require extended exposure to achieve effective antimicrobial action.

These larger AgNPs are often favored for their stability, longer-lasting effects, and reduced potential for toxicity, making them particularly suitable for industrial or environmental applications. Therefore, optimizing the size of AgNPs is essential for maximizing

their antimicrobial efficacy in various biomedical and environmental applications, balancing the need for rapid action with sustained protection depending on the specific use case.

2.2. Effect of Shape on Silver Nanoparticles (AgNPs) Antimicrobial Activity

Nanoparticles exist in diverse shapes, including spheres, rods, cubes, stars, and triangles, as illustrated in Figure 2, influencing their physicochemical properties and interactions with microbes.

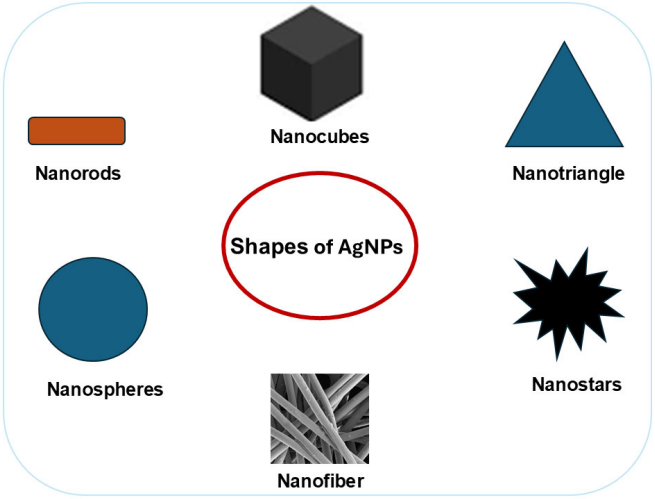


Figure 2. Various shapes of AgNPs.

Shape plays a crucial role in antimicrobial efficacy by modifying the surface area, charge distribution, and reactivity [53,54]. Spherical silver nanoparticles are the most extensively studied due to their ease of synthesis, stability, and consistent antimicrobial activity through controlled silver ion release. As shown in Table 1, most of the AgNPs in the studies presented are spherical. However, anisotropic and sharp-edged structures, such as triangular or spiked AgNPs, exhibit enhanced antibacterial potency by increasing bacterial membrane disruption and ROS generation. These properties make them more effective antimicrobials than their spherical counterparts. For instance, Wang et al. investigated the antibacterial activity of AgNPs by comparing nanospheres and nanotriangles against *E. coli* and *S. aureus*. Their findings highlighted the "tip effect", where the sharp edges of nanotriangles significantly enhanced bacterial inhibition. Nanotriangles generated higher ROS levels and caused more extensive bacterial cell wall damage than nanospheres, reinforcing the influence of nanoparticle shape on antimicrobial performance [55]. Similarly, Bharti et al. examined the bactericidal efficiency of decahedral and spherical AgNPs against *E. coli*, *P. aeruginosa*, *Bacillus subtilis*, and *S. aureus*. Their study revealed that decahedral AgNPs demonstrated superior antibacterial activity at lower concentrations. This enhanced efficacy was attributed to their unique geometric structure, which increased surface reactivity, strengthened bacterial membrane interactions, and promoted more ROS production, emphasizing the impact of nanoparticle morphology on antimicrobial effectiveness [56]. Further supporting this trend, Holubnycha et al. assessed the antimicrobial and antibiofilm activities of spherical and cubic AgNPs against clinical ESKAPE pathogens. Cubic AgNPs exhibited superior antibacterial effects, effectively inhibiting biofilm formation and disrupting existing biofilms. Both nanoparticle types induced bacterial membrane damage and reduced viability, highlighting their potential as potent antimicrobial agents [57].

These studies highlight the significance of nanoparticle shape in optimising antimicrobial activity. While spherical AgNPs remain widely utilised, anisotropic and structurally distinct nanoparticles offer enhanced bactericidal and antibiofilm properties, such as trian-

gular, decahedral, and cubic AgNPs. Understanding these shape-dependent mechanisms can aid in developing more effective nanoparticle-based antimicrobial strategies.

2.3. Effect of Surface Chemistry and Functionalization on Silver Nanoparticles (AgNPs) Antimicrobial Activity

The surface chemistry and functionalization of AgNPs are crucial in enhancing their stability, effectiveness, and antimicrobial performance [20,58]. Uncoated AgNPs, while highly reactive and capable of rapidly releasing silver (Ag^+) ions, tend to aggregate over time [59]. This aggregation reduces their surface area and hinders their ability to interact with bacterial cells, decreasing their antimicrobial efficiency. Surface functionalization, achieved by attaching specific ligands, polymers, or other molecules to the nanoparticle surface, can enhance properties like solubility, stability, biocompatibility, targeting specificity and antimicrobial efficacy [58].

Various coating strategies are employed to address the nanoparticles' stability and functionality. As illustrated in Table 1, coatings from synthetic polymers, biopolymers, and plant extracts have been utilized. Polymer-coated AgNPs, such as those coated with polyvinyl alcohol (PVA), polyurethane (PU), or polymethyl methacrylate (PMMA), not only enhance the nanoparticles' stability by preventing aggregation, but also improve their adhesion to surfaces. These coatings allow for controlled and sustained release of Ag^+ ions, thereby providing long-term antimicrobial action against many pathogens. Velgosova et al. developed nanocomposites composed of PVA and AgNPs, which exhibited improved antibiofilm activity against a one-cell green algae *Pseudokirchneriella kessleri* [60]. Similar studies revealed that AgNPs incorporated into PMMA inhibited the growth and maturation of bacteria such as *S. aureus*, *E. Coli*, *Staphylococcus epidermidis*, and *C. albicans* [61–63].

Biopolymer-coated AgNPs, including those functionalized with alginate, chitosan or carrageenan, offer additional benefits such as improved biocompatibility, non-toxicity, and the ability to deliver targeted antibacterial effects [64,65]. These properties make them particularly valuable in medical applications such as wound dressings, dental products, and other biocompatible materials where antimicrobial efficacy and safety are essential. For example, Mendez-Pfeiffer et al. reported that chitosan-coated silver nanoparticles (CT-AgNPs) exhibit potent antibacterial and antibiofilm activity at concentrations as low as 12.5 μg/mL while significantly reducing the adherence of uropathogenic *E. coli* (UPEC) to mammalian cells at 1.06 and 0.53 μg/mL [66]. These findings show the potential of CT-AgNPs in biomedical and healthcare applications, including antimicrobial coatings for catheters and medical devices to prevent urinary tract infections, wound dressings with antibacterial and tissue-regenerative properties, and dental products to inhibit plaque formation and biofilm-associated infections. Additionally, CT-AgNPs show promise in food packaging to prevent bacterial contamination and extend shelf life, emphasizing their broad applicability in antimicrobial technologies.

Metal oxide hybrid AgNPs, incorporating materials like titanium dioxide (TiO_2), zinc oxide (ZnO), or silicon dioxide (SiO_2), combine the inherent antimicrobial properties of silver with photocatalytic activity [67]. This synergy enhances the overall antimicrobial effect, making them ideal for self-cleaning surfaces where continuous disinfection is required under exposure to light. For instance, the work by Nguyen et al. demonstrates that AgNPs significantly enhance the antibacterial activity of titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles when integrated into hybrid nanomaterials. These AgNP-functionalized hybrids exhibit strong antibacterial efficacy against *S. aureus* and *E. coli*, even at concentrations below 40 mg/mL. Moreover, their antibacterial performance improves under light irradiation, suggesting a synergistic interaction between AgNPs and the photocatalytic properties of TiO_2 and ZnO. However, at higher concentrations (40 mg/mL),

the antibacterial effect remains consistent regardless of light exposure, indicating that the AgNPs direct bactericidal action becomes the dominant factor [68].

Furthermore, integrating graphene oxide with AgNPs creates a highly effective combination for preventing biofilm formation and inhibiting bacterial adhesion [69,70]. Graphene oxide-AgNP composites are particularly useful in medical device coatings and implant materials, where bacterial colonization poses significant challenges. By preventing biofilm formation, these composites ensure that the surface remains free from bacterial buildup, thus enhancing the longevity and functionality of medical devices [47]. Overall, the surface chemistry and functionalization of AgNPs are essential in tailoring their properties to meet specific antimicrobial needs across various applications, ensuring both effectiveness and safety.

As shown in Table 1, AgNPs with various coatings exhibit broad-spectrum antimicrobial properties across multiple applications. Incorporating AgNPs into materials such as polyurethane nanofibers, chitosan thiourea/PVA nanofibers, and surgical masks enhances their efficacy against pathogenic bacteria, fungi, and viruses [22–28]. These coatings are utilized in self-disinfecting materials, antimicrobial wound dressings, personal protective equipment, antiviral surfaces, antimicrobial textiles, surgical products, bioactive surfaces, antifouling agents, water treatment systems, antibacterial fabrics, food packaging, and dental applications, underscoring the versatility of AgNPs in enhancing antimicrobial properties across various substrates [71].

The antimicrobial performance of AgNPs in coatings is strongly influenced by their size, shape, and surface chemistry. As demonstrated in Table 1, smaller AgNPs (4–12 nm) exhibit superior efficacy due to their increased surface area and enhanced interaction with microbial cells. Spherical-shaped AgNPs are the most effective and widely used, likely because of their uniform and consistent contact with microbial membranes. Surface modifications further improve nanoparticle stability, bioavailability, and target specificity. Optimal antimicrobial activity is typically achieved at concentrations ranging from 1 to 6 wt% or $\leq$200 μg/mL, providing a balance between performance and material compatibility. Therefore, careful optimization of these physicochemical properties is essential for maximizing the effectiveness of AgNP-based coatings across biomedical, environmental, and industrial applications.

3. Mechanisms of Antimicrobial Action of Silver Nanoparticles (AgNPs)

AgNPs exert antimicrobial effects through multiple mechanisms, as illustrated in Figure 3, targeting various cellular structures and processes in bacterial cells.

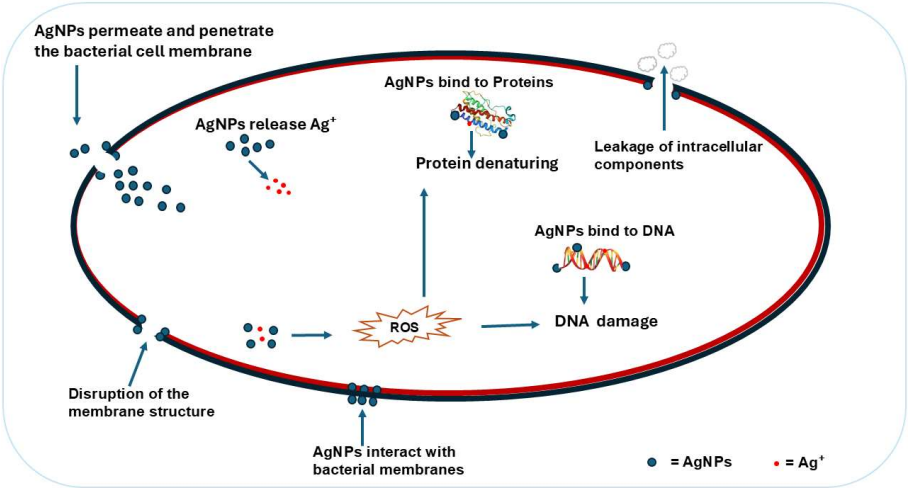


Figure 3. Schematic representation of AgNPs antimicrobial mechanisms.

3.1. Cell Membrane Disruption and Increased Permeability Nanoparticles

AgNPs, due to their positive charge, interact electrostatically with negatively charged bacterial membranes, which are composed of lipopolysaccharides in Gram-negative bacteria and peptidoglycan layers in Gram-positive bacteria [72,73]. This interaction disrupts the structural integrity of the membrane, weakening its defensive barrier. Additionally, silver has a strong affinity for phosphorus, allowing it to form Ag-P bonds with phosphorus-containing biomolecules within the bacterial membrane. Phospholipids, essential for maintaining membrane stability, contain phosphate groups that readily bind with silver ions (Ag^+) or AgNPs. This interaction compromises the lipid bilayer, leading to structural instability [74]. Furthermore, the small size and high surface area-to-volume ratio of AgNPs enhance their ability to bind and penetrate the bacterial membrane. Park et al. showed that their insertion into the lipid bilayer disrupts membrane fluidity by altering the organization of lipids and membrane proteins. This destabilization results in increased membrane permeability, structural deformation, and, ultimately, membrane disintegration, leading to the leakage of intracellular components and bacterial cell death [75].

Jin et al. demonstrated that sodium dodecyl sulfate (SDS)-coated AgNPs enhance antimicrobial efficacy by targeting amphiphilic bacterial membranes. The SDS coating imparts amphiphilic properties to AgNPs, enabling them to penetrate the bacterial hydrophilic-hydrophobic barrier and induce severe membrane damage. Transmission electron microscopy (TEM) revealed extensive structural disruptions, including membrane thinning, deformation, crumpling, blebbing, and complete disintegration. In contrast to silver ions ($AgNO_3$), AgNPs caused total bacterial cell rupture, accumulating nanoparticles in the membrane, cell wall, and intracellular regions. Increased lactate dehydrogenase (LDH) activity in bacterial supernatants confirmed membrane damage, while elevated protein leakage and reduced sugar concentrations indicated increased membrane permeability and cytoplasmic leakage, particularly in *Listeria monocytogenes* and *E. coli* [33]. The leakage of essential intracellular components such as ions, proteins, and nucleic acids disrupts cellular functions and homeostasis, weakening bacterial defence and making them more susceptible to further AgNP-induced stress, including ROS generation, enzyme inhibition, and lipid peroxidation [76]. The oxidation of membrane lipids and proteins further compromises structural integrity, increasing permeability. ROS-induced oxidative damage triggers lipid peroxidation, weakening the bilayer and disrupting fluidity. Similarly, the oxidation of membrane-associated proteins alters their conformation and function, impairing nutrient transport and signal transduction [77]. This cumulative damage compromises membrane stability, leading to enhanced permeability, extensive leakage of intracellular components, and ultimately, bacterial cell death.

3.2. Penetration and Intracellular Damage

AgNPs, particularly those below 10 nm, can passively diffuse through bacterial membrane pores due to their nanoscale size and high surface area-to-volume ratio [78]. This passive entry mechanism allows AgNPs to bypass active transport systems and directly access the cytoplasm, where they exert antimicrobial effects. Their ability to enter bacterial cells without requiring energy-dependent transport mechanisms enhances their broad-spectrum antibacterial efficacy, particularly against drug-resistant pathogens. For instance, Dong et al. demonstrated that the antibacterial efficacy of silver AgNPs is significantly influenced by particle size, with smaller AgNPs (10 ± 5nm) exhibiting enhanced antimicrobial activity against *Vibrio natriegens*. Their study revealed that as the particle size decreases, the minimum inhibitory concentration (MIC) and minimum bactericidal concentration (MBC) values are reduced, indicating increased effectiveness against bacterial pathogens [79].

Upon entering the bacterial cell, AgNPs disrupt major intracellular components, leading to cellular dysfunction and, ultimately, bacterial death.

3.3. Silver Nanoparticles (AgNPs) Interaction with Microbial Deoxyribonucleic Acid (DNA), Proteins, and Enzymes

AgNPs exhibit strong antimicrobial activity by targeting essential cellular components such as DNA, proteins, and enzymes. Their disruptive effects are due to their high affinity for sulfur (S), phosphorus (P), and nitrogen (N)-containing groups within these biomolecules. By interacting with these critical molecules, AgNPs cause structural and functional damage, ultimately impairing microbial survival and leading to cell death [80].

3.3.1. Interaction with Deoxyribonucleic Acid

AgNPs interfere with microbial DNA by binding to phosphate groups in the DNA backbone and nitrogen-containing bases, such as purines and pyrimidines, forming silver–DNA complexes [81,82]. Additionally, AgNPs can intercalate between DNA base pairs, destabilizing the double helix and inducing structural alterations, including DNA unwinding, strand separation, and conformational changes. For instance, Shahabadi et al. investigated the interaction of biogenic Chloroxine-conjugated silver nanoflowers (COX-AgNPs) with calf thymus DNA (ct-DNA) and plasmid DNA using spectroscopic and electrophoresis techniques to understand their binding mechanisms and antibacterial potential. For ct-DNA, spectroscopic analysis revealed a partial intercalation mode, where COX-AgNPs were inserted into the DNA double helix and obstructed the groove. UV-Vis spectroscopy showed hyperchromism and a red shift, confirming adduct formation (binding constant, Kb = 4.18×10^4 $(g/mL)^{-1}$). Thermodynamic analysis suggested hydrophobic interactions, while atomic force microscopy (AFM) revealed DNA structural alterations. Molecular docking confirmed partial intercalation, showing interactions via hydrogen bonding, halogen interactions, metal–acceptor interactions, and hydrophobic forces. COX-AgNPs exhibited hyperchromism, intercalation, and a binding affinity of 8.19×10^3 $(g/mL)^{-1}$ for plasmid DNA. Fluorescence studies confirmed intercalation, and gel electrophoresis demonstrated COX-AgNP-induced DNA cleavage. These findings suggest that COX-AgNPs disrupt bacterial genetic integrity through DNA binding and cleavage [83]. These disruptions impair essential cellular processes such as DNA replication, transcription, and repair, ultimately hindering bacterial cell division and gene expression. By preventing DNA replication and interfering with transcription, AgNPs hinder protein synthesis, further compromising bacterial viability. The cumulative effect of these disruptions weakens the bacterial cell's ability to maintain vital functions, ultimately leading to cell death [16].

Furthermore, AgNP-induced DNA damage can activate cellular stress responses, including DNA repair mechanisms. However, excessive damage may overwhelm these repair systems, resulting in irreversible mutations, genomic instability, and, ultimately, bacterial cell death [81]. Studies on *E. coli* showed that bacteria with mutations in certain DNA repair genes (*mutY*, *mutS*, *mutM*, *mutT*, and *nth*) were more sensitive to AgNPs. This suggests that these genes help repair the DNA damage caused by AgNPs. When these genes are mutated, the bacteria become less resistant to AgNPs, making it easier for the NPs to kill them [84].

3.3.2. Interaction with Proteins and Enzymes

AgNPs disrupt bacterial proteins by binding to nitrogen- and sulfur-containing biomolecules, particularly thiol (-SH) groups in amino acids such as cysteine and methionine [85]. Jiang et al. investigated this mechanism by examining AgNP interactions with two model dehydrogenases, glyceraldehyde-3-phosphate dehydrogenase (GAPDH) and malate dehydrogenase (MDH). Their findings indicate that AgNPs primarily inhibit

enzyme activity by releasing silver ions (Ag^+), which bind to thiol groups in cysteine residues. Exposure to AgNPs and Ag^+ significantly reduced the number of free thiol groups in both enzymes, with mass spectrometry confirming silver binding, three Ag atoms per GAPDH monomer and eight per MDH monomer. Furthermore, pre-treatment with sulfur ions (S^{2-}) to block thiol groups prevented silver binding, confirming thiols as the primary interaction sites [86]. This Ag-S interaction disrupts protein conformation, leading to enzymatic inactivation, structural instability, and impaired cellular function. Since many bacterial enzymes depend on thiol groups for catalytic activity, AgNP-induced modifications disrupt their functionality, severely impacting essential metabolic processes [85]. Jahan et al. demonstrated that AgNPs effectively inhibited β-galactosidase production in thermophilic bacteria, including *Geobacillus vulcani*, *Anoxybacillus ayderensis*, *Bacillus licheniformis*, and *Bacillus paralicheniformis*. The degree of inhibition varied among strains and was concentration-dependent, with *B. licheniformis* showing nearly complete inhibition at 500 μg/mL. In addition to reducing intracellular enzyme biosynthesis, AgNP exposure significantly decreased extracellular β-galactosidase secretion across all tested strains, indicating that AgNPs interfere with both the synthesis and release of β-galactosidase, thereby disrupting bacterial metabolism [87].

Barbir et al. explored AgNP–protein interactions using circular dichroism (CD) spectroscopy, demonstrating that AgNP exposure induces structural changes in proteins, reducing ordered structures such as α-helices and β-sheets while increasing disordered conformations [88]. While silver binding to thiol groups alters protein folding and enzymatic activity, interactions with nitrogen-containing functional groups could further destabilize protein structure and function. AgNP-induced protein dysfunction disrupts critical bacterial metabolic pathways, including ATP production, nutrient transport, and oxidative stress regulation. By inhibiting enzymes involved in oxidative phosphorylation and glycolysis, AgNPs impair bacterial energy metabolism, leading to reduced ATP synthesis and compromised cellular activity [89]. Marutyan et al. reported a significant reduction in both total ATPase and H^+-ATPase activity in yeast homogenates and mitochondria upon exposure to royal jelly (RJ)-mediated AgNPs. At 5.4 μg/mL, total ATPase activity in yeast homogenates decreased significantly, while H^+-ATPase activity declined by approximately 50%, with further reductions at higher concentrations. Exposure to the fungistatic concentration of 5.4 μg/mL in yeast mitochondria resulted in an ~80% reduction in total ATPase activity and a similar decrease in H^+-ATPase activity [90]. Similarly, AgNPs and Ag^+ ions impair bacterial respiration by interacting with key redox-active enzymes such as NADH dehydrogenase. By binding to these enzymes, AgNPs block electron transport in the electron transport chain, leading to electron accumulation and unintended leakage to molecular oxygen [91]. The premature transfer of electrons to oxygen results in the formation of superoxide radicals (O_2^-), which can further react to produce other ROS-like hydrogen peroxide (H_2O_2) and hydroxyl radicals (•OH). The accumulation of ROS triggers oxidative stress, damaging critical cellular structures such as proteins, lipids, and nucleic acids. This oxidative damage disrupts essential cellular processes, ultimately contributing to bacterial cell death. AgNP-induced ROS formation has been shown to cause a significant increase in ROS levels in microorganisms, including *P. aeruginosa*, *E. coli* and *S. aureus*, following AgNP exposure [92–94]. Additionally, AgNPs deactivate antioxidant enzymes such as superoxide dismutase (SOD) and catalase, increasing oxidative damage and making bacteria more susceptible to environmental stressors [95].

Beyond enzyme inhibition, AgNPs interfere with bacterial ribosomal proteins, disrupting translation and leading to incomplete or defective polypeptides. This prevents bacteria from synthesizing essential proteins for survival, growth, and virulence. Furthermore, AgNP-induced ROS oxidize amino acid residues, leading to protein denaturation, misfold-

ing, and aggregation, further exacerbating bacterial dysfunction [96]. The combined impact of enzyme inactivation, metabolic disruption, impaired protein synthesis, and oxidative damage overwhelms bacterial defence mechanisms, ultimately leading to bacterial growth inhibition and cell death. These properties make AgNPs highly effective antimicrobial agents, particularly against antibiotic-resistant bacteria, by targeting bacterial proteins, disrupting enzymatic activity, and compromising essential metabolic functions.

3.4. Biofilm Inhibition and Disruption

AgNPs play a significant role in inhibiting bacterial adhesion and biofilm formation, which are critical steps in infection development [16]. Bacteria produce extracellular polymeric substances (EPSs) such as polysaccharides, proteins, nucleic acids, lipids, and humic substances, which form a matrix facilitating surface adhesion and biofilm formation. AgNPs interact with these EPS components, disrupting their structural integrity, which reduces bacterial attachment. Their high surface-to-volume ratio provides many binding sites for EPS components, preventing bacterial colonization [97]. For instance, Harris et al. demonstrated that biosynthesized AgNPs inhibited biofilm formation in *Serratia marcescens*, *Escherichia fergusonii*, and *Chromobacterium violaceum*, with microscopy (light microscopy, Scanning Electron Microscopy (SEM), and Confocal Laser Scanning Microscopy) confirming a reduction in biofilm biomass and structural disruption [98]. Another study found that green-synthesized AgNPs effectively inhibited *P. aeruginosa* biofilm formation at sub-minimum inhibitory concentrations (sub-MICs), with scanning electron microscopy (SEM) revealing reduced bacterial density and the absence of the biofilm matrix. AgNPs were also shown to disrupt mature biofilms, highlighting their effectiveness in combating the initial formation and established biofilm structures [99].

Biofilm formation is regulated by quorum sensing, a bacterial communication process where signaling molecules control gene expression related to adhesion, maturation, and antibiotic resistance. AgNPs interfere with quorum sensing by binding to these signaling molecules, preventing bacterial receptors from detecting them. This disruption weakens biofilm coordination, inhibiting development and impairing bacterial defence mechanisms [98,100]. For instance, AgNPs at sub-MIC levels have been shown to significantly reduce the production of key virulence factors regulated by the quorum sensing (QS) system in *P. aeruginosa*. These factors include pyocyanin, LasA protease, and LasB elastase, which play crucial roles in the pathogenicity and infection process of *P. aeruginosa* [99].

The combined antimicrobial mechanisms of AgNPs such as disrupting microbial membranes, penetrating cells, damaging genetic material, inhibiting key enzymes, generating oxidative stress, and preventing biofilm formation highlight their strong effectiveness against a wide range of pathogens. These multiple mechanisms of action not only improve their overall antimicrobial performance, but also lower the risk of resistance development, making AgNPs promising alternatives to traditional antimicrobial agents. Overall, AgNPs show great potential as next-generation antimicrobials with diverse applications in medical treatment, hospital infection control, industrial preservation, and environmental sanitation.

4. Applications of Silver Nanoparticles (AgNPs) Coatings in Antimicrobial Protection

The antimicrobial properties of AgNPs make them ideal for various biomedical, protective, and surface coating applications [19]. Their ability to inhibit bacterial, fungal, and viral pathogens has led to their incorporation into wound dressings, surgical tools, personal protective equipment (PPE), textiles, and food packaging materials [97]. However, several factors must be considered to ensure the effectiveness, safety, and sustainability of AgNP-based antimicrobial coatings. Since AgNPs tend to aggregate over time, diminishing

their antimicrobial effectiveness, surface modification, and the use of stabilizing agents is essential for maintaining stability and uniform dispersion. Common stabilizers include polyvinylpyrrolidone (PVP), polyethylene glycol (PEG), chitosan, and surfactants [72]. These additives form protective layers around individual nanoparticles, preventing clumping and preserving nanoscale properties.

Equally important is the compatibility of AgNPs with the coating matrix, whether polymeric, resin-based, or paint formulations, to prevent undesirable interactions and ensure consistent performance. The binder or matrix immobilizes AgNPs and determines the coating's integrity and adhesion to substrates such as metals, plastics, wood, and fabrics. For example, in the preparation of a carbamate starch (Sc), calcium lignosulfonate (CL), cellulose nanofibrils (CNF), and AgNP coating matrix for paper, Xia et al. demonstrated that AgNPs were effectively integrated into the Sc-CL-CNF matrix. This integration was likely facilitated by the structural support of the CNF network, weak interactions with the polysaccharide components, and the electrostatic environment created by the charged groups. TEM imaging confirmed a uniform dispersion of AgNPs, while the observed antibacterial activity further validated their functional compatibility within the coating [101]. Surface treatments like plasma etching or primer application further improve adhesion.

Controlled and sustained release of silver ions is critical to prolong antimicrobial activity while minimizing toxicity. This can be accomplished through strategies such as encapsulation, multilayer structures, or the incorporation of smart coatings [10,102,103]. Smart antimicrobial coatings are advanced surface modifications engineered to prevent microbial adhesion and growth by responding to environmental stimuli such as pH, temperature, humidity, or the presence of pathogens [104]. These adaptive, self-regulating systems are designed for long-lasting performance and targeted action, often incorporating nanomaterials like AgNPs to enhance antimicrobial effectiveness. For instance, Yan et al. demonstrated that the chitosan/AgNPs multilayer hydrogel coating provides controlled, sustained silver nanoparticle release modulated by environmental pH. At neutral pH 7.4, minimal hydrogel degradation prevents AgNP release, while under highly acidic conditions (pH 1.2), rapid dissolution leads to complete release within minutes. In mildly acidic conditions (pH 5.5), typical of bacterial infections, the multilayer coating exhibits a pulse-like, staged release over 30 min due to compact interlayer boundaries, in contrast to the slower, progressive release observed in single-layer hydrogels. This pH-sensitive, controlled release is ideal for wound dressings and implant coatings, ensuring targeted antibacterial effects and long-lasting performance [103].

Moreover, coatings must remain durable under mechanical wear, chemical exposure, cleaning, and environmental stress. This durability is largely influenced by adhesion quality, which depends on proper surface preparation, material compatibility, and the use of primers. Robust binders, cross-linkers, curing agents, and functional additives enhance mechanical strength, stability, and application properties. Application techniques such as spray-coating, dip-coating, and spin-coating also play a critical role in determining coating uniformity and must be tailored to the substrate and intended use.

A well-formulated AgNP-based coating integrates these design elements to deliver a stable, safe, long-lasting antimicrobial solution suitable for diverse surfaces and industries. The coating's composition, environmental conditions, and application method collectively determine its mechanical integrity, uniformity, and resistance to degradation [105]. For instance, Tandel et al. applied AgNPs to cotton knitted fabric using a pad-dry-cure method, enabling continuous and uniform nanoparticle deposition. This approach utilizes an entrapment mechanism, where AgNPs become embedded within the voids of the amorphous regions of cotton fibers during the padding, drying, and curing stages. This internal lodging enhances the durability of the antimicrobial effect. The effectiveness of this method

was demonstrated by the fabric's ability to retain significant antimicrobial activity even after 50 wash cycles, highlighting the strong binding and long-term performance of the AgNP coating [106]. AgNP-coated materials can be developed by incorporating these considerations to provide highly effective, durable, and safe antimicrobial solutions.

Techniques for fabricating AgNP-based coatings are critical in defining nanoparticle distribution, long-term stability, and the overall functional performance of the resulting composite materials. These fabrication approaches significantly influence the final morphology, mechanical strength, and suitability of the coatings for biomedical implants, wound dressings, and antimicrobial surfaces. The process typically begins with formulating AgNP–polymer composites using in situ chemical reduction, sol-gel synthesis, or solution blending [35,107,108]. In the in situ chemical reduction, AgNPs are generated directly within a polymer matrix by reducing a silver precursor such as silver nitrate ($AgNO_3$) with a chemical reducing agent. This technique ensures a homogeneous nanoparticle dispersion and enhanced stability within the matrix [107]. Simultaneous polymerization of the host polymer can further improve the mechanical integrity of the nanocomposite, making it particularly suitable for robust biomedical applications. The sol-gel method involves dissolving silver precursors in a solvent and gel-forming agent, followed by chemical reduction, gelation, drying, and thermal curing. This results in a porous yet stable AgNP–gel nanocomposite with excellent adhesion characteristics [108]. In solution blending, pre-synthesized AgNPs are physically dispersed into a polymer solution to achieve a uniform mixture [35]. Once the AgNP–polymer composite is prepared, various application techniques are employed to deposit the material onto target substrates.

Spray coating uses an airbrush or automated spray system to distribute the AgNP formulation evenly over large or irregular surfaces. Dip coating involves immersing substrates such as surgical instruments, implants, sutures, or textiles into the nanoparticle formulation and withdrawing them at a controlled rate to ensure uniform film formation and strong adhesion. Repeated dipping cycles can build multilayered coatings [109]. Electrochemical deposition applies a controlled electric current to reduce silver ions onto conductive substrates, forming compact, adherent layers with tunable thickness [110]. DC magnetron sputtering, a form of physical vapor deposition (PVD), uses a plasma of argon gas and DC voltage to sputter silver atoms onto substrate surfaces, with post-treatment processes like annealing further enhancing adhesion and stability [111]. In situ photoreduction reduces silver ions directly on the substrate using ultraviolet or visible light, forming a well-distributed AgNP layer, ideal for substrates sensitive to high temperatures [11]. Laser-induced deposition involves applying a silver ion precursor solution (such as $AgNO_3$) to a substrate, followed by focused laser irradiation. The laser energy initiates silver ion reduction via photothermal or photochemical mechanisms, resulting in a thin, adherent layer of silver nanoparticles deposited precisely on the irradiated regions [112]. In electrospinning, AgNPs are embedded within a polymer solution, which is then transformed into ultrafine fibers under a high-voltage electric field. This method generates nanofibrous mats with high surface area, improved adhesion, and controlled AgNP release, making it highly effective for wound healing and antimicrobial textiles [113,114]. The layer-by-layer (LbL) assembly technique builds up multilayered coatings through sequential immersion in oppositely charged AgNP and polymer solutions. Crosslinking between layers adds structural integrity and allows for customization of release profiles and mechanical properties [115].

Other notable techniques include spin coating, where a small volume of nanoparticle formulation is rapidly spun on flat substrates to achieve thin, uniform films, and screen printing, which uses a patterned stencil to apply AgNP-based inks, commonly used in flexible electronics and antimicrobial fabrics. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) techniques involve vaporizing silver precursors and condensing

them onto substrates in a controlled atmosphere, producing coatings with high uniformity, purity, and adherence [116]. In sol-gel coating applications, AgNPs are incorporated into a gel medium and applied to the substrate, then dried and thermally cured to form a durable coating [17]. Lastly, immersion or hydrothermal coating methods involve submerging the substrate in a silver precursor solution, followed by chemical reduction or heating to induce in situ AgNP formation and surface deposition [29,117,118]. Each fabrication and application technique offers distinct advantages in coating uniformity, durability, and compatibility with various surfaces, allowing for tailored solutions for specific functional and biomedical needs. Tables 2–5 present current examples of silver nanoparticle-based coatings across various applications, including medical and healthcare uses, coated textiles, antifouling and environmental protection, as well as food packaging—highlighting the preparation methods and their respective effects.

4.1. Silver Nanoparticles (AgNPs) Coating for Medical and Healthcare Applications

Incorporating AgNPs into medical materials significantly enhances their antimicrobial efficacy, making them valuable in infection control [19]. These materials include wound dressings, sutures, surgical fabrics, medical gauze, surgical blades, extracorporeal biomaterials, dental materials, and hospital surface coatings, as illustrated in Figure 4.

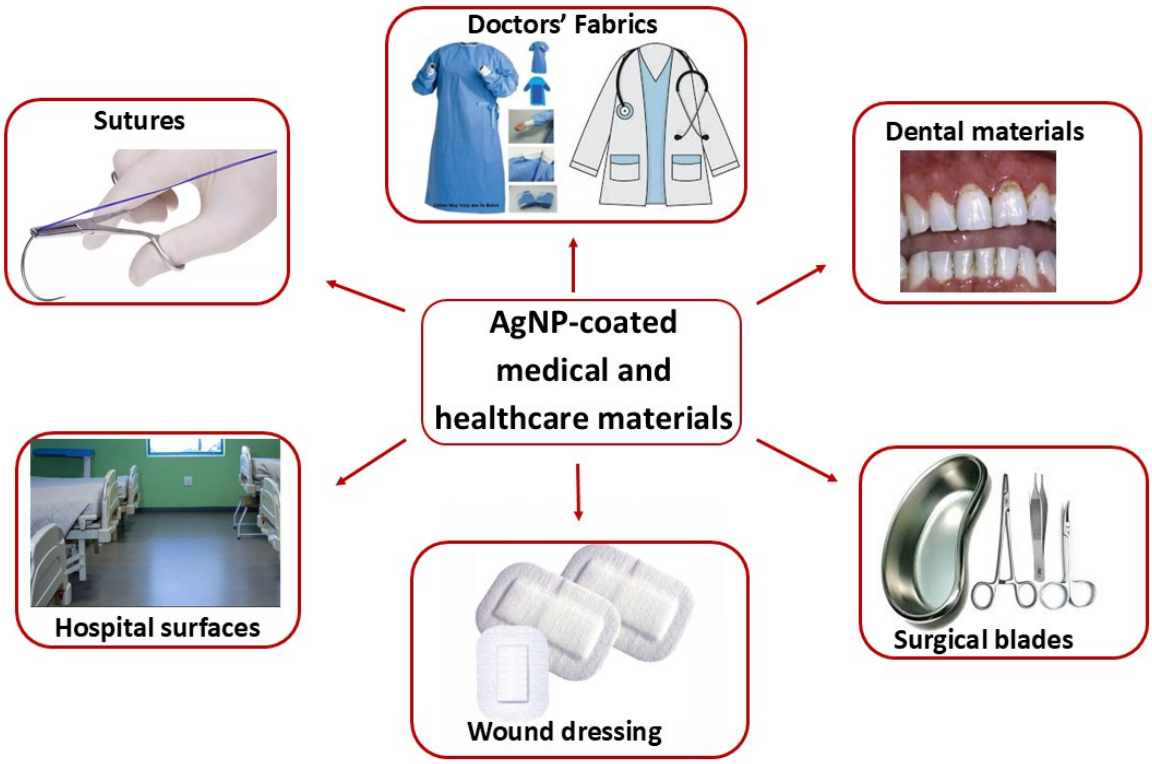


Figure 4. Antimicrobial AgNP-coated materials in medical and healthcare.

Table 2 highlights various medical and healthcare materials functionalized with AgNPs to improve their antimicrobial properties.

Table 2. Antimicrobial AgNP-coated materials in medical and healthcare applications—preparations and effects.

Material	Preparation	Effect	Ref
Poly(3-hydroxybutyrate) (PHB) combined with poly(ethylene glycol) (PEG) and esterified sodium alginate (ALG-e), enhanced with AgNPs for wound dressing	ALG was esterified to form ALG-e, then combined with PHB and PEG in chloroform to create polymeric gels. These gels were loaded with AgNPs and cast into composite films.	The composite film showed good antimicrobial activity in vitro against *S. aureus* and *E.coli.*	[119]
Polyglactin suture	A dip-coating method was employed, where sutures were first immersed in a polyethyleneimine solution and then dipped into an AgNP solution.	AgNP-coated polyglactin sutures exhibited activity against *E. coli*, *S. aureus*, and *P. aeruginosa*.	[120]
Silk sutures	Silk sutures were coated with AgNPs using a dip coating method	Highest antibacterial effectiveness against *S. aureus*, *E. coli*, and *P. aeruginosa*.	[121]
	Silk sutures were coated with AgNPs using a dip coating method	Significant inhibitory activity against *S. aureus.*	[122]
	The suture sample was immersed in a silver solution, where in situ photoreduction facilitated the synthesis of silver particles on its surface.	AgNP-coated silk suture showed significant antimicrobial activity against *S.mutans* and *S.aureus*, persisting for 7 days.	[123]
Surgical fabric and surgical blade	AgNPs were applied to surgical fabric using a layer-by-layer method, with fabric swatches alternately dipped in poly(diallyldimethylammonium chloride) and AgNPs solutions. Additionally, stainless steel surgical blades were coated with AgNPs via electrochemical deposition.	Antibacterial activity against *P. aeruginosa*, *E. coli*, *A. baumannii*, *K. pneumoniae*, *S. aureus*, and *E. faecalis* and antibiofilm efficacy against *P. aeruginosa.*	[110]
Medical protective masks	AgNPs and polyvinylidene fluoride (PVDF) solutions were mixed and electrospun into nanofibrous membranes.	AgNPs/PVDF membranes have antibacterial efficiency of 99.98% and 99.86% against *E. coli* and *S. aureus.*	[124]
	In situ synthesis was carried out by dissolving silver nitrate in a solution containing chitosan, polyvinyl alcohol (PVA), and poly-ε-caprolactone, followed by electrospinning to produce nanofibers.	AgNP-activated nanofibers provided potent, long-lasting antiviral protection against betacoronavirus.	[107]
AgNP-coated polypropylene surgical masks	AgNPs were deposited on the surface of the spun-bond polypropylene microfiber layer.	Antibacterial activity against *S. aureus* and *E. coli* and antiviral effectiveness against SARS-CoV-2.	[125]
Medical cotton gauze	Amino-modified cotton gauze was immersed in an AgNPs solution, leading to the formation of AgNP-loaded gauze.	Strong bactericidal activity and strong resistance to the adhesion of *E. coli*, *S. aureus*, and MRSA.	[126]
Extracorporeal biomaterials (hemodialysis blood tubing)	The dialysis tubing surface was coated with polyethylene glycol, with AgNPs immobilized on the coating.	Antimicrobial activity against *E. coli*, *P. aeruginosa*, *K. pneumonia*, *S. aureus*, and *C. albicans.*	[127]
Hospital room surface coating	The transparent acid siloxane-based sol-gel was combined with AgNPs and 4,5-dichloro-2-octyl-4-isothiazolin-3-one (DCOIT). The resulting coatings were then sprayed onto the test surfaces.	The coating consistently reduced bacterial load on frequently touched surfaces in a real-world clinical setting for 90 days.	[108]
Plasma-polymerized hexamethyldisiloxane (ppHMDSO) protective film on 3D printed polylactic acid substrates	AgNPs coatings were deposited on 3D printed polylactic acid substrates by DC magnetron sputtering.	Overcoating AgNPs with ppHMDSO results in a material with antibacterial properties against *P. aeruginosa* and antiviral activity against human rhinovirus species A/type 2.	[128]
Dental alginate	Dental alginate powder mixed with AgNPs suspension to create a paste.	AgNPs alginate exhibited broad-spectrum activity against the three tested microorganisms: *S. aureus*, *E. coli*, and *Candida albicans.*	[129]
	AgNPs mixed with alginate powder.	Incorporating AgNPs enhanced dental alginate's antimicrobial activity against *C. albicans*, *Streptococcus mutans*, *E. coli*, *S. aureus*, and *Micrococcus luteus*.	[130]
Denture resins	AgNPs were blended with heat-curing acrylic resin powder polymethyl methacrylate (PMMA) and then mixed with a resin monomer to create a paste.	The PMMA composite disks were active against *C. albicans* and *S. mutans.*	[35]

As shown in Table 2, various techniques are used to incorporate AgNPs into medical materials, including dip-coating [120–122], electrochemical deposition [110], in situ photoreduction [123], blending with polymers [35], electrospinning [124], and the layer-by-layer method [110]. These methods ensure robust adhesion of AgNPs to the material surfaces and influence the sustained release of silver ions, essential for prolonged antimicrobial activity. The resulting AgNP-coated materials demonstrate remarkable effectiveness against a broad range of bacterial pathogens [110,119–123,126], some of which are shown in Table 2.

The development of Smart Wound Dressings is a significant advancement in wound care and infection management. These innovative dressings are designed to dynamically respond to fluctuations in wound conditions, including pH, temperature, and moisture levels. When these conditions shift, the dressings activate the controlled release of AgNPs [131,132]. For instance, Deng et al. designed a bioresponsive hydrogel-based dressing composed of methacrylic anhydride-modified gelatin (GelMA) and sodium alginate (SA), embedded with AgNPs. This system responds explicitly to matrix metalloproteinase-9 (MMP-9), an enzyme upregulated during inflammation in chronic wounds. Upon detecting elevated MMP-9 levels, the hydrogel degrades, wirelessly transmits data, and releases AgNPs in proportion to inflammation severity, enabling real-time infection monitoring and targeted treatment [131]. Its flexibility and wireless design are ideal for continuous, wearable wound care. Similarly, another smart dressing fabricated from electrospun nanofiber material piezoelectric polyvinylidene fluoride (PVDF) embedded with AgNPs was developed for high-mobility areas. It generates self-powered electrical signals through body movement, promoting cell migration and collagen production to accelerate healing. Concurrently, AgNPs disrupt bacterial biofilms, which are structured communities of microorganisms that attach to surfaces and are embedded within a self-produced matrix of extracellular polymeric substances, and prevent infection, while the system modulates immune response by shifting macrophage activity toward the anti-inflammatory M2 phenotype, reducing inflammation and promoting tissue regeneration [133]. These multifunctional systems ensure the consistent, responsive, and localized delivery of AgNPs, improving antimicrobial effectiveness while minimizing systemic side effects. By combining real-time monitoring, controlled drug release, and immune modulation, smart wound dressings represent a transformative approach that enhances infection control and overall wound healing [131–134].

4.2. Silver Nanoparticle (AgNP)-Coated Textiles Applications

Incorporating AgNPs into textiles has emerged as a promising strategy for enhancing antimicrobial properties across various fabric types [9,132,135]. The broad-spectrum antimicrobial activity makes them valuable for applications in medical textiles, protective clothing, textile-based filtration materials, and consumer products as illustrated in Figure 5, helping to reduce infection transmission and enhance product lifespan [136].

The effectiveness of AgNP-treated textiles depends on factors such as the method of nanoparticle incorporation, fabric composition, and coating stability. Table 3 shows various AgNP-coated textiles, detailing their preparation techniques and antimicrobial efficacy.

Table 3. Antimicrobial silver nanoparticle-coated textiles—preparations and effects.

Material	Preparation	Effect	Ref
Cotton fabric	Cotton fabric soaked in AgNPs solution.	AgNP-treated fabrics exerted antimicrobial activity against *P. aeruginosa*.	[137]
	The fabric was immersed in the AgNPs solution with Tween 80, dried at 80 °C, and cured at 130 °C to ensure nanoparticle attachment.	AgNP-coated fabric exhibited superior inhibition against *Acinetobacter baumannii*, *Klebsiella pneumoniae*, *P. aeruginosa*, *S. aureus*, *E. faecalis*, and *C. albicans*.	[117]
Polyamide (PA) fabric	AgNP-treated fabrics were produced via a hybrid plasma reactor using surface activation and AgNP deposition. The PA-elastane fabric was plasma-activated to enhance adhesion before AgNPs were nebulized into the plasma region.	AgNP-treated fabrics exhibited significant antimicrobial activity against *S. aureus* and *K. pneumoniae*.	[138]
	In situ incorporation of AgNPs onto PA fabrics during the dyeing process.	Significant inhibition against both *S. aureus* and *E. coli*.	[139]
Three-layer mask with water-repellent mulberry silk, oil-repellent eri silk, and a cotton middle layer treated with AgNPs.	AgNPs coated on the cotton middle layer of a silk face covering.	Silk face coverings treated with AgNPs inhibited *S. aureus* and *E. coli* by over 99.9%, maintaining effectiveness even after 20 wash cycles.	[140]
Polyimide nanofibers (PINFs), AgNPs, carbon nanotubes (CNTs), and waterborne polyurethane (WPU) nanofabric.	AgNPs are embedded in PINFs using electrospinning and in situ reduction, followed by thermal imidization to form Ag@PINFs. A conductive CNT layer was then added via suction filtration of a CNT/WPU mixture and sandwiched between two Ag@PINF layers.	Inactivation of *E. coli* and *S. aureus*.	[114]
Polyester Fabrics	The polyester surface was chemically modified with hydrazide groups. Silver ions were then adsorbed and reduced using either glucose to form AgNP-loaded polyester or dopamine to simultaneously create AgNPs and a polydopamine (PDA) coating	AgNP-loaded polyester hydrazide exhibited a bactericidal effect against *E. coli* after 24 h and a bacteriostatic effect against *S. aureus*. In contrast, the PDA-coated AgNP-loaded polyester hydrazide composite demonstrated a bactericidal effect against both pathogens.	[141]
	Polyester fabrics were functionalized via spray deposition with AgNPs dispersed in ethanol. Formulations incorporating chitosan or hexamethyldisiloxane enhanced AgNP adhesion and minimized release during washing.	Adding chitosan or HMDSO layers affected the antimicrobial performance and stability of AgNPs on polyester textiles. Chitosan enhanced adhesion and showed a synergistic effect, particularly against *E. coli*, while HMDSO contributed to a more controlled release of AgNPs.	[142]
Polyester and cotton fabrics	Polyester and cotton fabrics were silver-plated using electroless plating. Fabrics were pre-treated with tin(II) chloride and hydrochloric acid for uniform metal deposition, then immersed in silver nitrate for 30 s. Daylight facilitated silver nucleation, creating catalytic sites for plating.	AgNP-coated polyester reduced *E. coli* by 95% in 30 min and 100% in 120 min, while cotton achieved a 78% reduction. Against SARS-CoV-2, cotton achieved a 100% reduction in 30 min and polyester in 60 min. Both fabrics rapidly inhibited Feline Calicivirus, reaching 100% in 30 min.	[9]
Cotton, nylon and cotton/nylon fabrics	The antibacterial fabrics were prepared by coating them with chitosan, using triethyl orthoformate as a crosslinker to enhance durable attachment. For silver nanoparticle immobilization, the chitosan-coated fabrics were immersed in an AgNP solution for 24 h at 0 °C, allowing effective nanoparticle binding to the modified fabric surface	AgNP-loaded fabrics demonstrated significant and durable antibacterial activity against both *E. coli* and *S. aureus* in laboratory tests and showed strong bacterial control in a real-life scenario, even after repeated washing cycles.	[135]
Viscose fabric	The viscose fabric undergoes pre-treatment with a polysiloxane matrix to improve AgNP absorption. Functionalization is achieved through either in situ synthesis or pre-functionalization of AgNPs within the poly(N-isopropylacrylamide)/chitosan hydrogel, leading to the development of an e-textile.	Modified viscose textiles exhibited excellent antibacterial activity, achieving over 90% growth reduction against both Gram-negative *E. coli* and *S. aureus*.	[132]



Figure 5. Antimicrobial AgNP-coated textiles.

Table 3 outlines various fabric types and AgNP integration methods, such as soaking, in situ synthesis, plasma activation, electroless plating, and spray deposition, along with their antimicrobial effectiveness against bacterial, fungal, and viral pathogens. These methods make AgNP-coated textiles stable, durable, and highly valuable for medical, protective, and consumer applications where antimicrobial resistance and hygiene are paramount. In medical settings, they are utilized in hospital linens, surgical gowns, masks, and wound dressings to reduce bacterial contamination and healthcare-associated infections [110]. They are also incorporated into protective clothing, sportswear, and personal items to prevent odor-causing bacteria and maintain hygiene. Home and commercial textiles, including bedding and upholstery, benefit from antimicrobial coatings that prevent microbial growth. In the food industry, AgNP-coated textiles are applied to reduce cross-contamination and foodborne illnesses [143]. Furthermore, these textiles are used in air and water purification filtration systems.

Emerging smart textiles offer advanced functionalities such as self-cleaning, microbial detection, and real-time health monitoring. Their antimicrobial action can be stimulus-responsive, triggered by pH, humidity, or temperature changes, enabling targeted intervention in high-risk environments like wounds or perspiration-prone areas [144]. Glažar et al. developed a smart viscose textile coated with a poly-(N-isopropylacrylamide)/chitosan (PNCS) hydrogel embedded with biosynthesized AgNPs. This hydrogel exhibited temperature and pH responsiveness, swelling below 32 °C or in acidic conditions, and shrinking under alkaline or elevated temperatures, facilitating moisture regulation and controlled AgNP release. AgNPs enhance antibacterial efficacy against *S. aureus* and *E. coli* while imparting strong UV protection (UPF 50+) through the combined effects of AgNPs and phenolic compounds [132]. Similarly, Li et al. engineered a pH-responsive textile with superhydrophobic and antibacterial properties by integrating (3-mercaptopropyl) trimethoxysilane (MPTMS), AgNPs, and a pH-sensitive polymer. The textile transitions from superhydrophobic and superoleophilic under neutral or alkaline conditions to superhydrophilic

in acidic environments, enabling efficient and reversible oil–water separation (98% efficiency). AgNPs provided 90.4% inhibition of *E. coli*, while MPTMS enhanced bonding and durability. The fabric maintained its multifunctionality across 10–15 cycles, resisting abrasion, heat, UV radiation, and solvents [145]. Such smart textiles are now being explored for additional functionalities like immune modulation, inflammation reduction, and tissue repair. AgNP-coated smart textiles represent a versatile platform for improving hygiene, infection control, and health monitoring across medical, consumer, food safety, and environmental applications.

4.3. Silver Nanoparticles (AgNPs) Coating for Antifouling and Environmental Protection Applications

AgNPs coating into various materials has emerged as a promising approach for antifouling and environmental protection applications. AgNPs exhibit strong antimicrobial and antifouling properties, making them highly effective in preventing bacterial adhesion, biofilm formation, and microbial-induced material degradation [17,28,29,146–153] on different surfaces, as illustrated in Figure 6.

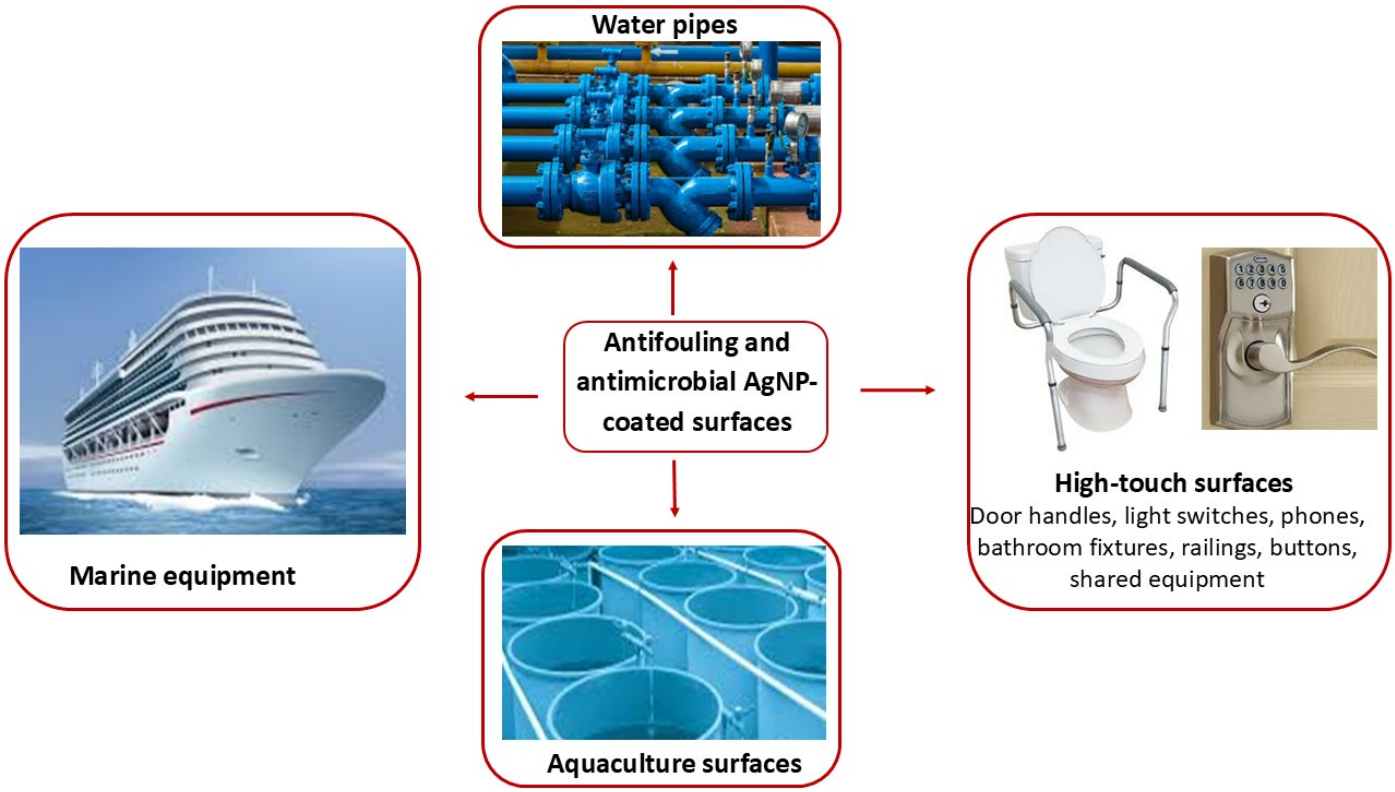


Figure 6. Antifouling and antimicrobial AgNP-coated surfaces.

By leveraging different fabrication techniques, AgNP-based coatings can be applied to diverse substrates, including polymeric membranes, ceramics, paints, and polyurethane foams, enhancing their functional performance and durability. Table 4 presents AgNP-incorporated coatings developed for antifouling and environmental applications.

Table 4. Antimicrobial AgNPs surface coatings for antifouling and environmental protection– preparation methods and effects.

Material	Preparation	Effect	Ref
Polymeric membrane ion-selective electrodes	Immersing the electrode in $AgNO_3$ solution, followed by immersion in a $NaBH_4$ solution to reduce the silver ions into AgNPs.	Surface modification demonstrated long-term antifouling and anti-biofouling effectiveness against *P. aeruginosa* in bacterial suspension.	[147]
Microfiltration membrane	A membrane for anti-biofouling microfiltration was prepared using non-solvent-induced phase separation followed by mild alkali treatment for in situ AgNP formation. Polyacrylonitrile and silver nitrate were dissolved in N-methyl-2-pyrrolidone, cast onto a patterned mold, and immersed in isopropyl alcohol for phase separation.	Confocal laser scanning microscopy confirmed that the bacteria that adhered to the membrane surfaces were non-viable. A prolonged anti-biofouling effect was observed.	[148]
Ag/ZrO_2-SiO_2 composite ceramic membranes	Ag/ZrO_2-SiO_2 composite ceramic membranes were synthesized via the sol-gel method by incorporating $AgNO_3$ into the ZrO_2-SiO_2 matrix, leading to AgNP formation within the membrane. The process involved preparing SiO_2 and ZrO_2 sols, combining them to obtain Agx/ZrO_2-SiO_2 sols, followed by dip-coating α-Al_2O_3 substrates, drying, and calcination.	Antibacterial efficacy against *E. coli* and *S. aureus* was observed.	[17]
AgNP-enhanced nanofiber membrane made of polyvinyl alcohol (PVA) and thermoplastic polyurethane (TPU)	AgNPs were incorporated into the prepared PVA and TPU solutions. The resulting Ag-polymer solutions were then electrospun into nanofibrous membranes.	TPU-AgNPs and PVA-AgNPs showed significant antiviral activity against HIV-1 and SARS-CoV-2 and broad antibacterial activity.	[149]
Urushiol-based benzoxazine coating	Urushiol-based benzoxazine monomers (UOB) are synthesized via a Mannich reaction using urushiol, n-octylamine, and paraformaldehyde. AgNPs are in situ generated by reducing silver ions with the phenolic groups in UOB. The UOB/AgNPs composites are cast onto glass slides, cured, and thermoset, resulting in dark-brown coatings.	Antimicrobial activity towards *E. coli*, *S. aureus*, *Vibrio alginolyticus*, and *Bacillus* sp. Strong inhibition of the settlement and attachment of marine microalgae.	[28]
Water-based acrylic paint	In situ synthesis of AgNPs for water-based acrylic emulsion or polymeric dispersion paint involves stirring a polymer solution, adding silver nitrate, and refluxing under argon. Sodium acrylate is then introduced, resulting in polymer-coated AgNPs. These coatings are applied to wood via brush coating and to stainless and mild steel through dip coating.	The water-based acrylic paint doped with AgNPs exhibited strong antimicrobial activity and remarkable resistance against *E. coli*, *B. cereus*, *A. baumannii*, *Klebsiella pneumoniae*, *Aspergillus niger*, *A. terreus* and *Rhizopus arrhizus*.	[150]
Silicone–epoxy resin (hydrophobic tetramethyldis-iloxane eugenol–epoxy resin, HMME-EP) modified by poly(N-isopropylacrylamide)–thiol (PNIPAM-SH)	Silicone–epoxy resin (HMME-EP) and isophoronediamine (IPDA) were prepolymerized under stirring, then combined with reduced graphene oxide (rGO)-AgNPs and PNIPAM-SH dispersed in anhydrous ethanol. After stirring and vacuum degassing, the mixture was bar-coated onto a steel substrate and cured at room temperature, forming an anti-fouling coating.	After 24 h, rGO/AgNP-based coating demonstrated a 100% elimination rate against *E. coli*, *Vibrio parahaemolyticus*, and *S. aureus*, along with effective anti-algae activity against *Phaeodactylum tricornutum*.	[151]

Table 4. *Cont.*

Material	Preparation	Effect	Ref
Commercial white painting	Natural zeolite (NZ) was combined with AgNPs to form the NZ-AgNPs composite, which was mixed with commercial white paint (CWP) and agitated to produce CWP-NZ-AgNPs paint. A 35-mm test specimen was dip-coated twice by immersing it for 5 s, allowing for proper drying between applications.	CWP-NZ-AgNPs exhibited significant antibacterial activity, producing a 41 mm inhibition zone against *E. coli*.	[152]
Polyurethane foams	Polyurethane foams were incubated in a 1:1 mixture of Amba turmeric extract and $AgNO_3$, enabling the in situ synthesis of AgNPs on their surfaces. The foams were subsequently heated in a water bath to enhance nanoparticle formation and adhesion.	High-density foams demonstrated bactericidal activity, achieving a 1.2 log reduction in *E. coli* within 30 min of treatment.	[153]
	An open-cell polyurethane foam sample is immersed in a silver nitrate solution containing dopamine hydrochloride under continuous stirring for 24 h. This process facilitates the simultaneous deposition of polydopamine and in situ synthesis of AgNPs on the foam surface.	Exhibited strong antimicrobial activity against *C. albicans*, *E. coli*, *S. aureus*, and *Legionella pneumophila*.	[29]
Polydopamine/chitosan hydrogels-functionalized polyurethane foams	Chitosan (CT) hydrogels are grafted onto polyurethane foam (PUF) to form CT/PUF, which is then coated with polydopamine (PDA) by immersion in a dopamine solution. AgNPs are in situ immobilized by soaking PDA/CT/PUF in silver nitrate for 24 h, followed by reduction with sodium borohydride.	PDA/CT/PUF@AgNPs exhibited excellent reusability over five cycles, consistently achieving effective disinfection of *E. coli*. It successfully purified the water sample, meeting microbial safety standards for drinking water.	[146]

Table 4 highlights the wide range of materials and fabrication methods used to develop AgNP coatings, with in situ synthesis emerging as the most prevalent strategy. This approach enhances nanoparticle dispersion and anchorage within various matrices, improving coating stability and ensuring prolonged antimicrobial effectiveness [150]. Techniques such as chemical reduction, sol-gel processing, electrospinning, immersion, and dip-coating have enabled the uniform integration of AgNPs into substrates like membranes, ceramics, textiles, foams, and paints. Including functional materials such as polydopamine, chitosan, graphene oxide, and urushiol further enhances their durability, biocompatibility, and multifunctionality [17,28,29,146–153]. As shown in Table 4, these coatings demonstrate broad-spectrum activity against pathogens.

AgNP-coated membranes, foams, and hydrogels inhibit microbial growth and biofilm formation in water purification systems [17,148], maintaining filtration efficiency and water quality, especially in portable and remote applications. In marine environments, these coatings prevent the colonization of algae and bacteria on ship hulls, pipelines, and offshore structures, reducing drag, corrosion, and maintenance costs [151]. They are also applied in aquaculture systems to control pathogens. In healthcare, AgNP-coated medical devices such as catheters, implants, and wound dressings provide effective barriers against infection by preventing microbial adhesion and biofilm formation [154]. Additionally, on high-touch surfaces in public and clinical spaces, AgNP coatings offer continuous antimicrobial protection, lowering the risk of disease transmission [155]. Their integration into commercial paints, hydrogels, and foams supports widespread application across consumer and industrial sectors.

The development of smart coatings has led to the creation of antifouling coatings designed to prevent non-specific adsorption of proteins, cells, and other biomolecules, thereby maintaining the sensitivity, functionality, and reliability of biomedical and analytical devices. These coatings render surfaces energetically unfavorable for biomolecular

attachment through precise chemical and physical modifications. Key strategies include enhancing hydrophilicity to form protective hydration layers, utilizing steric hindrance via dense polymer brushes, employing electrostatic or zwitterionic repulsion, and modulating surface energy. These mechanisms help reduce fouling, prolong device lifespan, and ensure stable performance in complex biological environments [156]. For instance, Gao et al. designed a multifunctional, flexible smart fabric designed for wearable electronics in harsh environments. The fabric features a dual-layer coating: the inner layer incorporates AgNPs within waterborne polyurethane (WPU) to provide high conductivity and mechanical durability, while the outer layer, composed of WPU and modified silica nanoparticles, imparts superhydrophobicity. Additionally, the fabric demonstrates excellent self-cleaning, antifouling properties, low water adhesion, drag reduction, and significant antibacterial activity. These attributes ensure long-term functionality, making the fabric ideal for applications such as underwater motion detection and safety monitoring in wet environments [157].

AgNP-based coatings offer a robust, durable, and multifunctional solution for antimicrobial and antifouling protection across diverse environments.

4.4. Silver Nanoparticles (AgNPs) Coating for Food Packaging Applications

AgNPs are increasingly used in food packaging due to their strong antimicrobial properties. When integrated into both biodegradable and non-biodegradable polymers, AgNPs enhance the preservation of perishable foods. These NPs are commonly applied as coatings on food containers or packaging films, as illustrated in Figure 7, forming a protective barrier against microbial contamination [158].

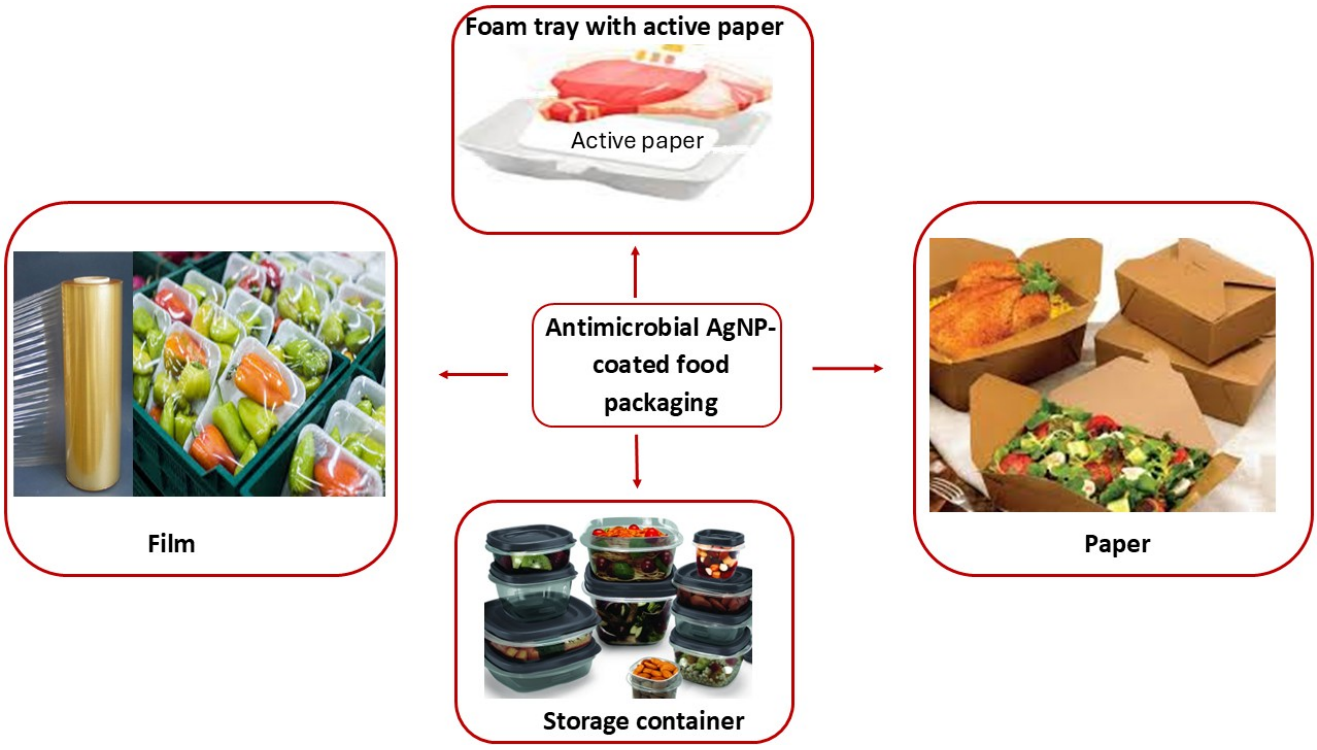


Figure 7. Antimicrobial AgNP-coated food packaging.

AgNPs also play a key role in active packaging systems, which release antimicrobial agents to extend shelf life and maintain food quality during storage and transportation. This reduces food spoilage and minimizes the risk of foodborne illnesses, improving overall food safety. AgNPs are known for their broad-spectrum antibacterial, anti-mold, anti-yeast, and anti-viral properties, making them crucial for modern food packaging solutions [159–166].

Table 5 presents various methods for preparing AgNP coatings on food packaging materials and their effects on microbial inhibition, highlighting their effectiveness in enhancing food safety and shelf life.

Table 5. Antimicrobial AgNPs surface coatings for food packaging—preparation methods and effects.

Material	Preparation	Effect	Ref
Cellulose acetate (CA)-based films intended for food packaging	CA films were fabricated using the solution casting method. CA was dissolved in glacial acetic acid, and silver nitrate was added. The mixture was then heated, forming a gel that facilitated the controlled reduction in silver ions.	The films exhibited antimicrobial activity against *E. coli*, *S. aureus*, *C. albicans*, and *A. niger*.	[159]
Sugarcane bagasse-derived carboxymethyl cellulose, cassava (CMC) starch (CV), and chitosan (CT) bioplastic film	A bioplastic film was produced using the film casting method. The cassava starch solution was first gelatinized, then CT and CMC solutions were heated to 65 °C. Subsequently, the vanillin solution was incorporated, and AgNPs were introduced into the mixture before casting to a film.	The film demonstrated significant antibacterial activity against *S. aureus* and *E. coli*.	[160]
Polylactic acid (PLA) films doped with carob pod (CP) powder	CP and AgNPs were integrated into the PLA matrix to produce eco-composite films. The process involved CP pretreatment with citric acid, PLA dissolution, ultrasonication, extrusion, and film formation using injection molding or hot pressing.	Adding AgNPs enhanced antibacterial activity against both *S. aureus* and *E. coli*.	[161]
Sodium alginate (SA), persimmon polysaccharide (PP) AgNPs film	The SA-PP-AgNPs film was produced using a casting method, where PP, SA, and PPE-AgNPs were combined, followed by the addition of glycerol, thorough stirring, ultrasonication, and casting.	The film showed excellent antibacterial activities against *E. coli*, *S. aureus*, *Saccharomyces cerevisiae* and *Aspergillus niger*.	[162]
Pectin-derived biopackaging film	Films were prepared using the evaporation casting method. Pectin from grapefruit was dissolved in water, mixed with sorbitol, $CaCl_2$, and acetic acid for demethylation, then combined with AgNPs before casting.	Pectin/AgNPs films demonstrated effective antibacterial activity against both *E. coli* and *B. subtilis*.	[163]
Bacterial cellulose (BC) for food packaging	A bacterial cellulose membrane was immersed in an $AgNO_3$ solution, allowing for the incorporation of AgNPs to form the BC-AgNP membrane. This membrane was then immersed in a montmorillonite (MMT) solution, forming the BC-Ag-MMT membrane.	BC-Ag-MMT membranes showed inhibitory effects against *Salmonella paratyphi*, *E. coli*, *S. aureus*, *Bacillus subtilis*, and *Salmonella enterica*.	[118]
	Bacterial cellulose (BC) was oxidized and reacted with a silver-ammonia solution to form BC/AgNPs. These were dispersed in ethanol and ammonium hydroxide, followed by TEOS addition to create BC/AgNPs/SiO_2 composites. The composites were emulsified with octadecenyl succinic anhydride (ODSA) to form pickering emulsions and applied to paper and fruits for preservation.	The coating exhibits strong antimicrobial activity against *E. coli*, *Salmonella typhimurium*, *S. aureus*, and *Listeria monocytogenes*.	[164]
Paper-based packaging	AgNPs are incorporated into the starch solution and then applied to paper-based packaging. The coating is evenly distributed using the bar coating method, and the treated paper is subsequently left to air dry.	Strong and concentration-dependent activity was observed against *E. coli*.	[165]
Paper	Carbamate starch, calcium lignosulfonate, and cellulose nanofibrils were mixed with water to form a coating solution, to which AgNPs were added and dispersed ultrasonically. The resulting coatings were then applied to paper using a rod coating method.	The coated paper exhibited inhibition zones against *E. coli* and *S. aureus*.	[101]

Table 5. *Cont.*

Material	Preparation	Effect	Ref
Polypropylene film	Dried nisin and montmorillonite K10 were dispersed in distilled water and then combined with AgNPs. The mixtures were thoroughly homogenized and coated onto the plasma-treated polypropylene (PP) films, followed by air drying to produce stable antimicrobial coatings.	Incorporating AgNPs significantly enhanced its antimicrobial effectiveness against *E. coli* and *S. aureus*.	[166]
	Biopolymers like cellulose nanocrystals, alginate, chitin nanocrystals, or chitosan were combined with $AgNO_3$ for in situ AgNP reduction. The polypropylene (PP) film was plasma-treated, then subjected to a layer-by-layer deposition using polyelectrolytes (poly(allylamine hydrochloride) (PAH) and/or poly(sodium 4-styrenesulfonate) (PSS)) and biopolymer/AgNP hybrid suspensions to form a uniform, antimicrobial coating.	-	[167]

Table 5 presents a range of materials, including cellulose acetate, sugarcane bagasse-derived bioplastics, polylactic acid (PLA), bacterial cellulose, paper, and polypropylene, all infused with AgNPs using various preparation methods. The addition of AgNPs enhances the antimicrobial properties of these materials, offering strong protection against foodborne pathogens and significantly improving food safety. This approach extends the shelf life of perishable goods by effectively preventing microbial growth [118,161–163]. The materials are processed through techniques such as in situ reduction in silver ions, layer-by-layer deposition [167], casting [163], and film-forming, which ensures the efficient integration of AgNPs into packaging films. Biopolymers like cellulose acetate, chitosan, and bacterial cellulose provide antimicrobial benefits and biodegradability, making them ideal for sustainable food packaging. The antimicrobial effectiveness of these coatings varies based on the AgNP concentration and preparation method, showing the broad potential of AgNP-infused packaging in food preservation [158].

Advancing this field, Guerraf et al. developed a multifunctional smart coating for food packaging by embedding AgNPs into conducting polymers polyaniline and poly(3,4-ethylenedioxythiophene), anchored to cellulose fibers. These nanocomposites are sensors for volatile organic compounds such as ammonia and acetone, which signal food spoilage. When exposed, the coatings undergo reversible changes in electrical resistance and exhibit visible color shifts, enabling real-time spoilage detection. In addition to their sensing ability, the coatings display strong antibacterial activity against *E. coli* and *S. aureus*, and provide antioxidant protection by scavenging free radicals, thereby reducing oxidative degradation [168]. These innovations indicate the potential of AgNP-infused films and coatings as smart, active packaging solutions that enhance food safety, reduce spoilage, and extend shelf life. By combining antimicrobial protection, spoilage detection, and oxidative stability, these materials offer a sustainable and innovative approach to minimizing food waste and preserving the freshness of products in modern food systems [169].

AgNP-coated materials have emerged as effective tools for combating microbial contamination in diverse fields such as medicine, textiles, environmental protection, and food packaging. Their broad-spectrum antimicrobial effectiveness and innovative coating methods enable durable adhesion and long-lasting performance [170]. The development of smart applications further highlights these advanced technologies' adaptability and multifunctional nature.

5. Biocompatibility Considerations in Silver Nanoparticle (AgNPs)-Based Coatings

The application of AgNP-based antimicrobial coatings in biomedical devices, wound-care materials, and hygiene-related products offers significant potential for infection control, particularly in clinical settings where antimicrobial resistance is a growing concern [158]. AgNPs, due to their effectiveness against a wide spectrum of pathogens, are valuable agents for preventing infection. However, their successful integration into medical and environmental applications hinges on their biocompatibility, the ability of the coating to interact with host tissues without inducing adverse effects such as cytotoxicity, inflammation, or immunogenic responses [97].

5.1. Role of Silver Nanoparticles (AgNPs) Physicochemical Properties in Determining Their Biocompatibility

The physicochemical properties of AgNPs, especially particle size and shape, play a critical role in determining both antimicrobial efficacy and compatibility with mammalian cells. Smaller NPs exhibit a larger surface area-to-volume ratio, promoting higher Ag^+ ion release and stronger interaction with microbial membranes [48]. While this enhances antimicrobial action, it also increases the likelihood of cytotoxic effects, as ultrasmall AgNPs (<10 nm) can penetrate mammalian cell membranes and accumulate intracellularly, potentially disrupting mitochondrial function, oxidative homeostasis, and DNA replication [171].

Similarly, particle shape significantly influences biological interactions and biocompatibility. While spherical AgNPs are the most used due to their relative stability and ease of synthesis, anisotropic shapes, such as nanorods, nanoplates, and triangular prisms, exhibit distinct surface energies and facet-dependent reactivities that alter their interactions with cells [53,54]. For instance, sharp-edged or high-aspect-ratio structures may induce stronger membrane disruption or facilitate enhanced cellular uptake compared to their spherical counterparts [57]. These shape-dependent differences can lead to variable levels of cytotoxicity, immunogenicity, and oxidative stress responses in host tissues. Therefore, the careful selection and engineering of AgNP size and morphology are essential for optimizing the balance between antimicrobial effectiveness and biocompatibility [171], particularly in biomedical applications where prolonged contact with human tissues is anticipated.

5.2. Role of Silver Nanoparticles (AgNPs) Surface Chemistry and Functionalization in Determining Their Biocompatibility

Surface chemistry is a key determinant of the biocompatibility and overall biological performance of AgNPs in antimicrobial coatings. The surface functionalization of AgNPs profoundly influences their physicochemical behavior, cellular uptake, biodistribution, and interactions with biological systems [58]. Unmodified or "bare" AgNPs are prone to aggregation and may elicit undesirable immune responses or cytotoxic effects due to uncontrolled silver ion release and non-specific interactions with cell membranes. To mitigate these issues and enhance compatibility with host tissues, surface modification with biocompatible agents is widely employed. Coating AgNPs with natural or synthetic polymers, such as chitosan, polyethylene glycol, or hydroxyapatite, has shown significant potential in improving biocompatibility while retaining or even enhancing antimicrobial efficacy [73]. Chitosan, a natural polysaccharide with intrinsic antimicrobial properties, not only stabilizes AgNPs but also promotes favorable interactions with mammalian cells due to its bioadhesive and biodegradable nature [22].

In addition to synthetic polymer coatings, green synthesis approaches have emerged as environmentally friendly and biologically safe alternatives for enhancing AgNP biocompatibility. Utilizing plant extracts, fungi, or bacteria as reducing and stabilizing agents

introduces natural capping molecules such as polyphenols, proteins, and polysaccharides, which act as benign surface coatings [162].

Collectively, surface functionalization strategies not only improve the colloidal stability and dispersibility of AgNPs, but also enable precise tuning of their biological interactions, offering a critical pathway to achieve a favorable balance between antimicrobial performance and host tissue safety [20]. As such, surface chemistry engineering is key in the development of safe and effective AgNP-based antimicrobial coatings for biomedical and environmental applications.

5.3. Controlled Silver Ion Release for Enhanced Biocompatibility

The biocompatibility of AgNP-based antimicrobial coatings is linked to the dynamics of Ag^+ release, which serves as the principal mechanism underlying their antimicrobial activity. Ag^+ ions interact with microbial cell membranes, disrupt metabolic processes, and induce oxidative stress, leading to effective pathogen inhibition. However, this same mechanism can become detrimental to host tissues if ion release is excessive or uncontrolled [171]. Rapid or high-concentrations of Ag^+ can result in cytotoxic effects on mammalian cells, including damage to cell membranes, mitochondrial dysfunction, and the induction of reactive oxygen species (ROS), ultimately compromising tissue viability and integration [172]. Therefore, balancing antimicrobial efficacy with host cell safety necessitates a regulated Ag^+ release profile that provides sustained, low-dose exposure over time.

To address this challenge, controlled release systems have been developed to modulate the liberation of Ag^+ from NP coatings [173]. Encapsulation of AgNPs within hydrogels, plasma polymer films, or biodegradable polymeric matrices offers a promising strategy for achieving this control [174,175]. These matrices act as diffusion barriers or degradation-controlled carriers, slowing down ion release and preventing the initial cytotoxic burst while maintaining effective antimicrobial concentrations over extended periods [176]. For instance, hydrogel-based systems can provide moisture-retentive environments ideal for wound healing, while simultaneously allowing for gradual silver ion diffusion [174]. Similarly, plasma polymer coatings can be engineered to fine-tune the permeability and degradation kinetics of the encapsulating layer. The use of biodegradable polymers, such as poly(lactic-co-glycolic acid) or chitosan, not only ensures sustained ion release but also improves the overall biocompatibility of the coating through their non-toxic degradation byproducts [177].

Ultimately, the biocompatibility of AgNP-based antimicrobial coatings is centered on achieving an optimal balance between antimicrobial potency and host tissue safety. Determining the minimum effective concentration that effectively inhibits microbial growth while avoiding cytotoxic effects is essential for the rational design of next-generation coatings. Controlled silver ion release is therefore key to the safe, effective, and sustainable application of AgNPs in clinical, hygienic, and environmental settings [178].

Silver nanoparticle-based coatings present a promising solution for infection control in biomedical applications. However, their biocompatibility must be rigorously evaluated and optimized to ensure safety and efficacy. Through careful selection of particle size, surface modifications, ion release profiles, and green synthesis methods, it is possible to engineer AgNP formulations that strike a balance between potent antimicrobial action and minimal cytotoxicity. Continued research and development are essential to expand their clinical utility while minimizing potential health risks.

6. Conclusions and Future Perspectives

AgNP-based antimicrobial coatings have proven to be a versatile and effective solution for microbial control across diverse industries, including healthcare, textiles, food pack-

aging, and environmental protection. The unique physicochemical properties of AgNPs, especially their size, shape, and surface functionalization, critically influence their antimicrobial efficacy by facilitating targeted interactions with microbial membranes, proteins, DNA, and biofilms.

This review highlights the multifaceted antimicrobial mechanisms of the AgNP-based coatings, including membrane disruption, intracellular damage, oxidative stress induction, and quorum sensing interference. Moreover, advancements in their fabrication and application techniques, such as electrospinning, in situ reduction, and the integration of smart, stimuli-responsive systems, have paved the way for the creation of durable and highly effective coatings. These innovations allow for customization of coatings to suit specific substrates and environmental conditions, broadening their practical applicability.

Together, these developments position AgNP-based coatings as a promising and adaptable solution for addressing the growing challenges of microbial contamination and resistance across diverse sectors.

Future research should prioritize the development of smart, responsive AgNP-based coatings that release nanoparticles only in response to specific triggers like microbial presence or favorable growth conditions (e.g., high humidity, pH, or temperature shifts). This targeted approach minimizes unnecessary silver exposure, reducing cytotoxicity and environmental impact while preserving antimicrobial efficacy. It also extends the coating's lifespan and improves cost-efficiency. Responsive systems may limit antimicrobial resistance by avoiding constant low-level exposure. Innovations such as stimuli-responsive polymers, and microcapsules offer promising paths forward, enhancing both safety and sustainability and expanding the practical applications of AgNP coatings across high-risk environments.

Green synthesis methods, which utilize natural materials for AgNP production, are gaining traction as an eco-friendly alternative to traditional techniques. Additionally, combining AgNPs with other nanomaterials, particularly naturally derived and biodegradable ones, offers a powerful strategy for boosting antimicrobial efficacy while reducing overall silver usage. These biocompatible co-active agents can serve multiple roles, including improving the dispersion and stability of AgNPs, providing additional antimicrobial mechanisms, and promoting environmentally benign degradation after use.

The potential impact of AgNP coatings on healthcare, industry, and environmental protection is substantial. With continued innovation and a focus on sustainable practices, AgNP-based coatings have the potential to play a pivotal role in shaping the future of antimicrobial technologies, providing safe, effective, and eco-friendly solutions to combat microbial contamination across various sectors.

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